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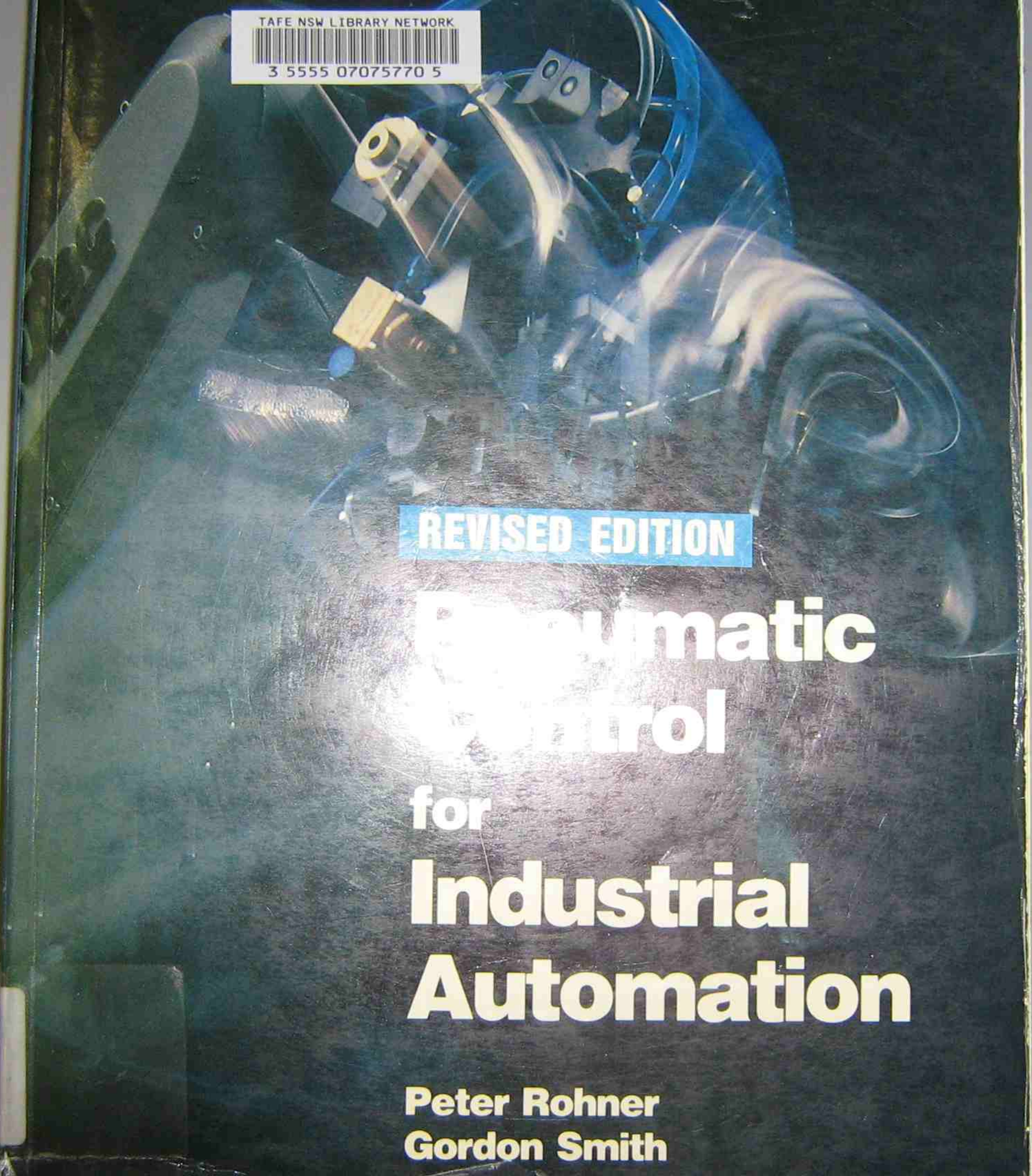

REVISED EDITION

Pneumatic Control for Industrial Automation

Peter Rohner
Gordon Smith

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Peter Rohner
Gordon Smith

John Wiley & Sons
Brisbane New York Singapore Chichester Toronto

First published 1987
by AE Press

Published 1989 by
JOHN WILEY & SONS
33 Park Road, Milton, Old 4064
1 Thomas Holt Drive, North Ryde, N.S.W. 2113
90 Ormond Road, Elwood, Vic. 3184
236 Dominion Road, Mount Eden, Auckland 3, N.Z.

Typeset by Abb-typesetting, Collingwood, Victoria

Revised edition 1990

Printed in Singapore

© Peter Rohner and Gordon Smith 1987, 1990

National Library of Australia
Cataloguing-in-Publication entry

Rohner, Peter, 1939–
Pneumatic control for industrial automation.
Rev. ed.
Includes index.
ISBN 0471 33463 4.

1. Pneumatic control. 2. Automatic control. I. Smith, Gordon. II. Title.

629.8'045

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Design by Peter Yates

Illustrated by Peter Rohner

Foreword

'Automate or perish', the emotive buzz words of the '80s which turn away the indolent and excite the progressives dependent upon individual knowledge and experience of applied automation.

'When you begin to teach you begin to learn', words that go back in time but which are still very relevant in today's climate. This catch phrase particularly applies to the two authors who have condensed their combined industrial experience and knowledge into this manual on applied automation.

The text with its illustrations brings to the reader a clear concept and understanding of applied automation techniques. Moreover, the authors recognise the importance of combining pneumatic automation technology and electronic programmable controllers (PLC), together with descriptive language and graphic illustrations.

This manual is an invaluable tool to the practitioner, and essential reading for the student of fluid power and its applications throughout industry.

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Acknowledgments

The authors wish to thank their respective wives, Heidi Rohner and Dilys Smith for the invaluable help and support they received in the preparation of this book for publication.

The cover photograph was obtained from Manutec, Gesellschaft für Automatisierungs-und Handhabungssysteme, D-8510 Fürth, West Germany.

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Figs. 3–16, 8–41, 12–1, 12–2, 12–3, 12–6, 12–11, 12–13, 12–14, 12–15	Norgren Martonair Pty. Ltd., Mt Waverley, Victoria
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Please Note

Colour coding of fluid pressure used throughout this book:

High pressure or system pressure

Exhaust pressure, or background tint

Reduced pressure

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Preface

Automation of manufacturing processes in industry today is extremely important, not only for its economic benefits but also for its role in producing a consistent quality product, and whilst much is said about the negative aspects of automation in industry, automation has taken over many work duties which are dirty, monotonous and hazardous.

Automation has also created numerous job opportunities for properly trained and qualified people in all areas of fluid power: engineers, technicians, mechanics, sales and service personnel are in great demand, and there is also a shortage of trained and experienced teachers of fluid power subjects in post secondary, vocational and tertiary education.

For many years pneumatics has played an important role in automated manufacturing and handling processes ranging from the so-called "low cost automation" applications to the sophisticated and complex powering and control of entire transfer machines and robots. Pneumatics must therefore be seen and respected for its dual role: that of power transmission and that of logic control. The latter is often poorly understood and the widespread ignorance that pneumatics can effectively and cheaply play an important role in logic control may be attributed to one or both of the following factors:

- Superficially, the application of pneumatics to sequential and combinational control seems to be so simple that many assume there is little one needs to know about it to make use of the control components available. Such people will apply the controls and actuators without the mandatory understanding of their inherent characteristics; characteristics which are in fact very simple and based on the fundamental principles of logic control laid down by the rules and laws of Boolean Switching Algebra, Pascal's Law, and the Gas Laws.
- Teaching institutes and curriculum bodies make ample provision for subjects related to all facets of machine design and maintenance but pay little attention to fluid power control and power transmission, thus ignoring the fact that most production and manufacturing machines are up to 60% fluid power controlled. On the power transmission side, this percentage of fluid power involvement is even greater.

The purpose of this textbook is to facilitate a thorough understanding of the fundamental principles of industrial pneumatic control and power transmission as well as production and distribution of clean, compressed air. It is also intended to provide a practical working knowledge of the commonly encountered components for designing, installing and maintaining industrial pneumatic systems. As such, it is aimed at those students who are preparing themselves for industry, whether this be in design, maintenance or sales of pneumatics and related control systems.

The book is part of a comprehensive learning and teaching package which also includes more than 350 overhead projectorial masters to enchance effective teaching of this devise and involved subject. (These, and a series of workbooklets to match the text, are available directly from Peter Rohner, 14 Turner Street, Briar Hill, Vic 3088.)

Modern teaching method principles are applied throughout this book to stimulate and facilitate learning. Basic formulae, where introduced, are coloured with pink background tint, component functions are extensively described and simple circuits show their application and integration. Most components (actuators, valves, compressors, etc.) are depicted as sectioned illustrations together with their matching I.S.O. graphic symbol. The circuit design chapters show a variety of fully worked-out but typical industrial control circuits applying the widely used step-counter and cascade design methods. These are followed by a chapter dealing with the often least understood design of combinational logic circuits. Integrated into that chapter are such topics as truth tables, Boolean algebra concepts and Karnaugh-Veitch maps as used for the effective design of combinational controls. A complete chapter is dedicated to the programming of Electronic Logic Controllers (P.L.C.). The principles of circuit design set out in Chapters 2, 8 and 9 are also applicable to P.L.C. programming and are therefore repeated and integrated with electronic P.L.C. control in Chapter 12.

The book is divided into two sections: Chapters 1–12, written by Peter Rohner, explain the use of compressed air for control and power transmission, while Chapters 13–16, written by Gordon Smith, explain the production and distribution of compressed air. Also included in this section is a chapter on circuit construction and documentation.

The appendix contains a concise formulae collection, applicable I.S.O. fluid power symbols, units of measurement, prefixes for fractions and multiples of base units, an extenisve conversion table and, last but not least, a comprehensive index with over 800 listings.

Peter Rohner Gordon Smith

1 Physical Principles in Pneumatics

Personnel who operate, service, or design fluid power systems should have a thorough understanding of the physics and properties of fluids and their behaviour under different circumstances.

Liquids and gases flow freely, and for that reason both are called fluids (from the Latin word *fluidus*, meaning flow).

A fluid is defined as a substance which changes its shape easily and adapts to the shape of its container. This applies to both liquids and gases. Their characteristics are discussed throughout this book.

Transmission of force by fluids

When one end of a bar of solid material is struck, for example with a hammer, the main force of the blow is transmitted straight through the bar to the opposite end. The direction of the blow determines the direction of the major force transmitted, and the more rigid the bar, the less force is either lost in it, or transmitted at angles different to the direction of the blow (fig. 1-1).

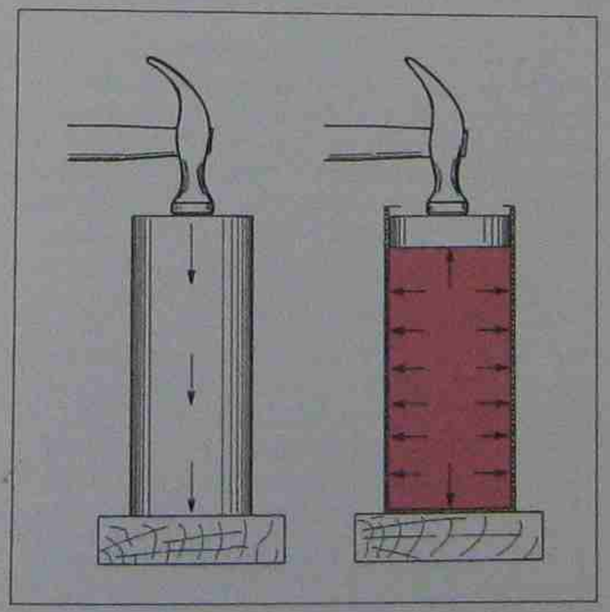


Fig. 1-1 Transmission of force through a solid material and through a static fluid.

When a force is applied to the end of a column of a confined liquid (fig. 1-1), that force is transmitted straight through the column to its opposite end, but also—equally and undiminished—in every other direction, sideways, downwards, and upwards. This physical behaviour is defined by Pascal's Law (fig. 1-2). Pascal's discovery has opened the way to the use of confined fluids for power transmission and force multiplication.

Blaise Pascal (1623-1662) also discovered that pressure is equal to force per unit area, or the force divided by the area on which it acts. Thus, we must now define these three important quantities: Force, Pressure and Area.

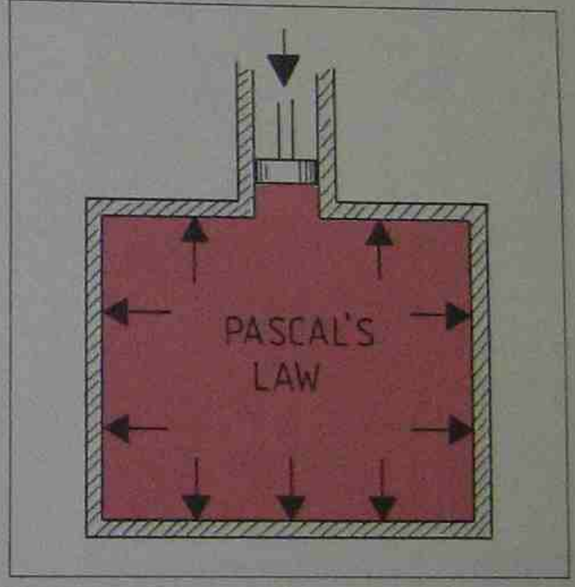


Fig. 1-2 Pascal's law states that pressure applied to a static and confined fluid is transmitted undiminished in all directions and acts with equal force on equal areas and at right angles to them.

Force

Forces cannot be seen but their effects can be. A force applied to an object has the effect of causing:

- a movement to begin or to change; or
- the shape of an object to change.

In pneumatic applications force is produced by air pressure acting onto a surface (usually a piston, a valve or a diaphragm (fig. 1-3)).

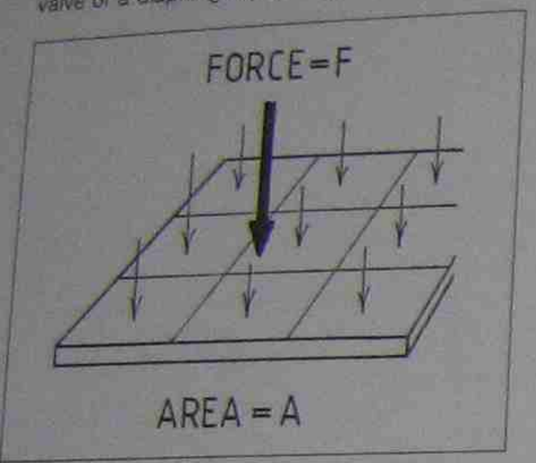
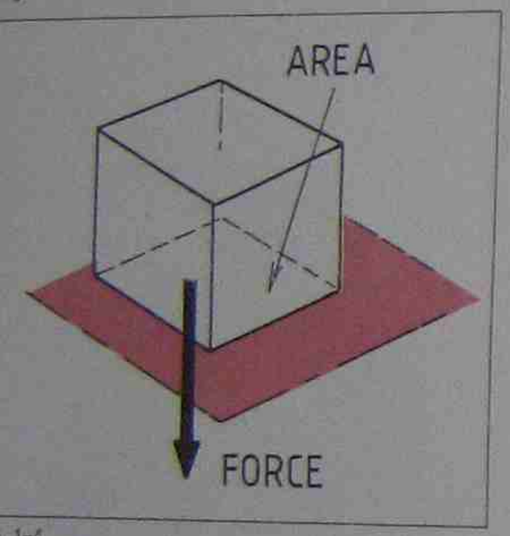


Fig. 1-3



1-4

essure

ssure is defined as force per unit area (figs. 1-3,). This means that if we want to find out the ssure required for a certain pneumatic applica- , we have to measure or determine two quan- s:

ie size of the force required; and
ie area over which the pressure is acting.

ea

only area we are concerned with is the area or ace on which the pressure can act that will pro-

duce the force required for the job. This area is called *effective area* (fig. 1-5). By using these three quantities (Force, Pressure and Area) we can define their relationship as:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \qquad \text{Area} = \frac{\text{Force}}{\text{Pressure}}$$

$$\text{Force} = \text{Pressure} \times \text{Area}$$

The effective area "A" on which pneumatic pressure can act to produce the required pneumatic force (fig. 1-5) is either the:

- projection of the ball-seat area (check valve),
- projection of the pressure exposed piston area; or
- calculated effective piston area (spool valve).

Circular area

In pneumatic power transmission calculations the area of the circle is often used.

To calculate the area of a circle you may use one of the following formulae:

$$\text{Area} = \pi \times r^2$$

$$\text{Area} = \frac{\pi \times D^2}{4}$$

$$\text{Area} = D^2 \times 0.7854$$

Mass Compared to Force

The newton is the S.I. unit for force and is defined as: "That force which when applied to a mass of one kilogram produces in it an acceleration of one metre per second, per second in the direction of the force".

This definition gives no reference to gravitational force either on the earth or anywhere else and thus the newton is described as a non-gravitational or *absolute* unit of force. Newton found by experiments that on the surface of the earth acceleration (g) due to gravity is approximately $9.81 m/s^2$. Thus Newton's Law states:

$$\text{Force} = \text{Mass} \times \text{Acceleration} \quad \text{or:} \quad F = m \times g$$

From the foregoing statements one can conclude that the mass of 660kg (fig. 1-6) exerts onto the platform on which it rests a force of 6474.4 newtons, calculated as follows:

$$660\text{kg} \times 9.81\ \text{N/kg} = 6474.4\ \text{newtons}$$

If one now assumes that the platform, the piston rod and the piston have a weight of an additional 140kg then the total weight to be lifted would amount to 800kg. Its force then is:

$$800\text{kg} \times 9.81\ \text{N/kg} = 7848\ \text{newtons}$$

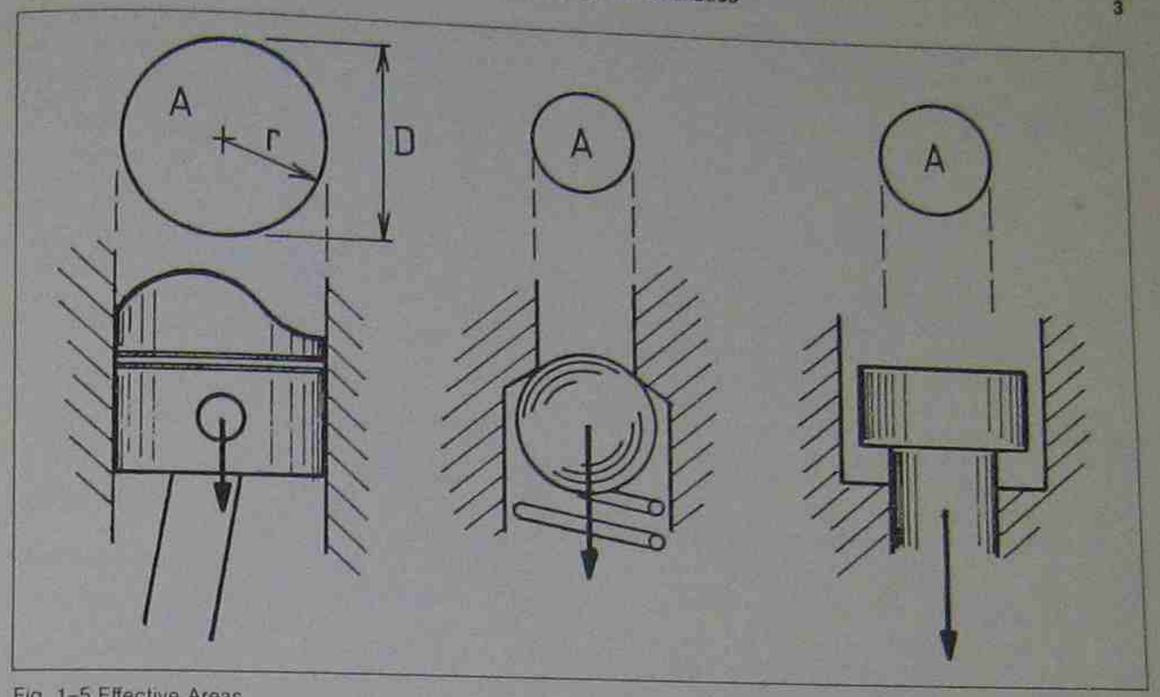


Fig. 1-5 Effective Areas.

The pressure in pascals (and bar) for this load to be lifted can now be calculated if one assumes the piston area to be $0.01 m^2$ and actuator friction is neglected.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{7848\ \text{N}}{0.01 m^2} = 784\,800\ \text{Pa}$$

$$= 784.80\ \text{kPa} = 7.848\ \text{bar}$$

Pressure in the S.I. system is expressed in *pascals*. Since the pascal is a very small unit, the prefixes kilo and mega are used to express pressure in industrial pneumatics. European countries predominantly use the unit "bar" to express pressure, whereby one bar equals 100 kPa or 100 000 Pa.

Flow and Pressure Drop

Whenever a gas is flowing a condition of unbalanced force must prevail to cause fluid motion. Hence, when a gas (and compressed air is a gas) flows through a pipe with a constant diameter, the pressure will always be lower downstream than at any point upstream (fig. 1-7).

The pressure differential or pressure drop is caused by the friction of the gas molecules amongst each other and friction of gas molecules on the walls of the pipe. Thus the inside surface

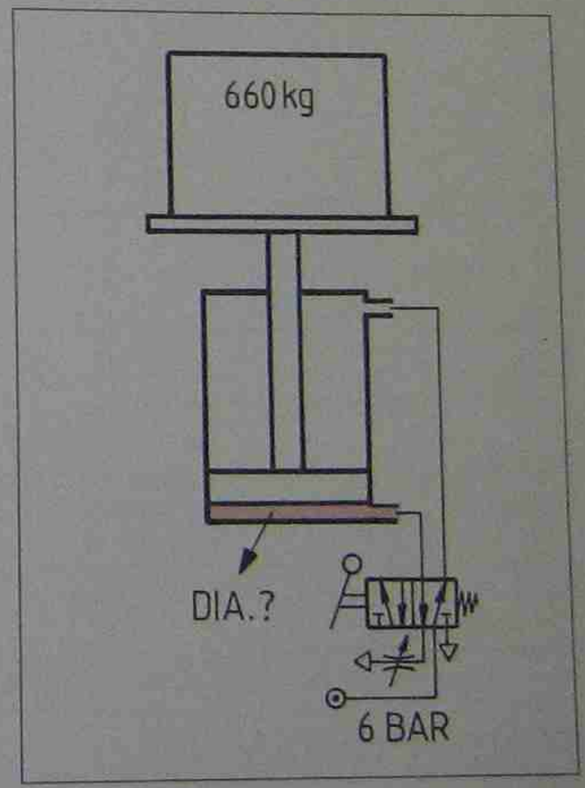


Fig. 1-6 Force-pressure-area relationship.

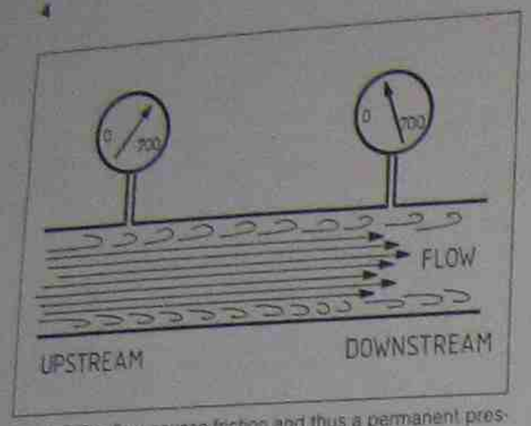


Fig. 1-7 The flow causes friction and thus a permanent pressure drop.

condition does influence the pressure drop in the piping system. This friction creates heat, and so the pressure drop (or loss) is a permanent loss, transferred into heat energy which cannot be regained (fig. 1-7).

As soon as the flow is stopped Pascal's Law must be applied for the now static condition, and pressures in all parts of the piping system (fig. 1-8).

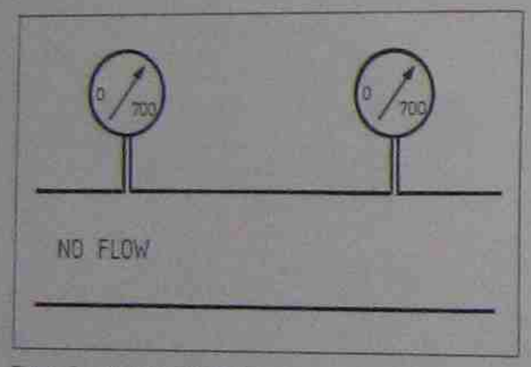


Fig. 1-8 Without fluid flow there is no pressure drop.

Flow through an Orifice to Atmosphere

An orifice is a hole with less cross sectional area than the pipes or cavities to which it is fitted. The orifice is generally used to control flow (speed control of actuators) or to create a pressure differential (pressure reducing valve).

When compressed air is discharged through an orifice to atmosphere, the speed at which it flows through the discharge orifice is either sonic (the speed of sound), or subsonic (slower than the speed of sound). This speed depends on two factors:

- the shape or type of orifice; and
- the pressure differential across the orifice.

If the pressure upstream of the orifice is 140 kPa (1.4 bar) higher than the downstream pressure then it can be surmised that the speed at which the compressed air flows is sonic. No matter how much the pressure upstream is increased now, the flow will remain sonic. This phenomenon is an important characteristic of compressed air on which the effective speed control of double acting linear actuators depends, and for that reason any pneumatic actuator or pneumatic motor (fig. 1-9).

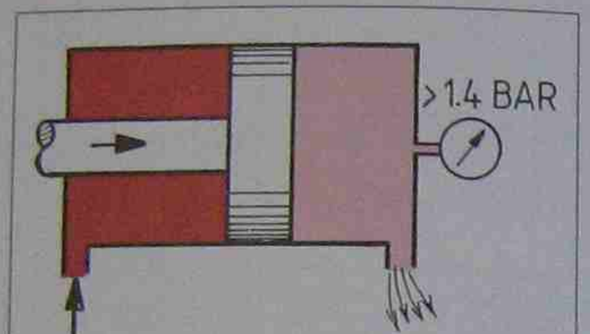


Fig. 1-9 Flow through an orifice to atmospheric pressure.

Air (Free Air) and Compressed Air

Air is a colourless, odourless and tasteless gas. In fact it is a mixture of individual gases, mainly nitrogen and oxygen.

Expressed in volumetric proportion the nitrogen makes up about 78%, the oxygen 20%, argon approx. 1% and the remaining 1% consists of other trace elements such as helium, hydrogen and neon.

Furthermore, atmospheric air has a great affinity with water, and unless dried for use in compressed air systems, may contain water in the form of vapour which sometimes can be as much as 6% by weight!

The air in the atmosphere contains not only gases and water-vapour, but also solid particles like dust, sand, soot and crystals of salt. In large cities and industrial areas, the number of such particles may reach 500 000 per cubic metre of air.

The force exerted on one square metre by an air column which reaches from sea level to the outermost layer of the atmosphere is approximately 101 300 newtons. Thus at sea level the absolute atmospheric pressure is about 101.3 kPa (1.013 bar).

At higher altitudes, the column of air to the outermost layer of the atmosphere is shorter, hence the mass of the gas (air) resting on each square metre is also less. For this reason the atmospheric pressure on top of Mont Blanc, the highest mountain in the European alps (4 810 metres above sea level) is only about 54 kPa. On the other hand, at the bottom of a deep mine shaft of about 800 metres below sea level, the atmospheric pressure is approximately 111 kPa (1.11 bar).

100 kPa	= 1 bar
98.0665 kPa	= 1 kg/cm²
100 kPa	= 14.5 p.s.i.
100 kPa	= 1.02 atm
100 kPa	= 750 torr
98.1 kPa	= 10 m WG
1 mm Hg	= 1 torr
101.3 kPa	= 14.7 p.s.i.
1 atm	= 14.7 p.s.i.
1 Pa = N/m²	= 0.00001 bar

Atmospheric Pressure

The weight of the air (every gas has a mass) causes *atmospheric pressure*. Atmospheric pressure at sea level is approximately 101.3 kPa. Atmospheric pressure can be measured with a barometer. Torricelli's mercury barometer is shown in fig.1-10. The atmospheric pressure acts upon the open surface of the mercury container and thus supports the mercury column in the vacuum tube. The distance "h" is proportional to the atmospheric pressure and varies with altitude.

Vacuum Pressure

Any pressure below normal atmospheric pressure is termed *vacuum pressure*. It can be measured with the same barometer, depicted in fig. 1-10. Pressure readings below the calibration mark "A" denote vacuum pressure. At absolute zero pressure, the mercury column in the vacuum tube will disappear entirely, since no pressure will be present to support a mercury column. Therefore, it can be said that any pressure reading on the scale is *absolute pressure*, or an absolute pressure measurement.

Gauge pressure versus absolute pressure

Most pressure gauges used in pneumatic systems, however, have a pressure calibration based on *atmospheric pressure*. This means that atmos-

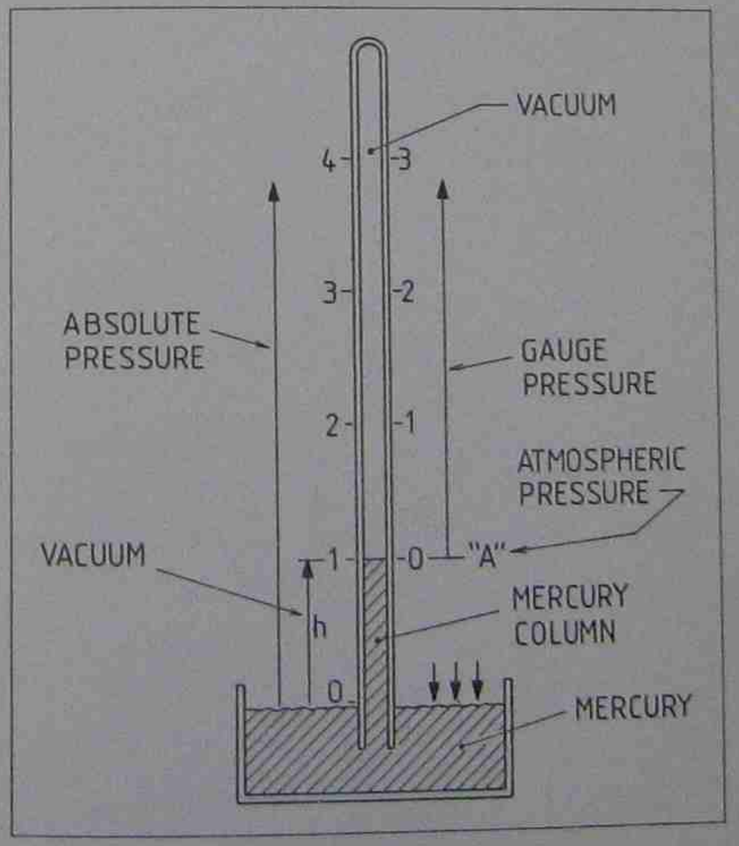


Fig. 1-10 Mercury barometer. Atmospheric pressure acting onto the mercury in the receptacle supports the mercury in the vacuum tube.

phere pressure is regarded as zero pressure, and any pressure above atmospheric pressure is thus a positive pressure reading. Most pressure gauges of this nature do not show pressure readings below atmospheric pressure. Pressure readings on such gauges are called *gauge pressure*, and pressure readings on gauges which start from absolute zero pressure are called absolute pressure (fig. 1–10).

Pressure in liquids

Under static conditions and without any external forces, the pressure at any point within a fluid system is proportional to the height of the fluid column above that point (fig. 1–11). Torricelli called the pressure at the bottom of the fluid column (tank) the *head pressure*. All that is required to work this pressure in Pa is the specific weight of fluid in the tank and the force that is produced by its weight. For example, a water column of 10 m height with a base area of 1 m^2 weighs 10 000 kg (specific weight for water is 1000 kg per 1 m^3).

Gas laws

Since gases are used in pneumatic systems it is important to mention at least some of the basic behavioural characteristics of such gases.

Boyle's Law

Robert Boyle (1627–1691) discovered by experimentation and direct measurement, that when the

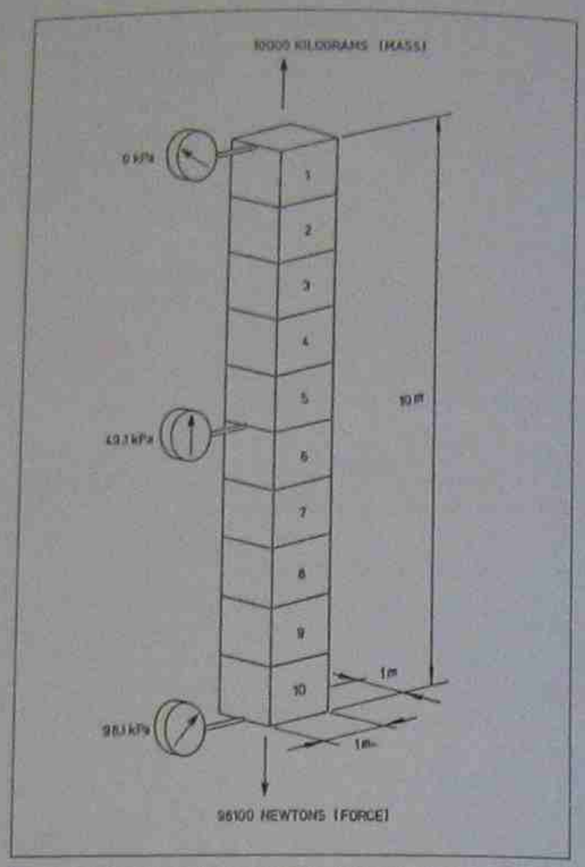


Fig. 1–11 A water column of 10 m with a base area of 1 m^2 produces a force of 98 100 Newtons, but its mass is 9.81 times less.

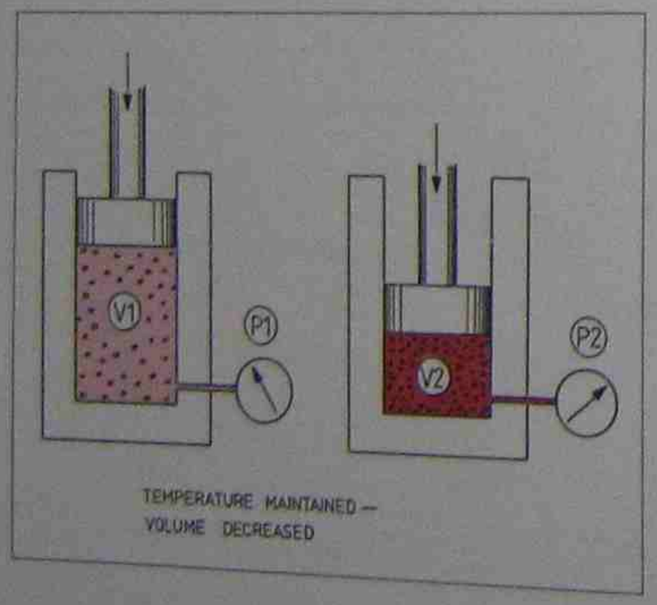


Fig. 1–12 Temperature maintained, volume decreased.

temperature of an enclosed sample of gas was kept constant and the pressure doubled by means of a piston (fig. 1–12) the volume was reduced to half the previous volume. As the piston retracted the volume increased again and the pressure decreased. Hence he concluded that the product of volume and pressure of an enclosed gas at a constant temperature remains the same (constant). Thus Boyle's Law states:

$$V_1 \times p_1 = V_2 \times p_2 = \text{constant, or } \frac{V_1}{V_2} = \frac{p_2}{p_1}$$

It must be remembered that for calculation purposes one has to convert all given gauge pressures to absolute pressures.

Example

An air receiver with a volume of 6 m^3 must be filled with compressed air to a maximum pressure of 900 kPa (9 bar). Calculate the volume of free air (F.A.) to be pumped by the compressor.

$V_2 = ?\ m^3$ $\quad p_2 = \text{Atmospheric Pressure} = 101.3\ kPa\ (1.013\ bar)$

$V_1 = 6\ m^3$ $\quad p_2 = 9\ bar + 101.3\ kPa$

$$V_2 = \frac{V_1 \times p_1}{p_2} \qquad \frac{6\ m^3 \times 1001.3\ kPa}{101.3\ kPa} = 69.3\ m^3$$

Since the receiver already contained 6 m^3 of free air before the compressor started to pump, the pumped volume must be

$69.3\ m^3 - 6\ m^3 = 63.3\ m^3$

Theoretically this is what would occur with an ideal gas. But because density changes with temperature (that is, gases expand when heated and contract when cooled (see fig. 1–14), there will be some minor changes in practice with regard to pressure and volume. (A more detailed explanation is given in Chapter 13.)

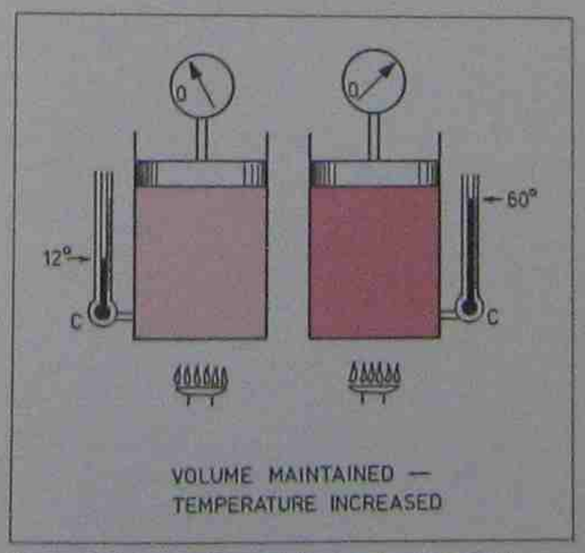


Fig. 1–13 Volume maintained, temperature increased.

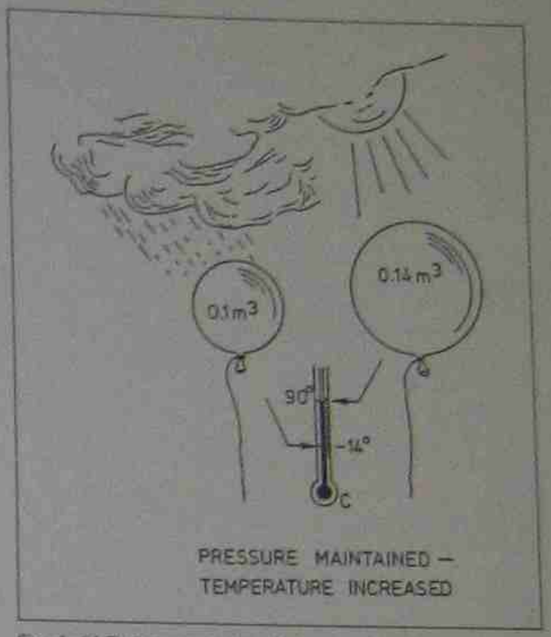


Fig. 1–14 Pressure maintained, temperature increased.

Charles' Law

Whereas Boyle's Law describes the change of state of a gas at a constant temperature, experimental work by Charles (in which pressure was maintained constant while temperature varied, and the change in volume was measured) enabled him to formulate another gas law. (Fig. 1–14.)

Charles' Law states: at constant pressure the volume of a gas varies in direct proportion to a change in temperature. Expressed in a formula this is:

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}, \text{ or, transposed } V_2 = \frac{V_1 \times T_2}{T_1}$$

To solve problems of this nature absolute values of temperature and pressure must be used.

Absolute zero on the Kelvin temperature scale is equivalent to −273 degrees Centigrade. One Kelvin temperature unit is equal to 1 degree Centigrade.

Thus 100°C = 373 Kelvin.

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Example
A balloon with a gas volume of 0.1 m^3 at a temperature of −14°C is heated to a temperature of 90°C (fig. 1-14). What is its increased gas volume if the pressure remains constant?

$$V_2 = \frac{V_1 \times T_2}{T_1} = \frac{0.1\ m^3 \times (90°C + 273°C)}{(-14°C + 273°C)}$$
$$= 0.14\ m^3$$

Gay-Lussac's Law

Gay-Lussac's Law supplements the gas laws of Charles and Boyle. He observed that if a volume of a gas is kept constant, the pressure exerted by the confined gas is directly proportional to the absolute temperature of the gas (fig. 1-13). Expressed in a formula this is:

$$\frac{p_1}{p_2} = \frac{T_1}{T_2}, \text{ or, transposed } p_2 = \frac{p_1 \times T_2}{T_1}$$

The combination of the three gas laws of Boyle, Charles, and Gay-Lussac results in the *general gas law* reads:

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} \text{ or } \frac{pV}{T} = \text{constant}$$

Advantages of pneumatic power transmission

- Freedom of location of pneumatic power converters such as compressors and actuators.
- Air for compression is available in almost unlimited quantities and can be exhausted again to atmosphere.
- Safety and overload protection by means of relief valves and the compressibility of the air.
- Compressed air can be stored and released from the air receiver (reservoir) which contains potential energy.
- Pneumatic systems work safely in explosion risk areas and are practically insensitive to high temperatures below 120°C.
- Pneumatic systems are clean, and should compressed air leak from a piping system, then there exists no contamination risk.
- Linear actuators operate with high speed (up to 2m/sec.) and their speed is infinitely variable.
- The operating elements (actuators, valve) are of simple construction and thus inexpensive.
- Pneumatic valves are ideally suited for logic functions and thus are used to control complex sequential and combinational machinery.

Transmission of power

There are four basic methods of transmitting the power of a prime mover to a machine. These methods are electric, mechanical, hydraulic and pneumatic. Each is used to transmit power (force over distance in time) and modify motion (accelerate, decelerate), and each method has its special capabilities and limitations. Pneumatic systems integrate all of these methods to accomplish a most effective and efficient form of power transmission (electrically operated valves, swivel actuators, hydro-check actuators, stored compressed air as potential energy).

The concept of power transmission

Power is the measure of a defined force moving through a given distance at a given speed. To understand this fundamental concept, the term force must now be explained.

Force may be defined as any cause which tends to produce or modify motion. Due to inertia, a body at rest tends to stay at rest, and a body in motion tends to maintain that motion until acted upon by an external force. Force is measured in newtons.

The concept of *pressure* must also be explained. Pressure is force per unit area and is expressed in pascals (Pa). Both force and pressure are primarily measures of effort. A force or pressure may be acting upon a motionless object without moving the object, if the force or the pressure is insufficient to overcome the inertia of the object.

Work is a measure of accomplishment. For example, the piston of a pneumatic actuator exerts a force on an object and moves the object over a given distance. Thus, work has been accomplished. The concept of work, however, makes no allowance for time. The work performed by the hydraulic actuator while moving the object from point A to point B in 8 seconds is precisely the same as when it moves the object from point A to point B in only 2 seconds, but the task performed in 2 seconds is obviously much greater. To explain the difference in performance one must resort to the definition of power.

Power is work performed per unit of time. Thus it can be said that power is the rate at which energy is transferred or converted into work. Power is expressed in watts. Mathematical relationships of force, pressure, area, work and power are shown in fig. 1-15.

Pressure (p) = $\frac{\text{Force}}{\text{Area}}$
Force (F) = Pressure × Area
Area (A) = $\frac{\text{Force}}{\text{Pressure}}$



Power (P) = Force × Velocity
Force (F) = $\frac{\text{Power}}{\text{Velocity}}$
Velocity (v) = $\frac{\text{Power}}{\text{Force}}$



Power (P) = Pressure × Flowrate
Pressure (p) = $\frac{\text{Power}}{\text{Flowrate}}$
Flowrate (Q) = $\frac{\text{Power}}{\text{Pressure}}$



Fig. 1-15 Relationships of force, pressure, area, work, and power.

The basic concept of a pneumatic system

Pneumatics is the engineering science of pneumatic pressure, pneumatic potential energy production, its use in linear and rotary actuators and finally the use of compressed air as a signal carrier for the achievement of logic sequential and combinational control. Such pneumatic systems may include:

- Compressors which convert available power from an electric motor or internal combustion engine to pneumatic power at the actuator.
- Valves which control the direction of fluid flow to the actuators or process logic signalling functions to achieve sequential control of pneumatic actuators.
- Pressure and flow control valves which control the level of power produced on the actuators and pneumatic motors.
- Actuators which convert the potential energy of the compressed air into usable mechanical power output at the point required.
- Connectors which link the various system components provide power conductors for the compressed air in motion or in static condition.
- Sufficient quality, conditioning and storage equipment which ensure quantity and cleanliness as well as lubrication of the compressed air to provide a troublefree working life for its actuators and valves.

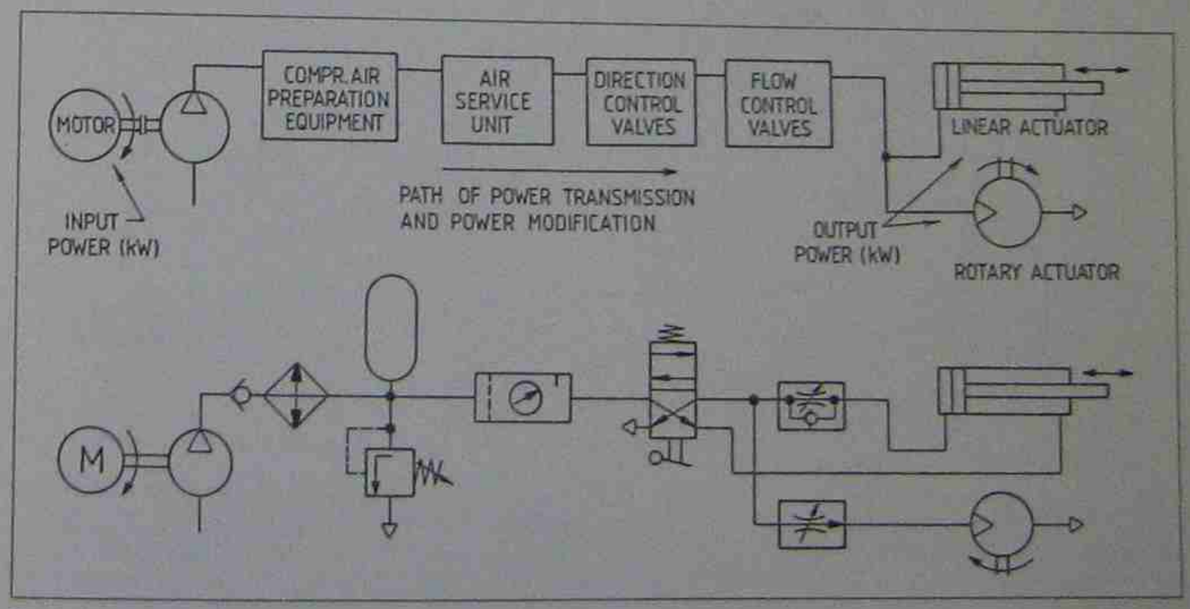

Fig. 1-16 Basic pneumatic system.

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2 Directional Control Valves

A valve is a device which receives an external command (either mechanical, fluid pilot signal or electrical) to release, stop or redirect the fluid that flows through it.

Directional control valves in particular, as their name implies, control fluid flow direction. They are applied in pneumatic circuits to provide control functions which.

- control direction of actuator motion (power valve);
- select an alternative flow path (shunt valve);
- perform logic control functions ("AND", "OR" functions);
- stop and start flow of fluid (on-off valve);
- sense machine and actuator positions (limit valves).

Directional control valves are classified according to their specific design characteristics:

1. Internal valve mechanism (internal control element) which directs the flow of the fluid. Such a mechanism can either be a poppet disc, a poppet ball, a sliding spool, a rotary plug, or a combination of poppet and spool.
2. Number of switching positions (usually two or three). Some valves may provide more than three, and in exceptional cases up to six switching positions (selector valves).
3. Number of connection ports (not called number of ways!). These ports connect the pneumatic pressure lines to the internal flow channels of the valve mechanism and often also determine the flow rate through it.
4. Method of valve actuation which causes the valve mechanism to move into an alternative switching position. Figs. 2-7, 2-9, 2-13 and 2-15 show an array of frequently used valve actuation methods.

Valve symbols

Symbols are an ideal way of drawing and explaining the function of fluid power components and of directional control valves in particular. Symbols exist for most of the more commonly used valves. They are standardised to provide and safeguard an internationally agreed form of circuit drawing. These standards should be closely adhered to, and only deviated from if they are not available for a particular valve, or if a valve consists of several standardised parts. Most fluid power valves are drawn according to I.S.O. standards (International Standards Organisation) or C.E.T.O.P. standards (European Fluid Power Standards Committee).

Valve switching positions

For each of the switching positions provided by a valve, the graphic symbol shows a square (sometimes called a box). This means the valve on the left in fig. 2-1 provides two switching positions and the valve on the right three. The *rest position* of a valve is assumed by its moving parts (the valve mechanism) when the valve is not connected, not pressurised and not actuated. In most pneumatic control circuits all valves are depicted in the rest position and by convention valves with two switching positions should normally be connected to the right hand square (figs. 2-1 and 2-3).

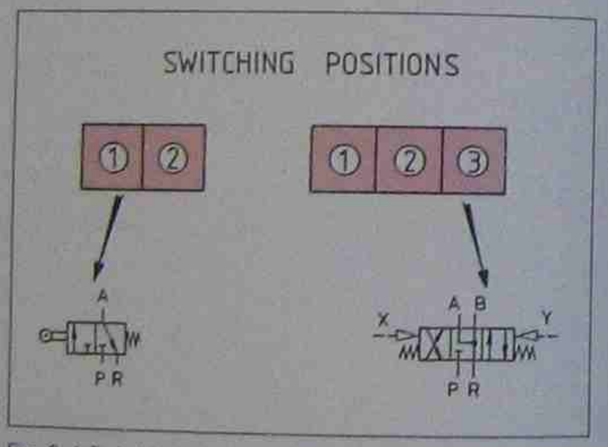


Fig. 2-1 Switching positions are represented by squares.

Valves with three switching positions should, however, be connected to their centre square (figs. 2-1 and 2-2), which again depicts the valve's rest position (or neutral position). However, it is sometimes the practice to draw valves in their actuated or *initial position*. This position is assumed when the valve is installed in the machine and a lever, a cam or a machine part is pressing onto the valve's operating element so the valve's

mechanism is no longer in the rest position. Since this is not a standard practice, it is imperative to state on the circuit diagram whether all valves are

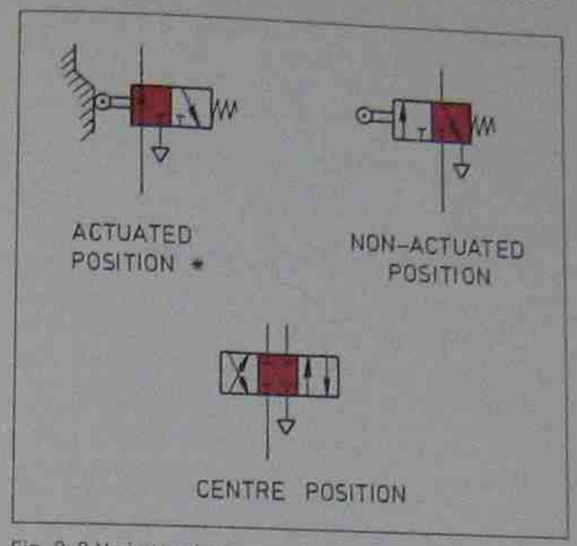


Fig. 2-2 Various valve connecting methods.

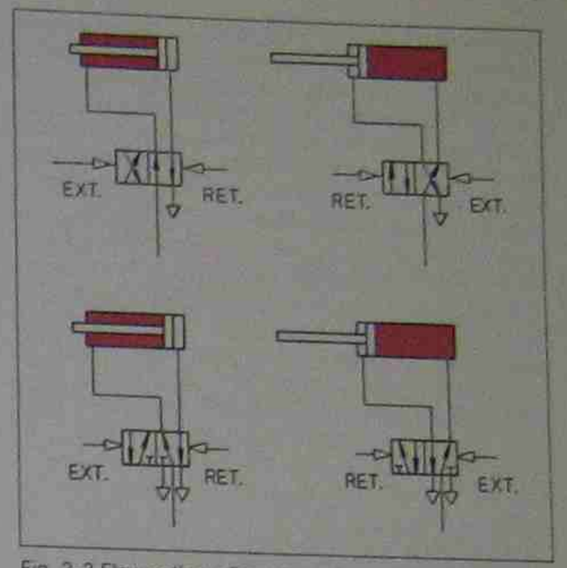
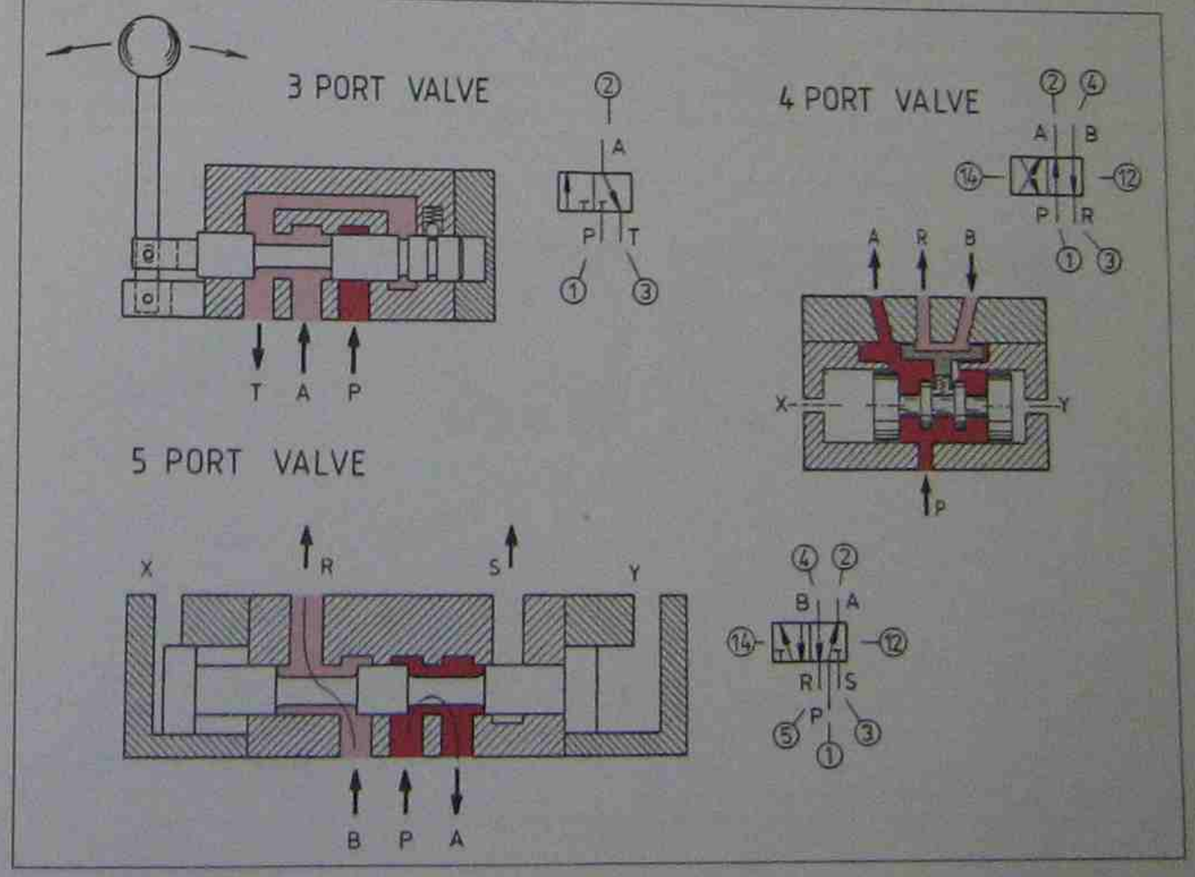


Fig. 2-3 Flow path configurations depend on initial actuator position.

shown in their rest position. Each of the valves being actuated must also be shown with a cam, and all pressure lines are to be connected to the left square (fig. 2-2).

Fig. 2-4 Valve ports.



Two-position valves which are not spring biased and can freely assume both switching positions (bi-stable or memory valve) may be drawn in whatever flow-path configuration is demanded by the actuator position. But here again the pressure lines must be connected to the right hand square lines should be avoided (see also fig. 2-26).

Valve ports and port labelling

Directional control valves are frequently described by the number of their working ports (flow openings). Two-port valves are only used to turn airflow either on or off (fig. 2-28).

Three-port valves have three working ports (fig. 2-4). If a three-valve has two inlet ports and one outlet port, it is used as a selector valve ("OR" function valve) to guide two flow lines to one common outlet (fig. 2-38). Three-port valves are predominantly used to create pilot signals (fig. 2-35) or make logic functions (figs. 2-33, 2-38, 2-39 and 8-7).

Four- and five-port valves are used to control double acting linear actuators or reversible motors (fig. 2-3). The pressure port connects the valve to the pressure source, the two outlet ports are connected to the actuator and exhaust air escapes through the exhaust port(s).

The labelling of ports is presently undergoing some radical changes. The new port numbering system is based on a very logical concept. The pilot signal 12 for example, connects the pressure port 1 to outlet port 2, and the pilot signal 14 shifts the valve mechanism so that pressure port 1 is connected to outlet port 4. For three-port valves with only one exhaust, the exhaust port is labelled 3 (for old and new labelling comparison, see fig. 2-4). It must be noted that pilot signal ports do not count for the valve classification. Thus the five-port valve in fig. 2-4 is not a seven-port valve and is classified as a 5/2 valve (see also fig. 2-8).

Valve mechanism

Directional control valves consist of a valve body or valve housing and a valve mechanism. Some valves are mounted to a sub-plate. The ports in the sub-plate or on the valve body are threaded to hold the tube fittings which connect the valve to the fluid conductor lines (tubes). Some valves have the tube fittings moulded into the valve body. This is normally the case where the valve body is made from plastic. The valve mechanism directs the pressurised fluid (compressed air) through the valve body to the selected output ports or stops the fluid from passing through the valve.

External signal commands (electrical manual or air pilot pressure), and internal signal commands (air pilot pressure, spring force) may be applied to shift the valve mechanism (figs. 2-6, 2-7, 2-9 and 2-12).

Poppet, spool, flat slide, toggle disc and spool/poppet mechanism are predominantly used

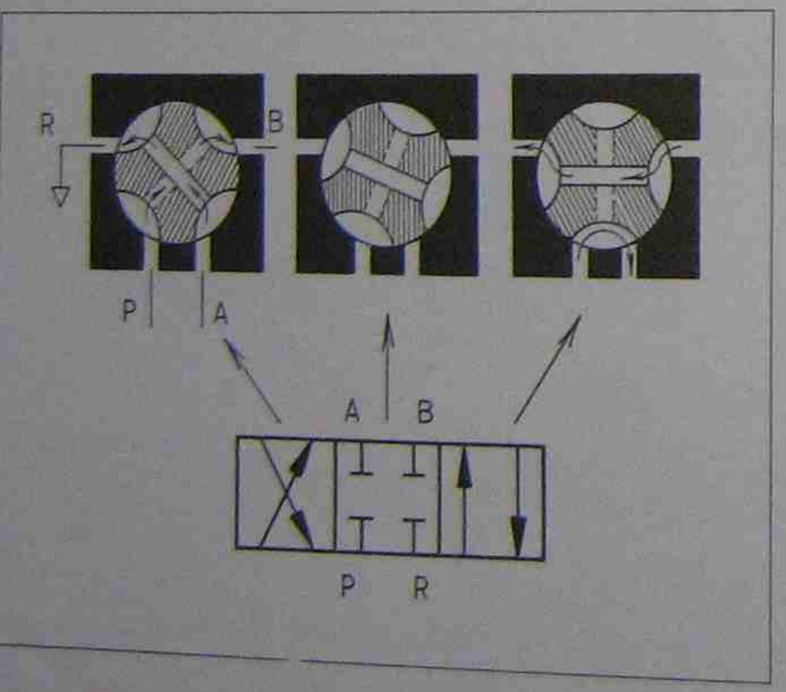


Fig. 2-5 Rotary plug valve as used in hand lever operated shunt valves.

in directional control valves whereas poppets and balls are the preferred mechanism in check valves and logic "OR" function and "AND" function valves. Rotary plugs or rotary plate valves are used only in hand lever operated selector or shunt valves (fig. 2-5).

Normally closed and normally open valves

These terms are generally applied to three-port valves. The valve shown in fig. 2-6 (top), a two-position valve with three ports, permits no flow from pressure port P to output port A in its normal (spring biased) position. In the case of a normally open valve (fig. 2-6, bottom), the supply is permitted to stream to output port A, while the valve is in its normal position. Both valves, when actuated, change their flow mode to the flow configuration depicted in the left-hand square of the valve symbol (fig. 2-6).

Methods of valve actuation

The term *actuation* in relation to pneumatic valves refers to the various methods of moving the valve mechnism into any of its alternative switching positions. Valves can be actuated by five basic methods: Manually, mechanically, electrically, hydraulically or pneumatically.

In complex machine applications any of these methods, or combinations of them, may be used to gain optimum control. Manual methods use hand or foot actuators such as levers, push buttons, knobs and foot pedals, electrical methods use A.C. or D.C. solenoids. For pneumatic/electronic control integration some manufacturers make low wattage coils for direct P.L.C. connection. Solenoids range from 12 to 240 volts. Most solenoid and air pilot valves are also equipped with a manual override button or plunger. Thus the valve mechanism can be operated even when the air pilot signal or the electrical signal should fail. In hydraulically and pneumatically operated valves the fluid pilot signal is made to act onto a piston or it may act directly onto the valve mechanism and thus moves it to its alternative position (figs. 2-4, 2-7, 2-9, 2-13 and 2-14).

Spring-actuated valves

The terms spring-biased or spring-offset, and in the case of three-position valves spring-centered, refer to the application of springs which return the valve mechanism to its *rest position* as soon as the pilot signal command is cancelled. Such commands, whether they be pneumatic, electric or manual, must be maintained as long as the valve is to remain in its non-normal or actuated position.

A valve without a spring bias is actuated entirely by its external controls, and can therefore "float" or "drift" between its two extreme positions wher-

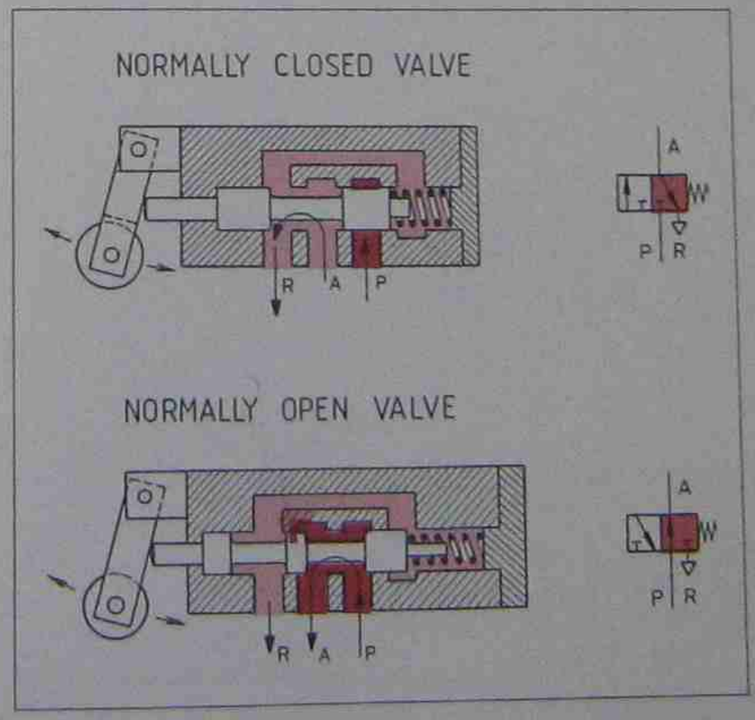
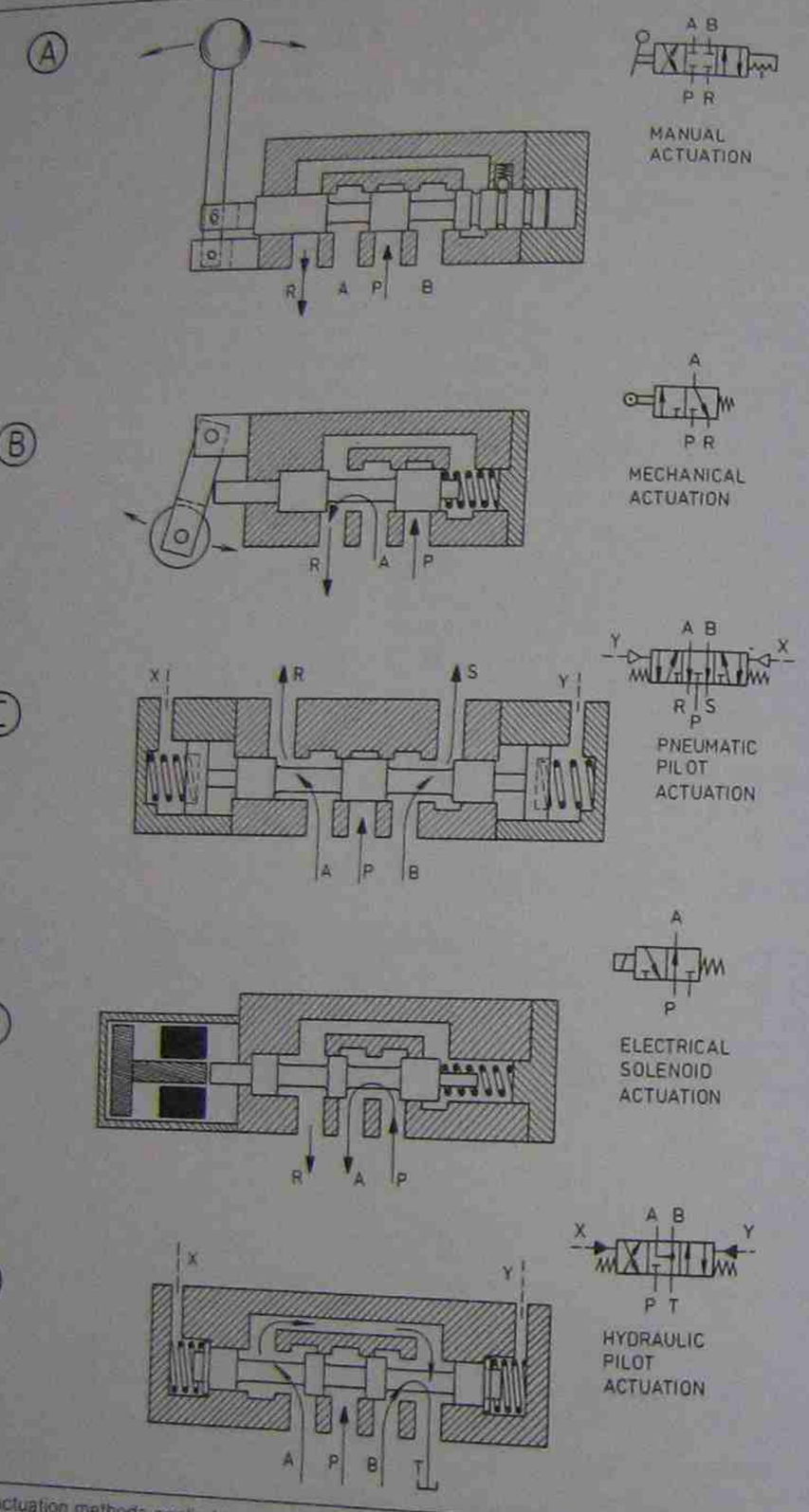


Fig. 2-6 Valves with spring bias (normal position).



2-7 Basic valve actuation methods applied to spool valves

SYMBOL	PORTS	POSITIONS	COMMENTS
	2	2	N/C (IF SPRING RESET)
	2	2	N/O (IF SPRING RESET)
	3	2	N/C (IF SPRING RESET)
	3	2	N/O (IF SPRING RESET)
	4	2	
	5	2	
	3	3	FULLY CLOSED CENTRE
	4	3	FULLY CLOSED CENTRE
	5	3	PRESSURE TO A & B, EXHAUSTS CLOSED
	5	3	FULLY CLOSED CENTRE
	5	3	PRESSURE CLOSED, A & B TO EXHAUST

Fig. 2-8 Commonly used valves

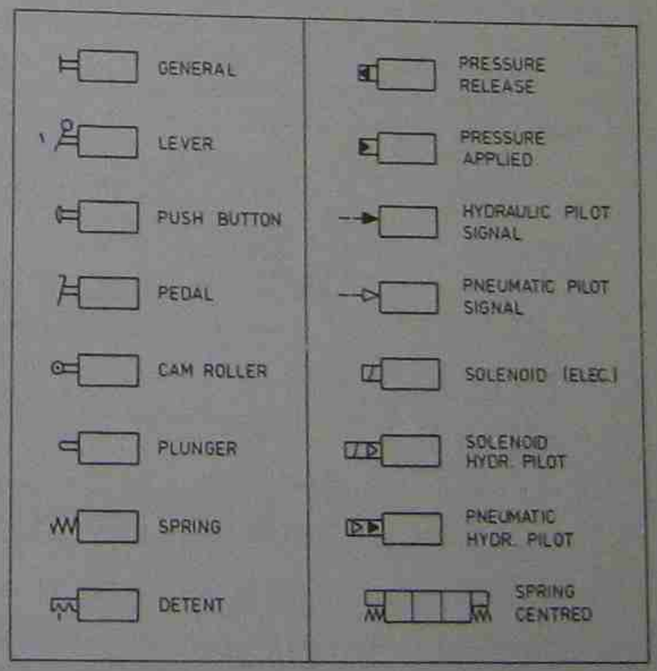


Fig. 2-9 Commonly used valve actuation methods

ever the external control is cancelled. To avoid this, a "detent" mechanism or friction-producing seal rings are used to give the valve a bi-stable (or memory) characteristic. Thus when the valve is switched (selected) into a specific flow condition, it will remain in that condition until switched into its alternative condition (figs. 2-7A, 2-12 and 2-17).

Spool valves

In modern valve designs, the spool valve (fig. 2-10) is most frequently used. Spool valves offer a number of advantages over poppet and flat-slide valves (fig. 2-12).

- Spool valves may be used for flow reversal. This is only possible with one other valve type, the spool/poppet valve (See also: spool/poppet valves, valve conversion).
- Since flow forces acting onto the lands are equal (equal pressure on equal area) the valve is said to be balanced and uses therefore only small actuating forces.
- Spool valves may operate without elastomeric seals if the spool to body tolerance is kept small (below 0.003 mm) and fluid pressure does not exeed 900 kPa (9 bar).
- Spool valves may be built for more than two switching positions, but then the spool is normally spring centered (fig. 2-10) or hand lever operated with detented positions (fig. 2-7A).
- Spool valves may be built for negative or positive overlap to achieve a specific cross-over condition or, if the centre is selectable, a specific centre condition (figs. 2-8, 2-10 and 2-21).

With spool valves one must be careful to mount the valve onto a reasonably flat (preferably machined) surface, since only slight body distortion may warp the valve body sufficiently to make the closely toleranced and lapped spool seize, or hinder it from moving freely when actuated. The same may also be said for bolting the valve too firmly against its mounting surface.

Spool valves are susceptible to contamination of the compressed air and therefore require a close monitoring of the air quality—its filtration and lubrication. The required filtration rate must not exceed 40 micrometres (40 μm).

Flat slide valves

Flat slide valves are a modern adaption of the old steam valve used on steam locomotives. The flat slide is carried to and fro by a grooved piston. The piston may either be air-pilot signal or spring or solenoid/air pilot operated (figs. 2-4 and 2-12). The valve can not be flow reversed (P cannot be used as R and vice versa) but it offers the advantage of a combined exhaust port which may be useful for actuator speed control (see speed control fig. 4-2). Since compressed air forces the flat slide against its bearing surface, the flat slide provides absolute leakfree (pressure assisted) sealing and does automatically adjust for wear on its gliding surface. Flat slide valves are also made with a double slide to gain two exhaust ports and some valves have also snap action toggle discs instead of carrier spools.

Poppet valves

Poppet valves are still used and offer at least two significant advantages over spool and flat slide valves (figs. 2-14):

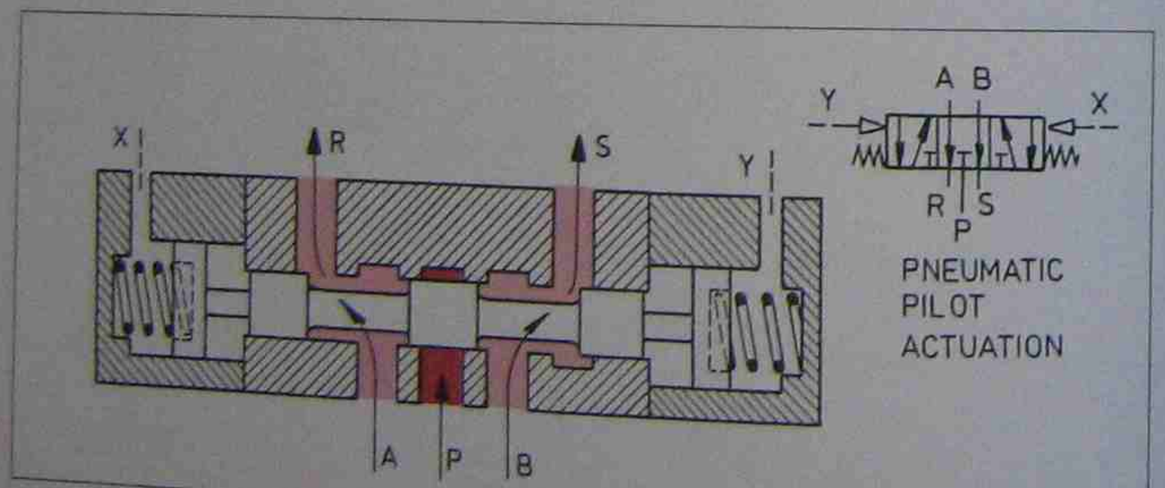


Fig. 2-10 Spool valve spring centred with specific centre condition and positive overlap

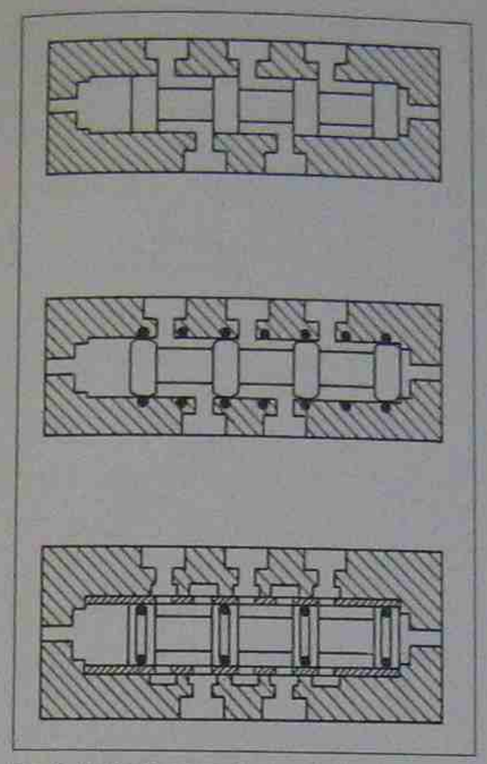


Fig. 2-11 Various spool valve designs

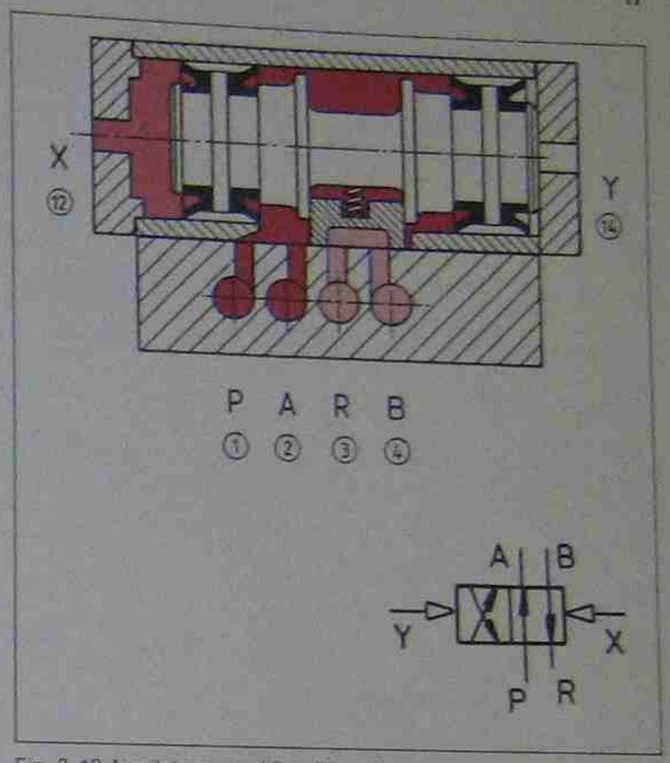


Fig. 2-12 Air-pilot operated flat slide valve

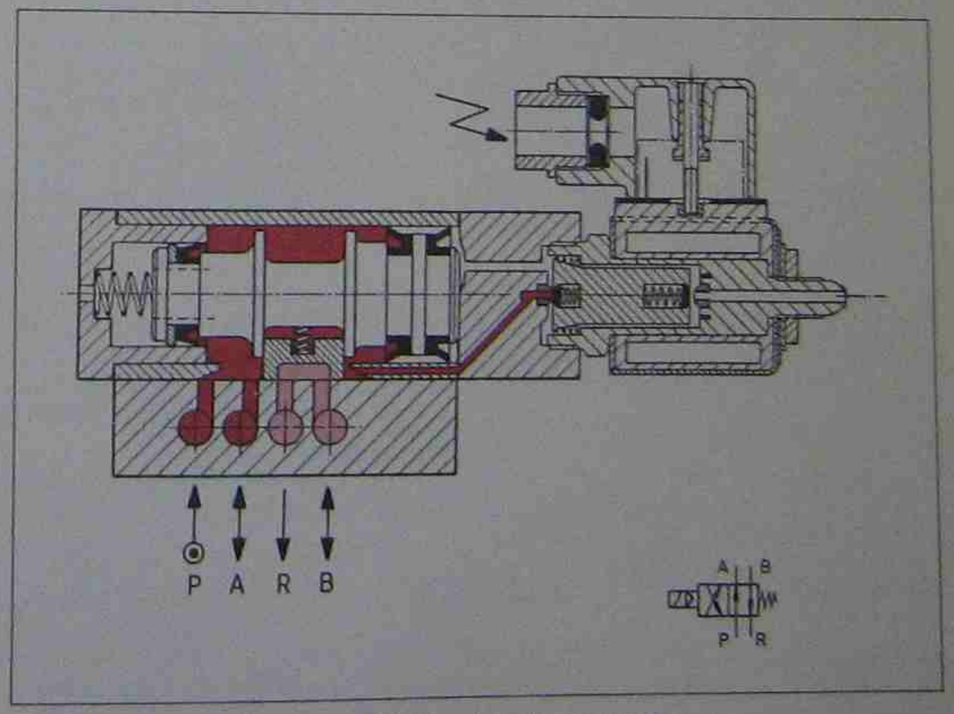
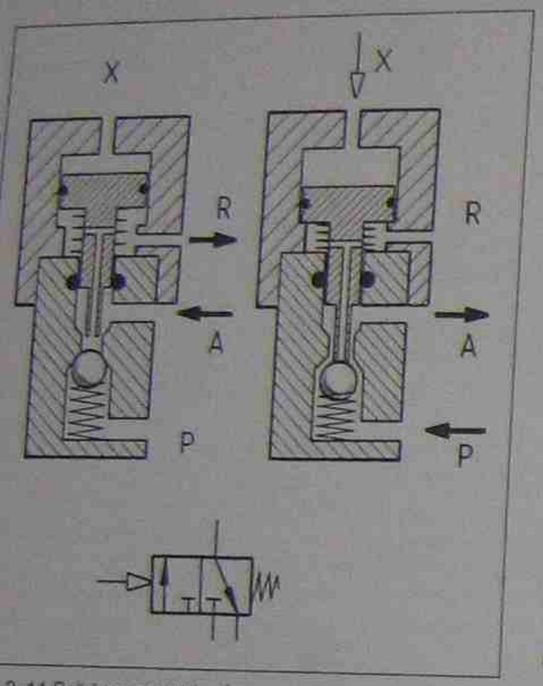
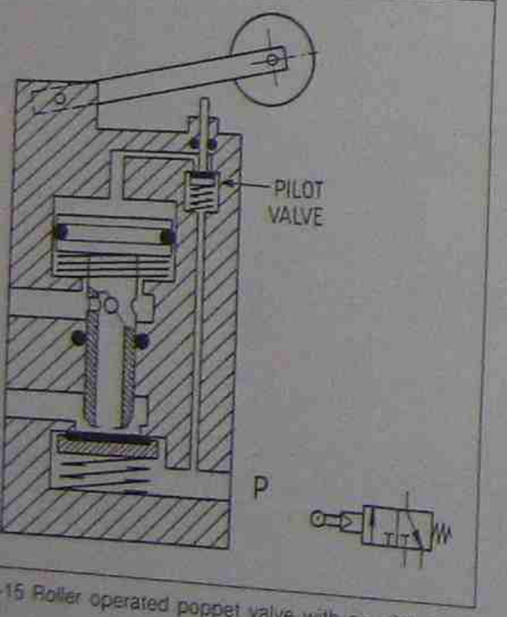


Fig. 2-13 Solenoid/Air pilot operated flat slide valve with reset spring

- Poppet valves are robust and do not require lubrication. They have no close tolerance gaps on moving parts since they provide head-on instead of dynamic sealing.
- Poppet valves provide positive and air pressure assisted sealing (air pressure acts onto the underside of the poppet, figs. 2–14 and 2–15).



2–14 Ball type poppet valve.



15 Roller operated poppet valve with air pilot assis

Because of the sealing design mentioned earlier, poppet valves require a much higher operating force than any other valve design type and thus are often built with air–pilot operating assistance. The operating mechanism (roller, plunger, lever) opens a small pilot valve. This pilot valve directs pilot air to a large piston or diaphragm which operates the poppet mechanism.

True poppet valves (figs. 2–14 and 2–15) are not flow reversible (port P can not be interchanged for port R). Hence some component manufacturers offer a poppet valve for normally open as well as for normally closed flow configuration (see: valve conversion).

Spool/poppet valves

Being a combination of spool and poppet, these valves offer advantages assigned to both design mechanisms (fig. 2–16). These valves may be connected as normally closed or normally open (they are flow reversible) and therefore they find frequent application as *logic valves* ("YES", "NOT", "AND", "OR" function. See also logic functions). When used as logic valves they are air pilot operated but with plunger or cam roller operation they are often used as position sensing valves (limit valves). Their obvious advantages are:

- Low operating force. Light springs suffice to provide leak free static sealing.
- Spool/poppet valves are flow reversible (port P may be exchanged with port R, port A remains the same).
- Spool/poppet valves provide positive overlap (pasage A to R is closed before passage P to A opens).

Friction free valves (toggle disc valves)

A new generation of friction free valves has emerged on the valve market. These valves are specifically designed to combine all the advantages of spool and poppet valves and at the same time eliminate all the disadvantages of spool and poppet valves. Friction free valves, as their name implies, work totally friction free and offer also the following advantages:

- High air flow characteristics. Equal or better than spool valves. Compare figures 2–10, 2–11 and 2–17.
- Static, long life sealing. The seal ring moves head-on against the sealing lips (same as in poppet valves).
- The seal carrier (spool) is suspended between the two pre-tensioned discs and moves friction-free to and fro.

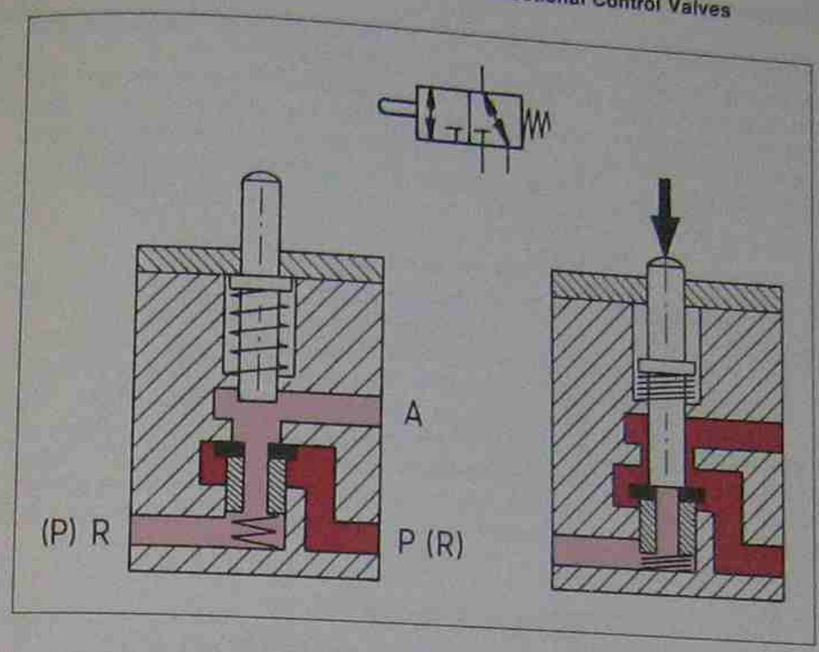


Fig. 2–16 Spool/poppet valve

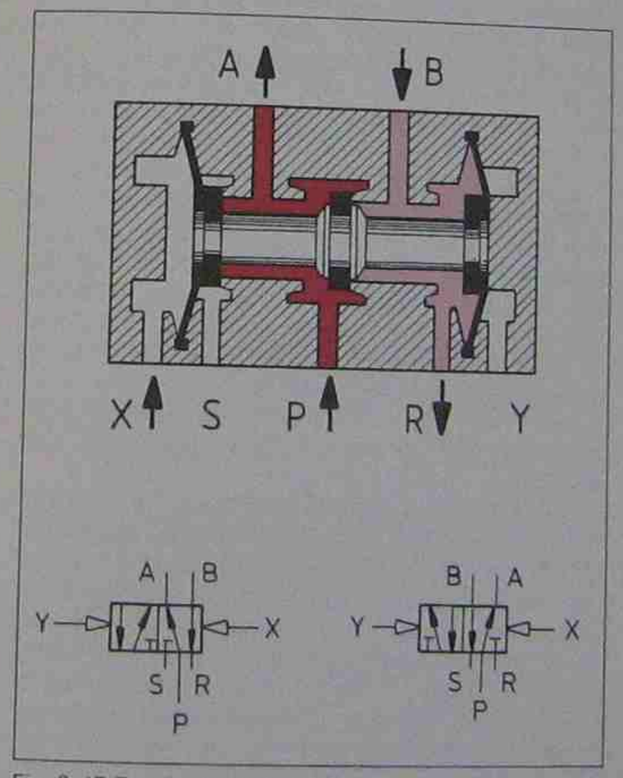


Fig. 2–17 Toggle disc valve (5/2).

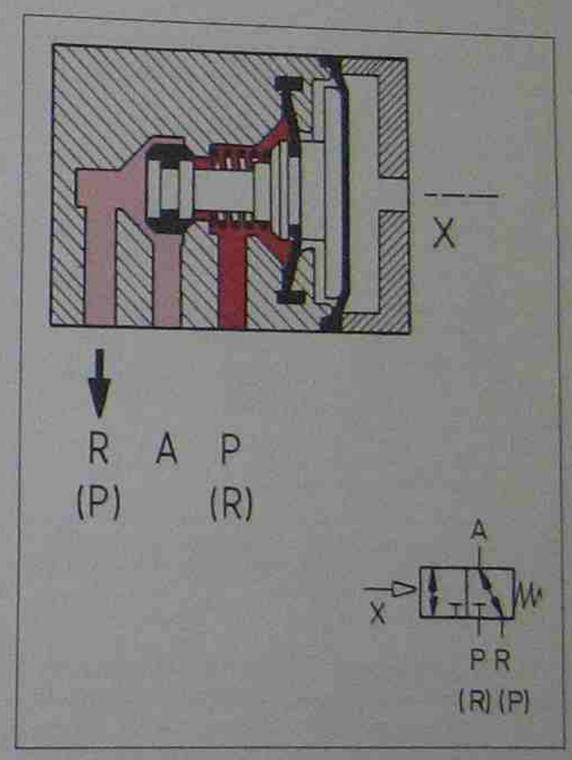


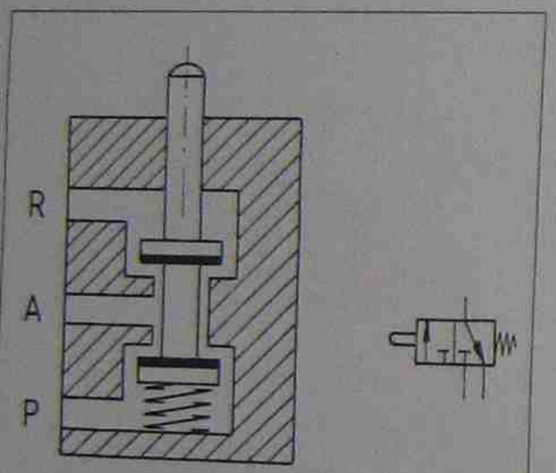
Fig. 2–18 Toggle disc valve (3/2)

- Actuation of the disc moves it over the toggle point and tension forces snap the disc rapidly into its alternate position, thus giving rapid flow switching and memory function!
- Air contamination cannot impair valve movement and lubrication of the compressed air is not required.
- The valve is flow reversible which means port P may become port R and vice versa. Port A remains (fig. 2–18).

It shows that these valves provide an impressive number of advantages and therefore will become the valve of the future. It must, however, be noted that these valves have negative overlap, but due to their extreme fast switching action this may not provide any problem for most industrial applications.

Cross-over condition

Directional control valves with only two selectable valve postions are in reality three-position valves with a special centre condition. This centre condition is known as the transition or cross-over condition. For pneumatic valves this cross-over condition should be "CLOSED" as otherwise compressed air would momentarily stream to all ports. This could produce faulty control, particularly where valves are used to provide logic switching, or it would mean an unnecessary loss of compressed air during the valve transition (fig. 2-19).



ig. 2-19 Cross-over condition for a poppet valve with negave overlap. Compressed air streams momentarily to both utlet ports (ports A and B).

For spool valves the closed condition cross-over s achieved with a positive spool overlap (fig. -21). For poppet and spool/poppet valves posive overlap (or closed cross-over) is achieved by he moving plunger. Here the plunger moves first nto the valve disc before the disc is being forced ff its sealing seat. Thus in a normally closed valve, he air passage A to R is closed off before the pasage P to A is opened (figs. 2-14, 2-15, 2-16 and -20).

For flat slide valves the groove in the flat slide is designed in such a way that the valve provides also positive overlap (fig. 2-12).

Toggle disc (or friction free) valves do not provide positive overlap, but their extremely fast switch-over compensates for this, and air loss during valve transition is minimal and tolerable (fig. 2-16)

Special centre condition

For three-position valves the centre position is a specially selected (switched) position; either by hand lever or centering springs. In such a case the centre condition has significance and is deliberately chosen for this application within the machine. Valve manufacturers offer a variety of valve centre flow configurations (fig. 2-8). These flow configurations are mainly determined by the land width of the spool (figs. 2-7C, 2-7E and 2-21).

Valve conversion

In order to achieve logic switching functions it is often essential and very practical to convert one valve to perform the function of another (figs. 2-22 and 2-23). The logic "YES" function for example requires a normally closed valve, and so does the logic "AND" function (figs. 10-3 and 2-33). The logic "NOT" function and the logic "INHIBITION" function, however, use a normally open valve (figs. 8-7 and 10-8). The logic "OR" function may be achieved using a double-sided check or shuttle valve but equally simple and often more practical is the use of a normally closed valve (figs. 2-36 and 2-38). Similarly the logic "AND" function may be achieved with a twin pressure valve, but (as mentioned before) the normally closed valve, air pilot operated, may be used instead (figs. 2-32 and 2-33).

In industry, for economy and stock-keeping, it is therefore practical to store only a small number of air-pilot operated normally closed valves which can be converted to normally open configuration. Should the need arise (sudden machine breakdown; replacement valves and spares not readily available) these valves can then be converted to perform any of the four previously listed logic functions.

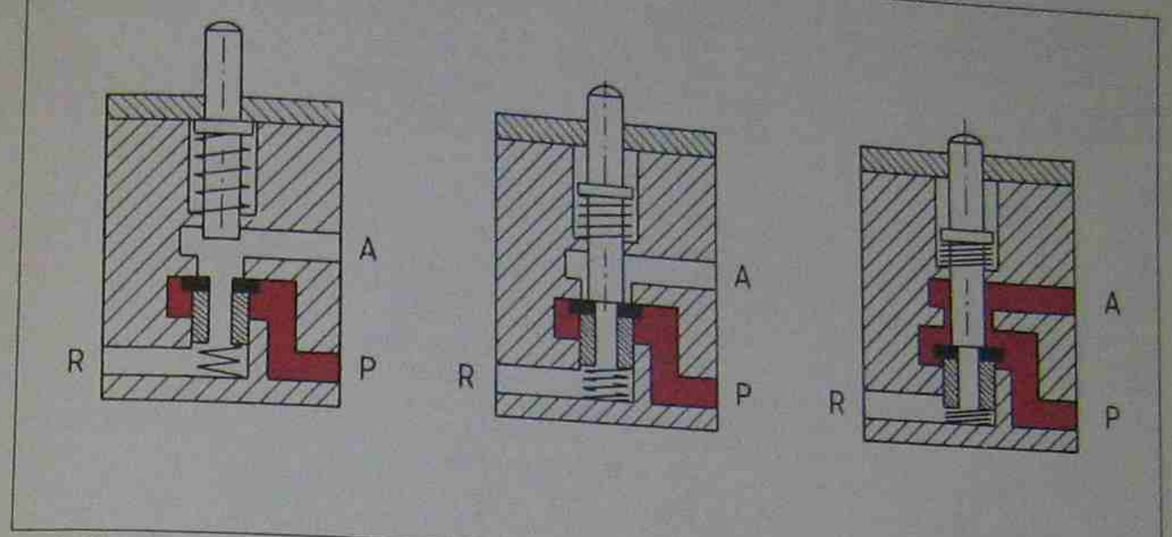


Fig. 2-20 Positive overlap cross-over for spool/poppet valve.

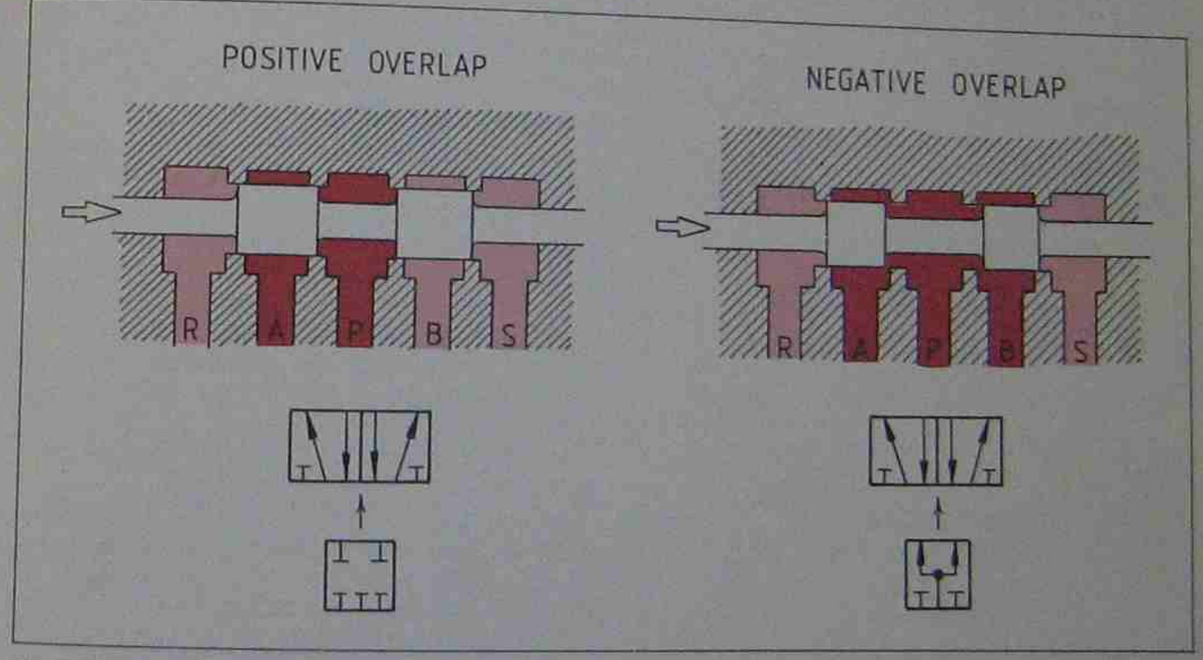


Fig. 2-21 Positive or negative overlap for spool valves.

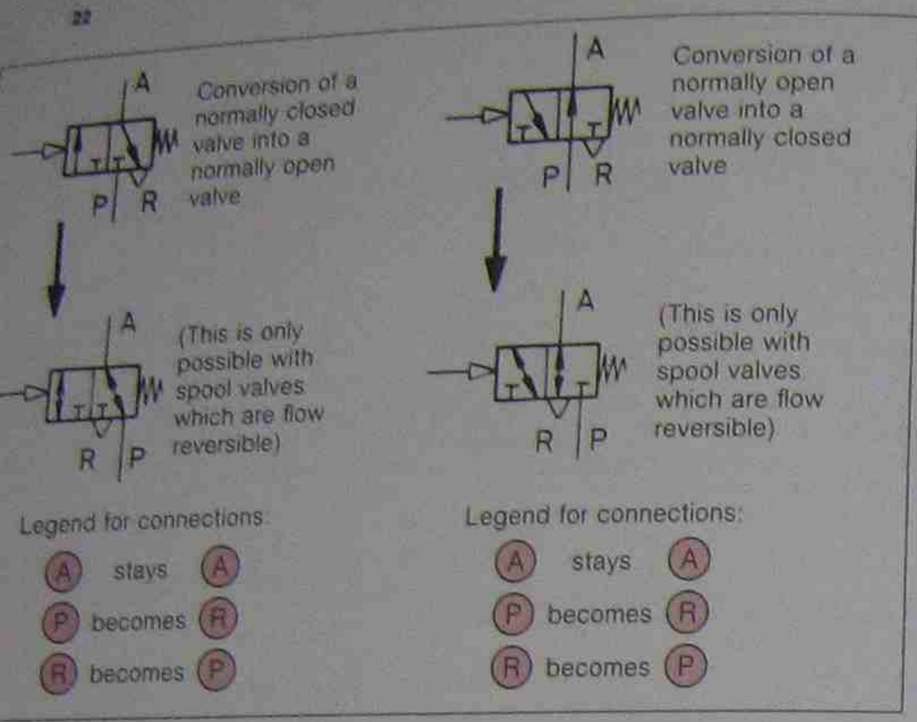


Fig. 2-22 Valve conversion.

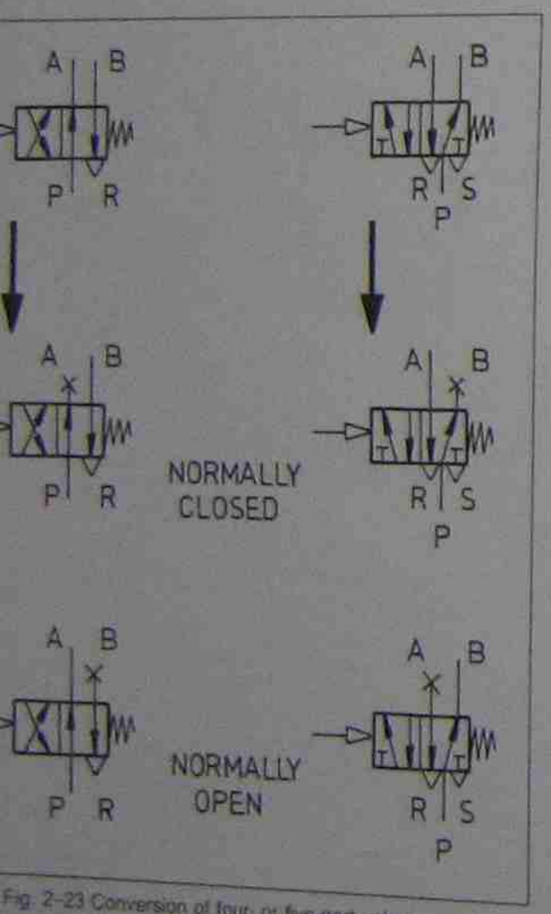


Fig. 2-23 Conversion of four- or five-port valves

Actuator Control

Directional control valves, when used for the controlling of linear or rotary actuators, are called power valves. Such power valves may have memory characteristics (*bi-stable*) or may reset to their normal position (*mono-stable*) when the pilot signal or any other valve actuation is cancelled.

Figure 2-24 shows the application of direct actuator control; e.g. the operator actuates the power valve directly. The following circuits show the principle of pilot or remote control: figs. 2-25 to 2-30. On machines pilot control is much more frequently used than direct control.

For the control circuits in fig. 2-25 and 2-26, when the pilot valve resets the power valve also resets (spring actuation) and the actuator will move into the retracted position. This form of control is called single pilot control. The control circuits in figs. 2-27 to 2-30 show double pilot control. Here the actuator is controlled by a power memory; e.g. the power valve has memory characteristics (bi-stable valve).

The actuator in fig. 2-27 (right) extends when the push-button pilot valve is actuated and retracts automatically when the position sensing valve a_1 (roller valve), being in the fully outstroked position, is actuated. The real position of the roller valve in

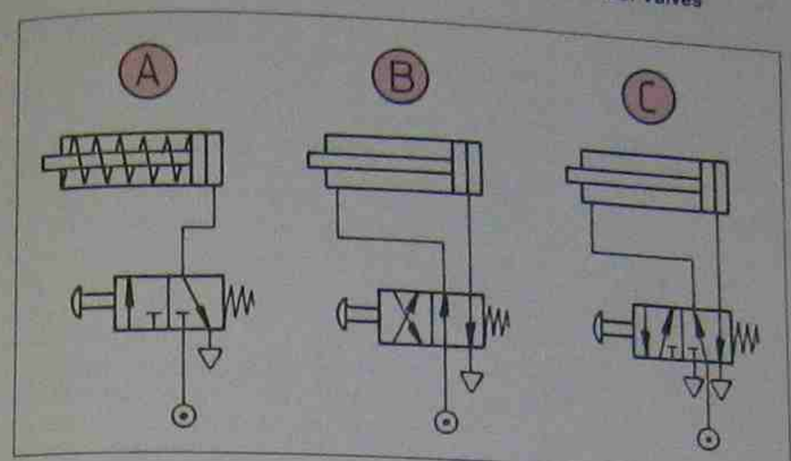
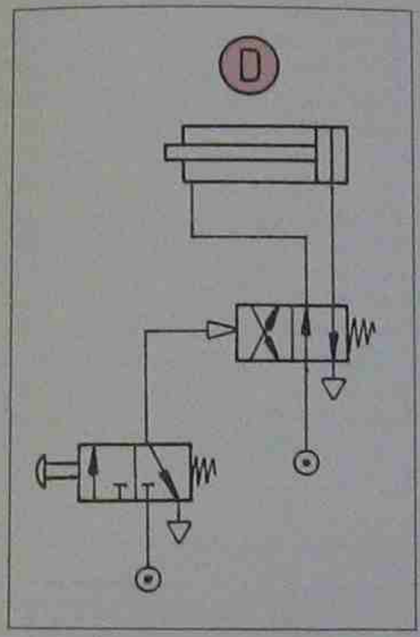


Fig. 2-24 Various direct control methods. Direct actuator control, however, is seldom used on machinery.



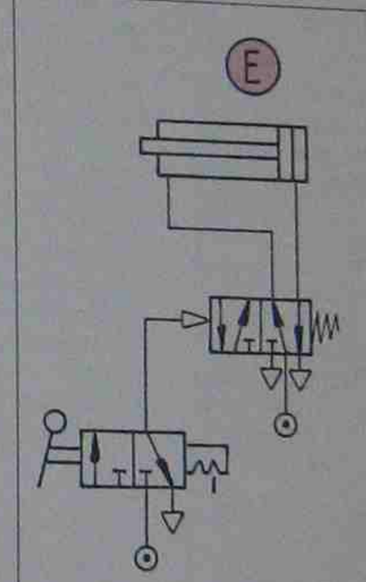


Fig. 2-25 *Far left*: Pilot control with push-button valve.

Fig. 2-26 *Left*: Pilot control with detented lever valve.

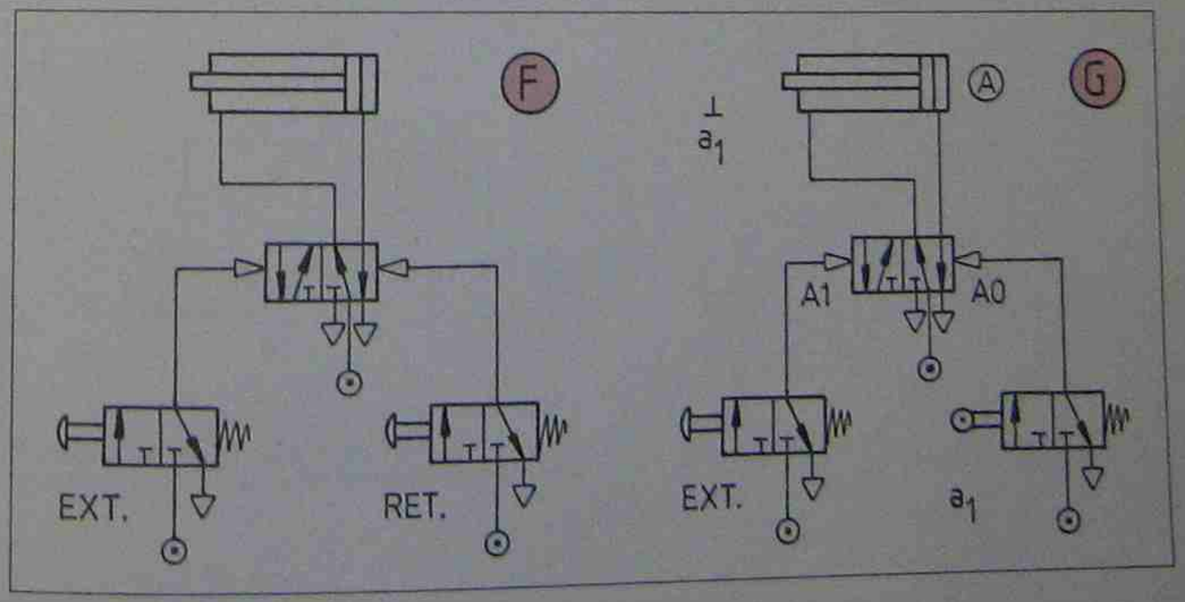


Fig. 2-27 *Below*: Double pilot control.

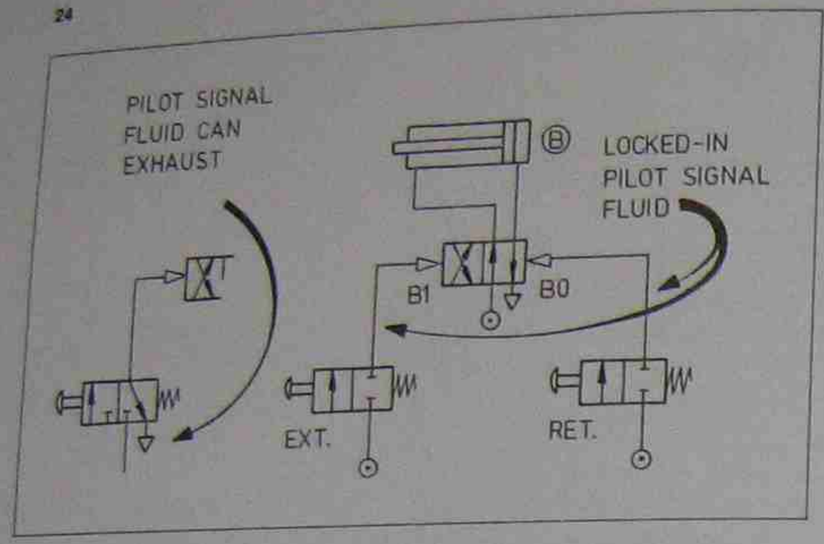


Fig. 2-28 Prevention of locked-in pilot signals

relation to the actuator is shown with an inverted T (⊥) and is labelled a_1 (see also circuit labelling).

Pilot signals must be able to exhaust when the opposite signal on the power valve is applied. Two-position valves as depicted in fig. 2-28 do not allow the trapped pilot signal to exhaust and are therefore not suitable for pilot control.

The control circuit in fig. 2-29 shows an actuator being extended in the rest position. The push-button pilot valve causes the actuator to retract (pilot signal AO). When fully retracted, the actuator will operate the position sensing valve a_0 (roller valve) and thus signals the actuator to extend (pilot signal A1) automatically. Compare this circuit with the circuit shown by fig. 2-27. Compare also the labelling of the two circuits and note the difference in the flow configuration of their power memory valves. The control circuit in fig. 2-30 is an extension of the circuit depicted in fig. 2-29. The full extension position of the second actuator is not controlled. Multiple actuator control of a common power valve is frequently used, but in order to achieve sufficient actuator speed, the power valve must be large enough to provide the air flow required. Uniform actuator movement, however, may only be achieved if both actuators are of equal size and equal load requirement.

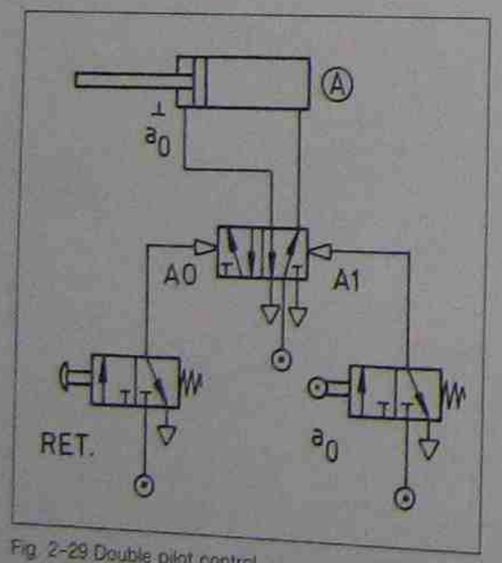


Fig. 2-29 Double pilot control

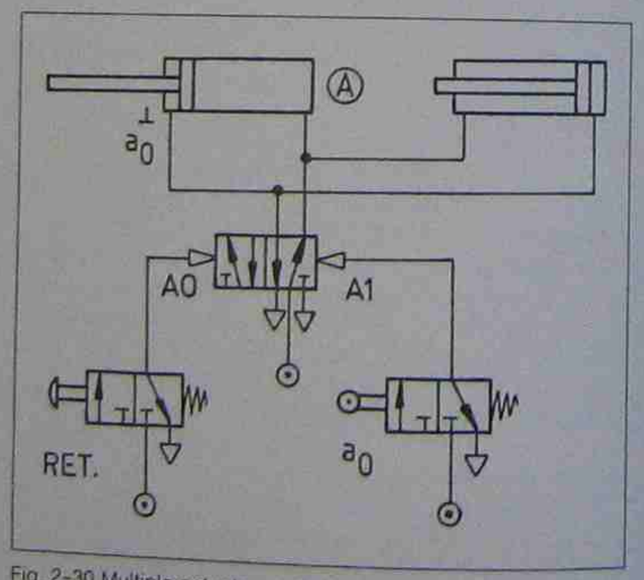


Fig. 2-30 Multiple actuator control.

Circuit labelling

In order to direct the reader to logical control design, this book uses only the binary movement expression and labelling method. Thus actuator extension signals (pilot signals) at the power valves are denoted with the binary figure 1 and retraction pilot signals with the binary figure 0. Power valves carry the letter of the actuator they control. In figure 2-31, the actuator for example is labelled A, hence its extension pilot command is A1 and its retraction pilot command is AO. In fig. 2-48 the second actuator is labelled B.

Position sensing valves also carry the letter of the actuator by which they are actuated. The valve placed in the fully outstroked position carries in addition also the binary figure 1 and the valve in the retracted position the binary figure 0. These letters, however, are lower case with subscripted figures (see figs. 2-31, 2-48) whereas the pilot signals on the power valves are capital letters with the figure on the same line (see also figs. 2-43 and 2-44).

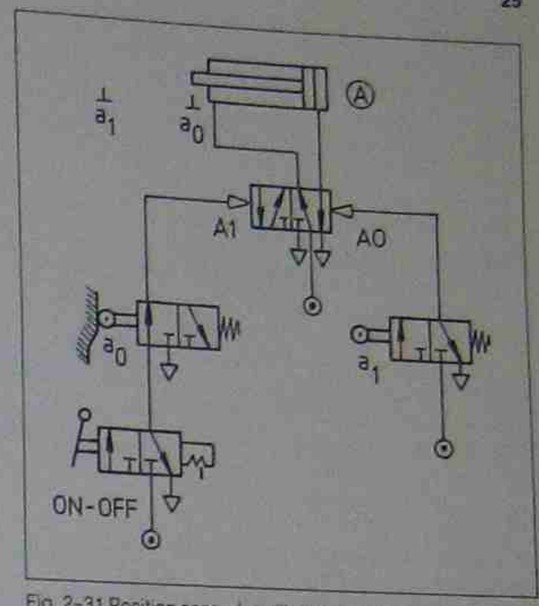


Fig. 2-31 Position sensed oscillation control. The two position sensing valves (a_1 and a_0) check full stroke movements. The on-off valve terminates these oscillations and causes the actuator to stop in position a_0.

Position sensed control (Limit valve control)

Cam roller operated pilot valves located at the stroke limits of an actuator are called position sensing valves or limit valves. Position dependent sequencing of an actuator (or other actuators) is controlled and signalled by these valves; hence their name (figs. 2-31, 2-29, 2-30 and 2-35). Figure 2-31 depicts an oscillation control using

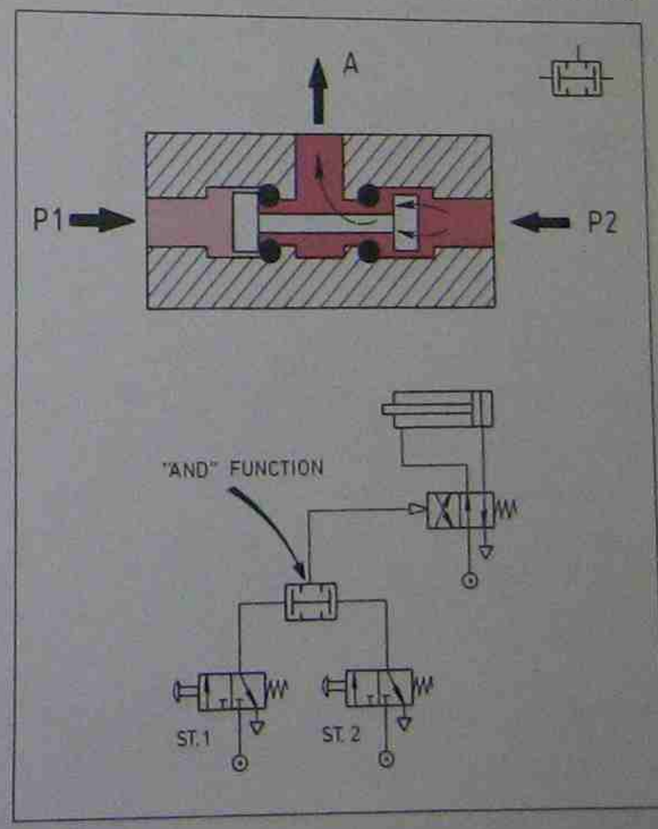


Fig. 2-32 "AND" function valve. Both input signals must be present. Then the weaker or second arriving passes through to the outlet port A.

two position sensing valves, one at each stroke limit. As long as the compressed air supply is switched on (on-off valve), the actuator will oscillate, but when the air supply is switched off, it stops in retracted position, resting on position sensing valve a_0

"AND" Function valve (two pressure valve)

Some component manufacturers make a special purpose "AND" function valve (two pressure valve). This valve ensures that *both* expected input signals *must be present* on the valve before either of them is permitted to pass through to outlet port A (see fig. 2-32). The first arriving signal shifts the valve element (twin poppet), and the weaker or second arriving signal finds its way to the outlet port; thus it may be said that both input signals are required. The valve is extremely simple in its construction and costs less than an air pilot operated spool or spool/poppet valve (see figs. 2-14, 2-16 and 2-18). As previously mentioned, the "AND" function valve (two pressure valve) may be replaced by a two position, normally closed and air pilot operated spool or spool/poppet valve (figs. 2-14, 2-16, 2-18 and 2-33). This type of valve is widely available and has the advantage that the weaker signal may be used as the pilot signal and the stronger signal passes through the valve.

The "AND" function may also be achieved by arranging the pilot signal valves contributing to the "AND" function in series order (series arrangement) as shown in fig. 2-34. Here the actuator is signalled to extend if the start valve is actuated and the actuator is fully retracted, thus actuating roller valve a_0. Pilot valves contributing to a series function may with the exception of time delay and impulse valves be arranged in any order. That means the start valve in fig. 2-34 could also be above the roller valve. Up to eight valves may be connected in series, providing the signal leaving the series chain is strong enough to switch the power valve at the end (pressure drop).

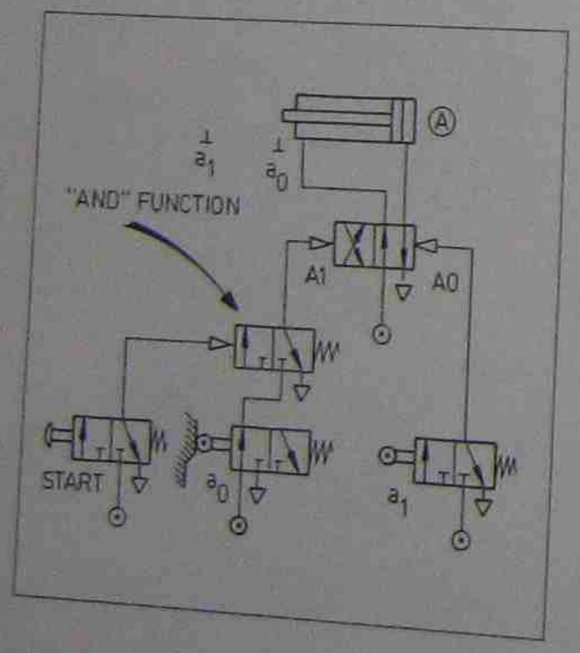


Fig. 2-33 "AND" function with 3/2 pilot operated normally closed valve.

"OR" Function valve (shuttle valve)

Most component manufacturers make a special purpose "OR" function valve (shuttle valve). This valve connects either input 1 or input 2 to the outlet port A, but prevents any cross flow from input 1 to input 2 or vice versa. It is to be noted that a *T-connector* must not be used to merge two pilot signal lines (compare figures 2-36 and 2-37). Using a T-connector as a substitute for an "OR" function valve would not suffice, since the pilot signal would immediately exhaust through the alternate push-button pilot valve (fig. 2-37). The "OR" function may also be achieved by using a

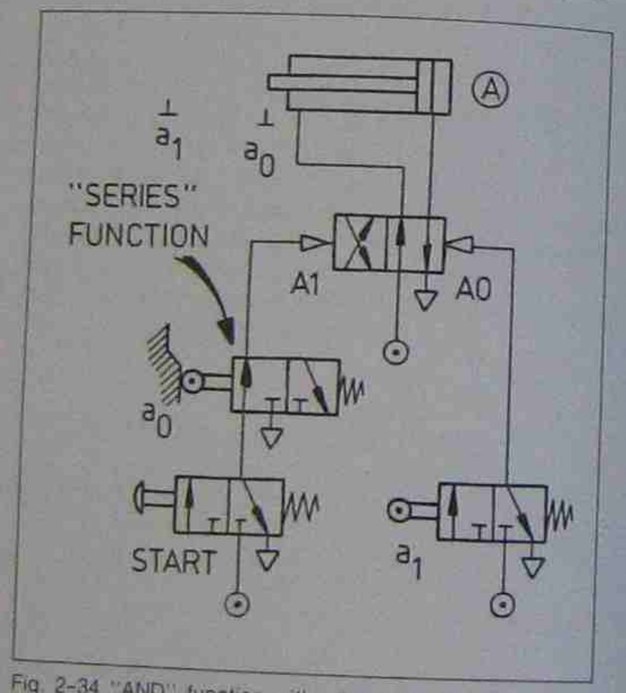


Fig. 2-34 "AND" function with pilot valves in series order.

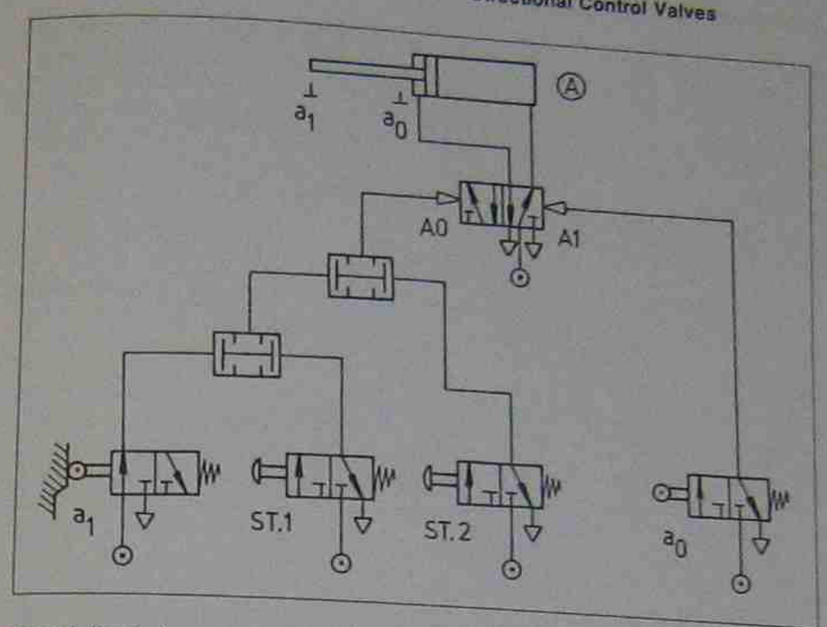


Fig. 2-35 "AND" function with three input signals. A multiple "AND" function of several inputs may be formed (up to 12 inputs without a significant pressure loss).

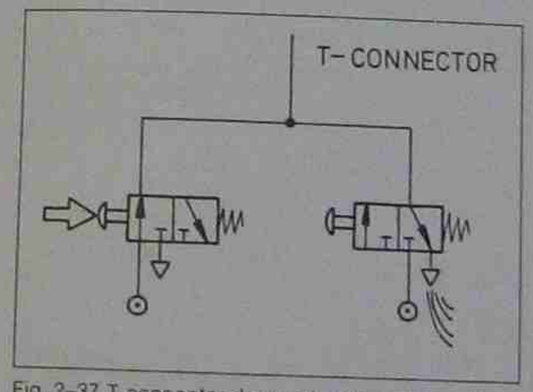


Fig. 2-37 T-connector does not work for the gathering of signals.

Fig. 2-36 "OR" Function valve

two position, normally open pilot valve (fig. 2-38) or by arranging the pilot valves contributing to the "OR" function as shown in fig. 2-39. All three circuit versions are equally effective, but the version depicted in figure 2-39 is obviously less expensive and thus should be given preference providing the second pilot valve is flow reversible (may be connected as normally open, with port R becoming port P).

The control circuit in fig. 2-40 shows how three pilot signals can be "OR" connected (three input "OR" function). This pattern may be extended for several more "OR" connected pilot signals, and it is obvious that the number of "OR" function valves required is one less than the number of "OR" connected input signals (fig. 2-40).

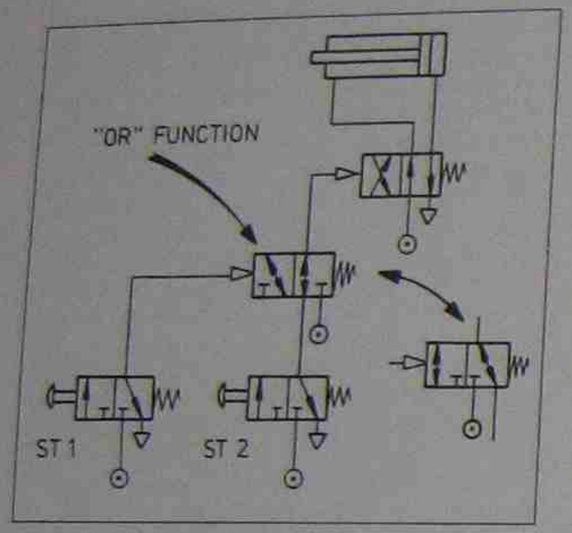


Fig. 2-38 "OR" Function valve.

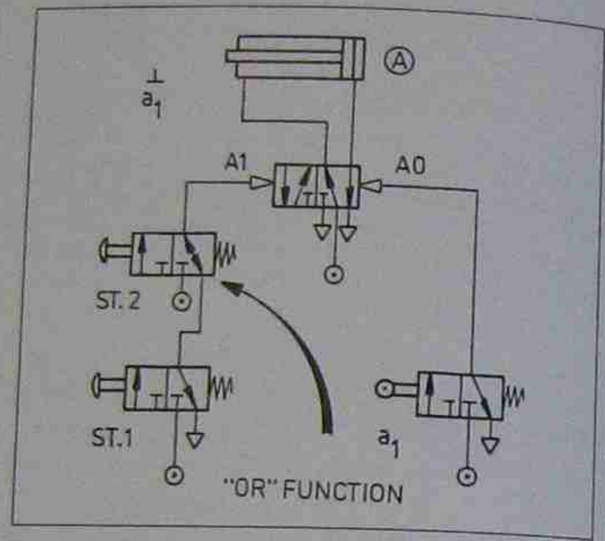
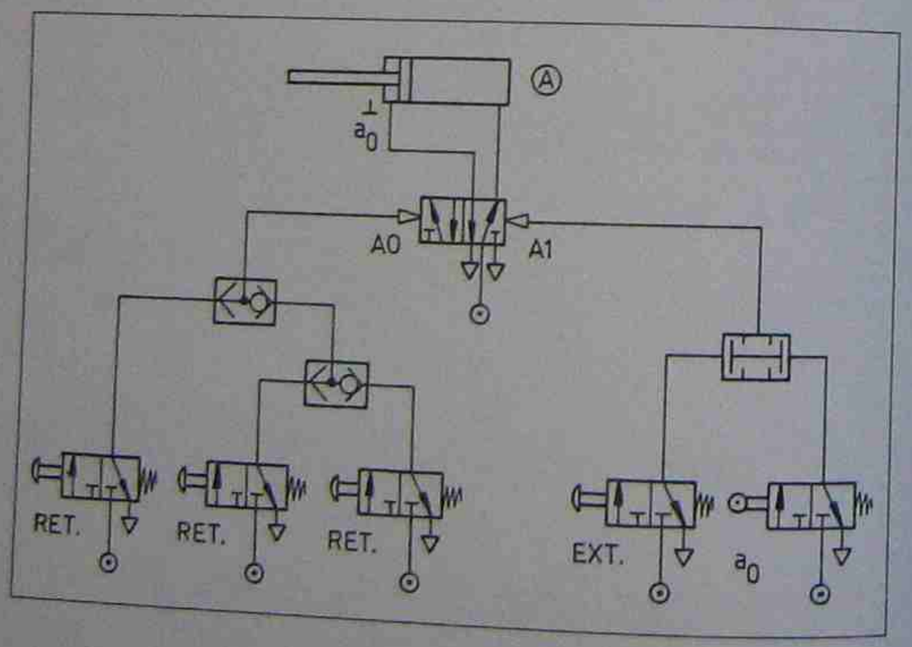


Fig. 2-39 Two start valves in "OR" function arrangement. Start valve 2 must either be flow reversible or a normally open valve.



ig. 2-40 Multiple "OR" connection permitting a cylinder etraction to be signalled om three different start cations.

Time delay valves

Pneumatic time delay valves (timers) are used to delay a pilot signal. The time delay valve is normally placed between the valve causing the pilot signal and the destination of the pilot signal (power valve, see fig. 2-41). The valve causing the pilot signal in the illustration (fig. 2-41) is a push-button valve; the valve receiving the delayed pilot signal is a spring reset type power valve. Figure 2-41A shows a pilot signal without delay. Figure 2-41B shows the pilot signal being delayed with a passive timer. Figure 2-41C shows the pilot signal being delayed with an "active" timer. Active timer integration has the advantage of "restoring" a weak signal to full system pressure.

As shown in fig. 2-41, a timer may be built from two separate valves; namely a flow control valve with free reverse flow and an air pilot operated normally closed 3/2 valve. For longer time delay functions, one must also connect a small air reservoir into the pilot line connecting the flow control to the 3/2 valve. However, most manufacturers of pneumatic components make a complete timer consisting of all three aforementioned components (fig. 2-42). Such time delay valves are predominantly of the spool/poppet or spool design which permit normally closed or normally open flow configuration.

Valve operation

Compressed air is connected to port P (figs. 2-41 and 2-42). Port A is connected to the pilot signal port of the power valve. The pilot signal valve (push-button valve) is connected to port X of the timer. Once the push-button valve is actuated, compressed air flows via the flow control valve orifice into the air reservoir and pressure inside the reservoir starts to build up. The spool moves to the right when the air pressure force from the reservoir exceeds the spring force holding the valve closed; thus the flow passage from P to A opens and the pilot signal is transferred to the power valve (fig. 2-43). The time required for the pressure build-up to reach spool shift force is equal to the required time delay and is adjusted on the flow control valve (flow rate = pressure build-up time).

For the time delay valve to resume its initial or spring reset position, the pilot signal connected to port X must cease and the compressed air inside the reservoir must exhaust. In order to make the timer quickly available again for the next time delay function, exhaust air can flow through the inbuilt

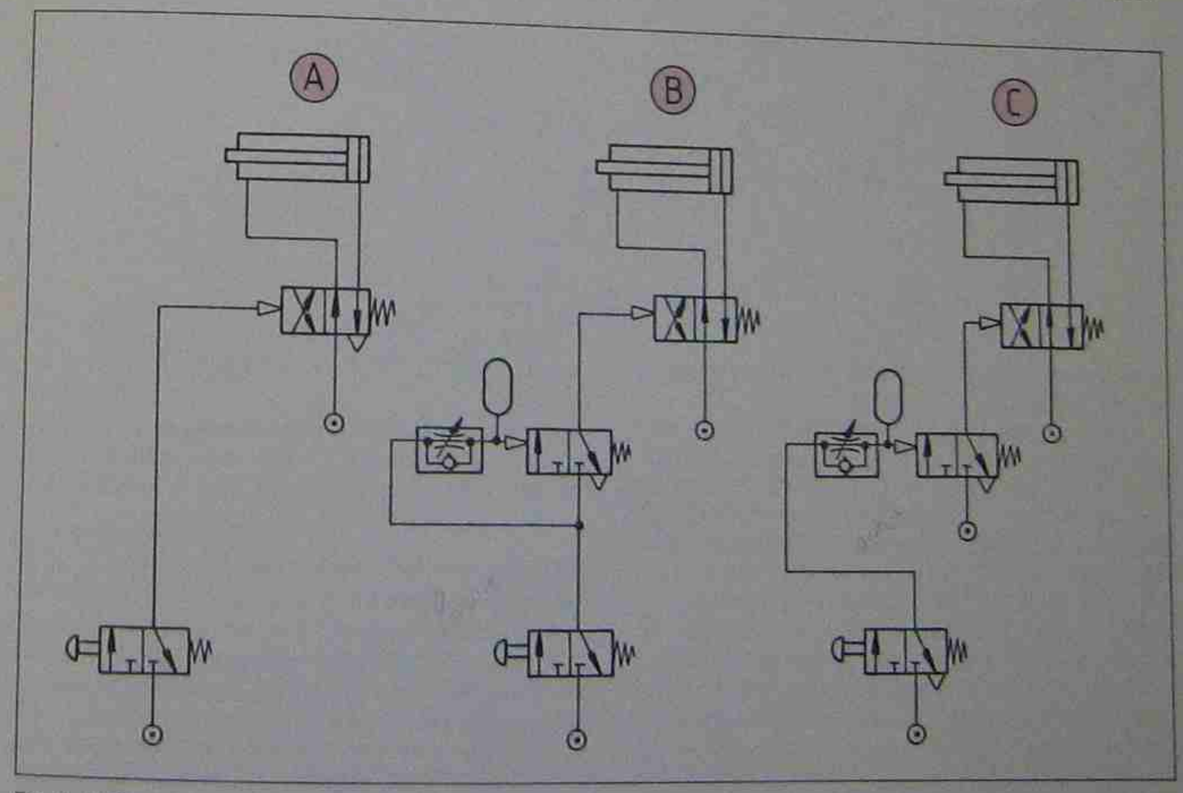


Fig. 2-41 Timer integration.

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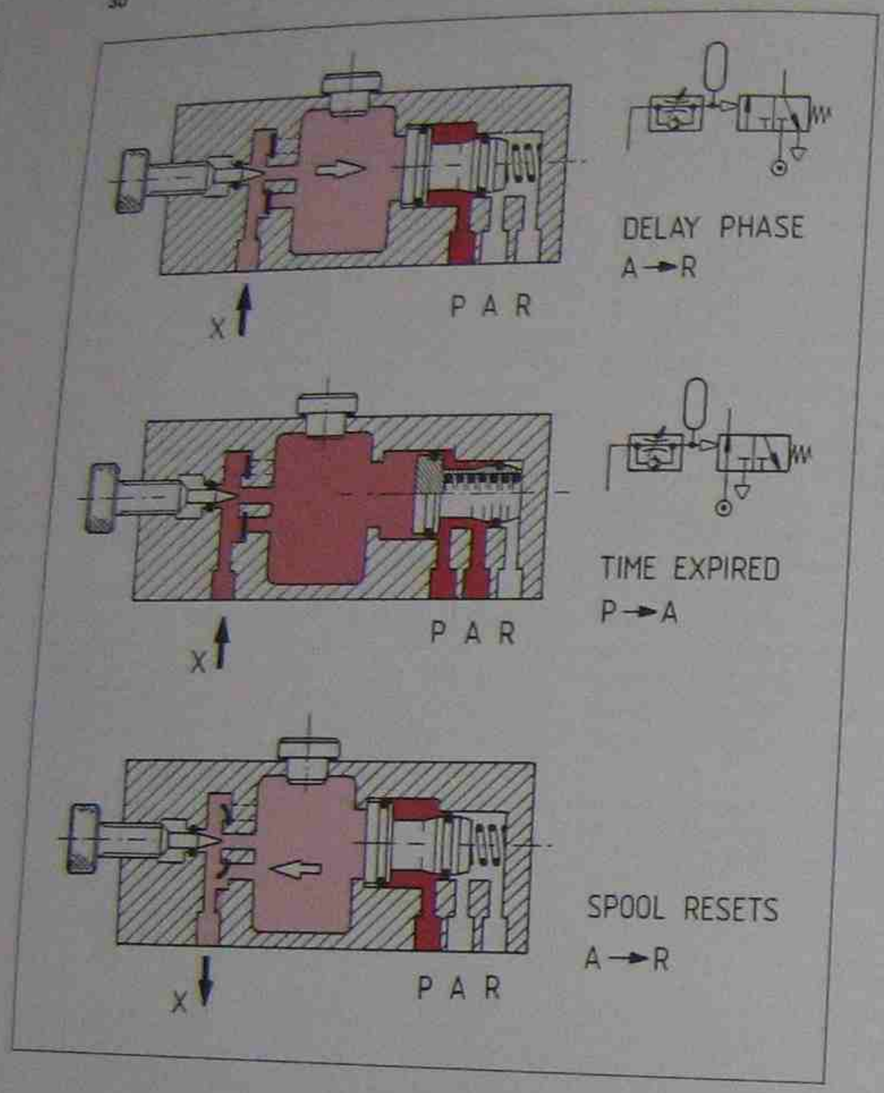


Fig. 2-42 Time delay valve consisting of a 3/2 spool valve, a flow control valve with free reverse flow, and a reservoir in between.

check valve (rubber disc) and thus the reservoir is rapidly emptied.

However, any pressure fluctuation on the pilot line will cause inconsistent time delay. It is therefore recommended to keep pressure in the pilot line as stable as possible or use reduced pilot pressure; set well below the minimum pressure fluctuation level.

Figure 2-43 shows a typical timer (time delay valve) application. The actuator is permitted to extend when the start valve is actuated and the position sensing valve a_0 is actuated. The actuator then must fully extend to valve a_1 and remain in that position for 15 seconds before it retracts automatically. Fig. 2-44 depicts a timer application to make the actuator extend automatically after having been in the fully retracted position for 7 seconds.

Note: The position sensing valve a_1 is shown in its actuated position; hence the valve is attached to the left hand square and the cam is indicated.

Impulse valve (pulse valve)

Impulse valves are used to shape a long signal into a short pulse. Their most frequent application is in sequential control circuits where persisting signals which could otherwise cause an opposing signal on a power valve have to be removed (fig. 2-45). The valve is placed into the pilot signal line between the pilot valve and the power memory valve (fig. 2-45).

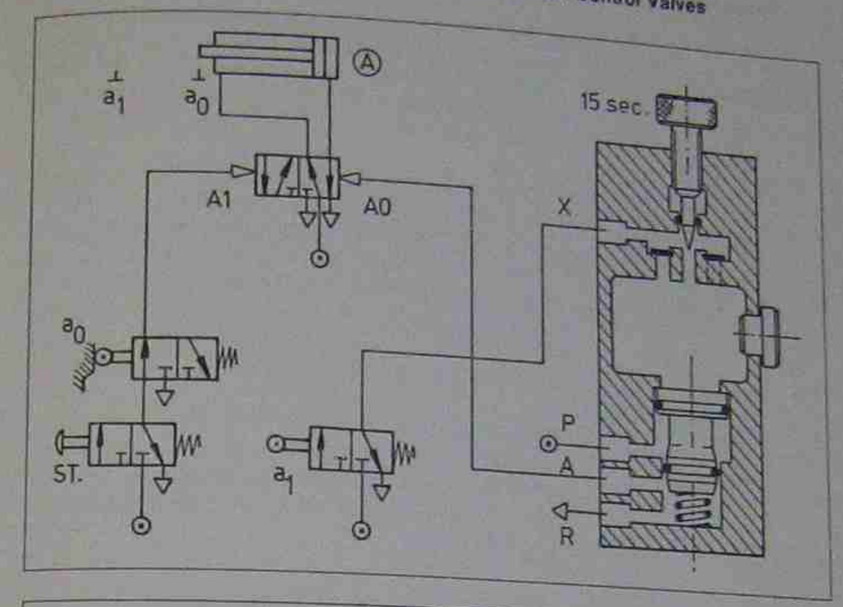


Fig. 2-43 Typical timer application.

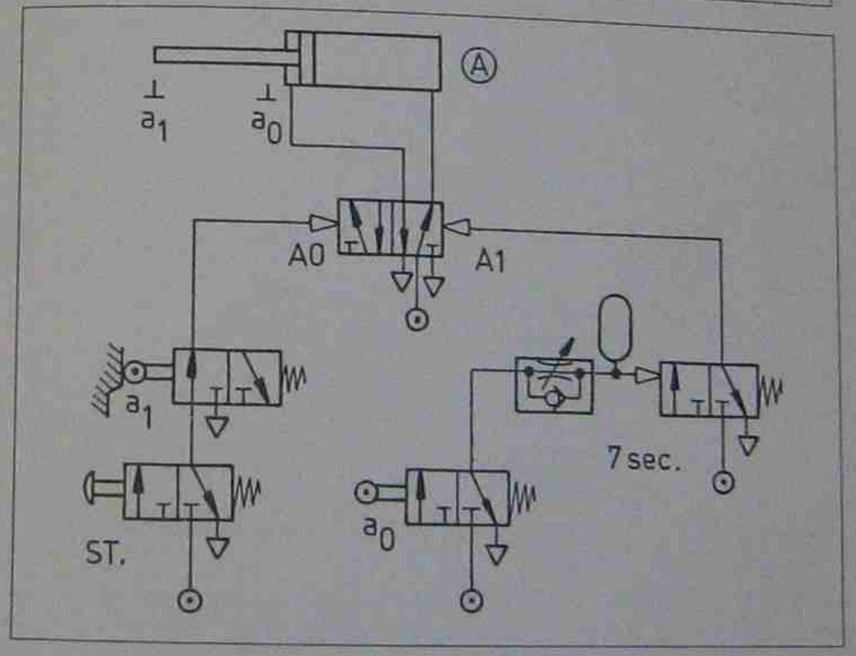


Fig. 2-44 Timer application.

Valve operation

The pilot signal is connected to port X and to port P. Port A is connected to the pilot signal line leading to the signal port of the power valve. Once the push-button pilot valve is actuated, the emerging pilot signal will flow immediately through the open pulse valve into the power valve signal port, where it actuates the power valve. Simultaneously the air pressure in the reservoir starts to build up. The spool moves to the right (fig. 2-46) when the air pressure force from the reservoir exceeds the spring force holding the valve open; thus the flow passage from P to A closes and the pulse expires. The time required for the pressure build-up to reach spool shift force is equal to the required pulse length and is adjusted on the flow control valve (flow rate is equal to pressure build-up time).

For the pulse valve to resume its initial or spring reset position, the pilot signal connected to ports X

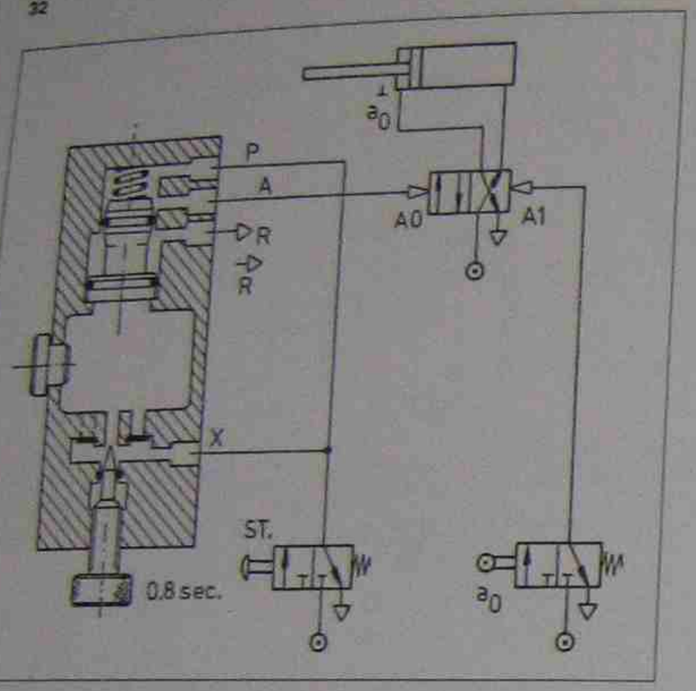


Fig. 2-45 Impulse valve integration.

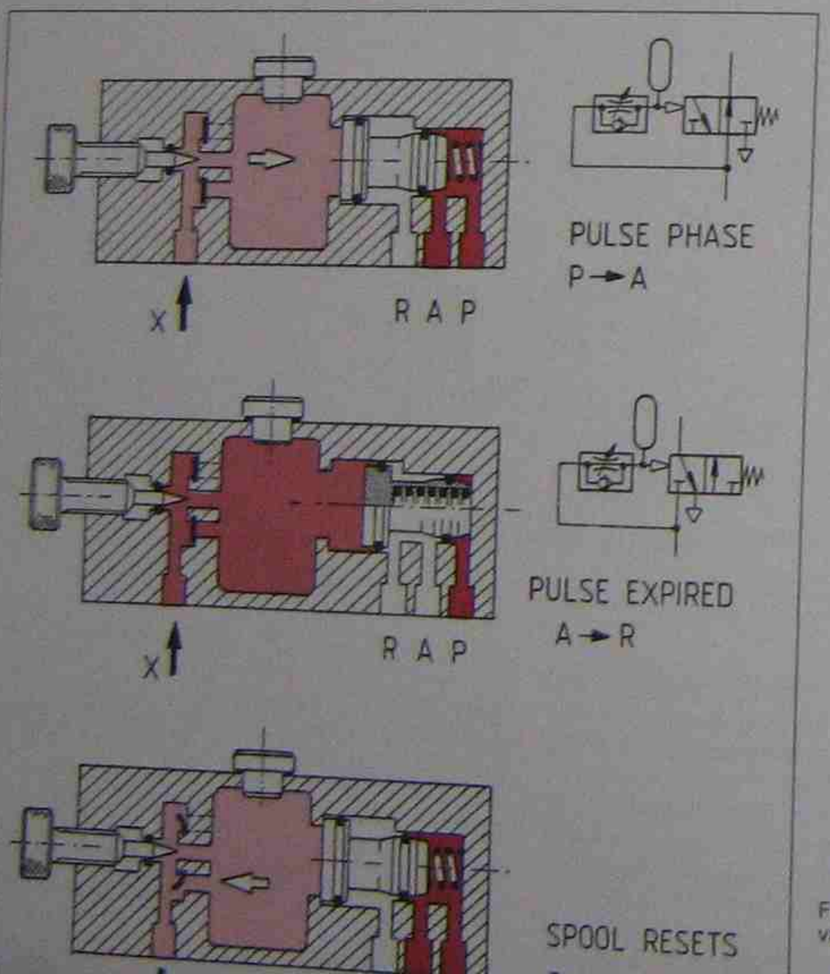


Fig. 2-46 Impulse valve (pulse valve).

and P must cease and compressed air inside the reservoir must exhaust. In order to make the pulse valve quickly available for the next function, exhaust air can flow through the inbuilt check valve (rubber disc) and thus the reservoir is rapidly emptied.

Figure 2-47 shows a typical impulse valve application. The actuator must retract immediately after having reached the fully outstroked position a_1. This could be foiled if an opposing signal on the power valve (caused by the operator remaining on the start valve) prevented the power valve from reacting to the AO pilot signal (fig. 2-47). The impulse valve shapes a persisting start signal into a pulse.

Impulse valves may also be used as normally open timers; e.g. to turn an actuation or machine function off after a predetermined time. A typical example of this is shown in fig. 2-48 (refer to: timer N/O).

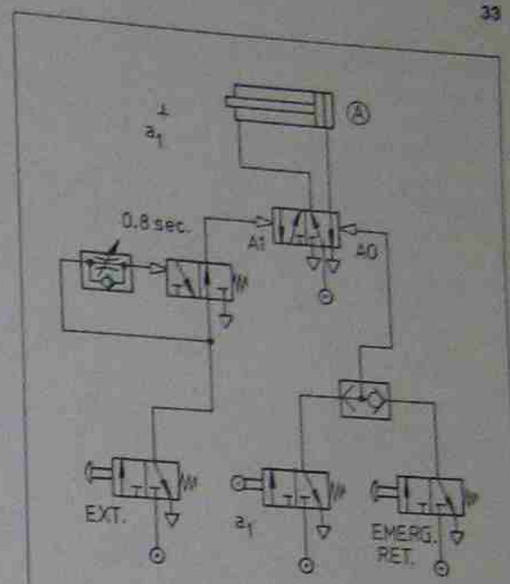
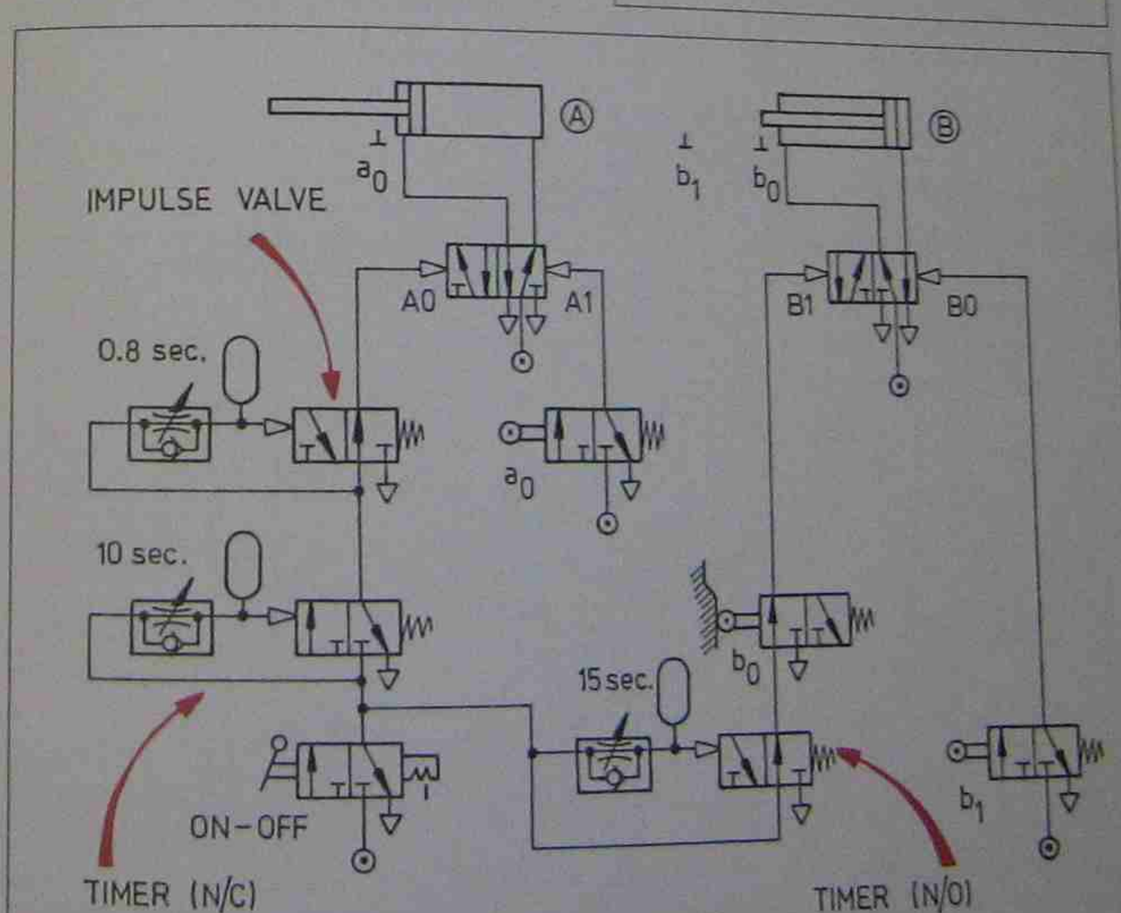


Fig. 2-47 Impulse valve application. The impulse valve shapes the start signal into a short pulse of 0.8 seconds.



Timer and impulse valve in series arrangement

Timers and impulse valves may be placed in series arrangement but the order of placement is important. Impulse valves are usually set to a pulse length of about 0.5 to 0.8 seconds. After this time the pulse expires. Timers need a constant input which exceeds the time setting. It is therefore imperative to place the timer upstream of the impulse valve (fig. 2–48).

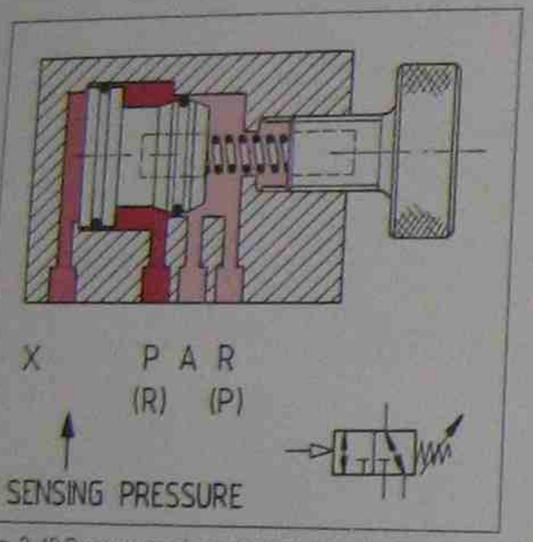


Fig. 2–49 Pressure sensing valve (spool type)

Pressure sensing valve (Pressure sequence valve)

The pressure sensing valve is basically a 3/2 spool valve which is predominantly used as a normally closed valve (fig. 2–49). The spool-shift spring can be adjusted to different spool-shift forces, thus the valve opens at different but selectable sensing pressures; normally from 100 kPa to 1000 kPa (1 to 10 bar). Pressure sensing valves are used where a specific pressure is required for a machine function (a clamping function for example). Figure 2–50 shows a control circuit for an actuator that is only permitted to extend if the system pressure is at least 600 kPa (6 bar) and the start valve is actuated. With a minimal pressure of 600 kPa the spool will move upwards and the start signal can pass through the valve (from P to A) and actuate the power valve at signal port A1. After being fully outstroked, the actuator retracts automatically.

The actuator in fig. 2–51 extends when either start 1 or start 2 is actuated ("OR" function) and retracts automatically when full stroke extension is reached and the extension pressure sensed on the actuator is at least 600 kPa ("AND" function with series arrangement).

Time and pressure sensed control

Very few controls use pressure sensing or time sensing in its pure form. Most controls use a combination of position sensing, time sensing and pressure sensing and in most cases manual sequencing in one form or another is added (fig. 2–52).

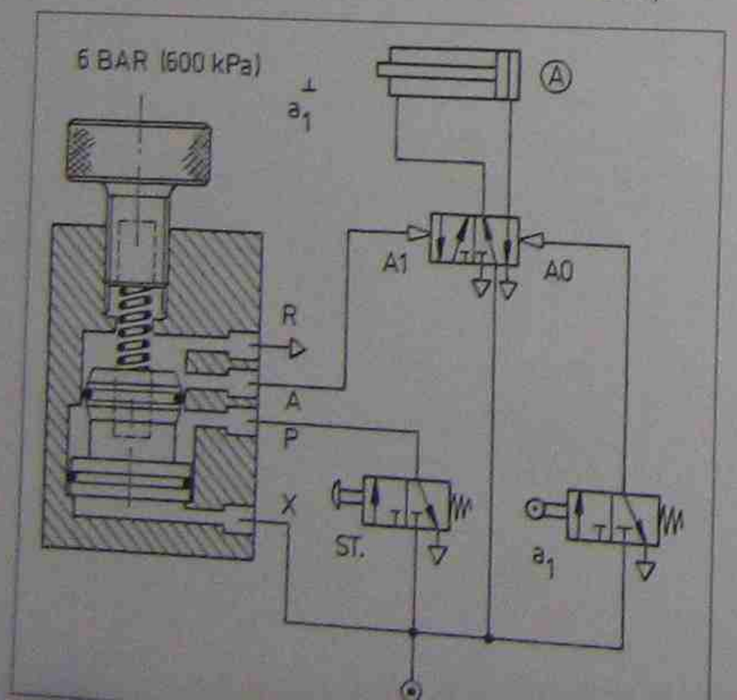
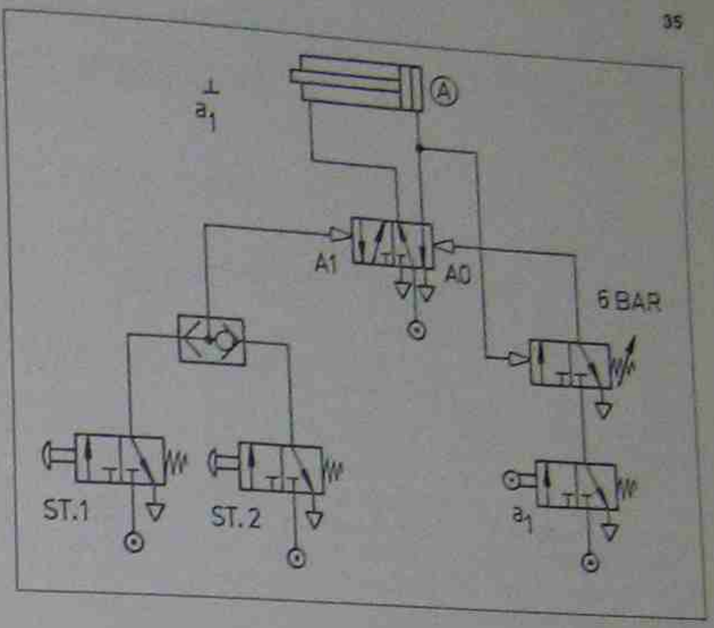


Fig. 2–50 Typical pressure sensing valve application.

Fig. 2–51 The actuator retracts automatically when position a_1 and an extension pressure of 600 kPa (6 bar) is reached.



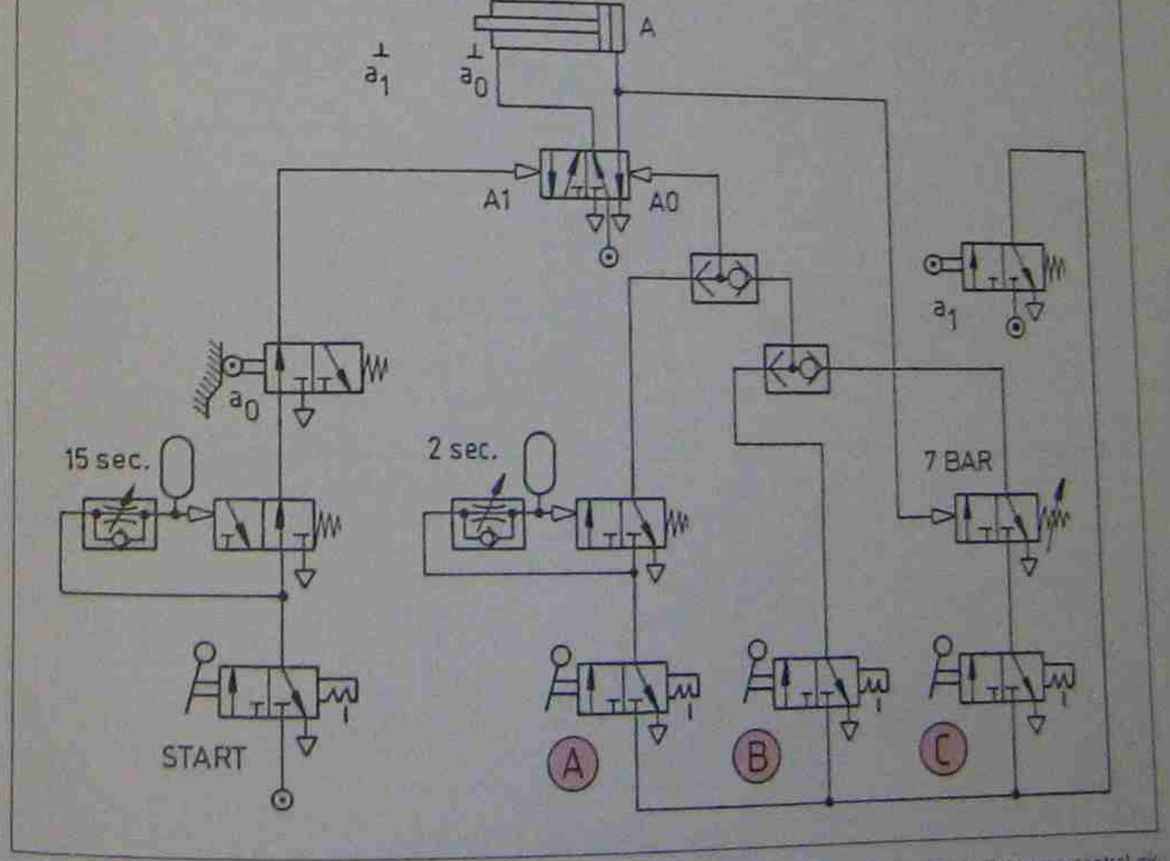


Fig. 2–52 Typical example where position sensing, time sensing and pressure sensing are applied in the same control circuit.

3 Linear actuators (cylinders)

Pneumatic linear actuators are used to convert the stored (static) energy of compressed air into linear mechanical force or motion. Although the actuator itself produces linear motion, a variety of mechanical linkages and devices may be attached to it to produce a final output force which is rotary, semi-rotary or a combination of linear and rotary. Levers and linkages may also be attached to achieve force multiplication or force reduction as well as an increase or reduction of motion speed (fig. 3-1).

The main parts of a pneumatic linear actuator are shown in figs. 3-2 and 3-5. A variety of refinements, additions and options can be added to this basic actuator to achieve a diversity of engineering features (figs. 3-6, 3-8, 3-10, 3-12 and 3-14). The generation of linear thrust force with a pneumatic actuator is very simple and direct. The compressed air when delivered to one end of the actuator, acts against the piston area and produces a force against the piston (force = pressure × area). The piston with the attached piston rod starts to move in linear direction as long as the reacting force is smaller. The developed force is used to move a load which may be attached either to the protruding piston rod or to the actuator housing (fig. 3-1). The distance through which the piston travels is known as the stroke.

Single acting actuators

Single acting actuators produce pneumatic force in one direction only. These actuators may be mounted in vertical direction, thus permitting the previously moved or lifted load to return the piston to its initial position. When the actuator must be mounted horizontally or when no external force can be used to return the piston, then an inbuilt spring is used to cause retraction or return of the piston (fig. 3-2).

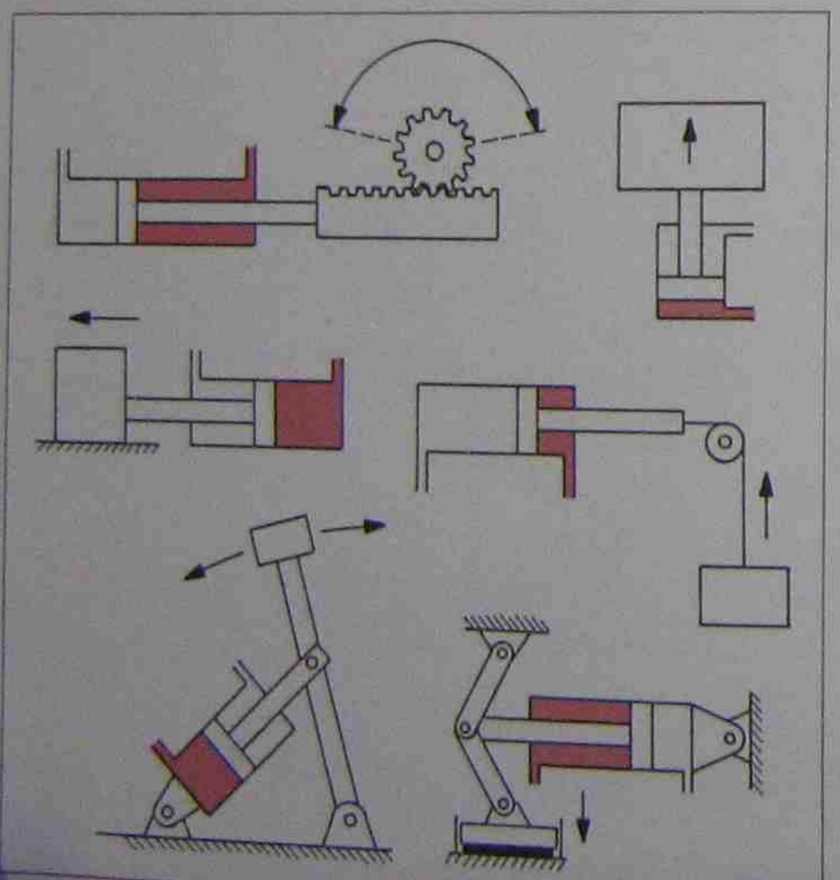


Fig. 3-1 Linkages and loads attached to linear actuators.

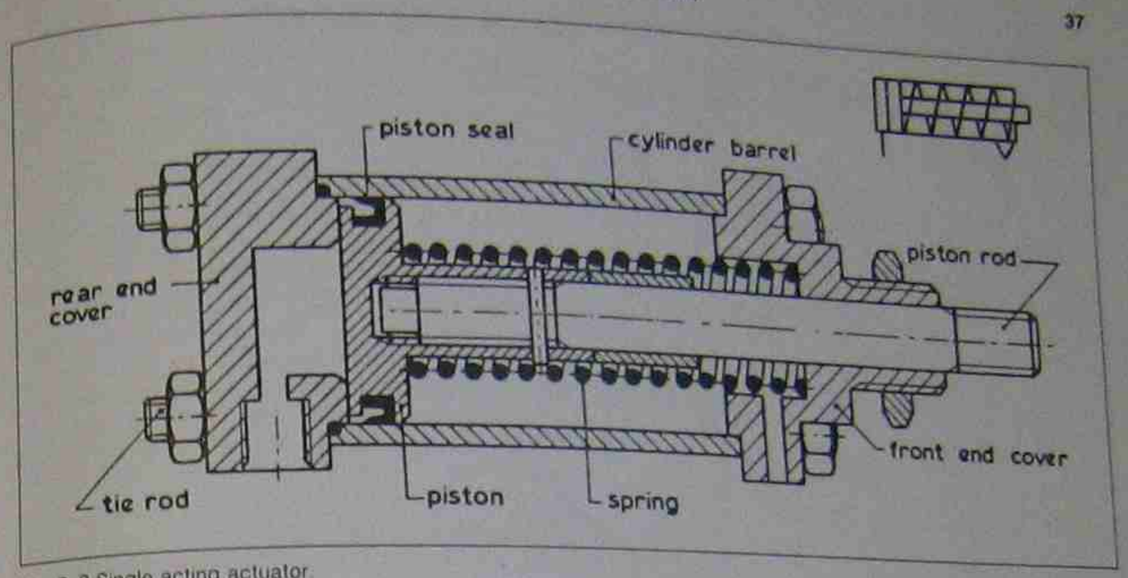


Fig. 3-2 Single acting actuator.

When using a single acting actuator the force available from the air operated stroke is reduced by the opposing spring force. It must also be borne in mind, that the force due to the spring compression is progressively decreasing along its stroke. Single acting actuators are usually built with a stroke length up to 100 mm.

Some manufacturers of pneumatic actuators make a special type of single acting actuator, called a short stroke clamping cylinder or diaphragm actuator. These actuators have extremely short strokes ranging from 1 to 10 mm and piston areas ranging from 100 to 3000 mm^2, whereby the large piston (diaphragm) actuators normally have the extremely short strokes of 1 to 2 mm.

Such clamping actuators are normally retracted by either an inbuilt spring or by the pre-tensioned diaphragm (fig. 3-3).

A very special type of single acting actuator is the air bag. The air bag actuator consists of a flexible "bellow" (or bellows) made from plies of nylon reinforced cord, encased by neoprene rubber. The cord is meant to provide a restraining effect as pressure is applied and helps to maintain the effective area of the internal air column, which provides the thrust when filled with compressed air. The bellows may be made in single, double or triple convolutions. "Girdle hoops" of metal or metal wire covered with rubber, provide additional restraint on multiple bellow types (fig. 3-4).

Metal end pieces are attached to the top and bottom of the bellow(s) and the air enters and exhausts through a port in the end piece. Manufacturers of air bags provide performance charts that contain such information as: useable stroke length, load-carrying capacity related to stroke and air pressure, air volume at various stages of inflation, and mounting methods. The main applications are heavy duty lifting, logging industry, air presses, isolation of vibration, cause of vibration, shock absorption and clamping.

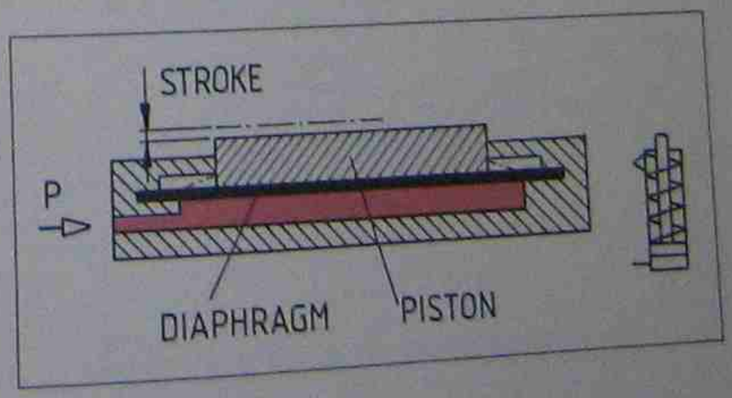


Fig. 3-3 Diaphragm actuator.

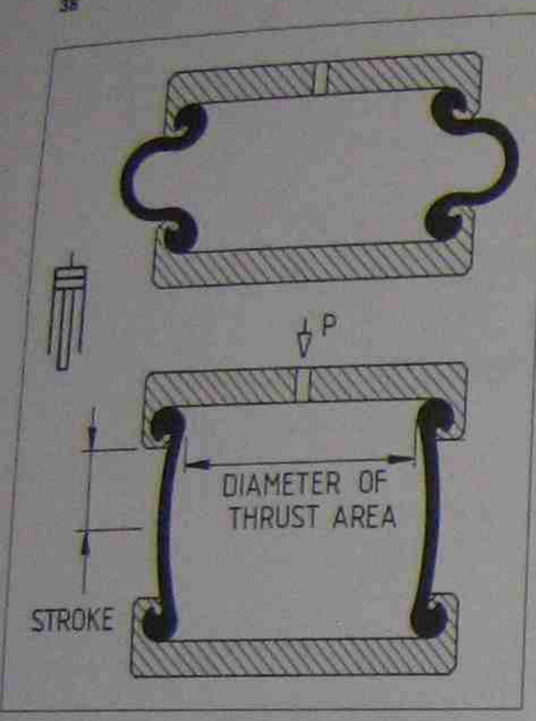
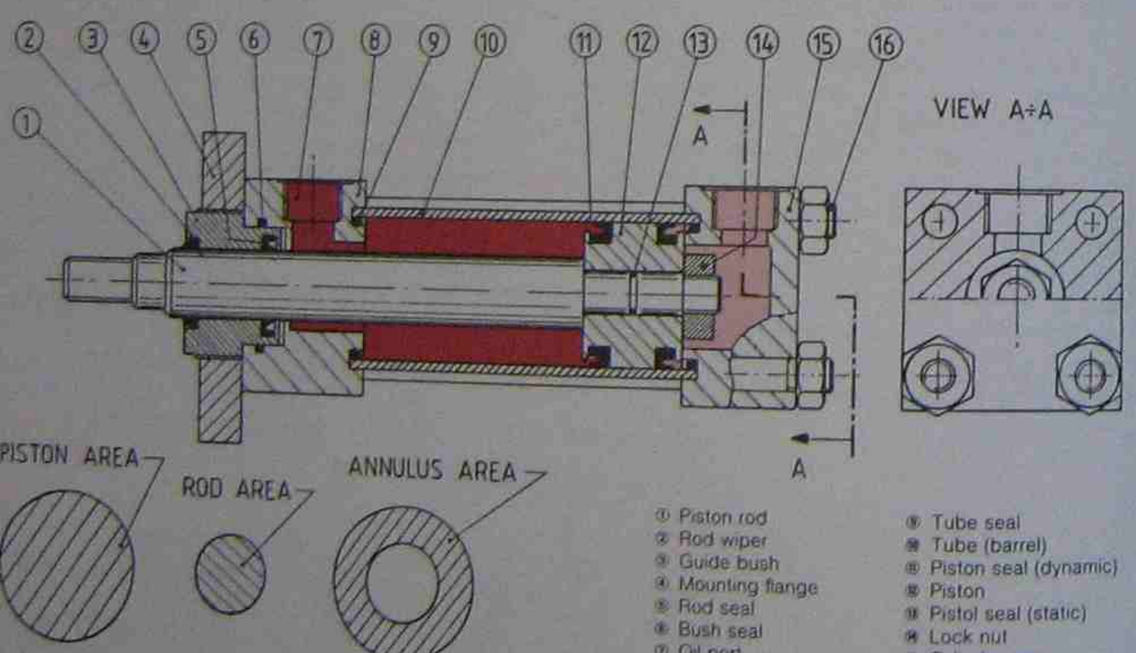


Fig. 3-4 Air bag

Double acting actuators

Double acting actuators permit the application of pneumatic force in both stroke directions. However, the retraction stroke develops a much smaller force than the extension stroke, since the compressed air acts on a smaller area known as the annular area (fig. 3-5).

Double-ended actuators with rods protruding on both actuator ends are used where the developed force must be equal for both piston-rod movement directions (extension and retraction). Since the voids to be filled with compressed air are equal for extension and retraction, the resulting piston speeds are also equal for both strokes. Double ended actuators provide also better piston rod guidance since loads are borne over two bearing bushes; one on each actuator end (fig. 3-6). Double ended actuators may also prove advantageous where the limit valves (position sequence valves) or electrical limit switches cannot be placed near the reciprocating piston rod. This may be the case where the transported load moves in a hostile environment, or in an area of extreme heat, or in a liquid. In such a case, the rear piston rod is used to actuate the limit valves and the front piston rod moves the load (fig. 3-7).



3-5 Pneumatic linear actuator (cylinder).

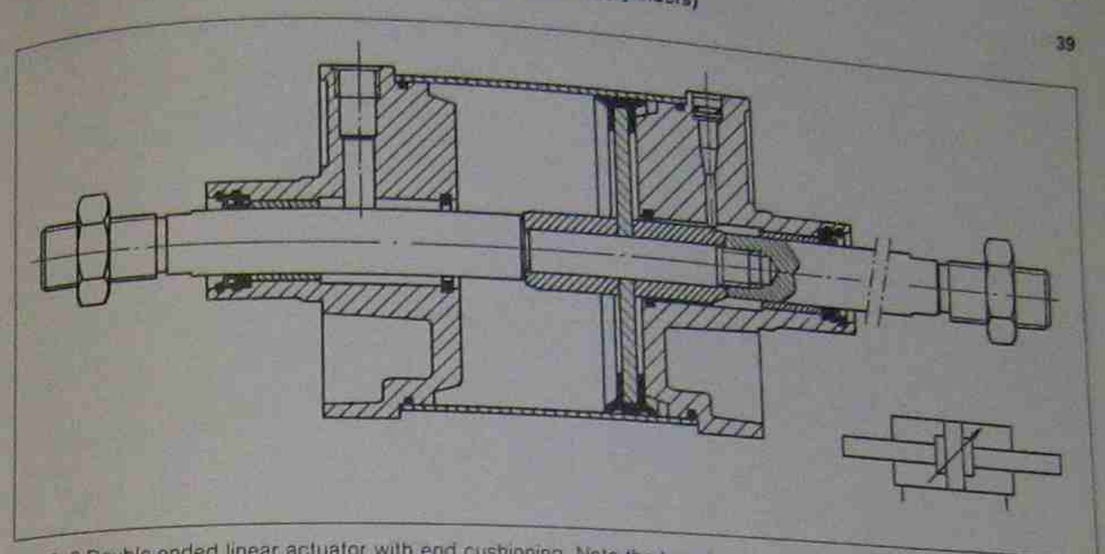


Fig. 3-6 Double-ended linear actuator with end cushioning. Note the two piston rods.

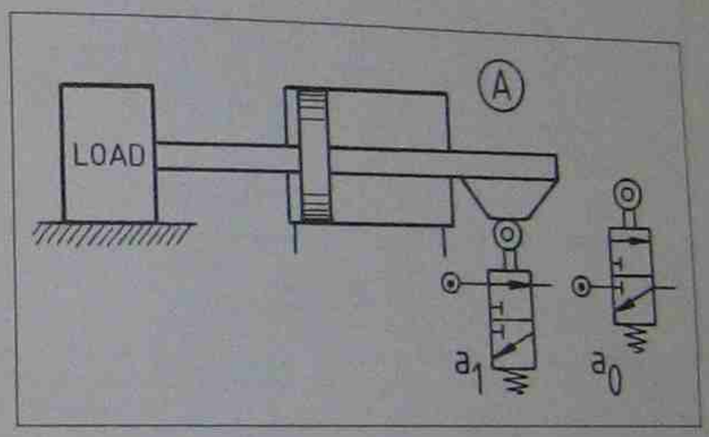


Fig. 3-7 Actuator with rear rod actuating the limit valves.

Pneumatic end-position cushioning

Pneumatic end-position cushioning (simply called cushioning) refers to the controlled deceleration of the mass in motion during its final part of the actuator stroke. The kinetic energy released on impact at the stroke end must be absorbed by the internal stroke limit stops. These stops are usually a protruding bush which is an extended part of the end caps. Their capacity to absorb shocks depends entirely on the elasticity of their material. On some actuator types the rubber seal shoulder of the piston seal is used to absorb the shock (fig. 3-6); other designs use a rubber or plastic ring embedded into the endcap as a shock or impact damper. For large and fast moving masses or for actuators with piston diameters above 25 mm a pneumatic end-cushioning is recommended. Figure 3-8 shows a cross-section of a pneumatic cushioning mechanism built into the end caps of pneumatic actuators. The piston is fitted with a tapered cushioning bush (boss). When this bush enters into the air exit bore of the end cap (during the final part of the stroke), the main air exit begins to shut until it finally closes off completely. This first stage of exit flow throttling may cause an initial slight speed reduction. The remaining air in the annular cavity around the cushioning boss is now trapped and the momentum of the mass carries the piston on against the trapped air; thus compressing it to a high pressure. As the pressure due to Boyle's Law rises, the resulting resisting force forms a cushion and begins to decelerate the piston and its mass (load).

As the kinetic energy is dispelled, the mass is slowed down to a much reduced speed which matches the rate of air flow permitted and adjusted by the cushioning valve. A check valve is also built in as part of the cushioning mechanism. This check

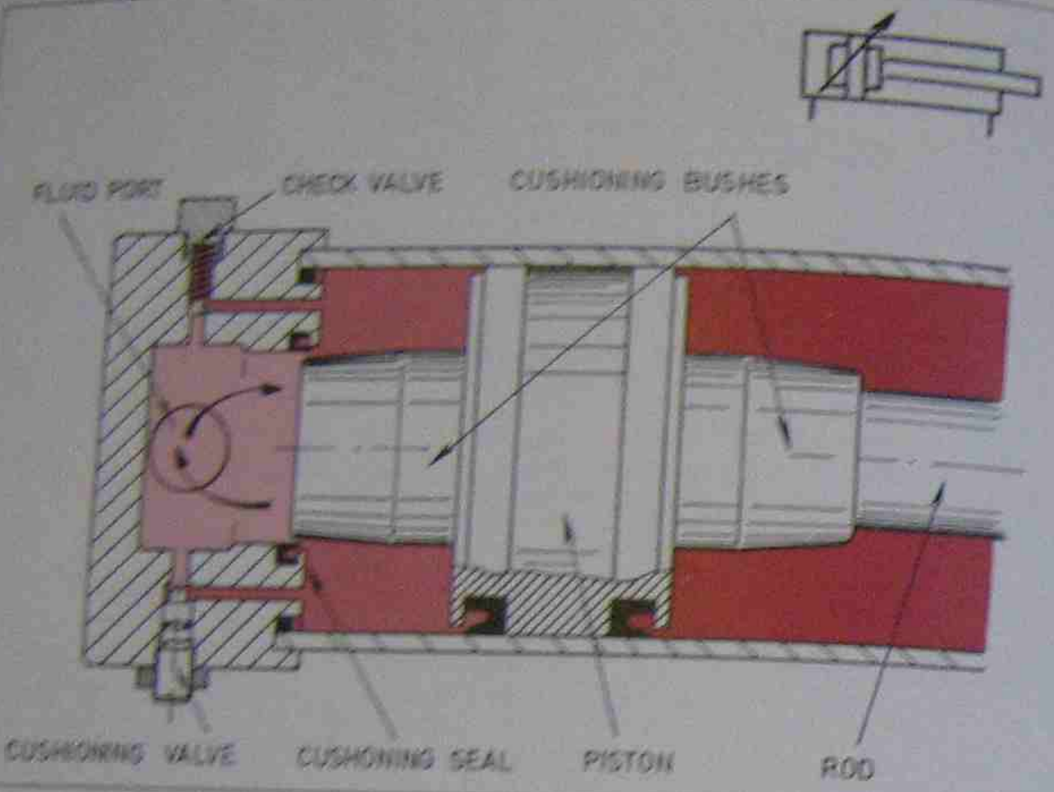


Fig. 3-8 Pneumatic end-cushioning

valve allows full air flow in reverse direction to achieve fast and full force break-away from the end position (fig. 3-8).

In order to utilize the full potential of a cushioning provision, the complete stroke length of the actuator must be used. An effective stroke under-utilization of as small as 5 mm would already diminish the cushioning effect to up to 50% and the machine stop had to bear the brunt of the impact, making the machine a noisy and self-destructive implement. If on the other hand the kinetic energy is gently dispelled, the machine can look forward to a long and trouble free life (see also cushioning curve, fig. 3-25).

Seals in linear actuators

Seals are grouped into static and dynamic applications. Static seals are fitted between two rigidly connected components. The seals between the piston rod and the piston in fig. 3-9G are static seals and so are the seals that prevent external leakage past the joint where the tube is mounted onto the endcap in fig. 3-9G and 3-9H.

Dynamic seals prevent leakage between components which move relative to each other. Therefore, dynamic seals are subject to wear, whereas static seals are essentially wear free. The seals between the moving piston and the stationary tube (barrel) are typical dynamic seals, and so are the seals that stop compressed air from escaping past the clearance gap between the moving rod and the end cap (figs. 3-9E and 3-9H). The rod wiper ring may also be regarded as a dynamic seal. It prevents contaminants from being drawn into the actuator when the rod retracts (figs. 3-9D and 3-9H). Rod wiper rings are made from extremely hard rubber to make them more wear-proof.

O-ring seals are generally used as static seals, whereas dynamic seals range from simple square rings to complex groove rings (lip seals) and specially designed and custom built double cup piston seals (fig. 3-9 and 3-6). Lip ring seals provide excellent sealing even under stationary piston conditions. When a lip ring is fitted, the lip must be slightly pre-tensioned. This alone produces satisfactory sealing even under low pressure conditions. This tension is of course increased when

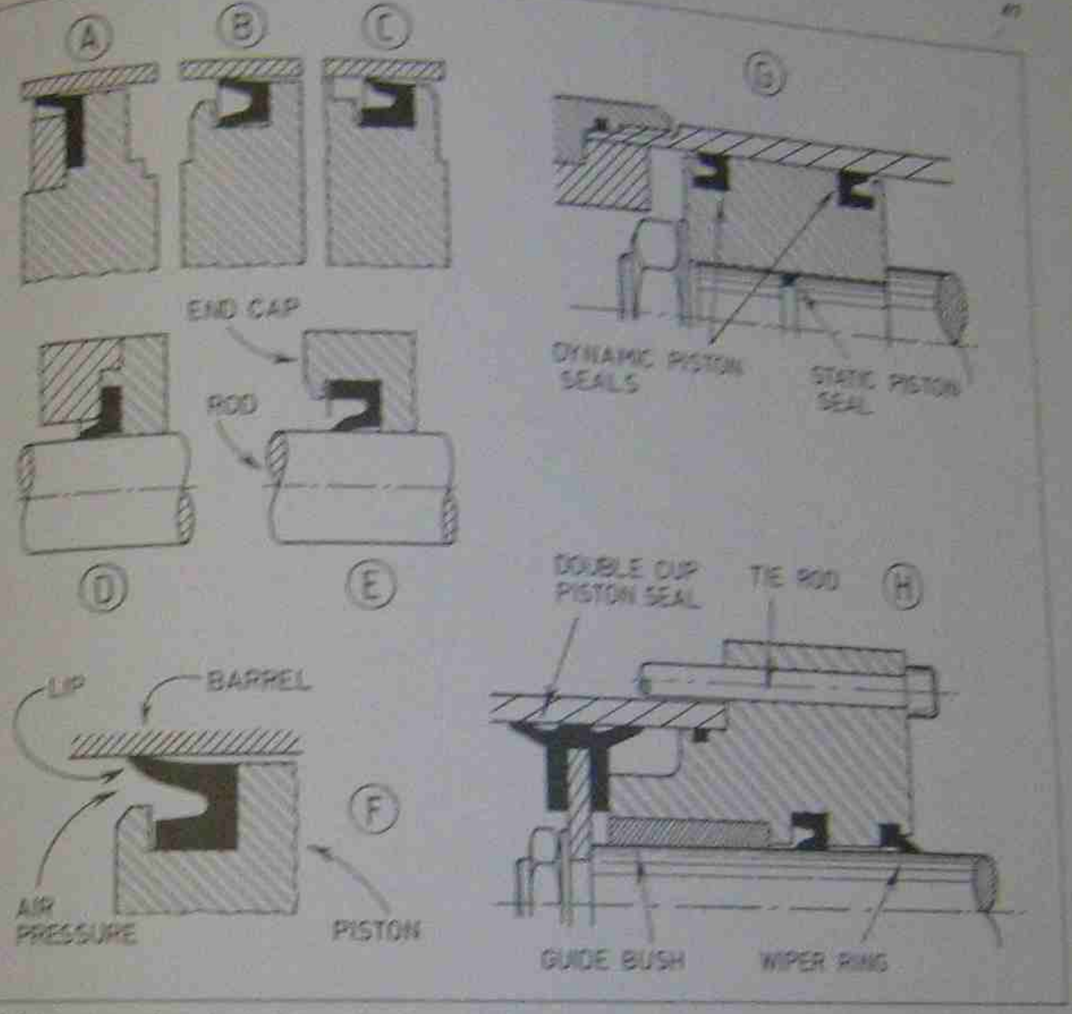


Fig. 3-9 Actuator seals and actuator construction methods

pressure increases and thus it adjusts itself for any wear occurring during its service life. Piston seals may be made from a variety of materials to suit a range of environmental conditions. Perbunan seals are suitable for temperatures from −20°C to +80°C. Viton seals range from −20°C to 190°C, and Teflon seals may be used for a temperature range from −80°C to 200°C.

Actuator construction

Pneumatic actuators are often required to work under adverse conditions. On the outside they may come into contact with abrasive or aggressive chemicals, water, extreme hot or cold temperatures, and often also with mechanical abuse. On the inside they invariably have to withstand the ever-present moisture contamination of the compressed air, and misalignment of the moving load takes its toll on the guide bush, the piston rod and the piston seals (figs. 3-5, 3-9).

Therefore, pistons, end caps, cylinder barrels and actuator mountings are either made from aluminium alloys, stainless steel, brass or plastics. Piston rods are fabricated from either stainless steel or hard chromium plated high-tensile steel. Guide bushes or linear-bearing bushes are made from brass, bronze, nylon, P.T.F.E., or self-lubricating (graphite impregnated) metals. More recent trends in material selection are yielding to the ever increasing demand for non-lubricated air, thus plastics are more frequently used and on some linear actuators today the only metal part to be found is the stainless steel piston rod.

The actuator end caps (fig. 3-10G) are either

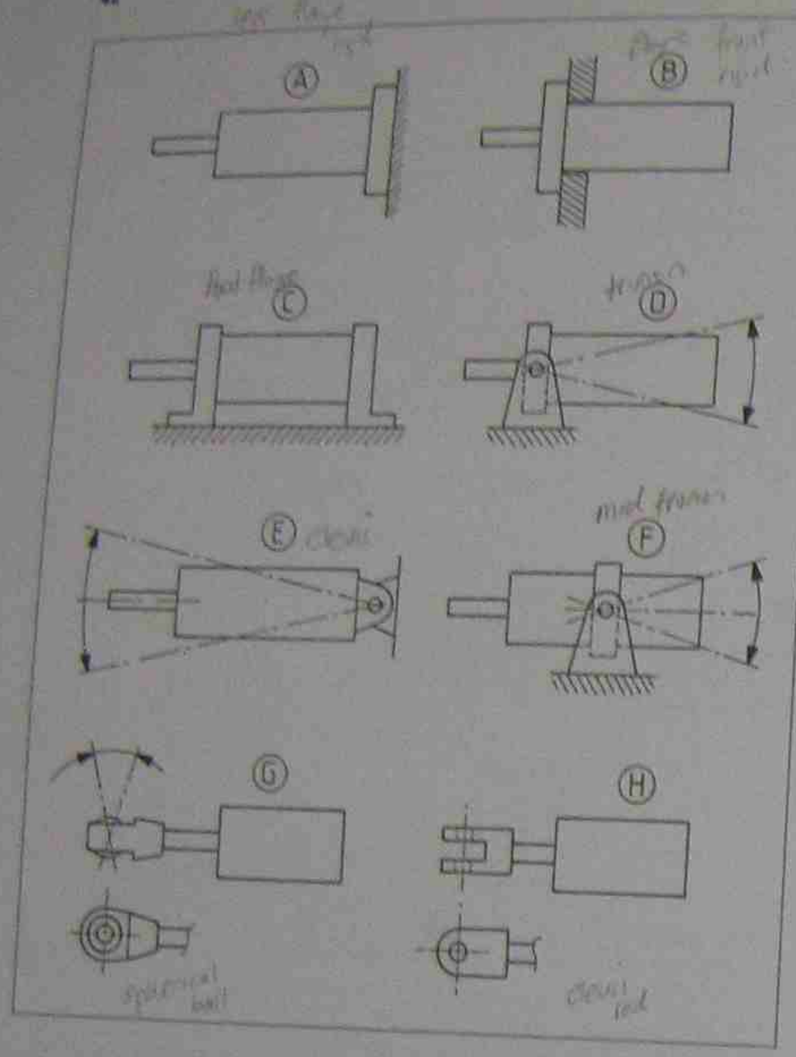


Fig. 3-10 Various kinds of actuator mounting methods.

screwed onto the cylinder barrel or, on cheaper actuators, the barrel may be crimped onto the end caps. With larger actuators tie-rods may be used to hold the end caps against the cylinder barrel. On smaller actuators stroke cushioning pads are embedded into the end caps and on larger actuators pneumatic end cushioning is standard equipment. For actuator mounting methods see figures 3-1 and 3-10.

Actuator failure

Standard type actuators are not designed to absorb piston rod side loading. Thus actuators must be mounted with care and accuracy, to ensure that the load moves precisely parallel and in alignment with the actuator centreline (fig. 3-11).

For many applications the piston rod is best fitted with a clevis or a spherical bearing rod-eye (fig. 3-10H and 3-10G) or the actuator must be allowed to swivel around a trunion mount, permitting it to swing as the direction of the load changes. A self aligning piston-rod coupling can also be used to compensate for both angular and radial misalignment, but the angular misalignment must not exceed 4°C in either direction and the radial alignment must not be more than 1 mm out (fig. 3-12).

Failure of the rod bearing (guide bush, fig. 3-9H) usually occurs when side load is not detected early enough or cannot be avoided. In such cases one may use a double ended piston rod type actuator (fig. 3-6), or an actuator with oversize piston rod which is less flexing than a standard size piston rod.

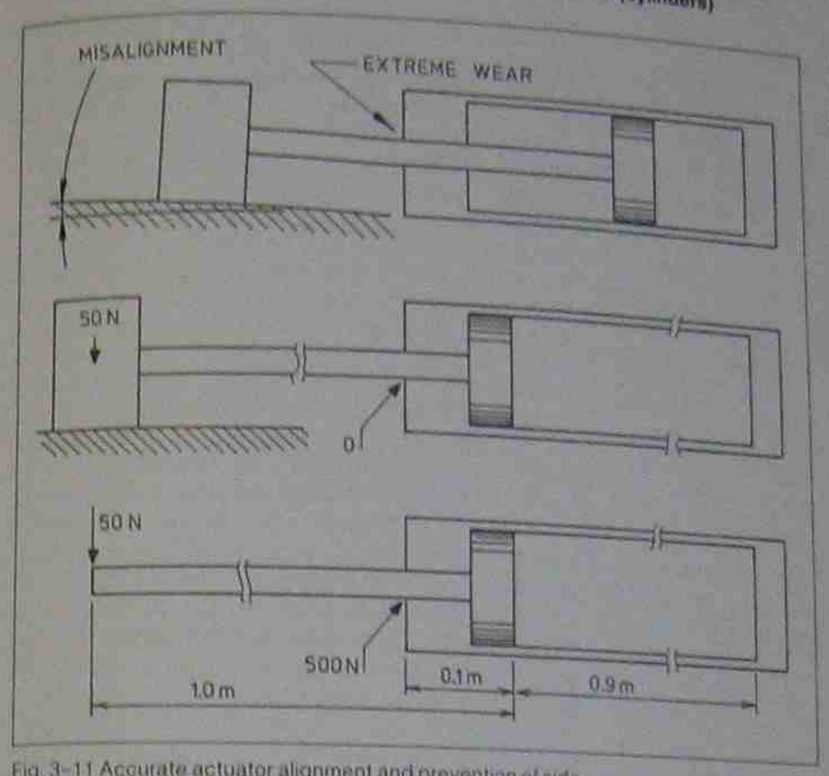


Fig. 3-11 Accurate actuator alignment and prevention of side-load.

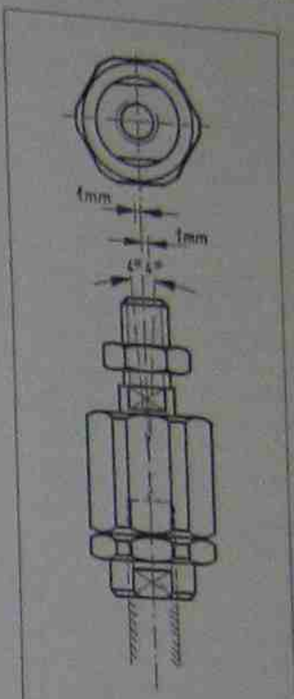


Fig. 3-12 Self-aligning piston rod coupling.

Special actuators

In pneumatic control systems one may find many special types of actuators built to perform in a unique situation to gain optimal mechanical advantage, force output, speed and impact control. The symbols for these actuators are depicted in fig. 3-13. The last three symbols are not standardised but may be used until adopted into the catalogue of international standardisation.

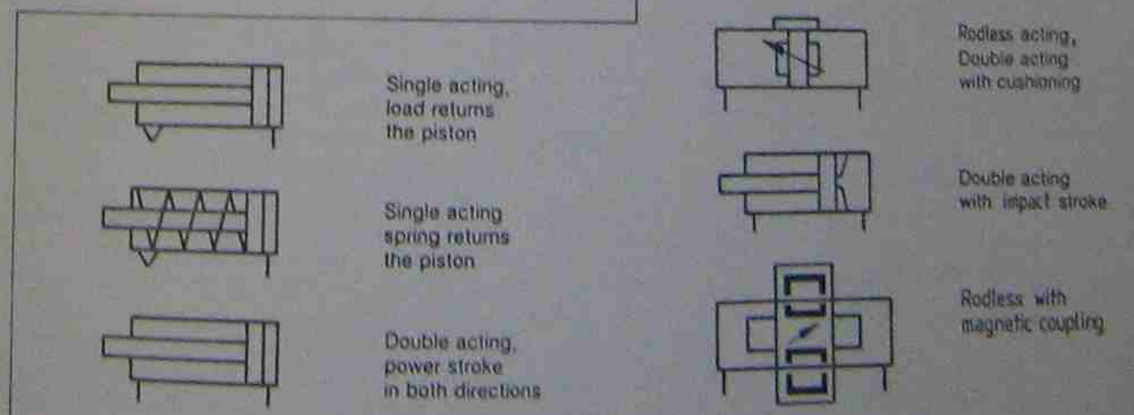


Fig. 3-13

Impact cylinder (special actuator)

For work functions requiring a sharp and massive impact force similar to that of a hammer, the *impact cylinder* has been developed. Its high kinetic energy is only developed during the extension stroke and is based on the formula:

$$E = \frac{(m \times v^2)}{2}$$

The mass (m) is a heavy duty piston rod about twice as thick as a normal piston rod and a heavy duty piston (fig. 3–14). In the start position air pressure acts onto the underside of the piston and when the power valve is changed over, a pressure (p_2) starts to build up in chamber A, which acts onto piston area A1. Simultaneously the air pressure in chamber B is being exhausted. As long as the piston is held against its upper end cap, the pressure exposed piston area (A1) is only about 1/9 of the annular area below. The piston will therefore not start to move down until the pressure in chamber B has fallen to below 1/9 of the pressure in chamber A. As soon as the piston starts moving downwards, the high system pressure in chamber A starts to act onto the now fully exposed upper piston area which is by now nine times larger than the previously, partially covered upper piston area. This causes an extremely sudden and great increase in force and results in a high acceleration of the mass of its piston and rod. The extent of this acceleration is governed by the pressure acting onto the full piston area and the resistance against the accelerating mass. After about 50 mm of piston travel, the piston will reach a speed of about 5 m/s. This is also the beginning of the work stroke. The speed will increase (if the moving mass is unopposed) and may reach a maximum speed of about 6–7 m/s at 75 mm of piston travel. The *kinetic energy* is governed by the velocity of the mass (see given formula); thus the first 50 to 75 mm should be a free and unopposed piston travel, and the work stroke should fall between 50 and 75 mm of the piston travel. Every impact cylinder has besides its acceleration and work-stroke travel also an overtravel distance, through which deceleration and impact cushioning takes place (see also impact cylinder calculation example).

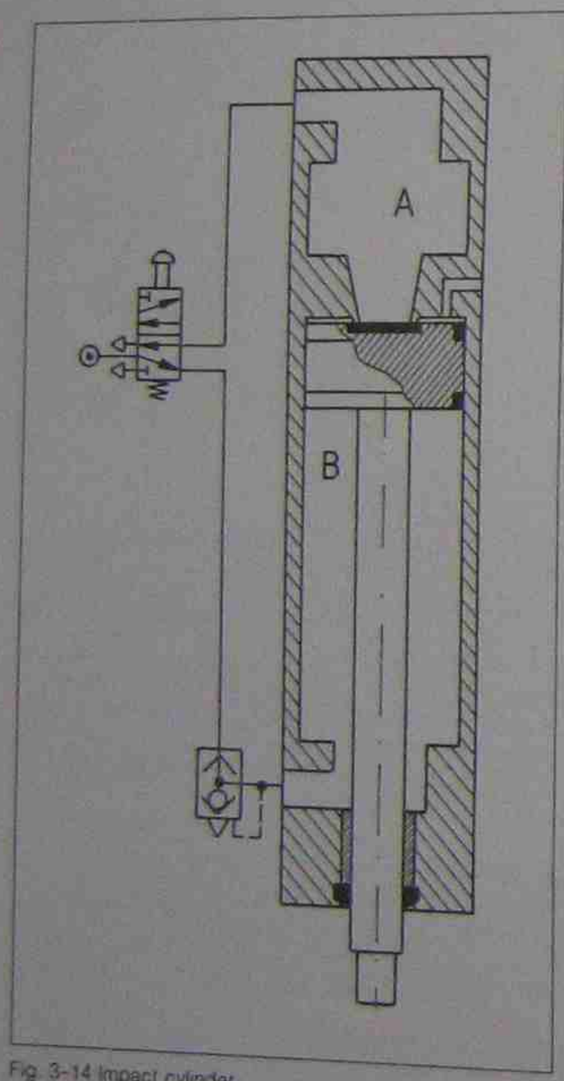


Fig. 3–14 Impact cylinder.

Rodless actuators

Few pneumatic devices have enjoyed such immediate success and widespread application as the rodless actuator. An ingenious design eliminates the piston rod and cuts installation length almost to half compared to conventional double acting linear actuators. Presently, there are four design types of rodless actuators available.

With the "FESTO" rodless actuator, a strong magnetic coupling transmits the force from the moving piston assembly inside the stainless steel tube to the guided carriage sleeve on the outside of the tube. Permanent magnets are embedded into both the piston assembly and the outer carriage sleeve. Together these magnets in the piston and in the carriage create a strong force field which acts through the fully closed actuator tube and holds them together. Thus piston and carriage move in unity along the guiding actuator tube when compressed air is applied to either end of the piston (fig. 3–15). To reduce friction the carriage sleeve slides along on nylon bearing liners, and bearing liners also guide the piston assembly which slides on the inside of the tube. Thus the magnets never "touch" the tube.

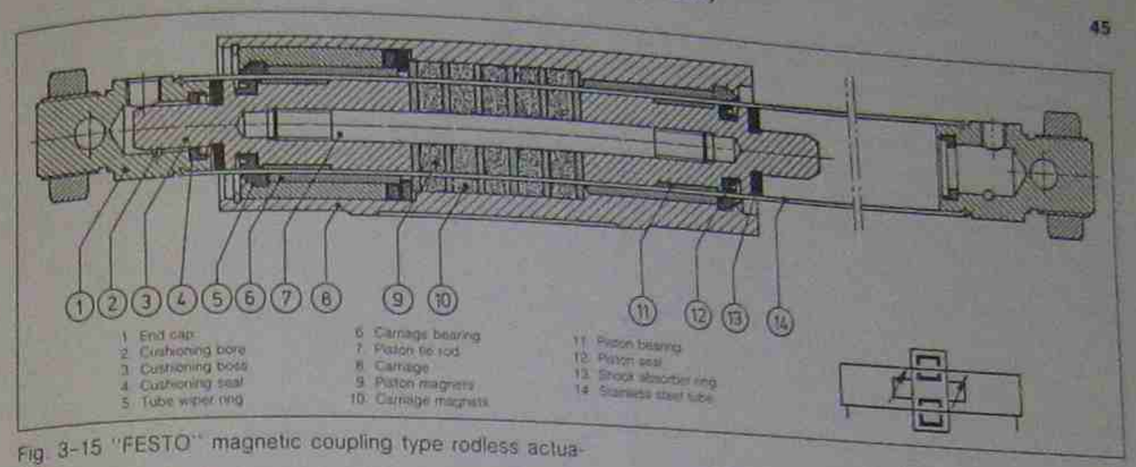


Fig. 3–15 "FESTO" magnetic coupling type rodless actuator.

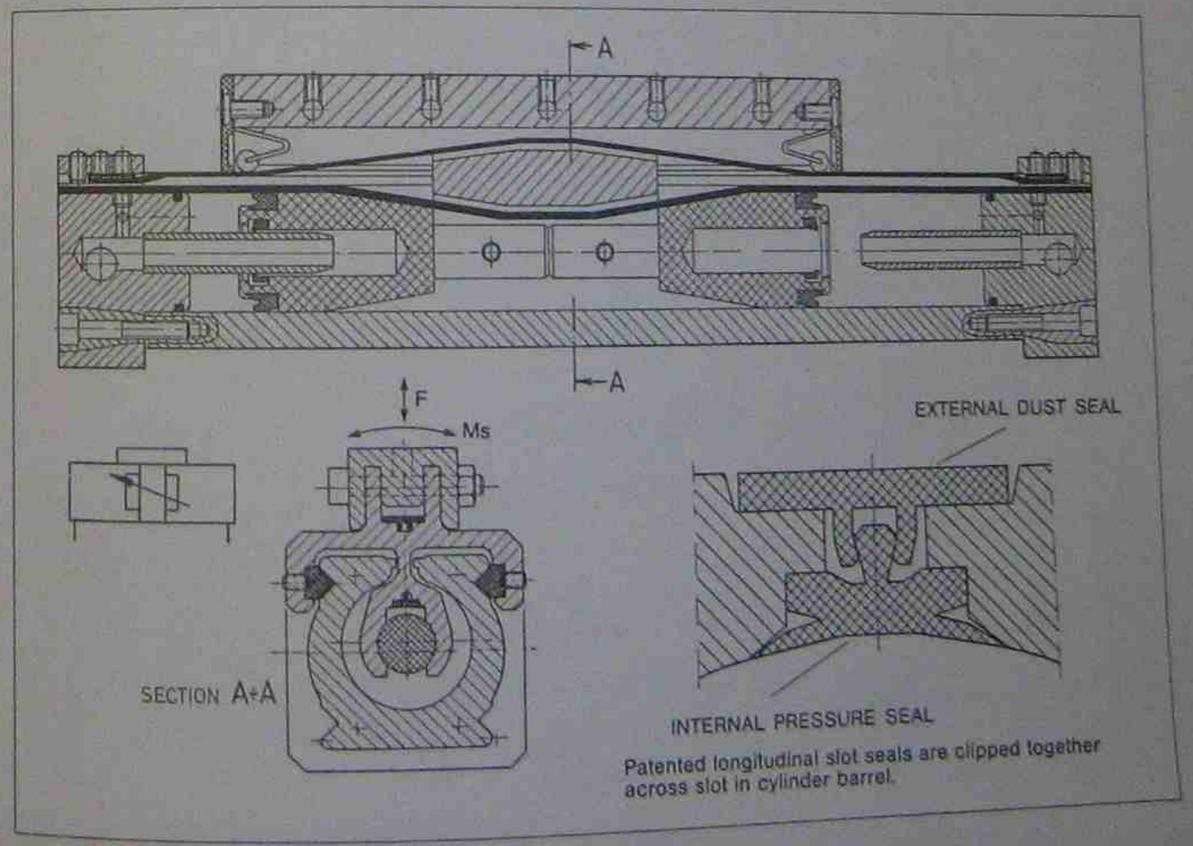
"FESTO" rodless actuators are built for piston diameters ranging from 16 to 40 mm and stroke lengths from 50 to 4000 mm. These actuators travel with extremely high speed (3 m/s) and thus come with standard built-in pneumatic cushioning. The magnetic rodless actuator offers a range of impressive advantages:

- Absolutely no leakage and hence the system is cheaper to operate and can be used with non-lubricated air.
- The actuator tube is hermetically sealed (no slot) and thus no dirt can enter the system from outside. This ensures trouble-free operation.
- The carriage can rotate around the stainless steel tube. This may prove advantageous for certain machine applications.

However, it must be noted that excessive pressure or force beyond 1.6 times the stated maximum output force may cause the carriage to break away from its magnetic coupling. But, should the coupling part, it can easily be united without dismantling the actuator.

The "LINTRA" rodless actuator consists of a slotted aluminium tube (barrel) with its longitudinal

Fig. 3–16 "LINTRA" rodless actuator.



pressure and dirt slot seal bands, a piston assembly that is connected through the slot to the outside carriage, and end covers for sealing the tube (fig. 3-16). The rodless piston with its two lip seals at each end runs inside the slotted aluminium extrusion tube and is sealed with two patented seal strips that prevent leakage and dirt ingression. The carriage onto which the load is attached runs externally and is guided on "V" slots extruded in the barrel.

The "LINTRA" rodless actuator sold by "MARTONAIR" offers an impressive range of advantages over standard double acting actuators and other brands of rodless actuators:

- The extrusion construction of the aluminium barrel allows high bending moments and transverse forces.
- The integrated adjustable guide system offers maximum simplicity as separate carriage guidance is not required.
- The rigidity of the aluminium extrusion barrel allows stroke lengths up to 10 m (10000 mm)!
- The unique sealing strip closure concept guarantees leak proof, long life sealing performance.
- The actuator can safely operate with air pressures up to 1000 kPa (10 bar), giving thrust forces up to 2650 newtons with a 63 mm piston.

With the "ORIGA" rodless actuator principle, force from the moving piston is transferred to the carriage by means of a piston yoke that slides along the barrel slot (similar to the "LINTRA" actuator principle). Its slot seal, also claiming to be absolutely free of air leaks, consists of a thin steel strip on the inside of the tube and a dust or dirt seal strip on the outside of the tube. Both steel strips pass through the piston yoke, which separates them as the piston slides along, and closes them again and forces them against a holding magnet attached to the barrel slot. The air inlet holes are located in the end-caps and so are the end-cushioning bushes.

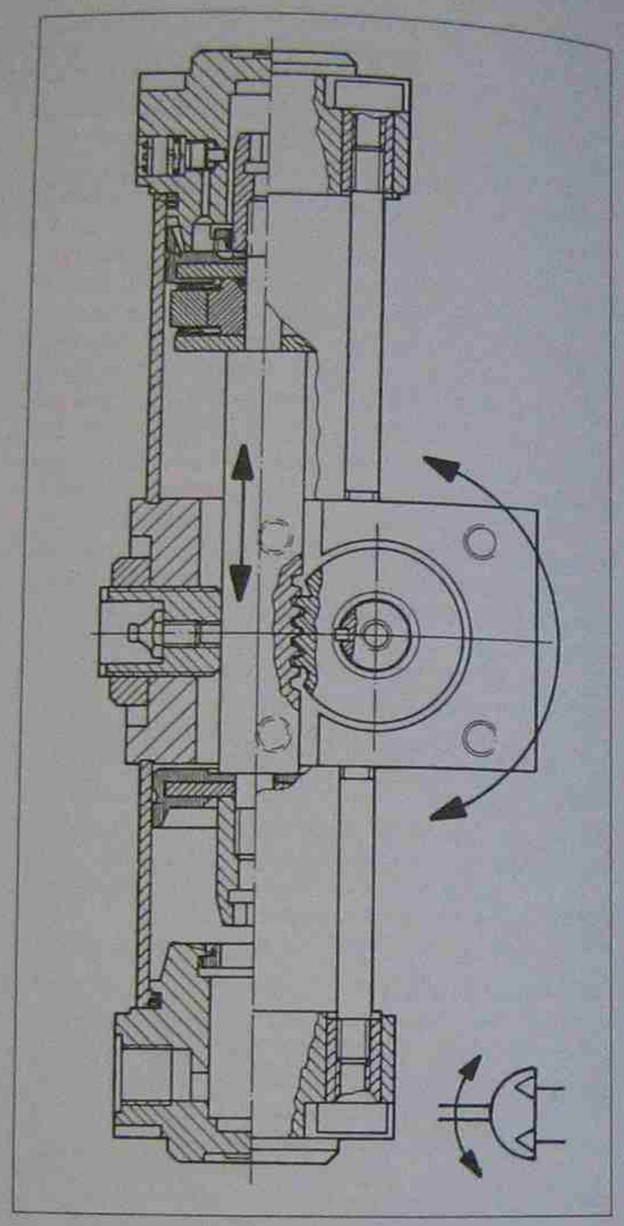


Fig. 3-18 "Bosch" swivel actuator.

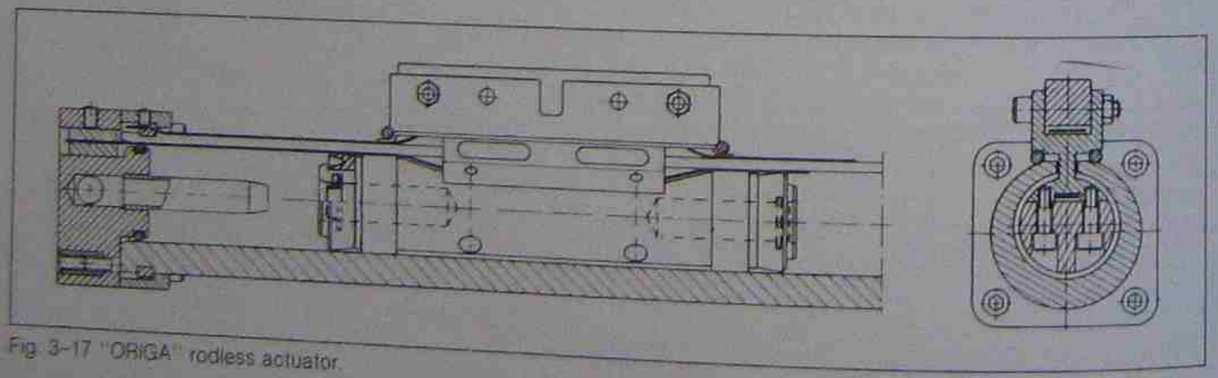


Fig. 3-17 "ORIGA" rodless actuator.

The "ORIGA" rodless actuator is extremely rigid due to its extruded type barrel construction and provides a maximum force output of 2600 newtons with a piston diameter of 80 mm at a maximum air pressure of 800 kPa (8 bar). "ORIGA" actuators are made with 80, 63 and 40 mm piston diameter and a maximum travel distance of 7000 mm (fig. 3-17).

Swivel Actuator

The swivel actuator is a linear actuator with a rack and pinion drive mechanism sandwiched between its two pistons. The angle of rotation can be chosen from 90° to 360°. These actuators are excellently suited for limited swivel action and are built with piston diameters from 32 to 100 mm and a torque range of 0.9 Nm to 23.5 Nm per 100 kPa (1 bar) pressure. Thus a 100 mm piston type actuator provides 235 Nm at 10 bar minimal system pressure. These actuators may also be ordered with or without pneumatic endcushioning (fig. 3-18).

Locking units for pneumatic actuators

Due to the compressibility of air, the locking of an actuator in any desired position between the two stroke limits has proved to be very unsatisfactory.

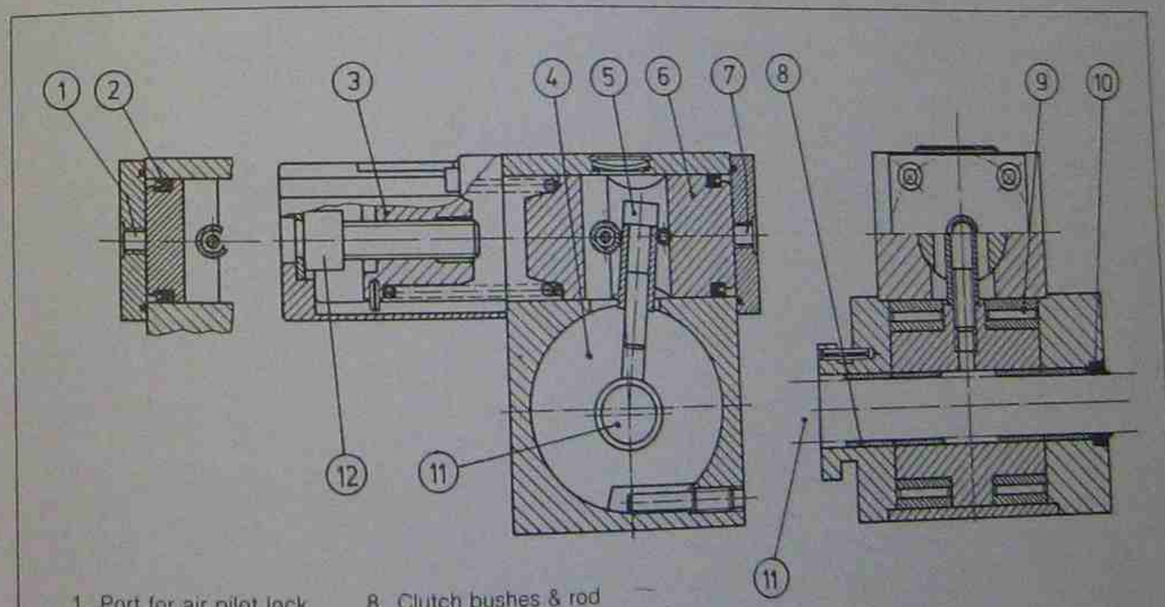
Mechanical locking units can hold any rod shaped mechanical part, especially piston rods of pneumatic actuators in any required stroke position. The locking unit can hold the piston rod absolutely creep free even when full system pressure is applied onto the piston. This means that it is also able to support a load of corresponding size to the full actuator force absolutely firm, regardless of direction. If when a locking unit is gripping a piston rod, pressure is also applied to the underside of the piston, it is possible to support a load which is nearly twice the normal load force. The locking unit described here may either be used with spring force locking and pneumatic pilot signal release or with pneumatic pilot signal locking and pneumatic pilot signal release (fig. 3-19).

Actuator sizing

The main criteria on which the size of a linear pneumatic actuator is based are:

- Force output for extension and retraction;
- Piston speed for extension and retraction;
- Impact cushioning at the end of the piston stroke;
- Mechanical stability of the piston rod.

The first three listed items are very complex to calculate, since they depend on a number of basic



1. Port for air pilot lock
2. Locking piston
3. Spring tensioner bush
4. Excenter bush
5. Locking pin
6. Unlocking piston
7. Port for air pilot release
8. Clutch bushes & rod guide
9. Excenter bearing
10. Rod wiper
11. Piston rod
12. Spring tensioner screen

Fig. 3-19 "Bosch" pneumatic rod locking unit.

concepts such as Boyle's Law, Pascal's Law, Amonton's Law, Flow of compressed air through a nozzle discharging to atmosphere, and finally friction and mass of the load as well as its direction of motion. Therefore each of these items is developed separately and explained in detail.

Calculation of external forces (load)

The load which the pneumatic actuator has to move can be separated into the lifting force, the friction force of the load, and the force required to accelerate the mass.

The lifting force depends on the mass (m) to be moved and the inclination angle (α) on which the mass is moved (fig. 3-20). Thus the lifting force (F_L) is calculated as follows:

$$F_L = m \times g \times \sin \alpha$$

If the mass is to be lifted vertically then the formula is:

$$F_L = m \times g \quad \text{(for g use 9.81)}$$

The friction force (F_F) depends on the force developed by the mass and the contact surface condition of the mass where it rests against the bearing surface, and the bearing surface below that mass (fig. 3-20).

If the two contacting surfaces produce low friction (due to finely machined surfaces and good lubrication), then the friction coefficient μ will be low. Conversely, if the two contacting surfaces produce high friction then the friction coefficient will also be high. The frictional force for a mass movement in the horizontal direction is calculated as follows:

$$F_F = m \times g \times \mu \quad \text{(for g use 9.81)}$$

The friction force for a mass movement in an inclined direction (other than horizontal) is calculated as follows:

$$F_F = m \times g \times \mu \times \cos \alpha \quad \text{(for g use 9.81)}$$

The force required to accelerate the mass (m) is also important for actuator calculations. This force, called inertia force (Fm), depends on the mass (m) to be accelerated, the stationary speed (v) which is obtained after acceleration stops (fig. 3-25), and the distance (s) over which the acceleration takes place. Assuming a constant acceleration (a) the formula to be used is:

$$F_m = m \times a \quad \left(a = \frac{v^2}{2 \times s} = m/s^2\right)$$

Thus the total force of all forces encountered by

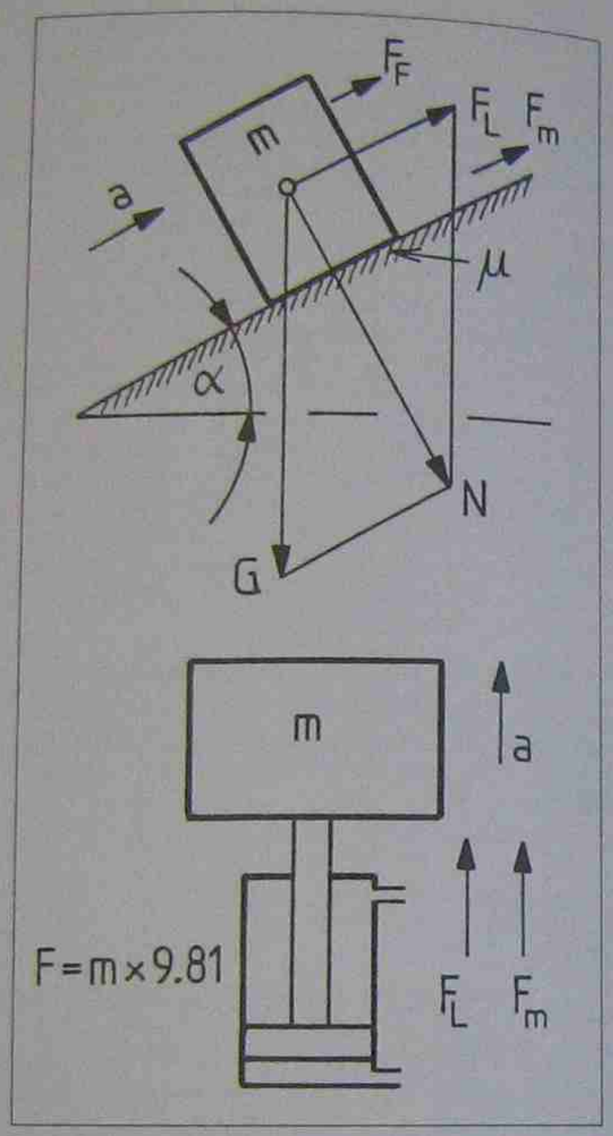


Fig. 3-20 External forces on the actuator.

the actuator piston, excluding frictional forces inside the actuator, is:

$$F_{TOT} = F_L + F_F + F_m$$

For an actuator which has to move a load supported or suspended by its piston rod, the calculation of the total force is simply: $F_{TOT} = m \times g$.

For an actuator moving a load in perfect horizontal direction the total force is: $F_{TOT} = m \times g \times \mu$. But both of these cases did not consider the inertia force for mass acceleration. Thus if only moderate acceleration is required, the inertia force (F_m) should be included when calculation of the total force is made.

Static thrust force calculations

The static thrust or pull can only be used for clamping actuators which usually have a very short stroke and produce no work until the component to be clamped is contacted. For such calculations the force produced is the product of the minimal system pressure times the effective piston area (fig. 3-21). The basic formula to calculate theoretical actuator force output (N), required system pressure (Pa), and effective piston area (m^2), can be presented in a simple triangular illustration (fig. 3-21). The letter F stands for force, the letter p for pressure, and the letter A for the effective piston area.

- Force = Pressure × Area → $N = Pa \times m^2$
- Pressure = $\frac{\text{Force}}{\text{Area}} \rightarrow Pa = \frac{N}{m^2}$
- Area = $\frac{\text{Force}}{\text{Pressure}} \rightarrow m^2 = \frac{N}{Pa}$

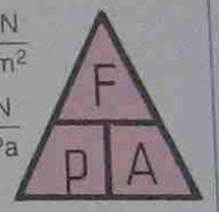


Fig. 3-21 Force-pressure-area relationship.

Three different formulae may be used to calculate piston area, these are:

$$\text{Area} = d^2 \times 0.7854 \quad = \frac{\pi \times d^2}{4} \quad = \pi \times r^2$$

If friction is to be included, the basic formula for force output is:

$$\text{Force} = \text{Pressure} \times \text{Effective Area} \times \frac{\text{Efficiency}}{100}$$

$$N = \frac{Pa \times m^2 \times \eta}{100}$$

Therefore:

$$\text{Force}_{(\text{EXTENSION})} = \frac{Pa \times d^2 \times 0.7854 \times \eta}{100}$$

$$\text{Force}_{(\text{RETRACTION})} = \frac{Pa \times (d_p^2 - d_r^2) \times 0.7854 \times \eta}{100}$$

where:

d_p = diameter of the piston (m)

d_r = diameter of the rod (m), and

η = mechanical efficiency (%)

Efficiency (%) = 100% force – friction loss (%)

The chart in fig. 3-22 shows an array of effective piston forces for "BOSCH" actuators. These fig-

dia. Cylinder	dia. Piston rod	Piston area A (cm²)		Effective force (N) at p (bar)															
				3		4		5		6		7		8		9		10	
		●	○	●	○	●	○	●	○	●	○	●	○	●	○	●	○	●	○
10	4	0,8	0,66	21	17	28	21	35	29	42	35	49	41	56	46	63	52	70	58
12	6	1,1	0,8	29	22	39	30	48	37	58	45	68	52	77	60	87	67	97	75
16	6	2,0	1,73	53	46	70	61	88	76	106	91	123	107	141	122	158	137	176	152
20	8	3,1	2,6	82	69	109	92	136	114	164	137	191	160	218	183	246	206	273	229
25	10	4,9	4,1	129	108	172	144	216	180	259	216	302	253	345	289	388	325	431	361
32	12	8,0	6,9	212	182	282	243	352	304	422	364	493	425	563	486	634	546	704	607
40	16	12,6	10,6	333	280	444	373	554	466	665	560	776	653	887	746	998	840	1109	933
50	20	19,6	16,5	517	436	690	581	862	726	1035	871	1207	1016	1380	1162	1552	1307	1725	1452
63	20	31,1	28,0	824	739	1098	986	1373	1232	1647	1478	1923	1725	2196	1971	2471	2218	2746	2464
80	25	50,0	45,3	1328	1199	1771	1598	2213	1998	2656	2397	3098	2797	3541	3196	3984	3596	4428	3995
100	25	78,5	73,6	2072	1943	2763	2591	3454	3238	4145	3886	4836	4534	5526	5181	6217	5829	6908	6477
125	32	122,7	114,6	3239	3028	4319	4037	5399	5047	6479	6056	7558	7066	8638	8075	9718	9084	10798	10094
160	40	201,0	188,4	5309	4976	7079	6635	8848	8294	10618	9953	12388	11612	14157	13270	15927	14929	17697	16588
200	40	314,1	301,4	8295	7962	11060	10616	13825	13270	16590	15924	19355	18579	22120	21233	24885	23887	27650	26541
250	50	490,6	471,0	12960	12442	17280	16590	21600	20737	25920	24885	30239	29032	34559	33180	38879	37327	43199	41474

● FULL PISTON AREA
○ ANNULAR AREA

Fig. 3-22 Effective piston forces for "BOSCH" actuators.

ures include a 12% friction loss for internal actuator friction and are based on the formulae:

$$N = \frac{Pa \times m^2 \times 88}{100} \quad Pa = \frac{N \times 100}{m^2 \times 88} \quad m^2 = \frac{N \times 100}{Pa \times 88}$$

Example 1 (static force calculation)
A pneumatic double acting actuator is used to clamp work pieces in a machine tool (fig. 3-23). The actuator available has a piston diameter of 125 mm. The required clamping force is calculated to be 6000 newtons. Select the appropriate minimal system pressure to achieve this force. Assume a friction loss of 5% (near static thrust).

Solution:

$$\text{Pressure} = \frac{\text{Force} \times 100}{\text{Area} \times \eta}$$

$$p = \frac{6000 \times 100}{0.125^2 \times 0.7854 \times 95 \times 10^5}$$

$p = 510$ kPa (5.1 bar)

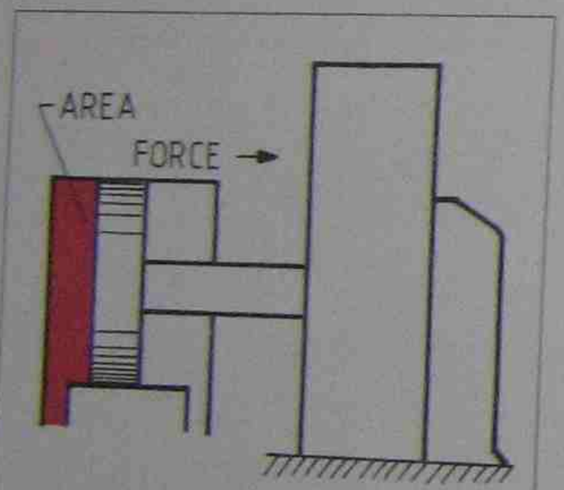


Fig. 3-23 Static force calculation applied to clamping.

Example 2 (static force calculation)
Calculate the force output for a double acting linear actuator with a piston diameter of 100 mm and a rod diameter of 25 mm. The minimal system pressure is 500 kPa (5 bar) and the internal friction loss of the actuator is 12% of its theoretical force. Calculate both the extension and the retraction force.

Solution:

$$\text{Force}_{EXT} = \frac{500 \times 10^3 \times 0.1^2 \times 0.7854 \times 88}{100}$$

$$= 3455 \text{ N}$$

$$\text{Force}_{RET} = \frac{500 \times 10^3 \times (0.1^2 - 0.025^2) \times 0.7854 \times 88}{100}$$

$$= 3240 \text{ N}$$

Example 3 (near static force calculation)
A pneumatic linear actuator must slowly raise a platform with a load on it (fig.3-24). The platform and the load have a mass of 660 kg. The actuator internal friction is assumed to be 12% and the minimal system pressure adjusted on the pressure

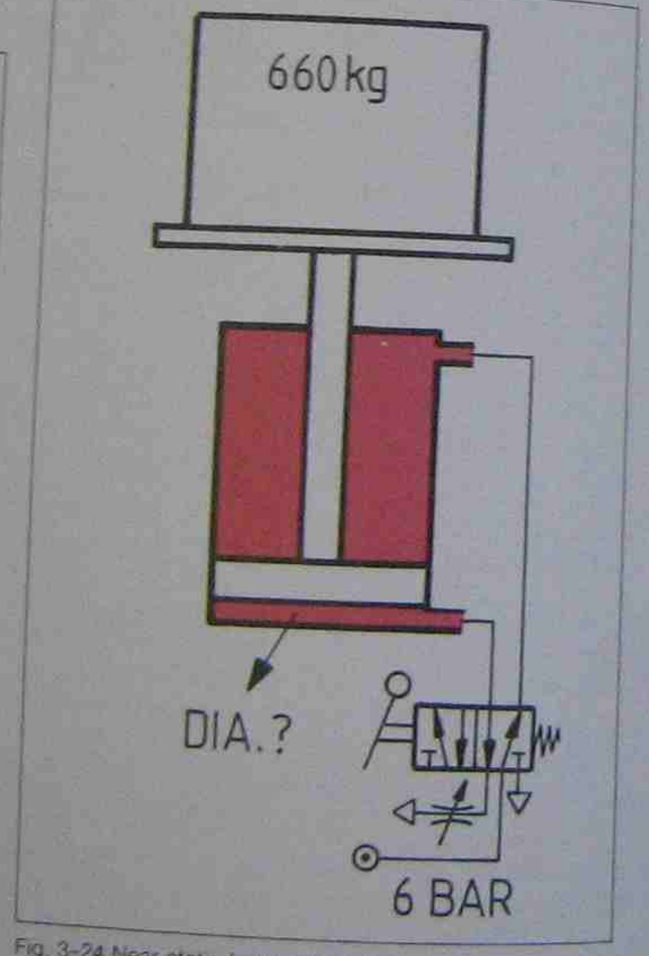


Fig. 3-24 Near static force calculation.

reducing valve of the air service unit is 600 kPa (6 bar). Inertia force can be neglected. Calculate the minimal required piston diameter for this load and from the chart in fig. 3-22 select the smallest possible standard piston diameter. Compare the calculated result with the listed force output figure in the chart.

Solution:

$$d = \sqrt{\frac{F \times 100}{p \times 0.7854 \times \eta}}$$

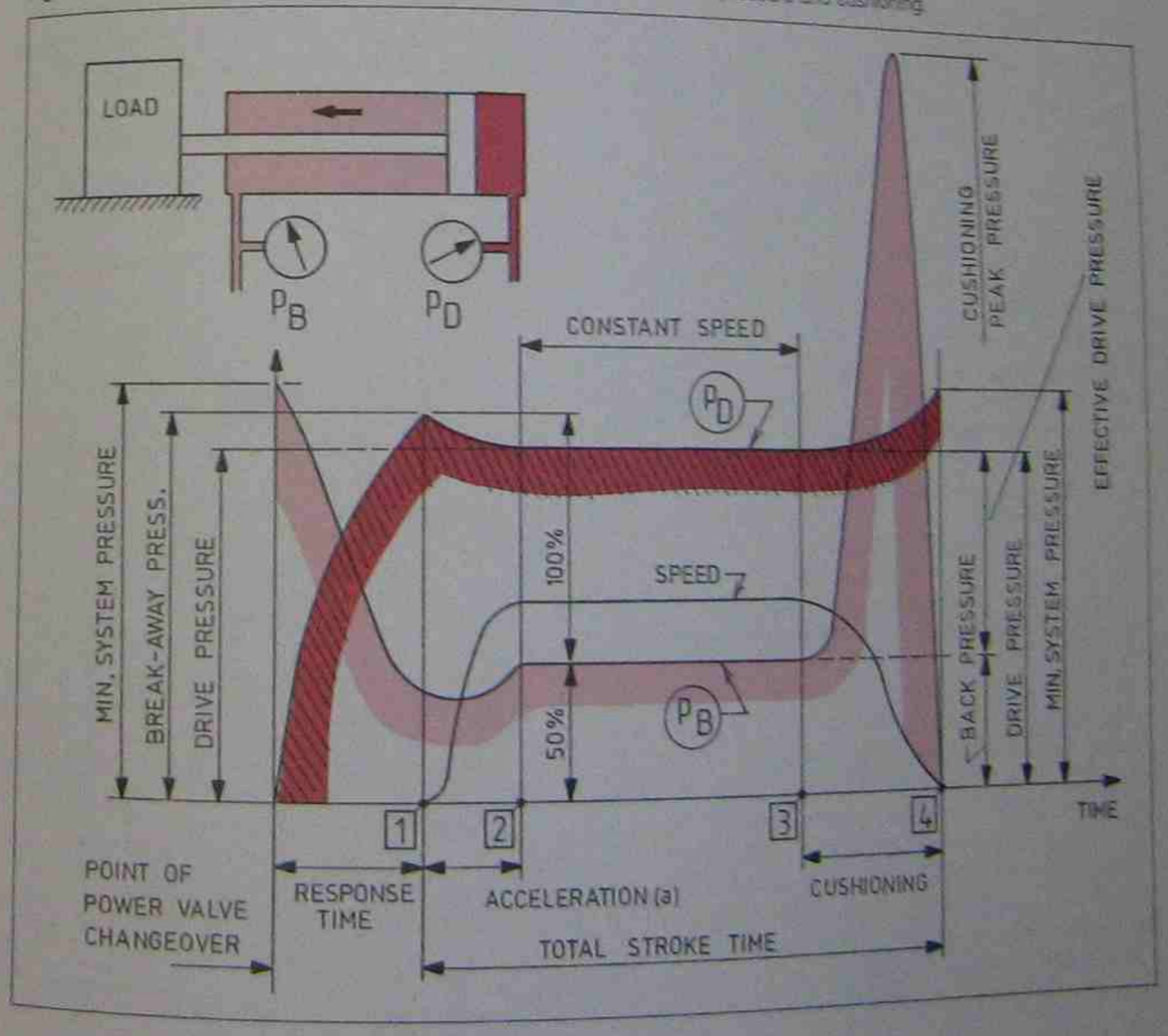
$$d = \sqrt{\frac{660 \times 9.81 \times 100}{600 \times 10^3 \times 0.7854 \times 88}} = 0.12495 \text{ m}$$

The chart shows for the force of 6474 newtons a piston diameter of 125 mm which renders an effective force of 6479 newtons. This is slightly more than the calculated force, so the piston of 125 mm is sufficient to raise the load if no back pressure is encountered.

Relationship of pressure to load

The diagram shown in fig. 3-25 explains the complex relationship of pressure and load to the speed of a double acting pneumatic actuator. It shows that the minimal system pressure should be about 10% above the breakaway pressure and that the back pressure is about 40% of the break away pressure if meter out speed control is used, thus the back pressure load which must be added to the maximum load force is also 40%. These figures are also in agreement with load curve Ⓒ in fig. 3-26. For this reason some circuit designers suggest that 50% extra load force should be added to the maximum load force calculated before, and the actuator should then be sized for this new load which automatically takes care of back pressure

Fig. 3-25 Relationship between pressure and load and speed and back pressure and cushioning.



and internal actuator friction losses. The diagram (fig. 3-25) shows that after the valve has been switched over, the back pressure (p_B) drops rapidly and the drive pressure (p_D) increases to a point where the force imbalance causes the piston with its attached load to break away (see fig. 3-26, point [1]).

As the load starts to move and accelerate, the back pressure continues to fall until the acceleration of the load and the piston catches up with the exhausting air [point 2] and forces it out of the actuator exhaust port. This also reestablishes the near balance of forces and with the load and back pressure remaining constant, the speed must also remain constant since the exhausting air exists at sonic speed (the speed of sound).

When the pneumatic cushioning starts to become effective [point 3], the back pressure starts to rise rapidly, thus providing the necessary counterforce to transfer the kinetic energy into heat (Amonton's Law). As the speed is reduced to a constant governed by the flow rate past the cushioning valve, the load comes eventually to a standstill at the end of the piston stroke at point [4] in fig. 3-25 (see also pneumatic end cushioning fig. 3-8 and Boyle's Law fig 1-12).

Dynamic thrust force calculations

For the sizing of double acting actuators which are to exert force while reciprocating or have to accelerate the load rapidly, the following practical aspects must be taken into consideration:

- Applied air pressure to the force side of the piston and the effective piston area must be large enough to cope with all calculated external forces (F_L, F_F and F_m, see fig. 3-20).
- There must be sufficient back pressure on the exhaust side of the moving piston to ensure that the exhausting air has a sonic flow rate; thus giving constant flow rate. This provides effective and constant speed control whilst the load is being moved (meter-out speed control). See also flow through an orifice to atmosphere (Chapter 1) and fig. 3-25.
- The exhausting air must have the minimal required back pressure for effective pneumatic cushioning. Should the exhaust air pressure drop to atmospheric pressure, then the pneumatic cushioning would no longer be effective and the piston with its attached load would have to be braked by hard impact on the endcaps.

The actuator sizing nomogram in fig. 3-26 makes this seemingly complex task very simple. Curve Ⓐ is to be used for static thrust force calculations. It includes a 12% friction loss for internal actuator friction. Figures obtained from this curve must only be used for clamping applications or slow moving loads with minimal acceleration and no back pressure!

For reciprocating actuators which must impart

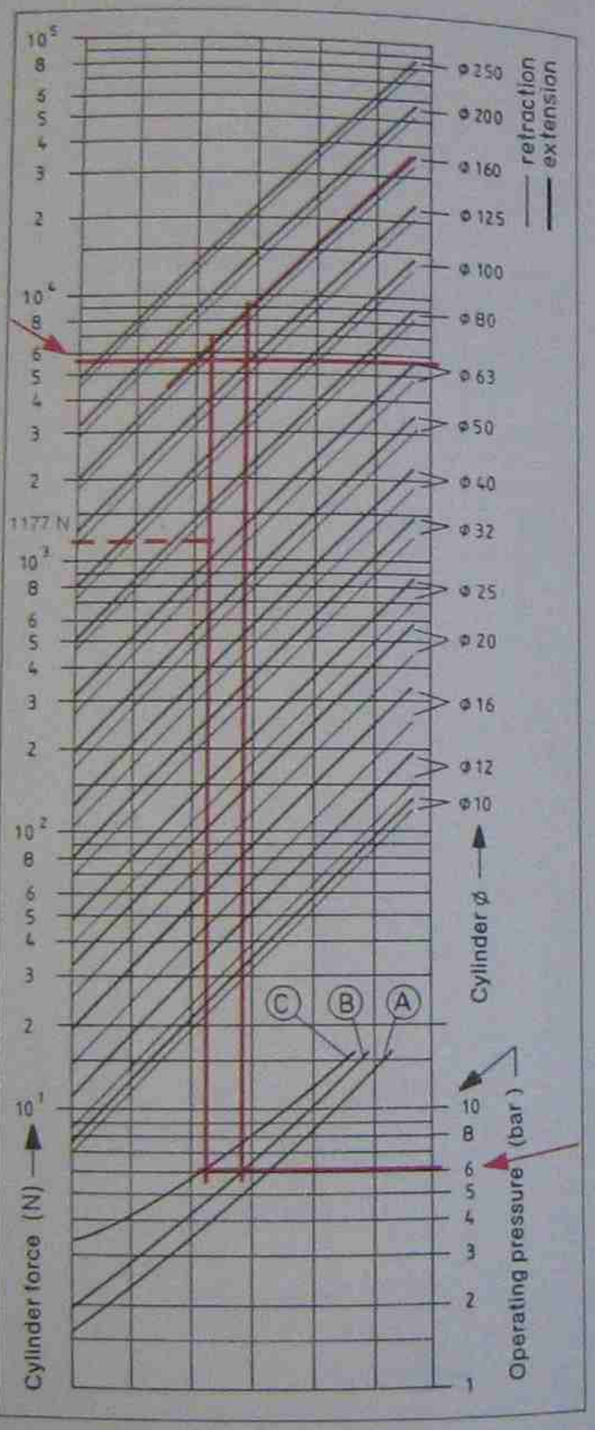


Fig. 3-26 Actuator sizing nomogram.

acceleration to the load attached to them, curve Ⓑ must be used (see fig. 3-25).

Now use Curve Ⓒ to check whether the actuator diameter selected with curve Ⓑ is also capable of moving the load at constant speed (stationary speed). The stationary speed distance spans from point [2] to point [3] in fig. 3-25. This speed must be kept constant despite the now higher back pressure. From the fig. 3-25 and 3-26 one can easily see that the back pressure increases for the constant speed phase. This causes the force output now to be lower than during the acceleration phase. Should the readings on the sizing nomogram (fig. 3-26) for curve Ⓑ and Ⓒ give different actuator diameters, then one must use the larger of the two piston diameters (see also effects of undersizing an actuator).

Example 4 (dynamic force calculation)

An actuator must reciprocate a load in horizontal direction (fig. 3-27). The load mass is 1000 kg, the friction coefficient is 0.12, the acceleration travel distance is 40 mm and the stationary speed after acceleration is 600 mm/s. The system pressure is 600 kPa (6 bar) calculate the piston diameter.

Solution:

The lifting force (F_L) is zero since the inclination angle α is also zero

$\longrightarrow (m \times 9.81 \times \alpha 0° = 0)$

The friction force (F_F) is:

$$F_F = m \times 9.81 \times \mu$$
$$= 1000 \times 9.81 \times 0.12 = 1177 \text{ N}$$

The inertia force (F_m) is:

$$F_m = \frac{m \times v^2}{2 \times s} = N$$

$$F_m = \frac{1000 \times 0.6^2}{2 \times 0.04} = 4500 \text{ N}$$

The total external force (F_{TOT}) is:

$$F_{TOT} = F_F + F_m$$
$$= 1177 + 4500 = 5677 \text{ N}$$

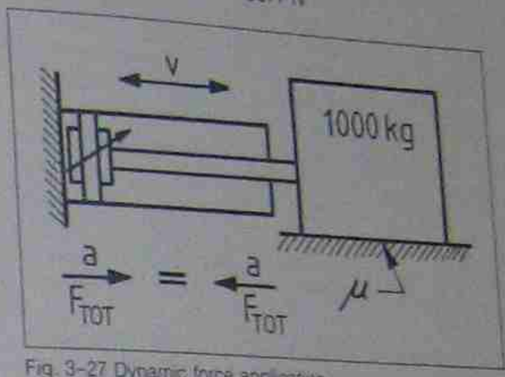


Fig. 3-27 Dynamic force application.

In fig. 3-26 of the actuator sizing nomogram one finds with a minimal system pressure of 600 kPa (6 bar) on curve Ⓑ and a total force output (F_{TOT}) of 5677 newtons a piston diameter (for the annular area) of 160 mm. The actuator is therefore suitable for imparting to the mass the envisaged acceleration to the stationary speed v (600 mm/s within the acceleration distance s (40 mm).

With curve Ⓒ in fig. 3-26 one now checks the actuator's suitability to hold that speed constant against the back pressure which is necessary to brake the mass with the inbuilt pneumatic cushioning. The so obtained reading of 5500 newtons is well above the necessary friction force of 1177 newtons, so the actuator is suitable.

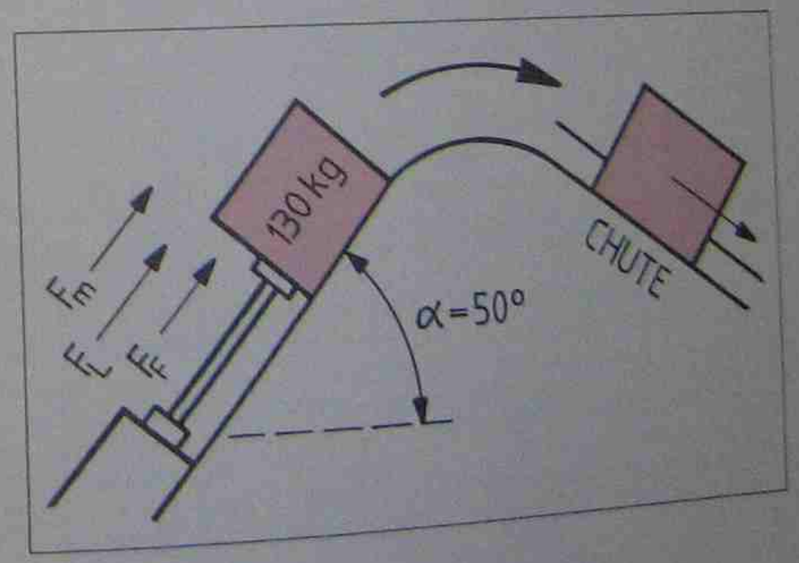


Fig. 3-28 (For example 5.)

Example 5

A pneumatic linear actuator must push parcels up a ramp onto a sorting shute. The ramp inclination is 50°. The friction coefficient is 0.10 and the mass of a parcel is 130 kg (fig. 3–28). A pneumatically cushioned actuator is used with a cushioning travel distance (l_c) of 0.028 m, the acceleration (a) of the load must occur within the cushioning travel distance (l_c) and must reach a stationary speed (v) of 0.5 m/s. Minimal system pressure is 600 kPa (6 bar). Calculate:

1. The total force (F_{TOT}) of all external forces including the lifting force (F_L), the frictional force (F_F), and the inertia force (F_m) (also called mass force).
2. The piston diameter for the extension stroke. Assume an internal actuator friction loss of 12%.
3. Compare the calculated figure with the effective force figure given in the chart (fig. 3–22).
4. Compare the figures obtained from calculation and chart (fig. 3–22) with the result obtained in the actuator sizing nomogram of fig. 3–26.

Solution:

The lifting force (F_L) is:

$$\text{Force } F_L = m \times 9.81 \times \sin\alpha = N$$
$$= 130 \times 9.81 \times 0.766 = 977\ N$$

The friction force (F_F) is:

$$\text{Force } F_F = m \times 9.81 \times \cos\alpha \times \mu$$
$$= 130 \times 9.81 \times 0.643 \times 0.1 = 82\ N$$

The inertia force (F_m) is:

$$\text{Force } F_m = \frac{m \times v^2}{2 \times s} = N$$
$$= \frac{130 \times 0.5^2}{2 \times 0.028} = 580\ N$$

The total external force (F_{TOT}) is:

$$\text{Force } F_{TOT} = F_L + F_F + F_m = N$$
$$= 977 + 82 + 580 = 1639\ N$$

The piston diameter for extension is:

$$d = \sqrt{\frac{F \times 100}{p \times 0.7854 \times \eta}}$$

$$d = \sqrt{\frac{1639 \times 100}{600 \times 10^3 \times 0.7854 \times 88}} = 0.063\ m$$

The next standard size actuator is 63 mm with an effective force output of 1647 newtons. Its standard size piston rod has a diameter of 0.02 m or 2 cm or 20 mm.

By using the actuator sizing nomogram (fig. 3–26) one finds that a piston diameter of 63 mm (0.063 m) would not suffice and thus the next larger piston diameter of 80 mm must be chosen.

Effects of undersizing an actuator

If an actuator is undersized it may either not cope with the given load force or it may just cope but the response and acceleration times become extremely long, such that the back pressure falls below the level required to maintain sonic speed. Thus the necessary back pressure needed to provide constant speed is no longer there and the speed becomes erratic. In addition, the pneumatic cushioning is totally ineffective since the initial back pressure used for cushioning is too low.

Speed control and impact control

Speed control is based on the flow rate either into or out of the actuator and is dealt with in the next chapter. Apart from speed control, pneumatic end cushioning must also be regarded as a form of speed control. Impact energy at the end of the piston stroke must be kept very small and if the load speed on impact should exceed 50 mm/s one should consider external impact cushioning or pneumatic internal end cushioning.

If the inbuilt pneumatic cushioning proves to be inadequate to break the load sufficiently, then one has only two possibilities available to remedy the problem.

1. The minimal system pressure (fig. 3–25) and the back pressure which depends on the minimal system pressure can be increased. If the back pressure is increased, the cushioning potential is also increased and thus the load may be sufficiently cushioned.
2. One may select an actuator with a larger piston diameter. This means a smaller pressure difference between drive pressure and back pressure is required to move the load. The back pressure throttling can then be increased, causing a higher back pressure, which in turn increases the cushioning.

Conclusion to thrust force calculations

An actuator can only be properly sized if all external forces are calculated and included in the total force. These forces include the load force, the friction force, and most importantly also the inertia force. Many actuators fail to perform as anticipated because the inertial force was not considered to be important and hence was not included in the total anticipated load force.

The load plus 50% rule of thumb can be used providing the inertia force is again included in the total force, and the back pressure force is not more than 40% of the drive pressure force (stationary speed force). However, it is advisable to use a precise actuator sizing nomogram similar to the one given in figure 3–26 which is based on calculation as well as on laboratory test figures (For friction figures see Appendix).

For downward moving loads the lifting force becomes negative and the friction force and inertia force remain the same.

Piston rod buckling

Column failure, or buckling of the piston rod, will occur if the actuator stroke is out of safe proportion in relation to the piston rod diameter, at a required force output (fig. 3–29). Piston rod buckling is calculated according to the *Euler formula*, where the piston rod is regarded as the buckling member. In pneumatics, Euler cases 3 and 4 are less frequent.

For pneumatic actuators the free buckling length (l) is calculated as follows (see figs. 3–10 and 3–29):

Euler case 1; rod end mounting: l = stroke length
Euler case 1; rear end mounting: l = stroke length*
Euler case 2; rod end swivel: l = stroke length
Euler case 2; rear end swivel: l = stroke length × 2**

Note: *The actuator barrel is assumed to be a stiff machine component which does not pivot. **The actuator barrel can pivot and thus permits rod side swing away from the straight force line.

$$\text{Euler formula: } K = \frac{\pi^2 \times E \times J}{{}^sK^2}$$

(At this load rod buckles!)

The maximum safe operating load (in newtons) therefore is:

$$F = \frac{K}{S} = \frac{\text{critical load}}{\text{safety factor}} = \text{permissible force}$$

K = critical load (N)

l = free buckling length (m) with actuator fully extended

S = safety factor (usually 2.5–5)

E = elasticity modulus (Pa) → for steel use: $2.1 \times 10^{10} \times 9.80665$

F = force (N)

J = moment of inertia (m^4) → $\frac{\pi \times d^4}{64}$

d = piston rod diameter

${}^sK$ = equivalent buckling length (m)

Example 6

Piston diameter	= 40 mm (0.04 m)
Piston rod diameter (d)	= 16 mm (0.016 m)
Stroke length	= 550 mm (1.10 m)
Euler case (fig. 3–26)	= situation 2
Safety factor (S)	= 5 (max. safety)
Mounting type	= rear end swivel

Find safe operating pressure.

Solution:

$$K = \frac{\pi^2 \times 2.1 \times 10^{10} \times 9.80665 \times \pi \times 0.016^4}{1.10^2 \times 64}$$

K = 5403.86 newtons → Rod buckles at this load!

$$\text{Safe loading: } F = \frac{K}{5} = 1081\ N \text{ (with safety factor 5)}$$

Safe pressure for this actuator is:

$$Pa = \frac{N}{m^2} = Pa = \frac{1081}{0.016^2 \times 0.7854} = 5375306$$
$$= 540\ kPa\ (5.40\ bar)$$

For ease of calculation the formula for safe operating load can be simplified by grouping all constants in the formula together:

$$F = \frac{K}{S} = \frac{\pi^2 \times 2.1 \times 10^{10} \times 9.80665 \times \pi \times d^4}{S \times {}^sK^2 \times 64}$$
$$= \frac{10^{11} \times d^4}{S \times {}^sK^2}$$

For ease of piston rod sizing, most manufacturers of pneumatic linear actuators provide sizing charts or nomograms (fig. 3–30). Such graphic aids are based on calculations as well as data obtained by experience in the field. The two parameters required are the system pressure and the required force. When plotted into the nomogram one can then derive the piston rod which *would not buckle* as long as the plotted parameters are not exceeded towards an unsafe condition.

Air consumption calculations

Air consumption of the various pneumatic actuators represents an important part of the operating costs of a pneumatic system. It also provides a guide for the proper sizing of the compressor plant, the air distribution system, and air preparation system with its air dryers, air receiver, after cooler and air service units.

For a given minimal system pressure (operating pressure), piston area and stroke length, the air consumption is calculated with the formula:

Compression ratio (ε) × geometrical volume (V)

The compression ratio is determined by the quotient of the absolute minimal system pressure and the absolute ambient pressure which is normally about 101.3 kPa (1.013 bar) at sea level.

$$\varepsilon = \frac{101.3\ \text{kPa} + \text{minimal system pressure (kPa)}}{101.3\ \text{kPa}}$$

The geometrical volume (V) for an actuator is calculated with the following formulae:

$V = d^2 \times 0.7854 \times$ stroke length (extension stroke)

$V = (d^2_{PISTON} - d^2_{ROD}) \times 0.7854 \times$ stroke length (retraction stroke)

For double acting linear actuators with a piston rod on one end only, the annular area geometrical volume is therefore less than the full piston area geometrical volume. For precise air volume calculations, one could therefore use this lesser volume for the retraction stroke.

However, it must be noted that the end cap "cavities" with their "dead" volume must also be filled with compressed air before the piston can move and the same applies for the air lines between the power valves and the actuator. As a rule of thumb one can therefore use for both strokes the full piston area geometrical volume, and assume that the oversizing for the piston rod volume makes up for the neglected end cap cavity volumes and air line volumes (fig. 3–5).

For single acting linear actuators one calculates only one stroke per one full cycle (extension and retraction) since the return stroke is not air powered and thus needs not to be included in the calculation.

Some typical end cavity volumes for "FESTO" actuators:

Piston Dia. mm	Rear End Cap cm^3	Rod End Cap cm^3
25	6	5
35	13	10
50	19	16
70	31	27
100	88	80
140	150	128
200	448	425

Fig. 3-31 End cap cavity volumes

Example 7

Minimal system pressure = 600 kPa (6 bar)
Piston diameter = 80 mm (0.08 m)
Stroke length = 400 mm (0.4 m)
Cycles per minute = 5, (which equals 10 strokes)

Calculate flow rate per minute (Q)

Solution:

$$Q = \frac{101.3 + 600}{101.3} \times 0.08^2 \times 0.7854 \times 0.4 \times 10$$
$$= 0.14\ m^3/min$$

By using the air consumption nomogram in fig. 3–32 one can find approximate values quicker and more easily. The actual piston stroke is plotted in the nomogram on the left and a line is drawn up to the appropriate piston diameter then reflected horizontally to the right hand graph where it intersects with the minimal system pressure (gauge pressure) chosen. The line drops now vertically to the bottom end of the nomogram where one can read off the air consumption in litres per cycle (double stroke). The air consumption is always calculated in free air!

To compare the calculated value from the previous example with the obtained free air volume in the nomogram one calculates:

27 litres × 5 cycles/min = 135 litres/min

This value equates to 0.135 m^3/min, which is very close to the previously calculated result.

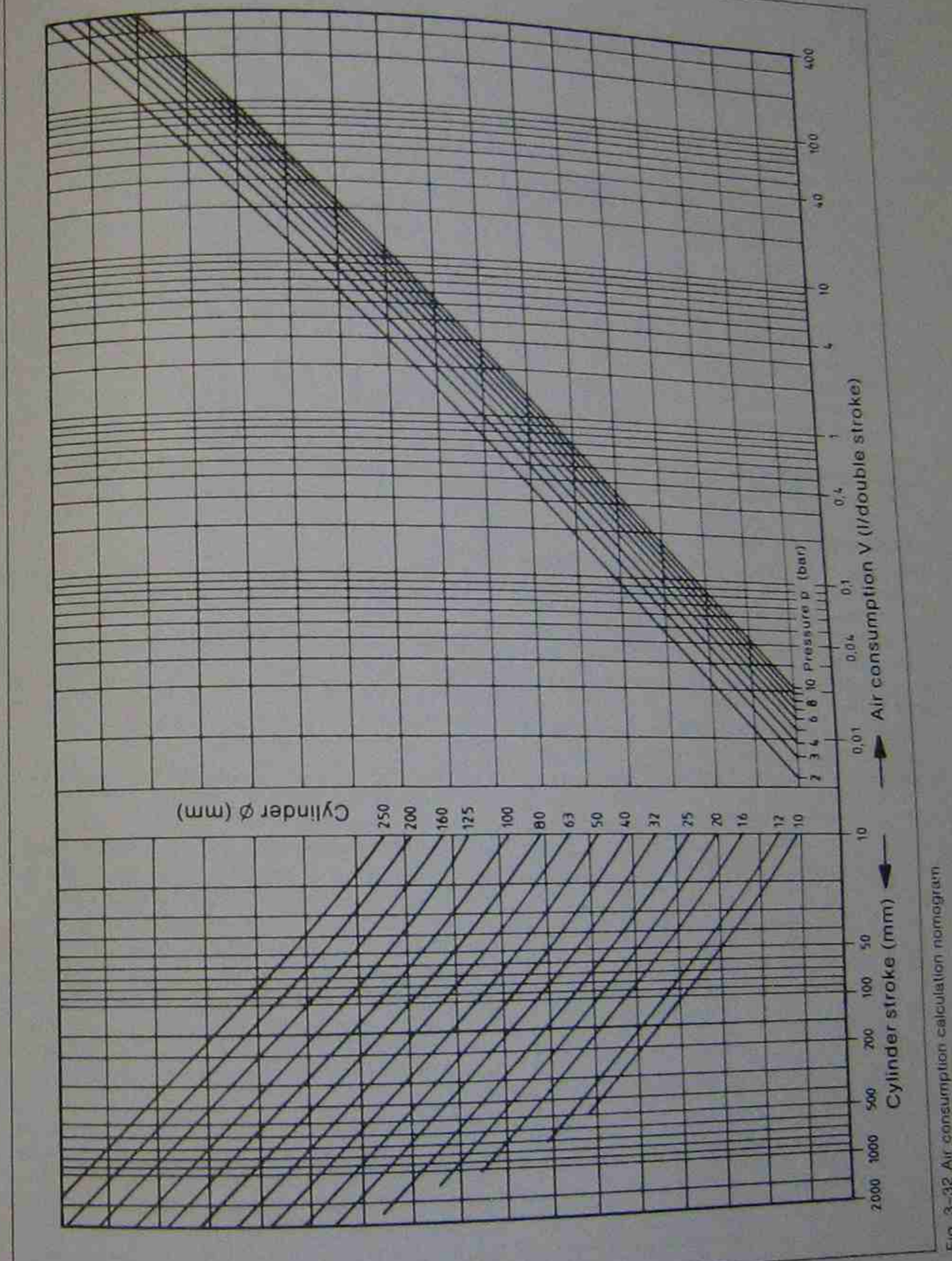


Fig. 3-32 Air consumption calculation nomogram

For a given minimal system pressure (operating pressure), piston area and stroke length, the air consumption is calculated with the formula

Compression ratio (ε) × geometrical volume (V)

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Fig. 3-31 End cap cavity volumes

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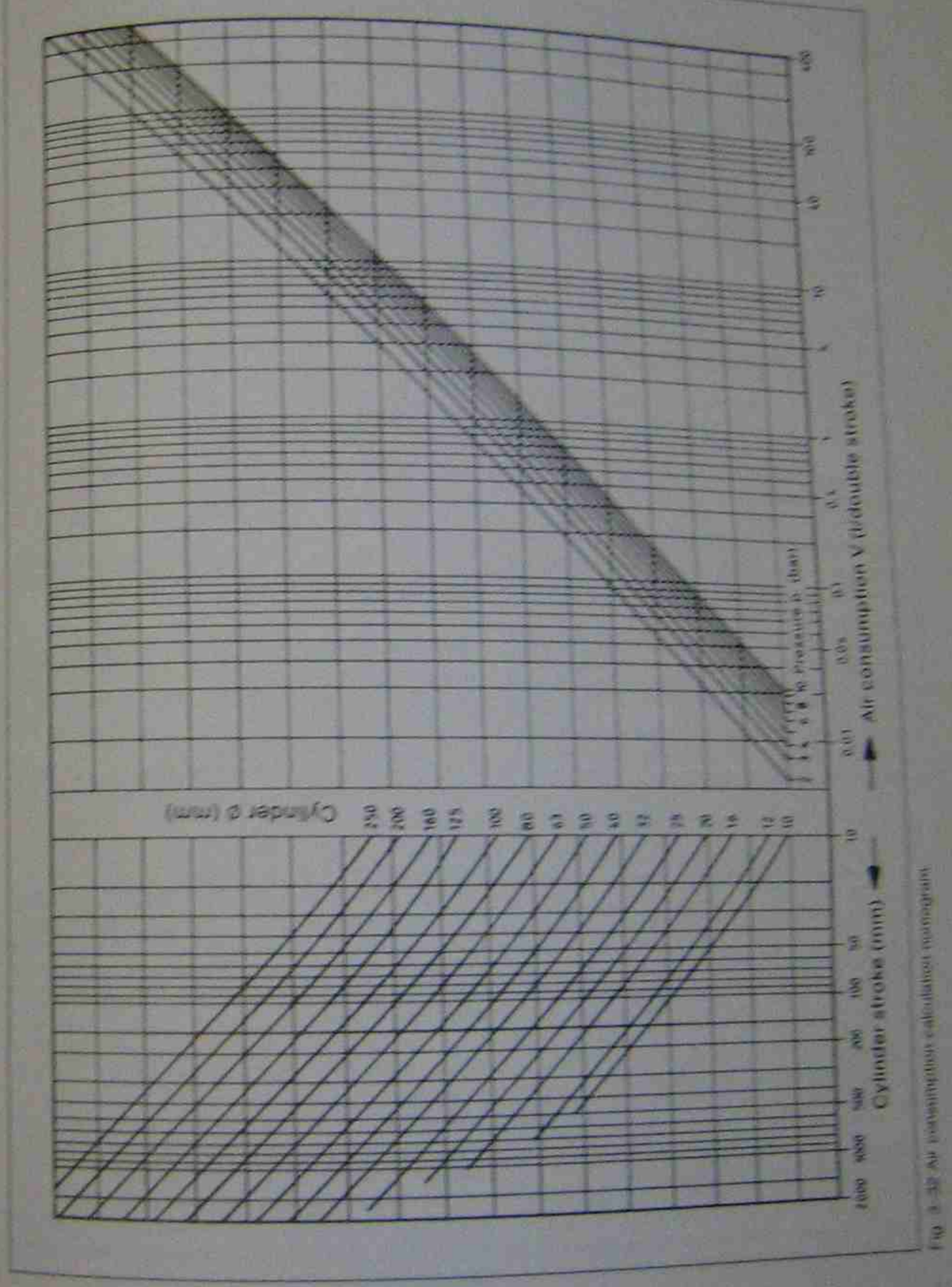


Fig. 3-32 Air consumption calculator nomogram

4 Flow Controls for Pneumatics

Flow control valves are frequently used in pneumatic systems. Their use is limited to the control of compressed air to and from the actuator and their main functions are,

- *to control the maximum speed of the actuator piston and its attached load,*
- *to provide constant speed for the main part of the actuator piston stroke when acceleration is completed,*
- *to cushion the load impact at the end of the actuator stroke or decelerate a load to a lower speed,*
- *to prevent free falling of a heavy load on the downward movement.*

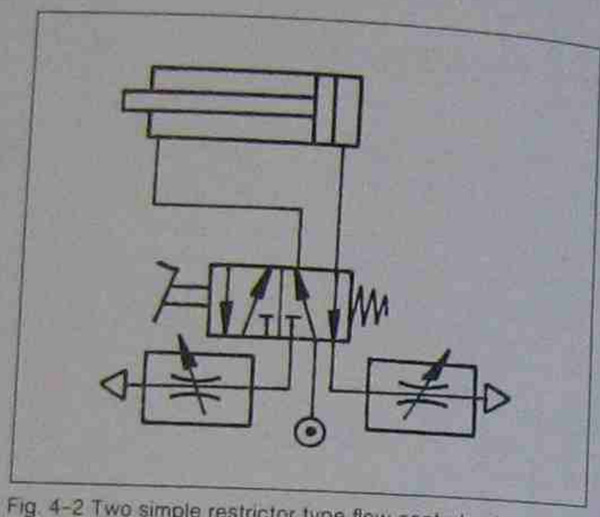
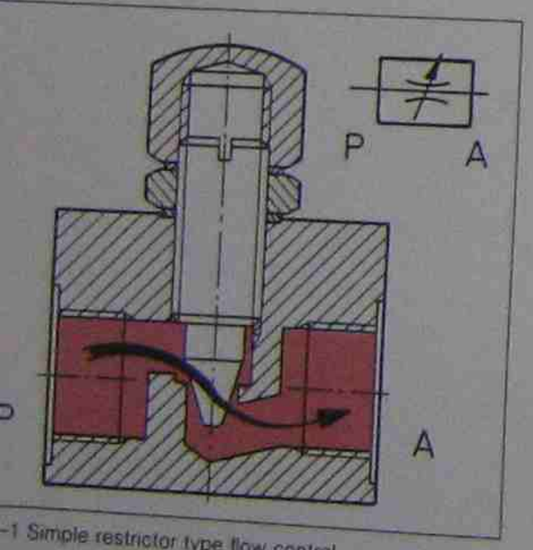


Fig. 4-2 Two simple restrictor type flow controls attached to the power valve exhaust ports.

Simple restrictor type flow control

This valve, being variable as far as the cross ection of the orifice is concerned, is therefore also alled variable restrictor flow control valve or vari- ble orifice flow control valve. It is mostly used n the outlet of the power valves (fig. 4-2) nd restricts the flow of air in both directions (fig. -1).

These valves consist of a valve body and a throt- ng screw which adjusts the orifice cross-section achieve the desired speed on the actuator.



-1 Simple restrictor type flow control.

Variable restrictor with free reverse flow

Where speed control (flow control) in only one valve direction is required, a check valve is built into the flow control. This permits unrestricted flow of air in the reverse direction (fig. 4-3).

The construction of this type of valve apart from the inbuilt check valve is identical to the simple restrictor type. The check valve consists of a rubber ring, which can flex upward if reverse flow is required, and a ring hub to hold the disc onto the check valve orifice during the throttling function.

Some pneumatic component manufacturers also make miniature type flow control valves which are directly built into the exhaust ports of the power valve. Others manufacture an actuator swivel-fitting which contains a small flow control valve with free reverse flow. Such inbuilt valves save space, extra connectors and installation costs.

Cam roller operated flow control

Cam roller operated flow control valves perform the same function as the previously explained flow controls but here a cam roller is used to alter the flow-rate (orifice area). Thus variable speed control during the stroking of the actuator can be achieved (figs. 4-4 and 4-5).

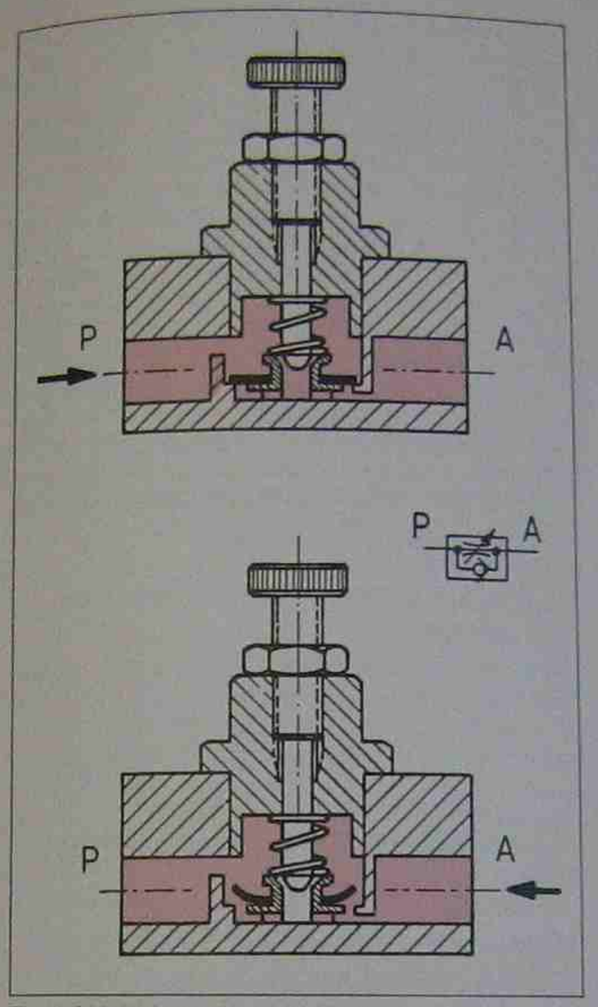


Fig. 4-3 Variable restrictor with free reverse flow.

The minimal speed (orifice opening) is limited on the rear end of the roller lever by means of a screw (fig. 4-4). A template is attached to the moving piston rod or to the moving machine part driven by the piston rod (fig. 4-5).

A downward movement of the roller reduces the cross section of the orifice and thus reduces the speed of the actuator under control.

The inbuilt check valve permits unrestricted air flow in the reverse direction. The check valve poppet moves to the left when unrestricted flow is required and resets itself when the flow is in the opposite direction (P → A).

Quick exhaust speed control

The quick exhaust valve, although used as a speed controlling device, is not a flow control valve in the proper sense, but rather a self steering direc-

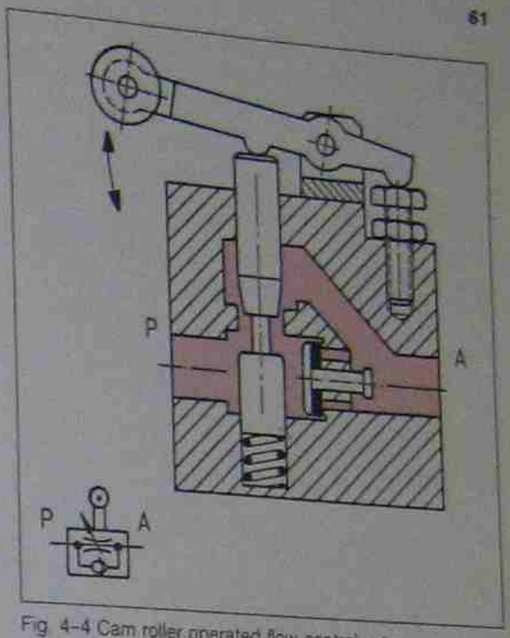


Fig. 4-4 Cam roller operated flow control valve.

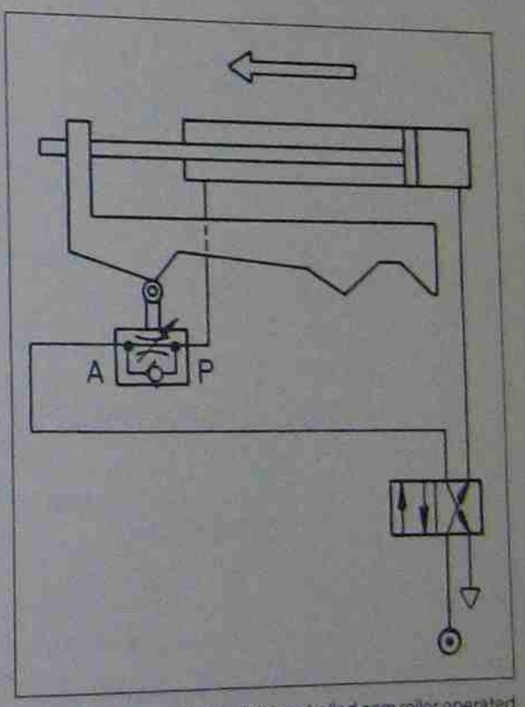


Fig. 4-5 Actuator with template controlled cam roller operated speed control (meter-out)

tional control valve similar to the "OR" function valve (fig. 4-6).

It allows air to flow from the power valve (port P) to the actuator to which it is attached (port A).

When the actuator is exhausting (flow in reverse direction), the valve element is shuttled to the left where it blocks port P and the exhausting air can rapidly flow through a large exhaust port (R) to atmosphere. Thus the exhaust air must not be forced all the way back through the power valve (fig. 4–7). This valve often permits a speed increase up to 2 m/s, but care must be taken to control load impact. The fitted exhaust silencer does not affect exhaust efficiency.

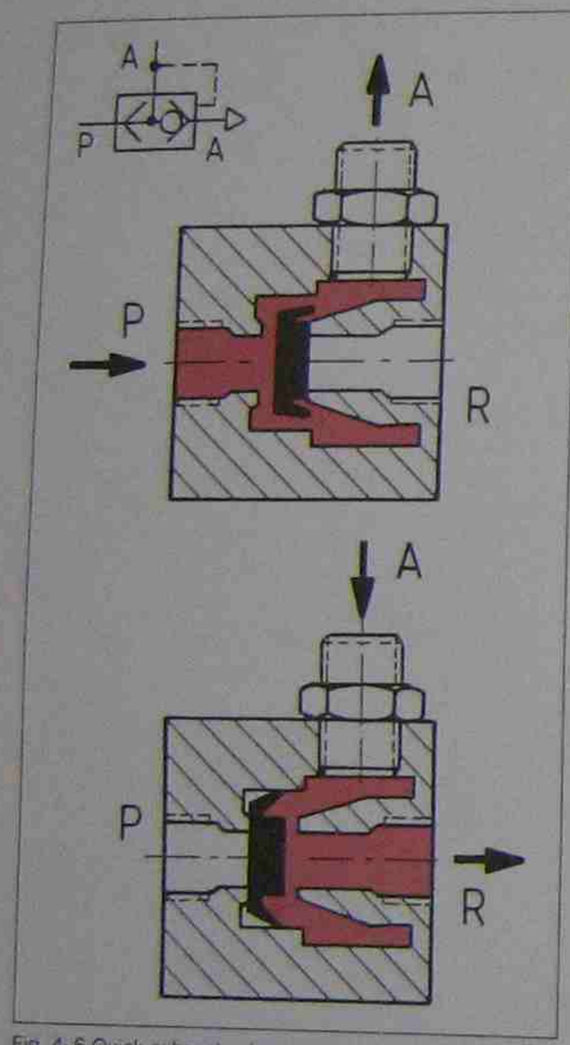


Fig. 4–6 Quick exhaust valve

Hydraulic check speed control

Any form of pneumatic speed control no matter how effective, can never provide absolute speed consistency. Speed consistency is imperative for machining operations or applications in manufacturing where the quality of the product depends on absolute uniform speed over the entire stroke length.

For such cases an hydraulic check cylinder may be used. The hydraulic oil, which is virtually incompressible, is used to provide precise and uniform speed control which is independent and unaffected by load variations of the pneumatic actuator. The pneumatic actuator is linked to the hydraulic check cylinder. The force needed to move the hydraulic piston and its piston rod comes from the pneumatic actuator which literally drags the hydraulic piston along. The displaced oil is forced via a hydraulic flow control valve which provides the required speed control. An oil reservoir with a spring loaded piston compensates for the differing oil volumes displaced by the hydraulic piston and makes up for oil losses due to piston rod lubrication (fig. 4–8).

Installation methods for restrictor type flow controls

Two basic methods are commonly used to install restrictor type flow controls such as shown in figs. 4–1, 4–3 and 4–4. These methods are widely known as *meter-in* flow control and *meter-out* flow control (figs. 4–9 and 4–13). Both methods have their distinct advantages and disadvantages, but where possible meter-out should be given preference.

Meter-in speed control

Where an actuator has insufficient air volume on the exhaust side of the moving piston, so that the exhausting air can not be sufficiently compressed by the flow control to cause an air-cushion, then meter-in speed control must be used. This is mainly the case with small diameter or short stroke actuators. Meter-in must also be used for single acting actuators (fig. 4–17).

Meter-out speed control

Meter-out provides the necessary back-pressure which is imperative for smooth and constant piston speed (see Chapter 3, fig. 3–25).

The back pressure brought about by meter-out speed control reduces the force output of the actuator, which demands that a larger piston must be selected to move the given load. The advantages gained from meter-out speed control are numerous and may be listed as:

- A free falling, suspended or supported load can be controlled with ease (figs. 4–10 and 4–11).

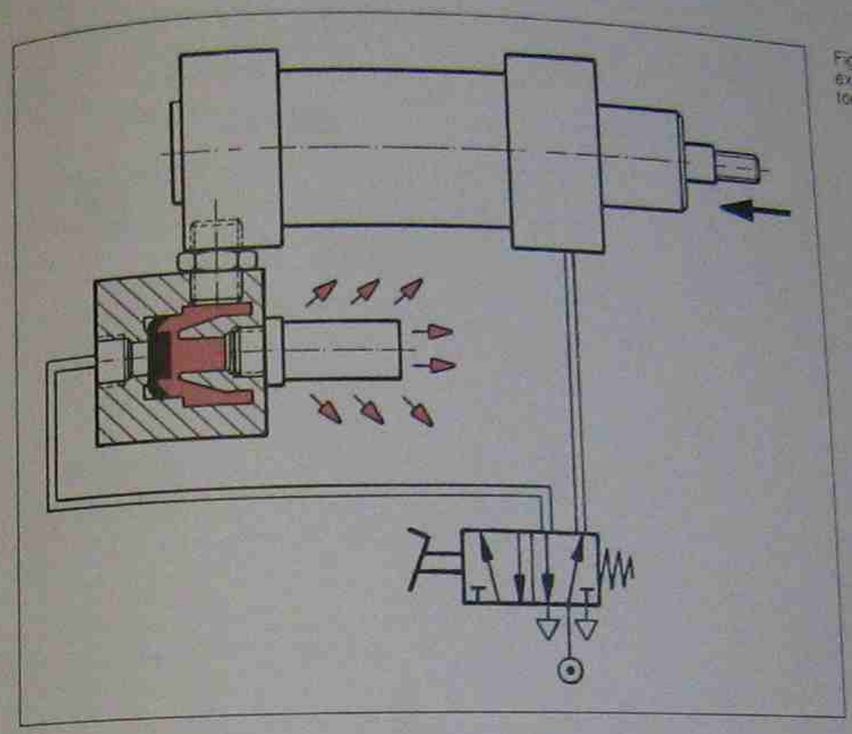


Fig. 4–7 Installation of quick exhaust valve on the actuator.

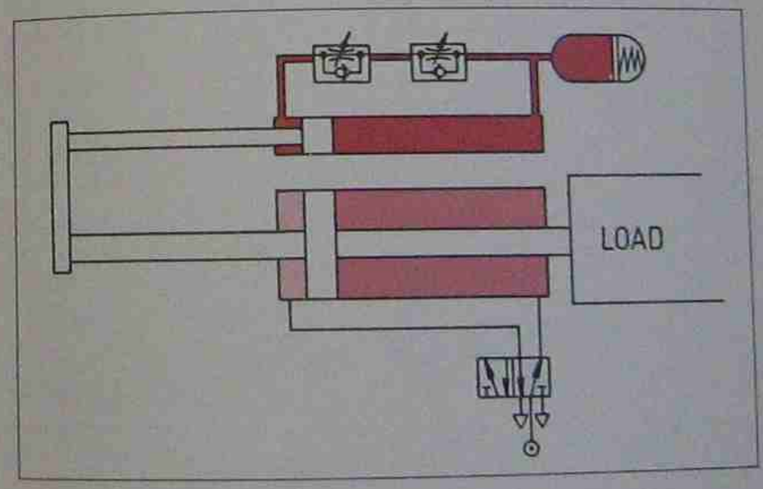


Fig. 4–8 Hydraulic check linked to a pneumatic double acting actuator

- The back pressure caused by a meter-out speed control restrictor (flow control valve or an orifice) resists the advancing piston which is driven forward by the pressure on the opposite side (note pressure readings on the pressure gauges in fig. 4–12). This form of speed control provides excellent and constant control of the stationary actuator speed (see fig. 3–25).
- Pneumatic end-cushioning is greatly enhanced with the air pressure cushion caused by the meter-out speed control restrictor valve (fig. 4–9, see also effects of undersizing an actuator in Chapter 3).

Power valve exhaust port speed control

To achieve optimal speed control it is advisable to mount the flow restrictors (speed control valves) directly onto the actuator (fig. 4–9).

One frequently finds these valves mounted onto the exhaust ports of the power valves (fig. 4–13). With this installation, however, one runs the risk of damaging the pneumatic seals inside the power

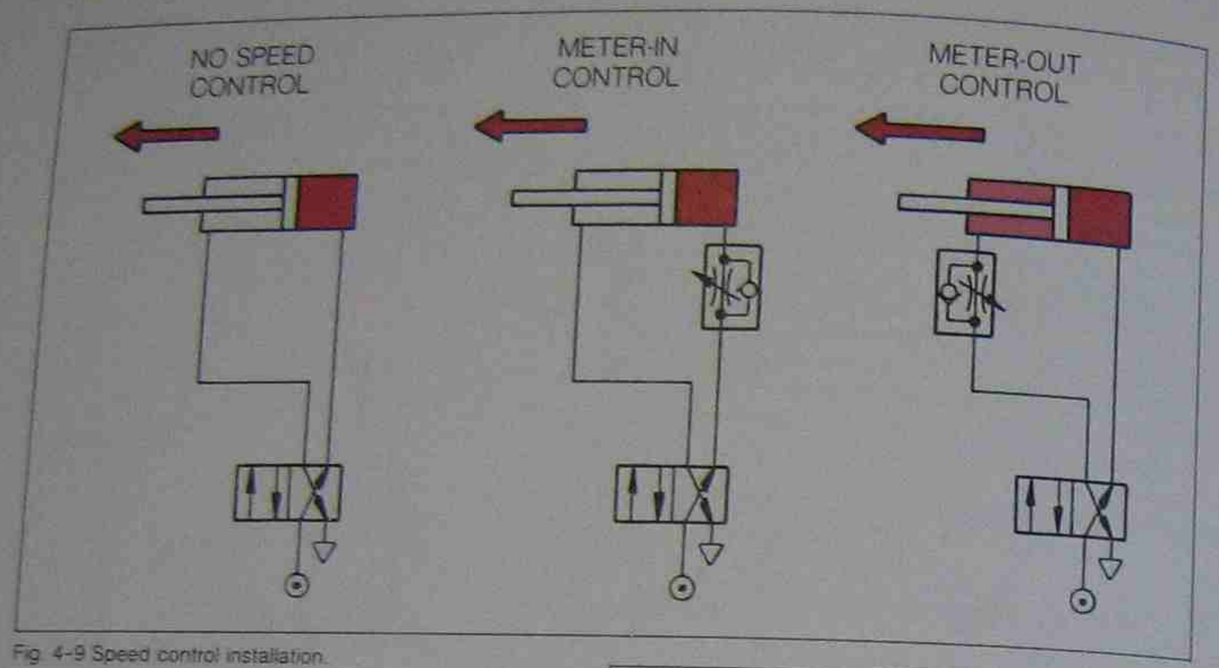


Fig. 4-9 Speed control installation.

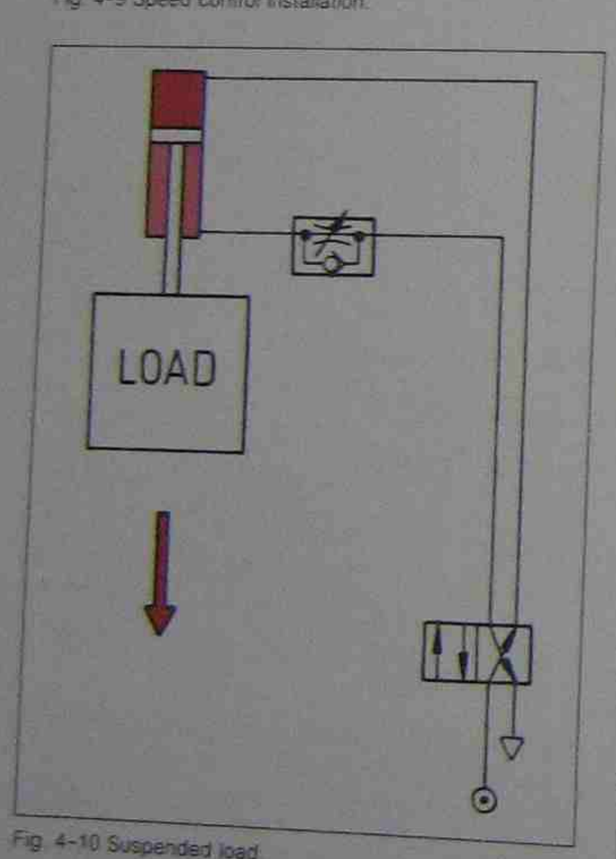


Fig. 4-10 Suspended load.

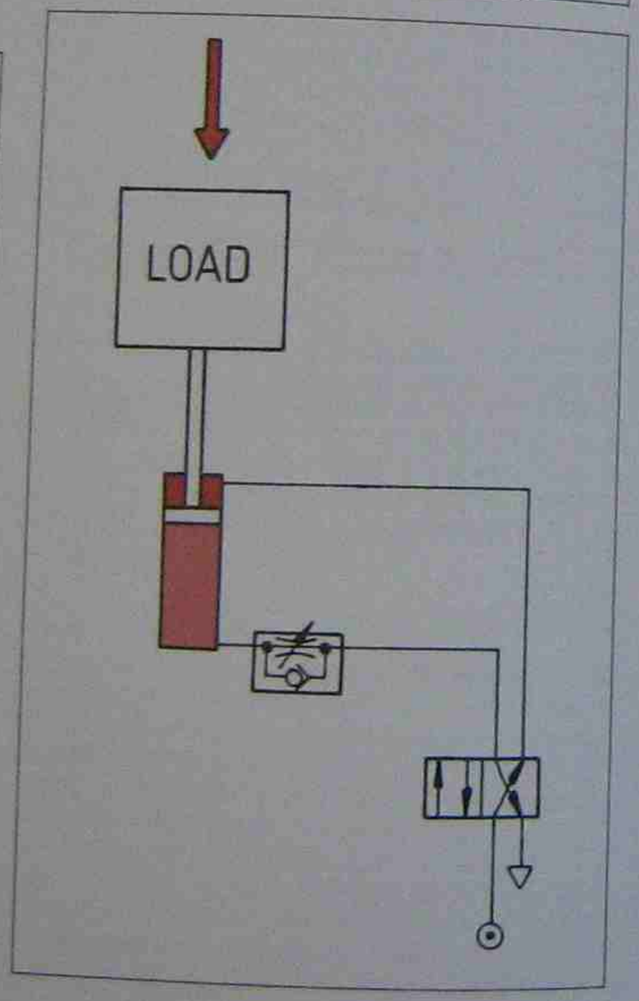


Fig. 4-11 *Right*. Supported load.

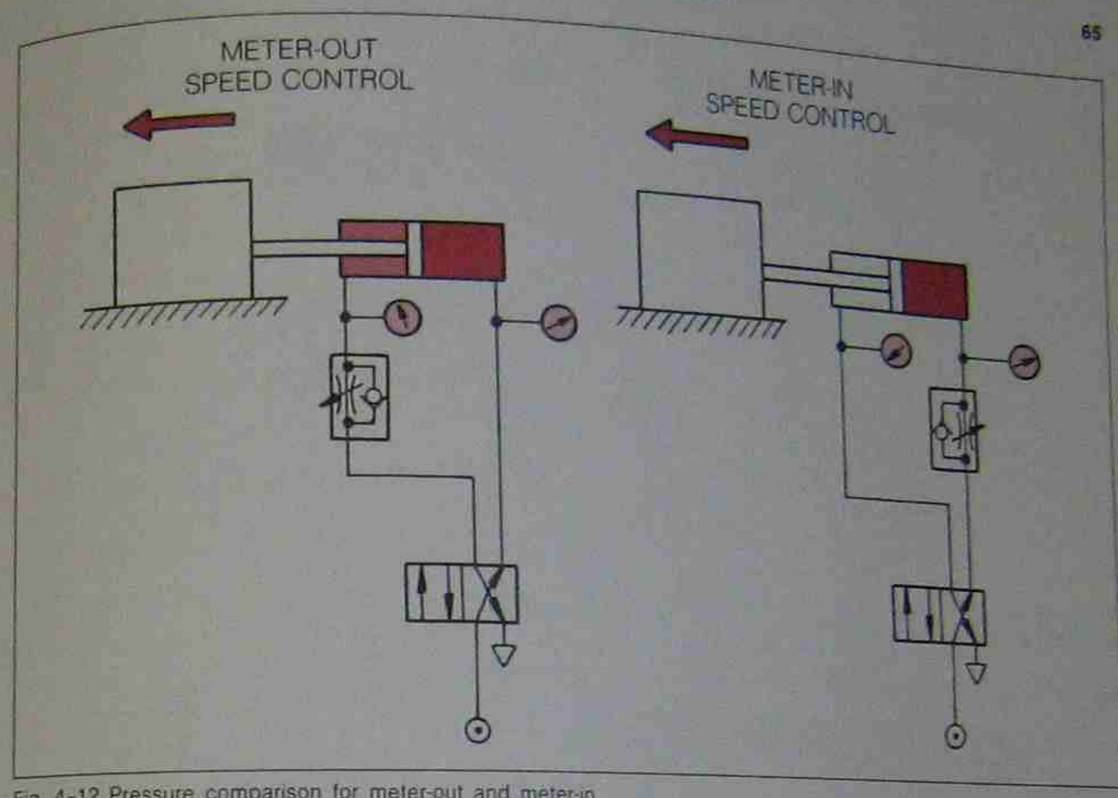


Fig. 4-12 Pressure comparison for meter-out and meter-in speed control.

valve or rupturing the air hose between the actuator and the power valve. This may occur because of pressure intensification induced by an oversize piston rod (see calculation fig. 4-14).

Example:
A custom built linear actuator has a piston diameter of 200 mm and an oversized piston rod diameter of 180 mm. The system air pressure is 1000 kPa (10 bar). Calculate the intensified pressure on the rod end air outlet, if the meter-out air outlet of the flow control valve is by mistake almost closed off.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \rightarrow \text{Pa} = \frac{\text{N}}{\text{m}^2} \rightarrow \text{Pressure}$$

$$= \frac{\text{Force to left}}{\text{Annular Area}}$$

$$\text{Pressure} = \frac{10 \times 10^5 \times 0.2^2 \times 0.7854}{(0.2^2 - 0.18^2) \times 0.7854 \times 10^5}$$

$$= \frac{0.4}{0.0076} = 5{,}263 \text{ kPa } (52.63 \text{ bar})$$

System sizing

System sizing is the simplest and least costly speed control method. Even if it does not provide adjustable speed control, it has a proper place especially in large series of identical controls. It is mostly established by trial and error but saves costly control valves. The fittings screwed into the actuator ports act as natural restrictors and where necessary, reduction fittings may be used to cause more flow restriction (fig. 4-15).

Pneumatic end-cushioning

Pneumatic end-cushioning is also a form of speed control. However, it only affects the very last portion of the piston stroke and, does, although adjustable, only count as an auxiliary to the other speed control methods discussed so far. Pneumatic end-cushioning is often used in addition to meter-out, quick exhaust control and system sizing (fig. 4-16).

Summary of speed control types

The speed control methods used to control the speed of pneumatic actuators are many and varied, but may be essentially summarized by the seven main methods discussed previously. They are listed in order of importance and frequency of use.

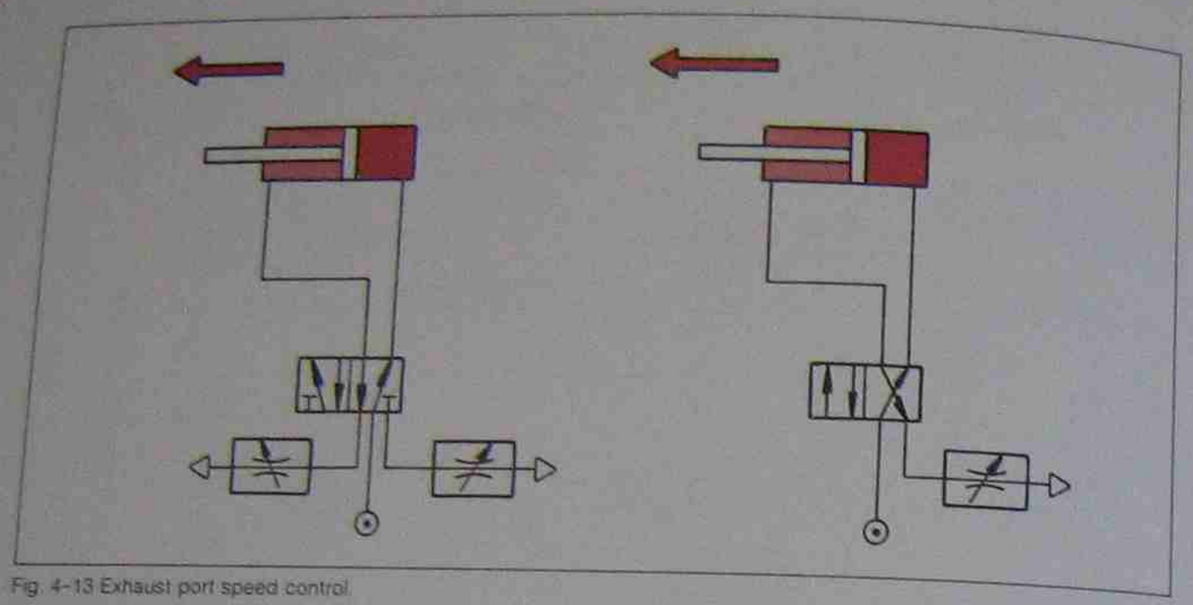


Fig. 4-13 Exhaust port speed control.

Fig. 4-14 Pressure intensification due to oversize piston rod.

- Variable restrictor with reverse flow installed as meter-out or meter-in (figs. 4-3 and 4-9).
- Simple restrictor type flow control installed mostly in power valve exhaust ports (figs. 4-1 and 4-13).
- Pneumatic end-cushioning in conjunction with other speed control types (fig. 3-8).
- System sizing used in conjunction with pneumatic-end cushioning (figs. 3-8 and fig. 4-15).
- Quick exhaust speed control in conjunction with other speed control types such as variable restrictors (fig. 4-18).
- Cam roller operated flow control in conjunction with other speed control types (fig. 4-5).
- Hydraulic check speed control usually installed as an ancillary unit atttached to an existing actuator.

Summary of installation methods

The most recommended method is meter-out, but power valve exhaust port installation, even if it is also a form of meter-out, is not as effective as having the speed control directly mounted onto the actuator. Meter-in speed control should be avoided where possible.

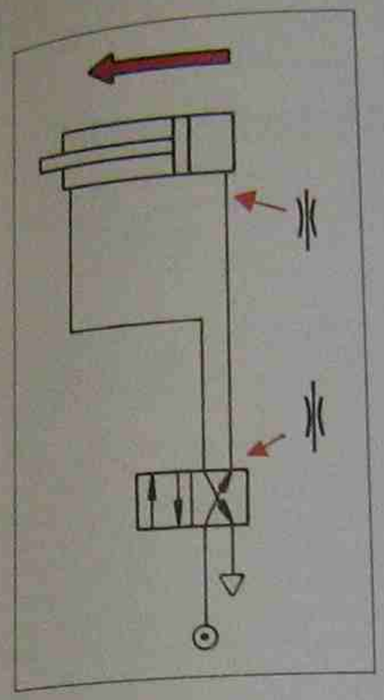


Fig. 4-15 System sizing.

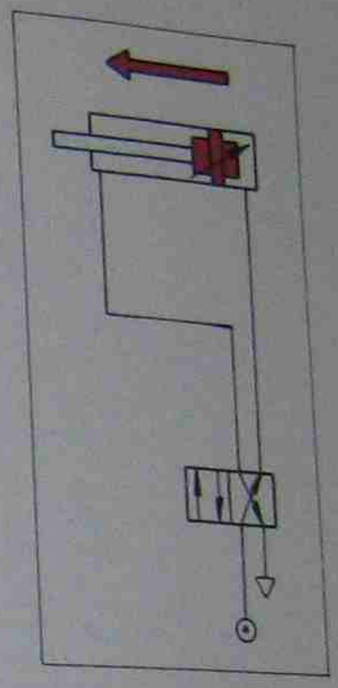


Fig. 4-16 Pneumatic end-cushioning.

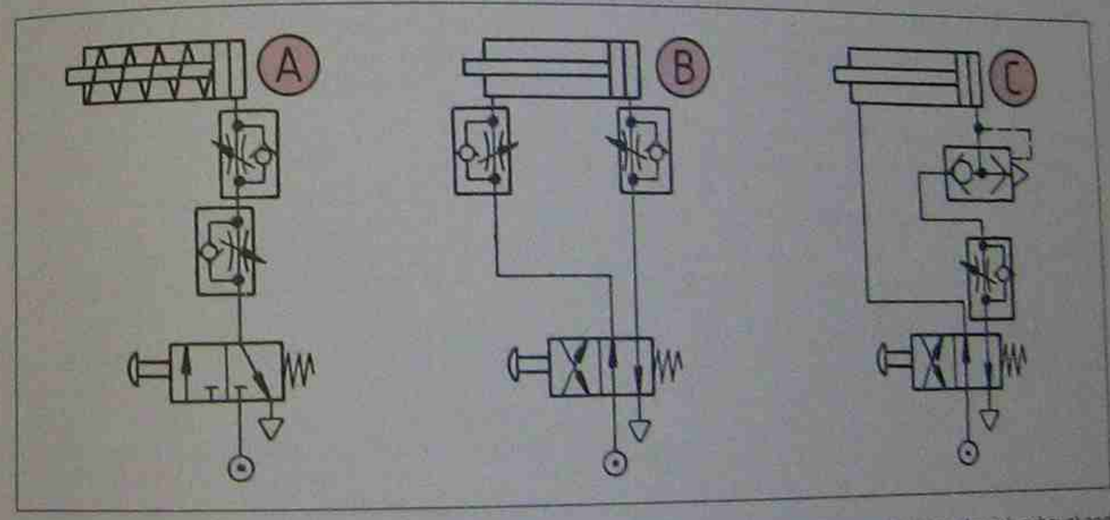


Fig. 4-17 Above: Shows a combination of quick exhaust and meter-in on the same port. Thus the actuator will retract rapidly but extend with adjustable speed.

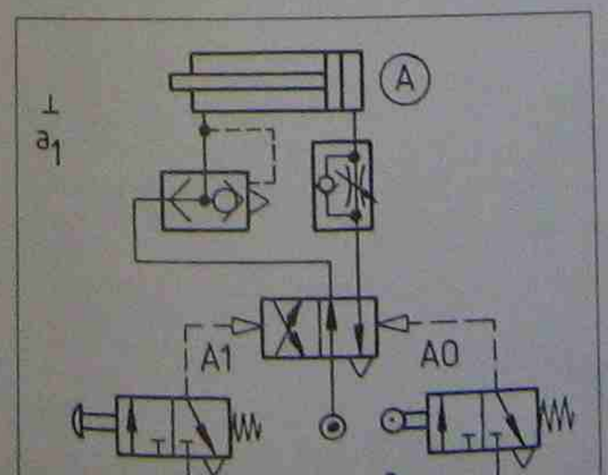


Fig. 4-18 Shows a combination of quick exhaust and meter-out speed control. Thus the actuator will extend rapidly but retract with adjustable speed.

5 Air Motors (Rotary Actuators)

By the use of rack and pinion drives or other mechanical systems the linear actuator (or cylinder) can be used to provide a rotary movement and so provide a torque output such as shown in fig. 3–18. Although such swivel actuators are suitable for many applications, they are not to be mistaken for air motors. Swivel actuators or semi-rotary actuators are generally built and designed to provide a rotary torque output up to a 360° rotation.

Air motors, however, produce a continuous torque output—thus driving a revolving drive shaft—and are regarded as the pneumatic counterpart to an electric motor. Revolving air motors are put to extremely diverse uses: from the not too popular dentist's drill to the drive for a caterpillar tracked tunnel boring machine. The manufacturing industry in particular is a large user of a wide range of types and sizes of air motor driven tools such as nut runners, drills, screw drivers, grinders and sanders.

Air motors use the characteristics of compressed air power transmission to their best advantage, which means they are easily adjusted for varying speeds and torque, can be reversed, can safely be operated in an explosive environment, and can be stalled indefinitely (thus are overload safe). These operational characteristics, combined with their excellent power features, that make air motors so versatile and widely accepted.

Air motors can be classified into five basic types, each of which produces a specific range of power output and has an operating characteristic which

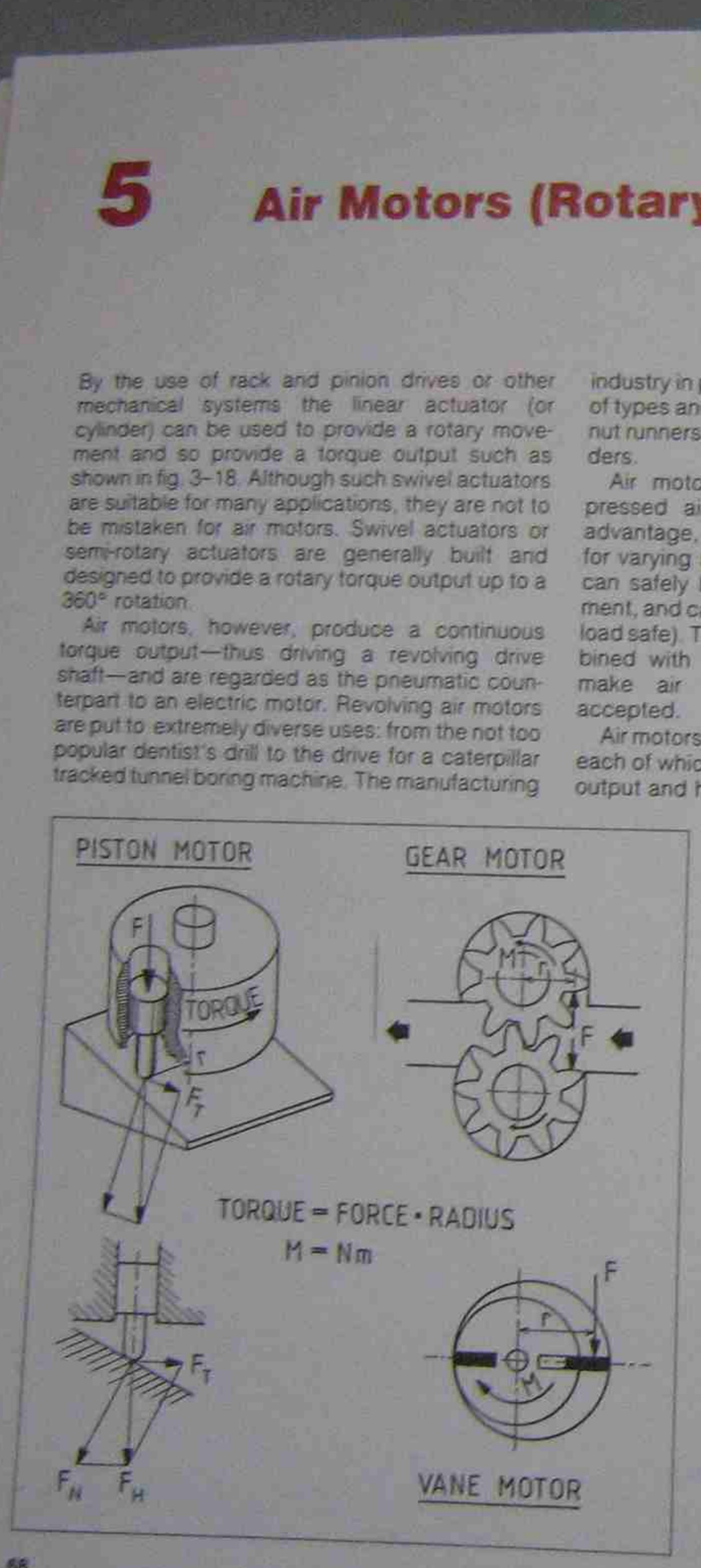


Fig. 5–1 Development of torque in pneumatic motors.

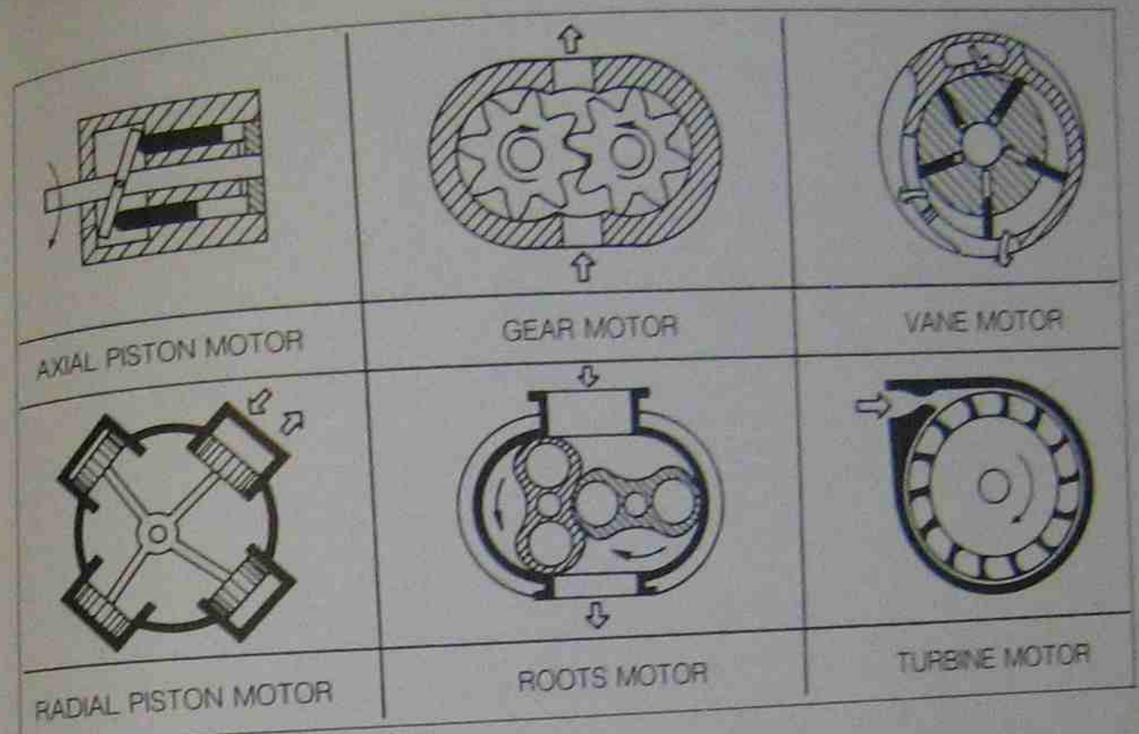


Fig. 5–2 Design concepts for air motors.

makes it ideally suited for a particular industrial application. These types are:

- vane motors (figs. 5–2 and 5–6)
- gear motors (figs. 5–2 and 5–10)
- piston motors (figs. 5–2 and 5–13)
- turbine motors (figs. 5–2 and 5–14)
- roots motors (fig. 5–2).

Each design type must have a driving surface area (A) subject to a pressure differential (Δ_p). For vane and gear motors, this surface is rectangular. For radial and axial piston motors the surface is circular (see fig. 5–1).

- In each design type the pressure exposed driving surface area (A) must be connected mechanically to the motor output shaft.
- Inlet and outlet air must have a timed porting arrangement to produce continuous rotation (this feature does not apply to turbine motors).

Maximum performance varies greatly between the various design types of air motors and is determined by:

1. the ability of its internal pressure exposed areas to withstand the forces acting upon them;
2. the internal leakage characteristics of the moving parts which seal the high pressure inlet from the low pressure outlet; and
3. the efficiency of the mechanisms which link the moving pressure exposed parts to the motor drive shaft (output shaft).

Torque (turning moment)

Torque is defined as a twisting or turning moment and is expressed in newton metres (Nm). Torque is a function of air pressure and leverage whereby the leverage is measured from the centre of the drive shaft to the centre of the pressure exposed area. The torque output of a typical air motor (except turbine motors) is at its maximum when the motor is stalled, and theoretically also at the start. This, however, is not so in practice due to various design characteristics such as the starting position of the pressure exposed surfaces relative to the air inlet port (see fig. 5–5).

It must therefore be noted that *breakaway torque* is generally much higher than *running torque*. Breakaway torque is the turning moment required to accelerate a load from standstill into motion. Running torque is the amount of torque required to keep a load in rotation after it has been accelerated (see figs. 5–1 and 5–3).

Motor speed

Motor speed (n) is a function of motor displacement (V) which is its geometrical volume and the input flow delivered to its input port (flowrate

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through the motor). This flowrate is usually given in m^3/min free air.

The unloaded maximum speed is called *free speed*, at which the motor's torque is zero (see fig. 5–3 for speed torque relationship). As the motor is loaded the speed drops and the motor torque increases linearly, thus showing an interdependent relationship of these two parameters.

Air motor driven machinery should, therefore, always be designed to permit the motor to rotate within its most optimal torque speed range. For this purpose air motors can be governed with a speed regulator which limits the operating speed to the point of maximum power and also conserves air consumption when the motor is not loaded (free wheeling). A typical speed–torque characteristics curve for a governed air motor is given in fig. 5–4.

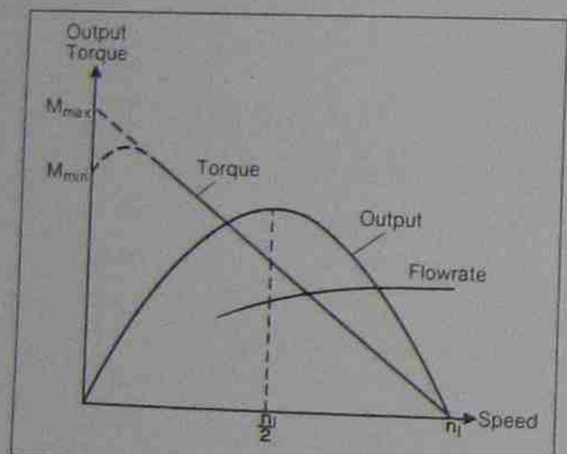


Fig. 5–3 Characteristics of an ungoverned air motor.

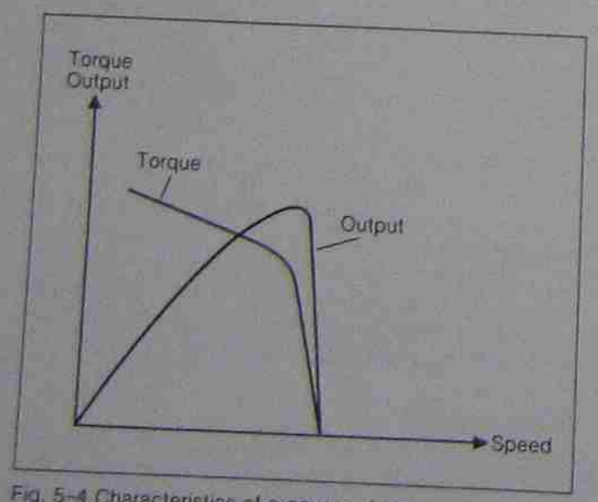


Fig. 5–4 Characteristics of a governed air motor.

Power output

The maximum power output for a typical ungoverned air motor is reached when the motor rotates at approximately half of its free speed (fig. 5–3). Power output for air motors is best applied with the formula

$$P = Q \times p \quad \text{OR.} \quad P = \frac{2 \times N \times n \times M}{60} = \text{Watts}$$

Selection of the correct design type and size of air motor for a particular application is most important, and the procedural steps for selection are given in a worked example at the end of this chapter.

Vane motors

The vane motor is the most common type of air motor used in the manufacturing industry. It covers a large range of power outputs from less than one kW to around 25 kW, which makes them versatile and widely accepted. Fig. 5–5 shows a cross section of a reversible vane motor. A rotor shaft which carries a number of sliding vanes is mounted eccentrically in a cylindrical casing or stator. The vanes are usually made of fibre which has excellent wear properties, and the more vanes used (up to a practical limit) the better the starting torque will be. However, increased friction from the vanes reduces efficiency.

In vane motors torque is produced by the compressed air acting onto the pressure exposed rectangular area of the vanes. These vanes in fact seal the low pressure exhaust port from the high pressure inlet port. According to Pascal's Law, which also applies to pneumatic systems, pressure acts undiminished in all directions and acts also with equal force on equal areas. It is therefore obvious that the motor depicted in fig. 5–5 must turn in a clockwise direction, since the sum of all vane areas being pressurised in a clockwise direction is much larger than the sum of vane areas being pressurised in an anticlockwise direction (see also fig. 5–2). As the rotor continues to rotate in this manner, any residual air remaining between the blades is vented via the anticlockwise supply port B. If the motor is to be operated to produce torque in the opposite direction, the anticlockwise port B is pressurized and port A is vented. The action is then exactly the reverse of that described for clockwise rotation.

As the motor turns the sliding vanes follow the contour of the cam ring (housing), thus forming sealed cavities. Since the vanes must seal and thus maintain cam ring contact at all times, and centrifugal force is absent during motor start,

these vanes are usually spring loaded or air pressure loaded for smaller motors (see fig. 5–6).

During motor rotation the compressed air in the pockets between the vanes is permitted to expand, since the pockets also expand as they rotate towards the exhaust opening. This permits the potential energy stored in the compressed air to be used and thus the "technical work" of the motor is increased and its efficiency is therefore also increased (see fig. 5–8). Figure 5–8 clearly shows which part of the potential energy in the compressed air can additionally be utilized. It must be noted that this principle also applies to radial and axial piston motors, but does not apply to gear motors.

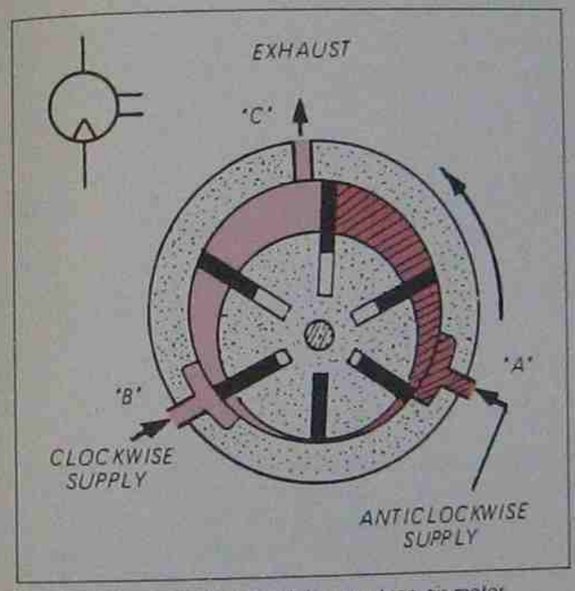


Fig. 5–5 Concept of a reversible vane type air motor.

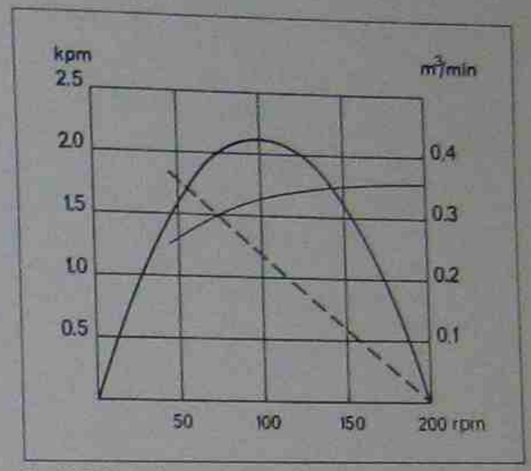


Fig. 5–7 Typical vane motor performance curves.

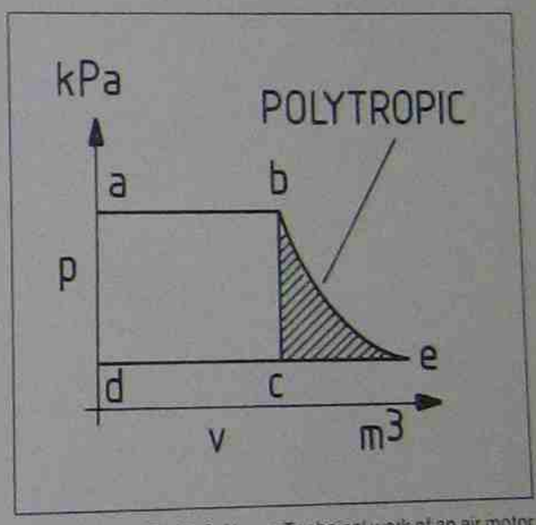


Fig. 5–8 *Above*: Technical work of an air motor with or without utilization of the expansion work. With expansion work it is a, b, e, d; without it is a, b, c, d.

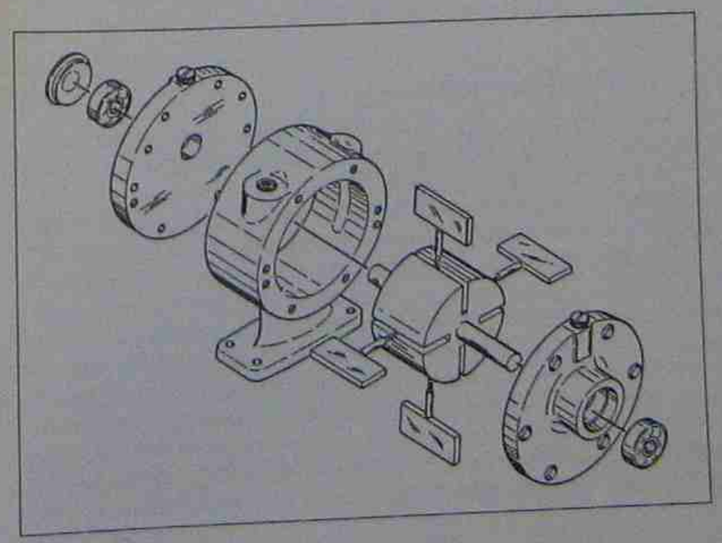


Fig. 5–6 Exploded view of a vane air motor.

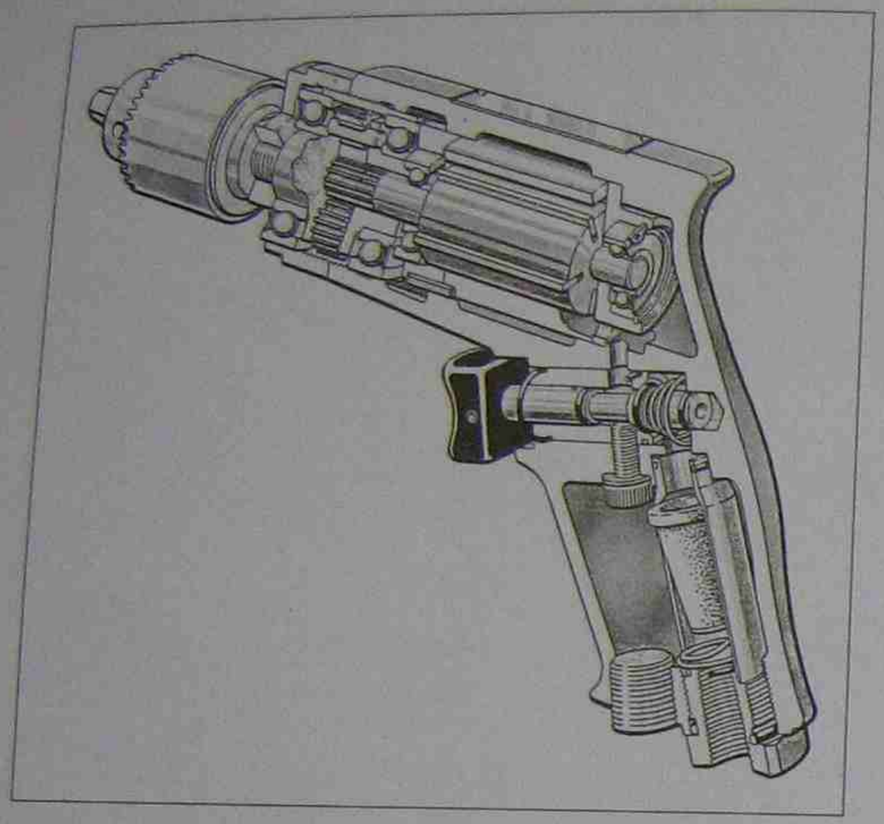


Fig. 5-9 Vane motor driven "ATLAS COPCO" hand drill.

Figure 5–7 shows power and speed curves for a typical vane motor and figure 5–9 illustrates a section through a hand drill using a vane motor.

Theoretically maximum torque should be available from the start, but due to internal leakage and depending on the position of the vanes relative to the inlet port, this maximum torque may not be available until the rotor has turned a number of revolutions. Maximum practical torque output, however, is produced at the stall point—used to advantage in many air tools. The highest power output is obtained at approximately half the free running speed of the motor, and this is generally the maximum performance characteristic specified for the power given data of air tools.

The power to weight ratio is good for vane motors, but because of their torque and power characteristics, they are not ideally suited to low speed applications. Where used in air tools, the drive torque is usually increased through reduction gearing to provide the required output torque. Nearly all air tools used on production lines, such as drills, screw drivers and nut runners, are vane motors. Vane motors are also used in sump pumps and concrete vibrators. By means of various design methods such as the addition of extra rotor vanes, the deficiencies in the starting and slow speed characteristics of vane motors can be overcome sufficiently to allow their use in many heavy duty applications such as hoists, winches and transmission drives for mining equipment.

Gear motors

Gear type air motors consist of two meshing spur gears in a casing which is provided with inlet and outlet ports. (Fig. 5–10.)

The pressurised air entering through the motor housing air inlet where the gears intermesh, impinges on a rectangular gear area and forces the gears to rotate. The air then exhausts through the outlet port after having completed part of a revolution. Gear motors are relatively inefficient due to their high leakage losses between the gear teeth. Free speeds of up to 3000 r.p.m. are possible with a power range of 1 to 15 kW. Their efficiency can be increased by the use of helical instead of spur gears, due to the greater area exposed to air pressure. Reduction gear drives can be used with these motors to increase their output if required. These air motors are not used to any great extent in industrial manufacturing, but are used in applications such as the driving of drill strings in deep bore drilling rigs.

No air expansion takes place in the fixed volume teeth pockets when the air is driven through the motor, thus power output of such motors occurs without utilization of the potential energy (expansion work) stored in the compressed air (see also fig. 5–8).

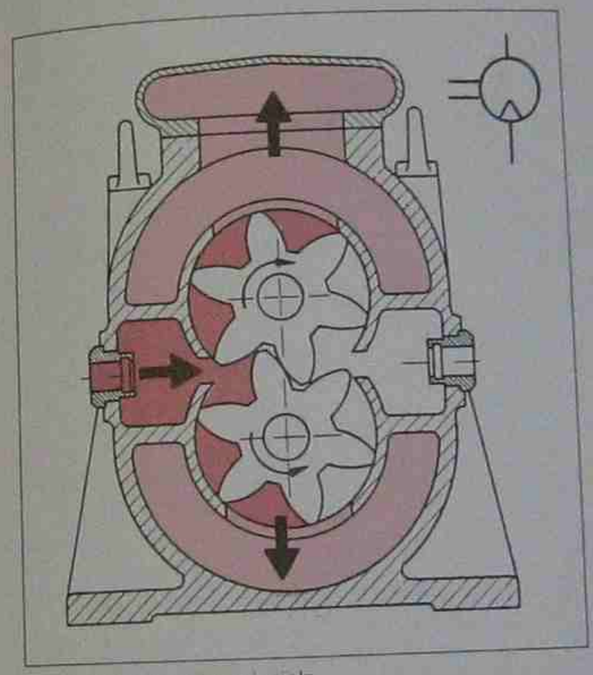


Fig. 5–10 Gear motor principle.

Radial piston motors

For applications where high running torque coupled with excellent starting torque is necessary, the radial piston motor is the ideal choice. These motors are specifically designed for low speed and high power output (with free speed nevertheless up to 4000 r.p.m.). Their power range may reach 25 kW, normally at about 25–40% of their free speed (fig. 5–12).

The cylinders in radial piston motors (up to five or six) are arranged radially around a crankshaft driven by the piston of each cylinder. Compressed air is ported and exhausted to and from each cylinder in turn by a rotary sleeve valve built into the pintle opposite the drive shaft. This causes the crankshaft to rotate. The reciprocating piston movements can be finely balanced to provide a very smooth torque output, and if required valve timing can be arranged for reverse rotation. This valve timing can also be constructed for modified output characteristics for motors used on special applications.

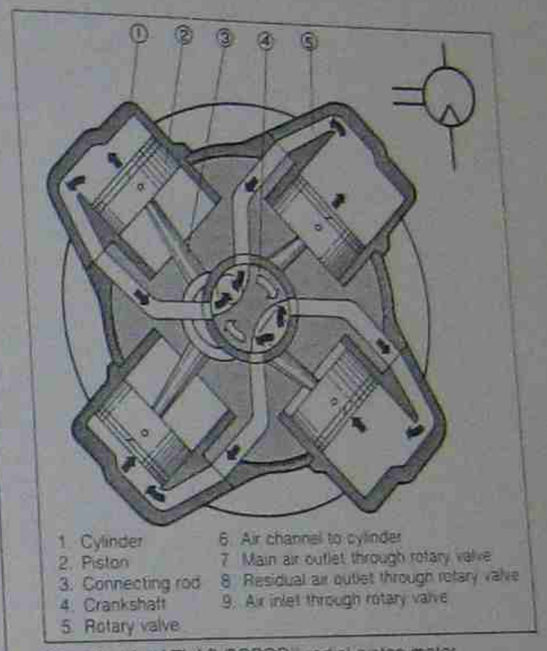


Fig. 5–11A "ATLAS COPCO" radial piston motor.

Description of the ATLAS COPCO piston motor

Depending upon whether the throttle valve is set for clockwise or anti-clockwise rotation, the compressed air passes through one or the other of two channels to the rotary valve ⑤ which is driven by the crankshaft ④. The rotary valve has three channels: air inlet ⑨, main air outlet ⑦ and residual air outlet ⑧. At an alteration of rotation, the channels of air inlet and residual air outlet change functions. When the rotary valve rotates, the compressed air is distributed in turn through channels ⑥ to the cylinders. The air trapped in the cylinder ① expands and presses the piston ② down to its lower position. The air is expelled from the cylinders in two stages, main air outlet ⑦ and residual air outlet ⑧. The main air outlet takes place through a separate outlet channel in the rotary valve ⑤ directly into the motor casing and, via a silencer chamber through the air outlet pipe to the atmosphere. This residual air passes from the rotary valve through the throttle valve and then into the motor casing and out through the air outlet

pipe. When the piston has resumed the inital position the working cycle is repeated. The motor is lubricated by oil in the crankcase and by oil that is supplied via the compressed air by a lubricator.

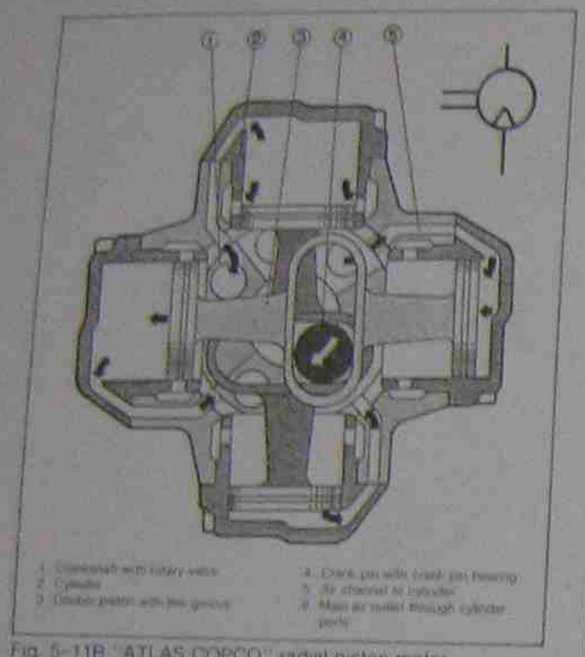


Fig. 5-11B "ATLAS COPCO" radial piston motor.

Description of the ATLAS COPCO piston link motor

The piston link type motor, which is reversible, has each opposed piston pair and associated by a link to a so-called double piston. The motor has two identical double pistons ③. The crankshaft ① has one crank pin ④, which runs in needle bearings in the two link grooves. A rotary valve controls the air supply to the cylinders ②, so that the pistons move and drive the crankshaft continuously. Air inlet and residual air outlet function in the same way as for radial piston type motors, while the air outlet passes through cylinder ports. The motor is lubricated by oil that is supplied via the compressed air by a lubricator.

Axial piston motors

These air motors, like the radial motors, are designed with up to six cylinders, arranged not radially with respect to the output shaft, but in line with (or axially to) the drive shaft. The cylinders are connected to the output shaft through an angled "swash" plate which in fact tumbles and converts the stroking action of the cylinder pistons into a rotary motion (see schematic diagram of figs. 5-1 and 5-13).

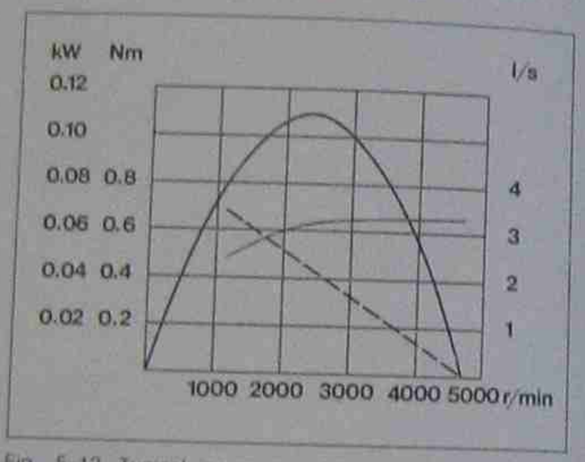


Fig. 5-12 Typical power-speed-torque diagram for an ungeared radial piston motor.

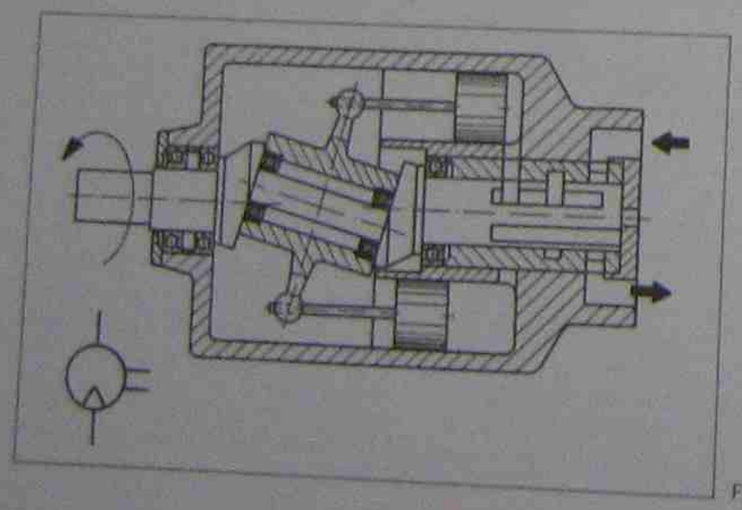


Fig. 5-13 Swashplate or axial-piston motor

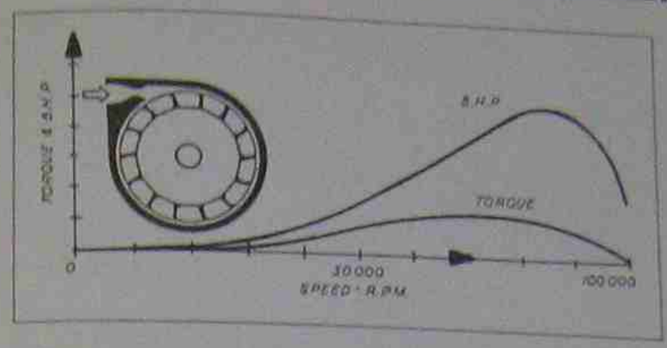


Fig. 5-14 Typical power speed curve for turbine motors

These air motors are at the bottom end of the torque and power output range of piston motors and provide operation speeds much the same as radial motors. However, their power output is generally not greater than 3kW.

Although there are other design variations in axial piston motors, this brief description refers to the type of motor shown in fig. 5-13. In operation compressed air enters the motor through valve ports incorporated on the output shaft similar to the radial motor. This enables the pistons to be pressurized in turn. The piston rods are fastened to the piston and to the wobble plate with ball bearings so they may be free to assume a non-axial direction. The pistons as they extend and retract in turn, impart a rotary motion to the wobble plate. The wobble plate, connected by bevel gears to the motor drive, transmits this motion to the output shaft.

Turbine motors

The turbine motor consists of a small turbine, where the kinetic energy of an air jet impinging on the turbine blades generates very low torque (in comparison with other air motors), but very high free running speeds of up to 100 000 r.p.m. Their applications are thus distinctly limited to those where very high speeds, but extremely light loads, are encountered (dental drills, small tool grinders, pencil sharpeners). Because there are no sliding parts in the construction of turbine motors, except for the spindle bearings, these air motors can be operated with oil-free air. Reduction gearing to increase the power output is not feasible with turbine motors because the friction losses incurred in the gearing would consume most of the available power output. Fig. 5-2 shows the concept of a turbine motor, and a typical power-speed curve for these motors is given in fig. 5-14.

Pressure and air flow regulation on air motors

Pressure regulation affects the torque output of the air motor, whereas air-flow regulation affects the motor speed (shaft revolutions). The output power, however, is altered if either of these parameters is changed (fig. 5-1). Figure 5-15 shows a motor control circuit which provides high pressure supply for start-up and automatic timer controlled change over to lower running pressure once the load is accelerated. Air motors should be sized on 75% of the available air pressure, leaving 25% available for start up and overload

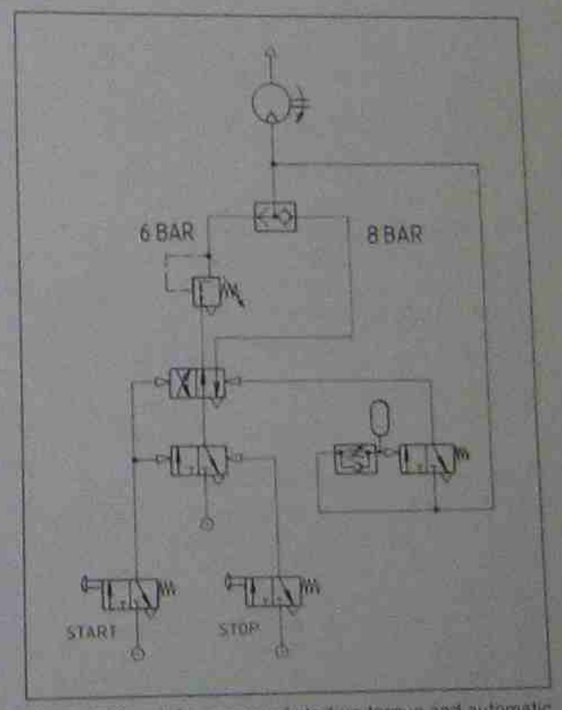


Fig. 5-15 Circuit for increased start-up torque and automatic (time-delayed) changeover to reduced running torque

Air pressure (e) bar	psi	Output power (kW)	Speed (r/min)	Torque (Nm)	Air consumption (l/s)
7	102	1.21	1.03	1.17	1.15
6	87	1.00	1.00	1.00	1.00
5	73	0.77	0.95	0.83	0.82
4	58	0.55	0.87	0.67	0.65
3	44	0.37	0.74	0.50	0.47

Example: The data for a specific air motor at 6 bar (600 kPa) is as follows:

Max output kW	Max output hp	Free speed r/min	Speed at max output r/min	Torque at max output Nm	Air consumption at max output l/s
0.57	0.77	800	400	13.7	14.2

At a pressure (e) of 400 kPa (4 bar) the following approximate data is obtained:

Max output kW	Idling speed r/min	Speed at max output r/min	Torque at max output Nm	Air consumption at max output l/s
0.57 x 0.45 = 0.31	800 x 0.87 = 700	400 x 0.87 = 350	13.7 x 0.67 = 9.2	14.2 x 0.65 = 9.2

1 bar = 100 kPa = 1.02 kp/cm² = 14.5 psi
1 Nm = 0.102 kpm = 0.7376 lbf ft
1 l/s = 0.06 m³/min

0.77 x 0.55 = 0.42 hp
1 kW = 1.341 hp
1 hp = 0.7457 kW

Fig. 5–16 Performance conversion table for different air pressures.

Motor Type	Max Free Speed R.P.M.	Typical Operating Speed Range R.P.M.	Torque Speed Ratio	Initial Torque	Typical Max Power Outputs kW
Vane	20,000	7,000–15,000	Low	Medium	15
Gear	3,000	1,500–2,000	Low	Low	15
Radial Piston	2,000	600–1,500	Medium to High	High	25
Axial Piston	3,000	600–1,500	Medium to High	High	3
Turbine	100,000	50,000–80,000	Very Low	Negligible	Less than 1

Fig. 5–17 Air motor performance characteristics.

In reversible air motors a suitable valve can accomplish change of rotation. No requirement for slow down or stopping between reversals is needed. If strong enough, an outside force can in fact reverse the motor against its direction of rotation without damaging the motor. In this manner it can be used as a break.

Data at different air pressures

The normal working pressure (e) for air motors is 600 kPa (6 bar). When the air pressure is lower than 600 kPa or somewhat higher, it is then valuable to be able to calculate the performance of the air motor at the air pressure in question.

By means of the table shown in fig. 5–16 it is possible to calculate the approximate speed, output power, torque and air consumption at different air pressures for an ungoverned motor.

Air motor performance comparison

The table (fig. 5–17) gives various characteristics for the types of air motors discussed in the preceding pages.

Air motor sizing and torque calculations

Exercise 1

Rotary power output of pneumatic motors is calculated:

Watt = 2π x revolutions per second x torque

$W = 2\pi \times n \times M$

Torque = newtons x metres

M = Nm

Using these formulae, calculate the required torque on the drive shaft of the cable drum in fig. 5–18, if the load shown must be held in suspension.

Torque = newtons x metres (radius)

Torque = 100 x 0.2

(10 kg = approx. 100 N; precisely 98.1 N)

= 20 Nm

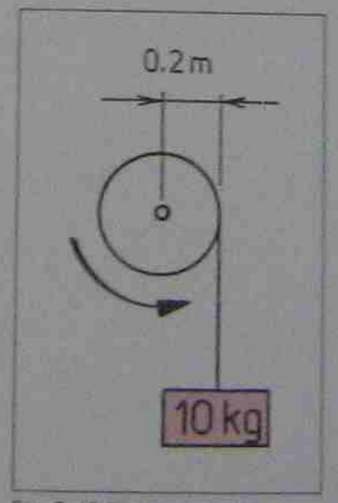


Fig. 5–18 Torque calculation.

Exercise 2

Using the results obtained in exercise 1, select a suitable air motor from the information given in fig. 5–19. The load must be lifted with a speed of 50 m/min. For friction loss and acceleration add approximately 25% to the required torque obtained in exercise 1.

$$\frac{20\ \text{Nm} \times (100 + 25)}{100} = 25\ \text{Nm}$$ (including friction loss and acceleration)

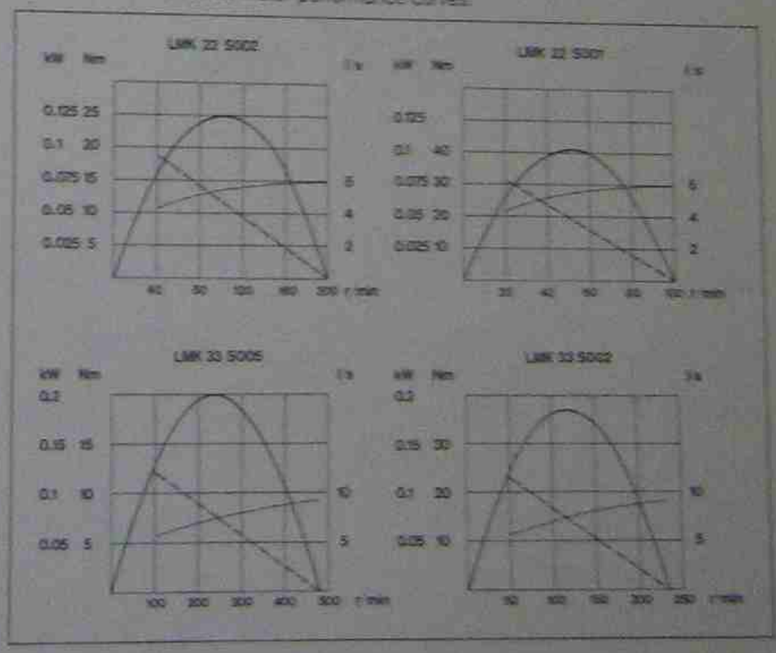
$$\text{Required r.p.m.} = \frac{\text{lifting distance}}{\text{circumference of cable drum}}$$

$$\text{Required r.p.m.} = \frac{50\ \text{m}}{0.4\ \text{m} \times 3.1416} = \frac{50}{1.2566}$$

= 39.78 r.p.m.

The selected motor is of the ATLAS COPCO type LMK 33 S002 but the LMK 22 S001 could also be used.

Fig. 5–19 Selection of air motor performance curves.



6 Pneumatic Sensors

In order to make pneumatics a better means of machine control, design engineers as well as maintenance engineers should have a thorough knowledge of the vast range and choice of sensing equipment available today. Position sensors are built for two different forms of sensing; contact and non-contact type sensing. A third form of actuator motion or event sensing, is the previously described form of pressure sensing (see Chapter 2).

One-way trip and roller valve for contact sensing

Contact type sensing is the most widely used form of actuator motion or position sensing. It is achieved with mechanically operated valves such as roller valves, plunger valves, one-way trip valves, whisker valves and fluidic back pressure sensors (figs. 2-7, 2-9, 2-31, 6-1, 6-2 and 6-3).

Where the complete linear or swivel movement of a mechanical part operated by an actuator must be detected with accuracy, the one-way trip valve, however, would be completely inadequate. One-way trip valves require an overtravel of the cam of at least 10 to 20 mm to allow the hinged roller lever to swing back.

This means that the signal from such a valve will emerge when the actuator movement tripping it, still has to go on for yet another 10 to 20 mm, thus precise end-position sensing is out of the question (fig. 6-1).

One-way trip valves render a pulse rather than a stationary signal. The pulse disappears as soon as the hinged roller is permitted to swing back (fig. 6-1). The following table compares this (only) advantage with the many disadvantages for the use of one-way trip valves.

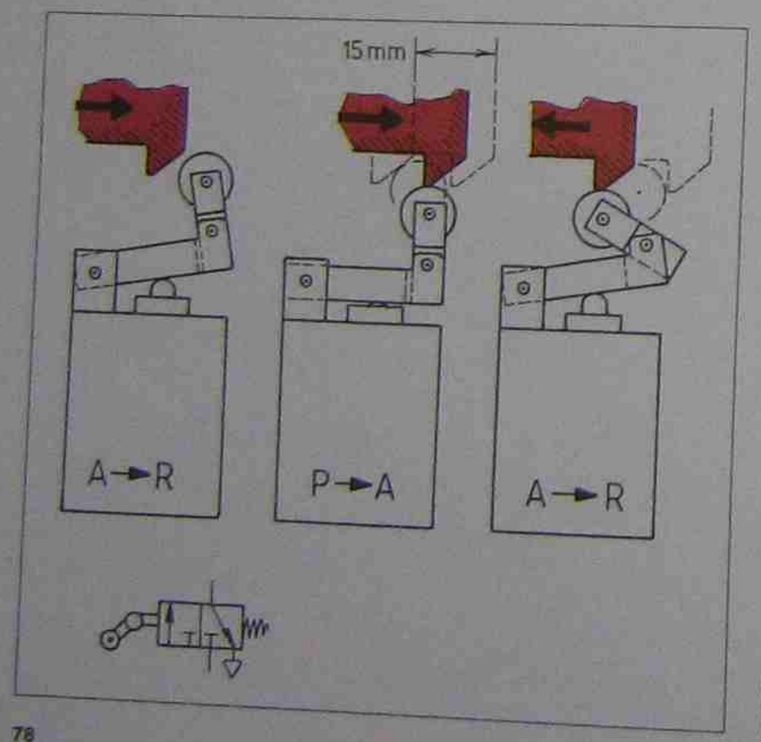


Fig. 6-1 One-way valve: 15 mm overtravel is required to trigger and thereupon cancel the signal.

Roller/plunger valves	One-way trip valves
Advantages: • Signal length not dependent on actuator speed. • Precise end-position control is possible. • Logic linkages of signals is possible. • Time delayed signal processing is possible. Disadvantages: • Opposing signals must be avoided with circuit design method (see: circuit design Chapter 8).	Advantage: • Gives no opposing signals (short pulse only). Disadvantages: • Precise end-position control not possible. • Logic linkages of signals not possible (pulse only). • Time delayed signal processing is not possible. • Fast actuator speed is not possible (signal too short).

In order to gain a fully controlled sequence of all actuators in an interlocking machine program, it is essential to install position sensors (position or limit valves) at all movement end positions (figs. 8-1 and 8-21).

This practice guarantees a completely interlocked and movement end-position depending sequence, where no machine movement or sequence step can occur unless the previous sequence step is completed. Such close machine movement monitoring eliminates costly machine down-time and work damage.

Machine and operator safety in fully automated manufacturing processes always outweighs the minor costs of a few more sensing valves and should never suffer from the "dollar thrifty" attitude on the part of some machine designers and maintenance engineers.

Back pressure sensor for contact sensing

The back pressure sensor is the only pneumatic position sensor which achieves a sensing accuracy better than 0.2 mm. It may be used for extremely short actuator strokes (less than 5 mm) where one or both actuator stroke end positions must be detected, or for applications where the sensing accuracy of roller or plunger valves (1-3 mm) is insufficient (fig. 6-2).

Compressed air of normal system pressure (4-8 bar, 400-800 kPa) is connected to port P. With no object resting against the protruding plunger, the

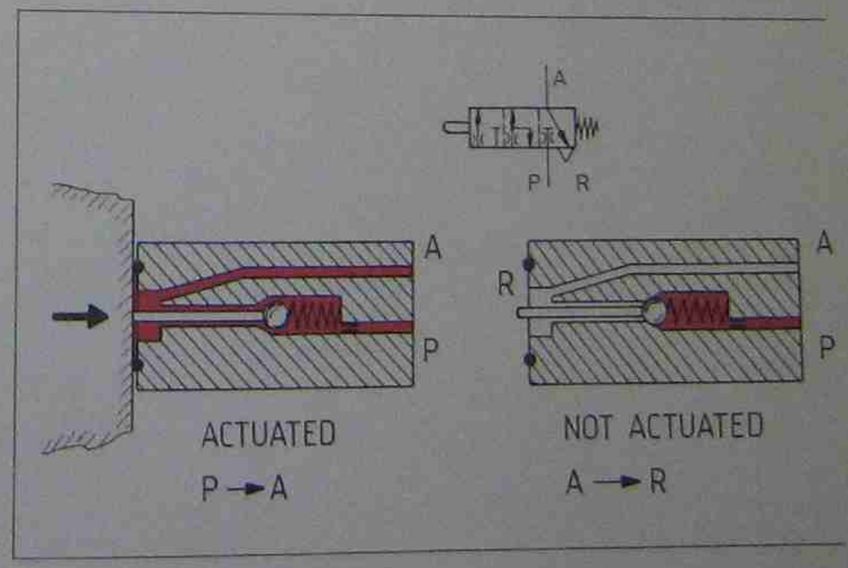


Fig. 6-2 Back pressure sensor.

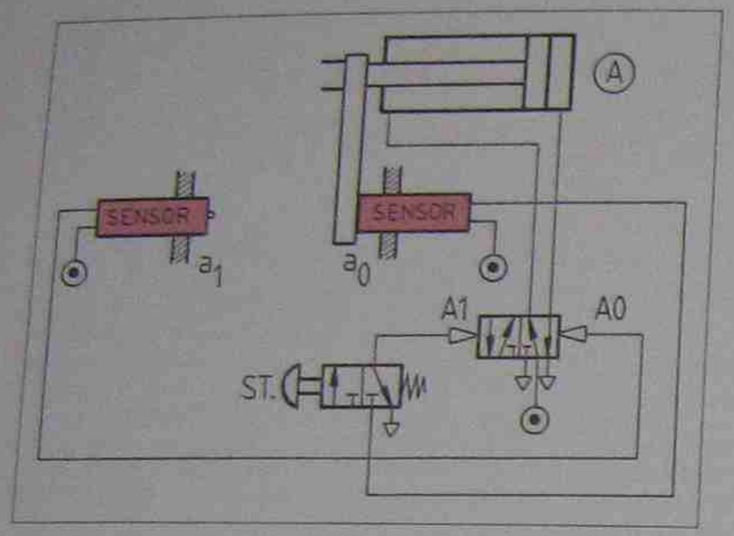


Fig. 6-3 Two back pressure sensors sequence the actuator to extend and to retract. The start valve is series connected with the a_0 back pressure sensor ("AND" function).

check valve will remain closed and hence no compressed air escapes at the sensing nozzle R, but the sensor pilot outlet line A (signal line) is vented to atmosphere through the nozzle opening R (fig. 6-2 and 6-3).

When an object approaches the sensor, the protruding plunger is contacted first. This forces the check valve off its seat and compressed air from port P can now escape through the nozzle R for a short time only, until the approaching object closes the nozzle completely (fig. 6-2). From then on, pressure starts to build up as compressed air flows in from port P and is redirected to port A (for an application circuit see fig. 6-3).

Back pressure sensors must be rigidly mounted (bulk-head mounting with a mounting block) to avoid deflection and thus ensure the extreme sensing accuracy for which they are usually required (fig. 6-3). If properly mounted, back pressure sensors can be used to limit the actuator stroke and can absorb a thrust force of up to 24 000 N. But in order to utilize the full cushioning stroke of the actuator, the back pressure sensor should not diminish the total actuator stroke by more than 1 mm (see Chapter 3, Pneumatic end position cushioning).

Back pressure sensors provide the following sensing advantages:

- Extremely accurate position sensing (better than 0.2 mm)—no other pneumatic sensor can achieve this accuracy!
- Suitable for extremely low actuating force (only 12 newtons at 6 bar supply pressure is required to open the check valve).
- Small dimensions make it suitable for mounting where space is limited.
- The sensor can be used as an actuator stroke limit stop and is easily adjustable (threaded mounting).
- The sensor may be used for extreme ambient temperatures (−10 to +80°C) and in extremely dirty environments, since the emitted air cleans the sensor nozzle.

Liquid level sensor

The liquid level sensor operates on a similar principle to the back pressure sensor. The sensor is also supplied with compressed air of either normal system pressure (400–600 kPa, 4–6 bar) or low pressure of 10–30 kPa (0.1 to 0.3 bar). If operated on low pressure, the pilot signal emerging from the sensor must be amplified with a pressure amplifier valve (see figs. 6-5, 6-4 and 6-16).

When the sensor tube is not in contact with the liquid to be sensed, the supply air escapes through the nozzle of the sensor tube (immersion tube). As soon as the rising liquid closes the opening of the immersion tube, pressure starts to build up as compressed air now flows in from port P and is redirected to the signal port A (for application circuit see fig. 6-5). This signal pressure is proportional to the level of the liquid above the tube nozzle and to the specific gravity of the liquid being sensed, and eventually reaches the pressure level of supply at port P (air bubbles are more buoyant in a heavy liquid than in a liquid with lesser specific gravity). The signal pressure remains as long as the outlet R of the immersion tube is closed by the liquid.

Where liquid surfaces subject to wave formation or rapid level fluctuations are to be sensed, a level cushioning jacket should be fitted around the immersion tube. Such a jacket has one or more small holes in the nozzle region which smooth out the rapid level changes and provide a more stable sensing result.

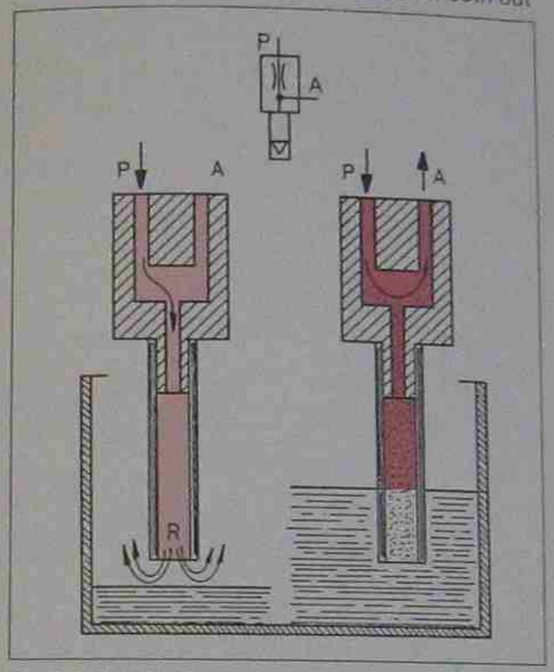


Fig. 6-4 Liquid level sensor.

Proximity Sensor for non-contact sensing

The sensors discussed so far require physical contact with the object being moved. Non-contact type sensors, however, must be chosen wherever physical contact of the sensing mechanism with the object to be detected is either impossible or undesirable. Such applications range from food processing, liquid sensing, extreme lightweight object sensing (such as paper sheets), to the sensing of gauge hands on pressure gauges or weighing machines, and strip material correction when being rolled onto reels or powder storage in tanks and silos (see figs. 6-6 to 6-9 and 10-26, 10-29).

With the proximity sensor (reflex sensor), low pressure compressed air at approximately 30 kPa (0.3 bar) escapes through a ring opening on the front end of the sensor (fig. 6-6). This causes a vacuum pressure cone to form in the centre of the air escape fan. If the escaping air is disturbed by an approaching object, the vacuum cone starts to collapse and turbulent air raises the pressure in the pilot line A. This pilot pressure, however, is extremely low (1–4 kPa, 0.01–0.04 bar) and must be increased with an amplifier valve for use in signal processing (see amplifier valve fig. 6-14 and proximity sensor application circuit fig. 6-7).

Typical air consumption figures for various prox-

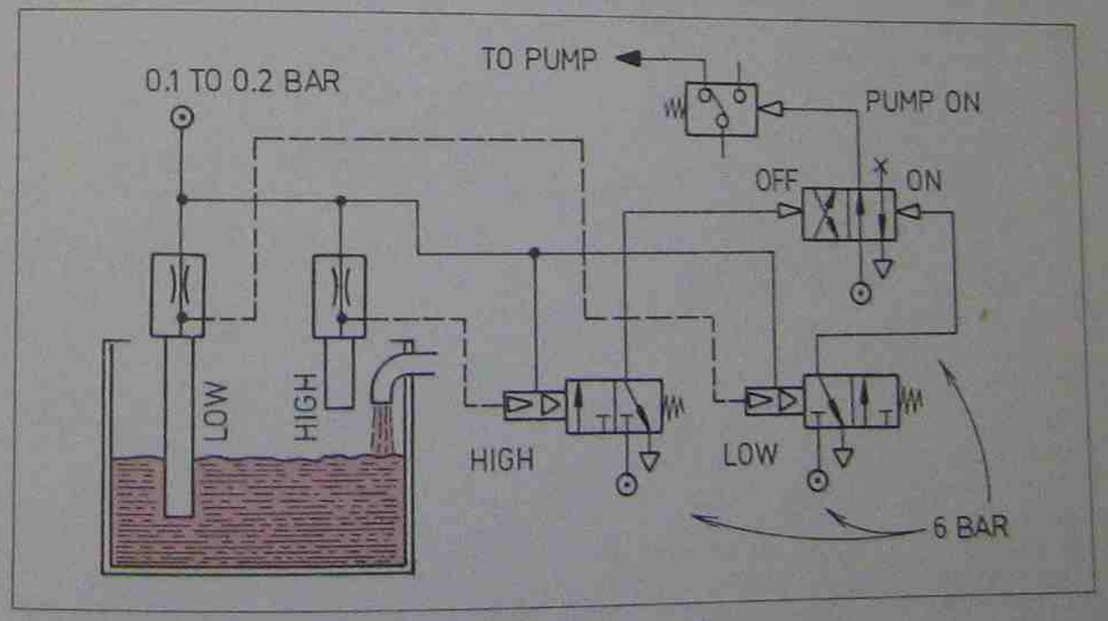


Fig. 6-5 Liquid level sensor application circuit.

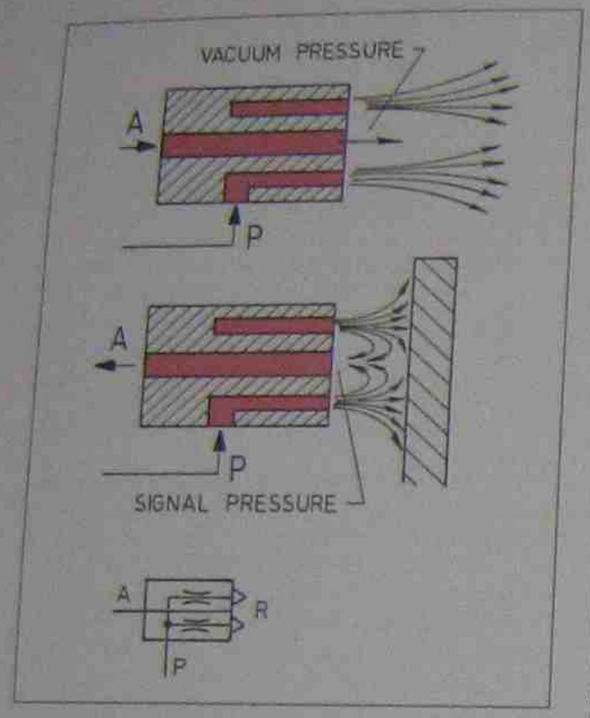


Fig. 6-6 Proximity sensor (reflex sensor).

imity sensors as depicted in fig. 6-6 are given in the air consumption graph in fig. 6-8. The air consumption depends on the size of the sensor (sensing distance 3.6 or 12 mm) and the magnitude of the supply pressure being fed into the sensor (see figs. 6-6 and 6-7).

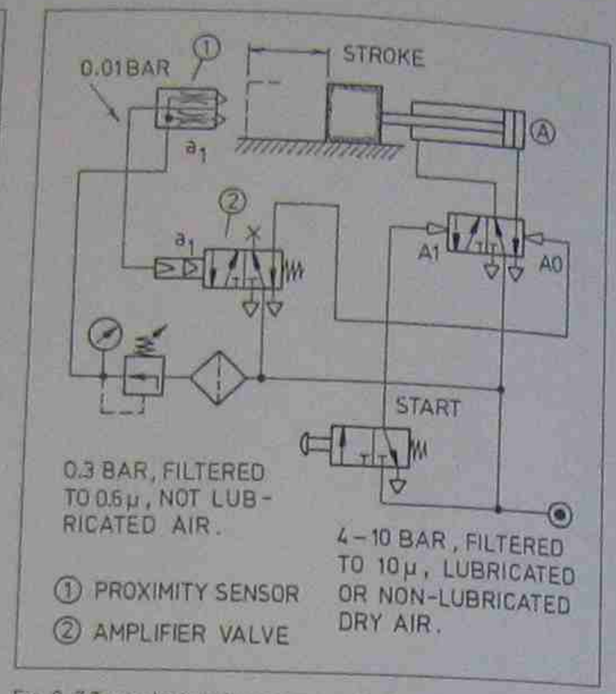


Fig. 6-7 Typical proximity sensor application circuit. The start valve signals extension, the proximity sensor and its amplifier signal retraction of the actuator.

For a 6 mm sensing distance sensor, the air consumption amounts to 30 L/min of free air, if the supply pressure is limited to 0.3 bar, and for a 12 mm sensor with the same supply pressure the air consumption rises to 96 L/min.

To minimize the high air consumption of such

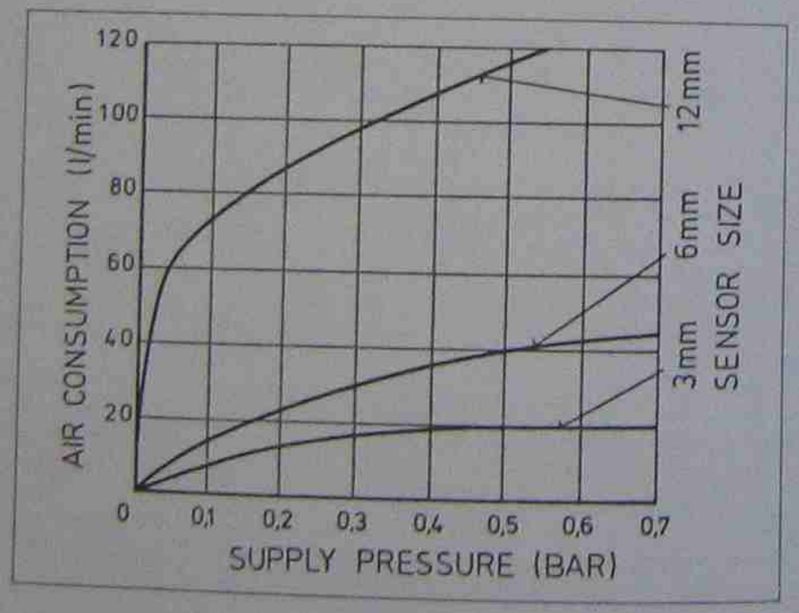


Fig. 6-8 Air consumption figures for proximity sensors 3, 6 and 12 mm sensing distance.

sensors, one can design a circuit interlock to switch the supply air on only when a sensing function is imminent (for a typical circuit of this nature see fig. 6-19).

Figure 6-9 shows how the low pressure pilot signal emerging from the proximity sensor depends on the sensing distance "a" and the supply pressure "P" which is connected to the sensor (see also figs. 6-7 and 6-8). For sensor size 12 mm, with a supply pressure of 20 kPa (0.2 bar), a sensing distance "a" of approximately 10 mm can be achieved if one assumes that the amplifier works on minimal pilot pressure of 1 kPa (0.01 bar). The same sensor may achieve over 14 mm sensing distance if the supply pressure is lifted to 4 kPa (0.04 bar).

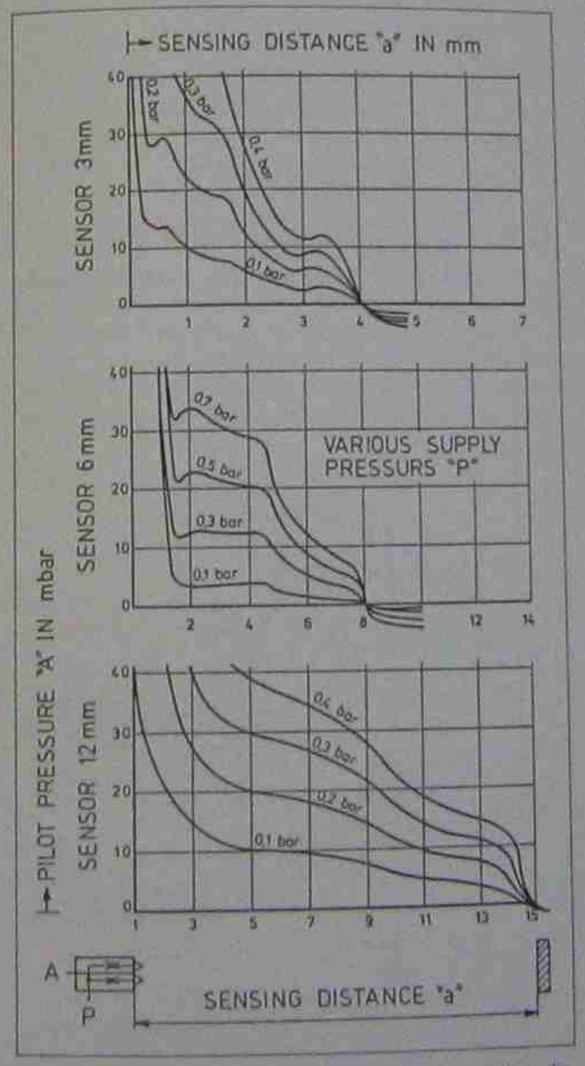


Fig. 6-9 Sensing pressure is dependent on sensing distance.

Gap sensor for non-contact type sensing

This gap sensor works on the Venturi principle. Compressed air at approximately 30-50 kPa (0.3 to 0.5 bar) flows from port P via jet 1 to outlet 2. At the same time air flow is also diverted via the detour passage to outlet 3. This escaping air from outlet 3 causes a back pressure at outlet 2 which induces a pressure build-up at port A. If the back pressure jet from outlet 3 is interrupted by an approaching object, the back pressure at outlet 2 vanishes and freely escaping air at outlet 2 causes a vacuum to build up at the venturi point 4. This vacuum build-up cancels the signal at port A (fig. 6-10). For circuit see fig. 6-11. Since the approach of an object in the opening of the gap sensor cancels the pilot signal at port A of the sensor, a normally open amplifier is used, which by the principle of signal inversion produces a pilot signal when the sensor detects an object.

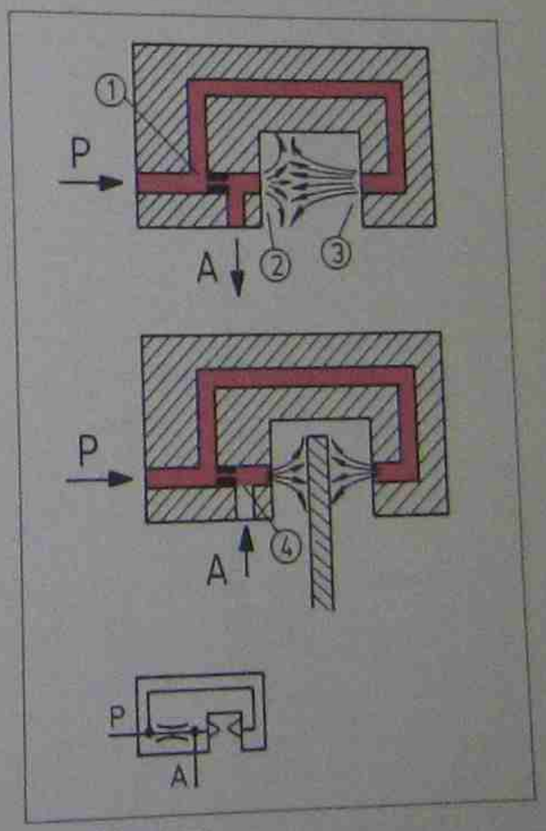


Fig. 6-10 Gap sensor.

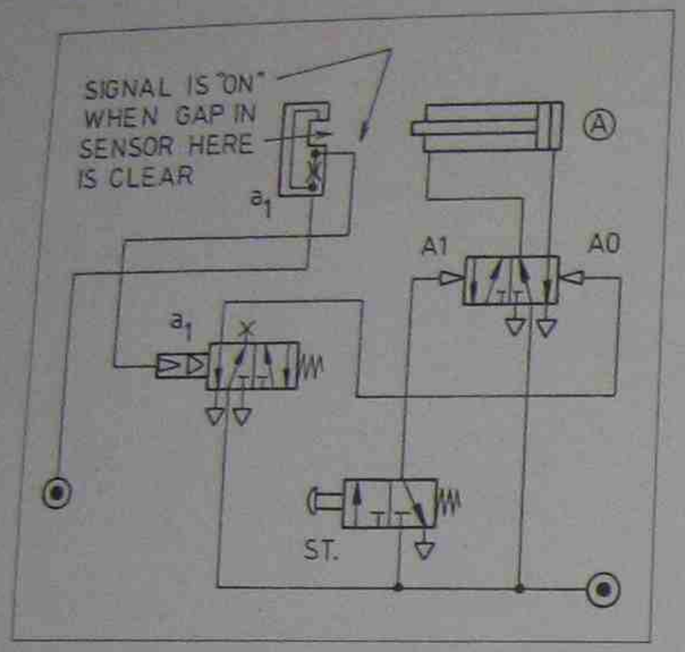


Fig. 6-11 Typical gap sensor circuit.

Air barrier for non-contact type sensing

The air barrier uses the previously explained and depicted gap sensor as a receiver unit on one end of the sensing gap and a jet nozzle as a sender unit on the other end of the sensing gap.

With this arrangement a sensing gap of 200 mm or more may be achieved. By carefully tuning the pressures of the gap sensor and jet nozzle using a flow control valve as shown in fig. 6-12, one may achieve much larger sensing gaps (for application circuitry see fig. 6-13). Here too, an amplifier valve is required, but with the air barrier an interruption of the air jet causes a signal at port A to appear (when an object is sensed), and thus a normally closed amplifier valve must be used.

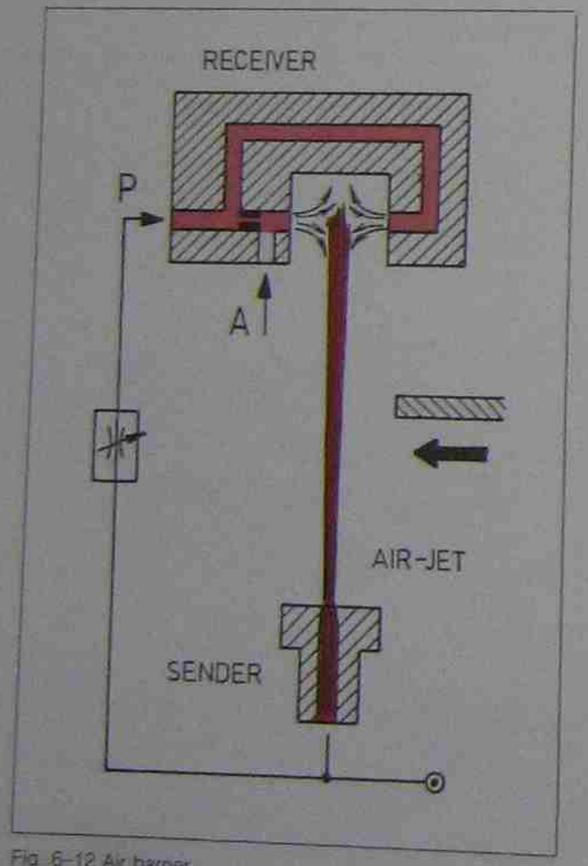


Fig. 6-12 Air barrier

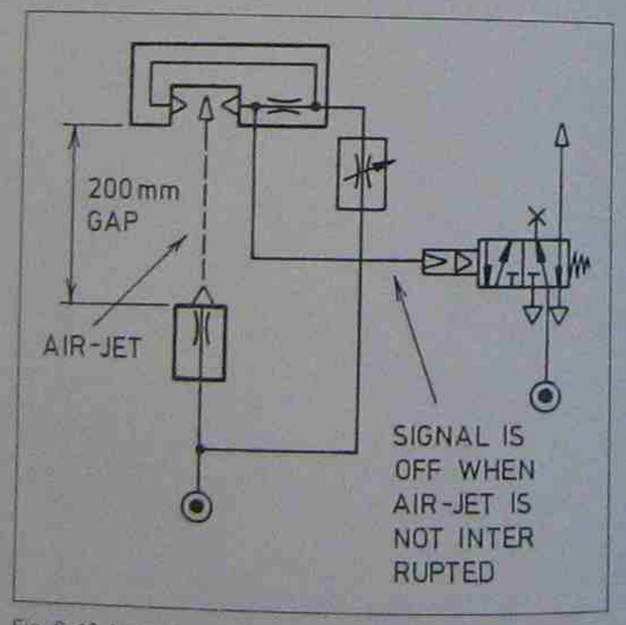


Fig. 6-13 Air barrier with amplifier.

Amplifier valves

Some of the sensors mentioned before, such as the liquid level sensor, the proximity sensor, the gap sensor and the air barrier require an amplifier valve to magnify the extremely low pressure signal from these sensors into a useful pilot signal of at least 200-400 kPa (2-4 bar) or more where required.

Single Stage Amplifier

The single stage amplifier shown in fig. 6-14 amplifies sensor pilot signals from as low as 0.6 kPa into any desirable output pressure between 200 and 1000 kPa (2 and 10 bar). The low pressure pilot signal enters the valve at port X and acts onto the diaphragm. This closes the air escape aperture on the left on the valve spool, so that the vented air flowing from port P through the hollowed out spool must build up pressure. This pressure build-up shifts the valve spool and thus compressed air is directed from port P to port A, whereby port B is vented to exhaust port S.

Figure 6-15 shows typical air consumption, pilot pressure and sensitivity figures in relation to the

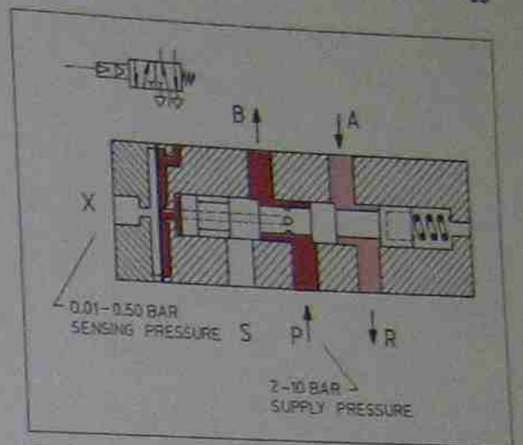


Fig. 6-14 Amplifier valve: the internal air pilot being channelled through the midst of the spool actuates the valve when the low pressure diaphragm closes the vent aperture.

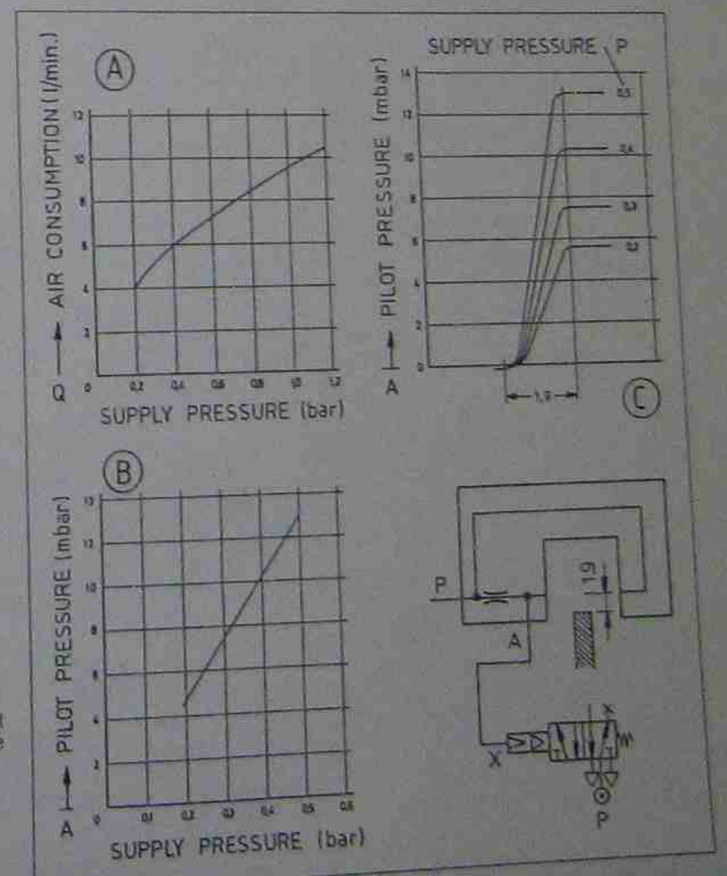


Fig. 6-15 Graph (C) is based on an object sensing distance of 1.9 mm from the centre of the air jet.

supply pressure as measured for the gap sensor depicted in figs. 6-10 and 6-11. Similar values must be used if the gap sensor is turned into an air barrier (fig. 6-12).

Two stage amplifier for high sensitivity

The two stage amplifier shown in fig. 6-16 is more sensitive than the single stage amplifier shown in fig. 6-14. This amplifier must be used for the liquid level sensor depicted in fig. 6-4 or where the pilot pressure from a gap sensor or air barrier is too low for the single stage amplifier.

The two stage amplifier shown in fig. 6-16 amplifies sensor pilot signals from as low as 5 Pa (0.0005 bar) into any desirable output pressure between 200 and 800 kPa (2 and 8 bar). The low pressure pilot signal enters the valve at port X and acts onto the low pressure diaphragm. This closes the medium pressure air escape aperture so that the previously vented medium pressure air is diverted to the underside of the medium pressure diaphragm. This lifts the diaphragm against the opposing spring and opens the poppet thus high pressure air (200–800 kPa) can flow from port P through the valve to port A.

When the low pressure signal at port X disappears, the valve operation is reversed and the high pressure pilot signal can exhaust from port A to port R.

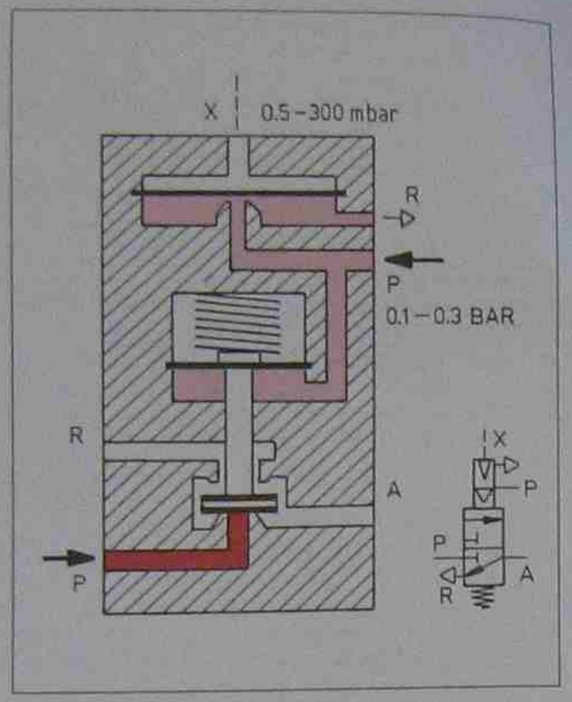


Fig. 6-16 Two stage amplifier for high sensitivity

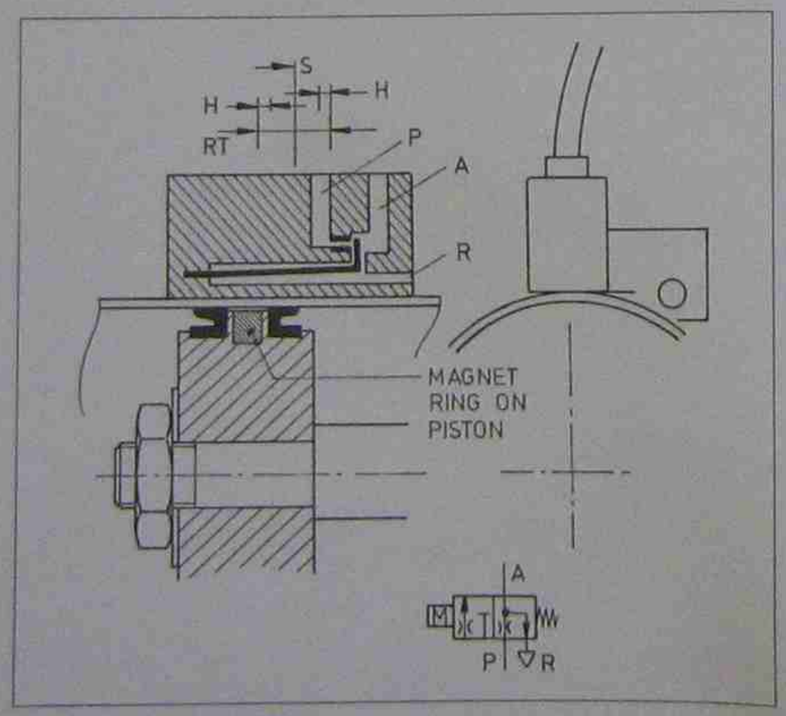


Fig. 6-17 Pneumatic reed sensor. This sensor may also be categorised as a non-contact sensor, and requires an amplifier valve.

Pneumatic reed sensor for non-contact sensing

The pneumatic "reed sensor" is directly mounted onto the actuator barrel. It is actuated by a magnetic ring embedded into the circumference of the piston. When the piston with the permanent magnet approaches the sensor, the reed becomes attracted by the magnet and the sensor is actuated (figs. 6-17 and 6-18).

The sensor operates on a similar principle to the air barrier. When the permanent magnet pulls the reed down, the air jet from passage P blows into air passage A, where the pressure rises. This increased pressure is amplified with an amplifier valve as shown in fig. 6-16. When the piston with its magnet has moved beyond the response travel point RT, the reed springs back again and the tongue on the reed interrupts the air jet again. Thus the pilot pressure in air passage A can exhaust to passage R and out to atmosphere. Any air leakage past and around the tongue can also exhaust to atmosphere.

The switching point S is normally in the centre of the sensor. H denotes the *hysteresis*, a distance in which switching *may* occur but is not guaranteed.

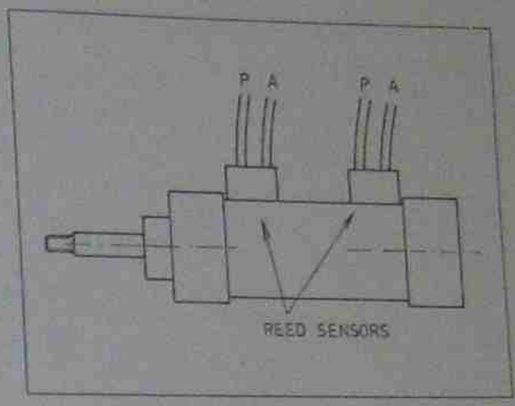
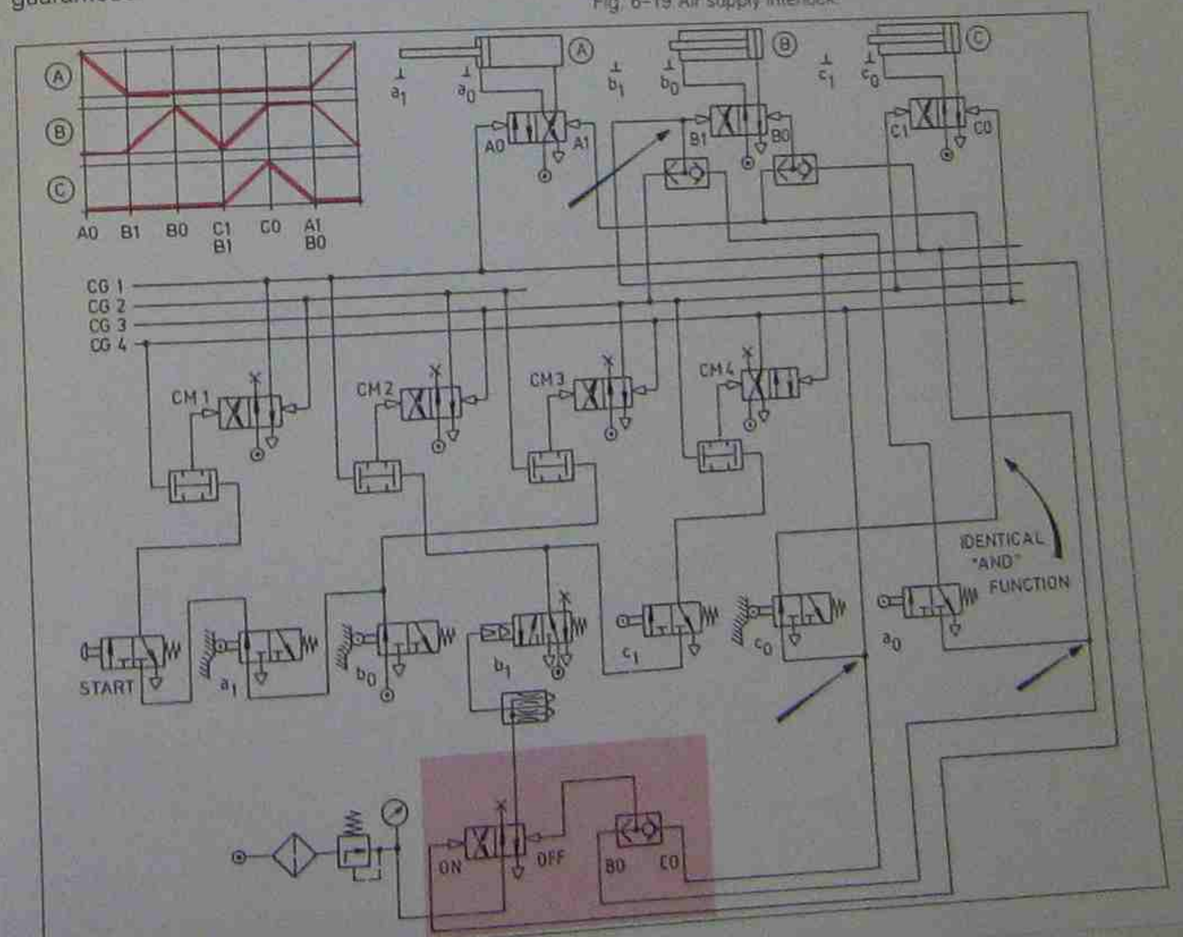


Fig. 6-18 Pneumatic actuator fitted with two pneumatic reed sensors.

Pneumatic reed sensors are either mounted onto the tie rod of the actuator or are fitted onto a specially designed mounting rail which spans from end cap to end cap. Pneumatic reed sensors can only be used with non-ferrous actuator barrels and the piston must be fitted with a permanent magnet.

Fig. 6-19 Air supply interlock



Reduction of air consumption for non-contact sensor

To minimise the high air consumption of non-contact type sensors one can design a circuit interlock to direct supply air to the sensor only, when a sensing function is imminent (figs. 6-19, 6-6 and 6-8).

Valve mounting and actuation methods

Care and accuracy must be applied when valves are mounted onto a machine. If a valve is mounted too close to the actuating cam or actuating machine member, the valve spool or poppet may "bottom out" and the valve mechanism is made to bear the full force of the approaching load driven by the actuator. This often causes return springs to become coilbound, or through constant abuse of the valve mechanism the valve may cease to function altogether.

Cam angles should never have more than a 45° inclination (fig. 6-20). The cam should be made with mounting slots, or the valve mounting bracket should have slots. This permits the valve to be mounted precisely, so that the switching point S is reached approximately 1 mm before the cam stops. The difference between that point and the maximum travel point then acts as a safety margin or safety overtravel so that the valve does not "bottom out" (see fig. 6-21). "Head-on" actuation, as shown in fig. 6-21, gives a more precise actuation (within 1 mm) than overtravelled rollers (fig. 6-20), which may only provide a switching accuracy of about 2-3 mm.

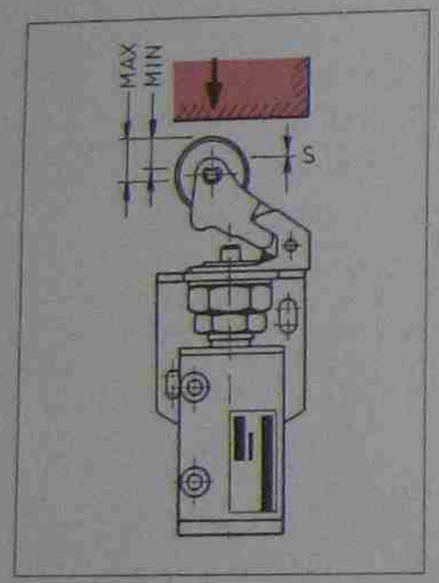


Fig. 6-21 Minimum and maximum travel: the switching point "S" is where the valve opens the desired air passage.

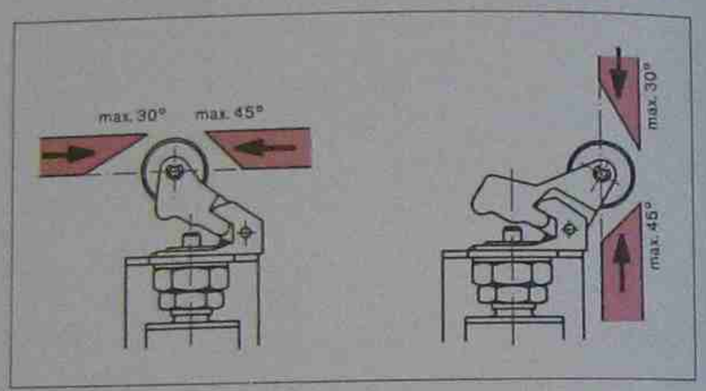


Fig. 6-20 Cam angle.

7 Circuit Presentation and Control Problem Analysis

At present, no international standards exist for uniform circuit array and circuit labelling. However, a well-presented circuit can facilitate circuit construction for the engineer and fault-finding for maintenance personnel, as well as making the total control package a more marketable item.

Circuit layout and presentation

The method of circuit layout shown in fig. 7-1 is still widely used. However, it is very impractical for large and complex circuits, since too many signal lines cross and thus cause confusion. For logically designed circuits, with their large number of "AND" function and "OR" function valves, this type of circuit layout proves totally inadequate. Hence the layout structure shown in fig. 7-2 is recommended. The circuit designer will soon become familiar with this type of layout and appreciate its many real advantages.

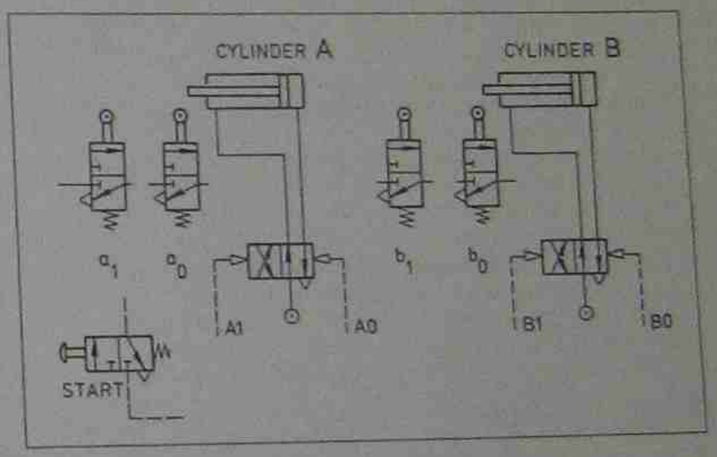


Fig. 7-1 Poor circuit presentation.

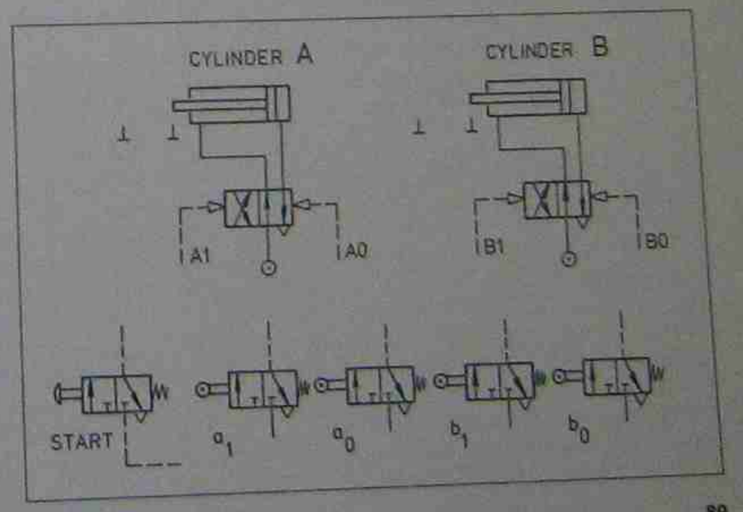


Fig. 7-2 Recommended circuit presentation.

Recommendations for circuit array

There are no international standards for circuit presentation and layout at present, so some well proven principles are listed below. These principles, either in their present form or after input from other experienced circuit designers, may be the forerunner of an international standard.

- Draw all symbols where possible in horizontal position and attach lines to the right hand square for two position valves or to the centre square for three position valves (figs. 2–2 and 7–2).
- Do not mirror-invert symbols if avoidable, since this practice confuses the comprehension of signal direction, fluid-flow and valve function (see fluid power symbols in Appendix).
- Draw all valves in their de-actuated, unpressurised rest position, except for those valves which are actuated either by a lever, cam or machine part, when the machine is at rest, or at the end of a cycle. For such valves one must indicate with a cam or similar device that the valve is actuated and all attachment and pressure lines are to be connected to the left hand square. (See also valve switching positions, Chapter 2 and fig. 7–3.)
- Two-position valves which are not spring biased and can freely assume both switching positions (bi-stable valves, memory valves or detented valves) may be drawn in whatever flow-path configuration is demanded by the actuator position or initial position when the machine is at rest. But here again, the pressure lines should be connected to the right hand square (figs. 7–3 and 2–3). An exception to this rule is frequently made for memory valves in sequential control circuits which maintain their last selected position to provide the start signal for a new machine cycle (see figs. 7–5 and 8–6).
- Draw all actuators in their machine rest position or initial position. For example, if an actuator is extended at the end of the cycle it should be drawn in the extended position (figs. 7–3 and 2–3).
- Where position sensing valve signals or pressure sensing valve signals have to be distributed to a number of destinations for circuit interlocking (fig. 7–5), it is advisable to adopt the "bus-bar" distribution system (figs. 7–4 and 7–5). The *bus-bar* should be regarded as a manifold line with both extremities closed off.

To ascertain the exact number of T-connections to be used for each valve outlet, one simply counts the number of connection dots on the bus-bar and deducts two. Thus, a bus-bar with four dots requires two T-connectors and a bus-bar with two dots requires none.

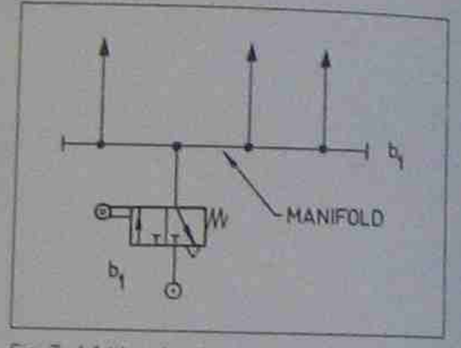


Fig. 7–4 A "bus-bar" with four connection dots requires in reality two T-connectors to distribute the position sensing valve signal to three users.

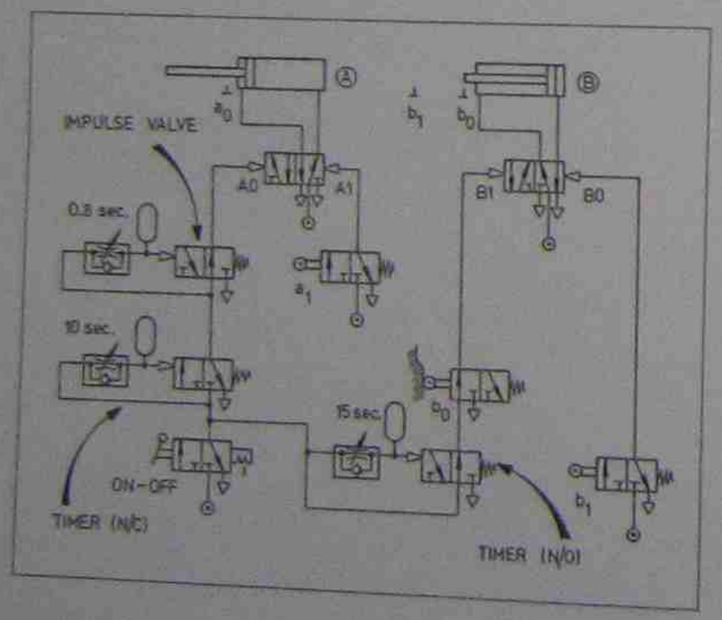


Fig. 7–3 Typical circuit layout showing all the recommendations made for proper circuit array.

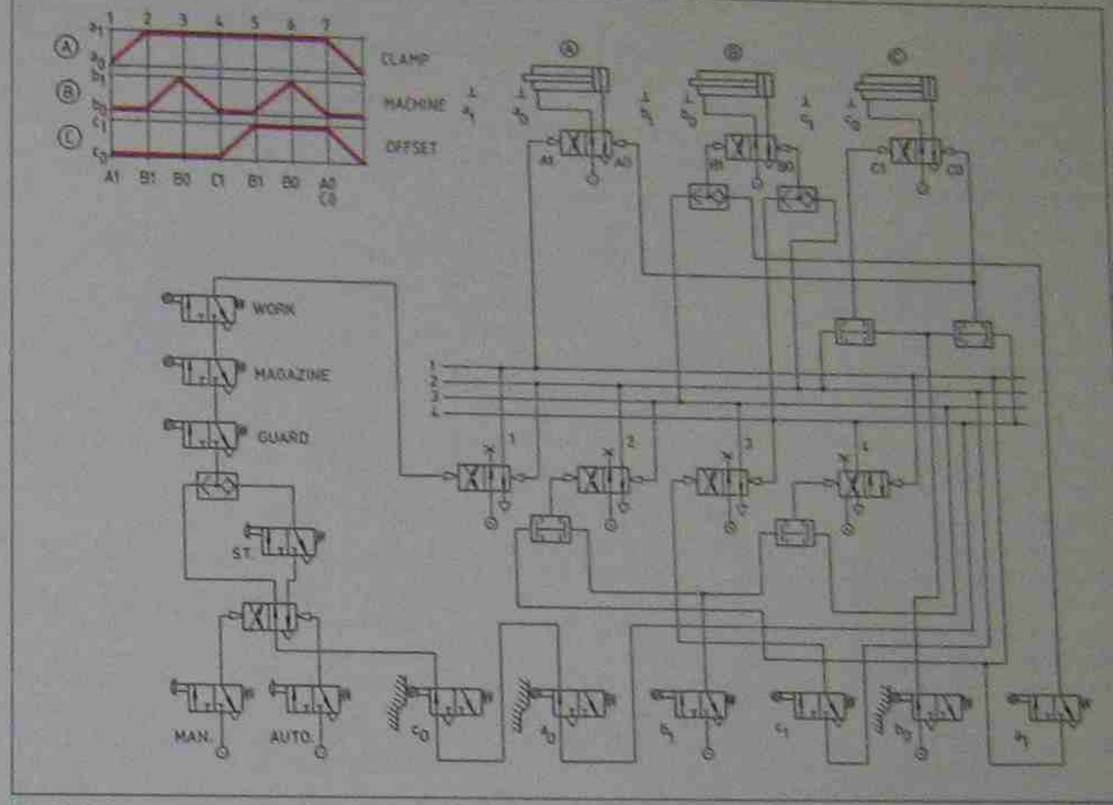


Fig. 7–5

- Clearly separate fringe condition modules such as used for emergency stop, cycle selection and start restriction from the sequential control circuit (figs. 7–3 and 7–6). These modules and the concept for designing sequential circuits are explained in the following chapters.
- Circuit labelling with the binary movement expression and labelling method, as explained in Chapter 2, should be adopted. This eliminates communication difficulties and simplifies circuit installation and fault-finding (figs. 7–3, 7–5, 8-14 and 8-15).
- Sequential control circuits with more than one actuator should include the traverse-time diagram, which depicts the sequence and if possible all specifications and sequence equations derived for the design of the control. Such equations must also include start restriction and combinational equations, where applicable (figs. 7–5, 8–17, 8–18, 8–21, 10–13 and 10–14).

Control Problem analysis

The grouping of the total control circuit into su circuits seems to be one of the main difficult which confront circuit designers. However, the obstacles can be drastically reduced by analys the total control problem and then splitting design into four main categories:

- power circuit
- sequential circuit
- fringe condition modules
- combinational circuit

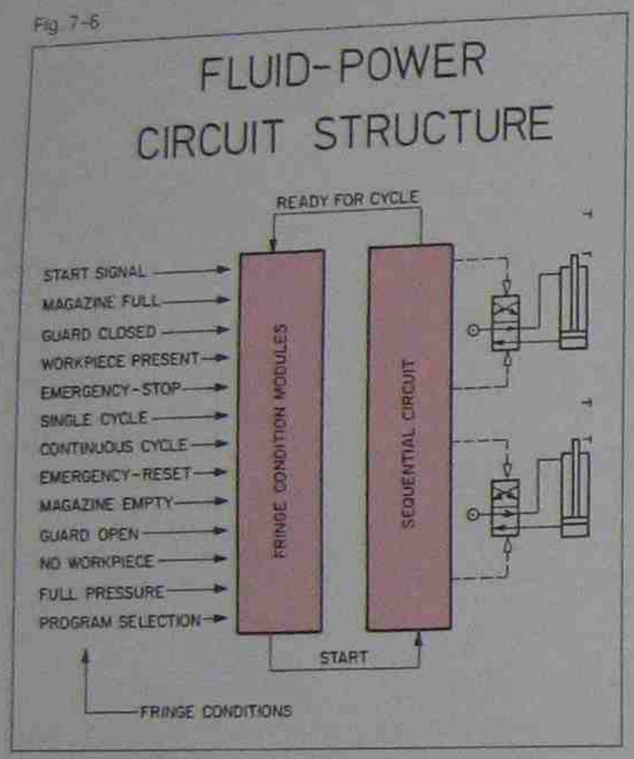
The *power circuit* consists of the actuators their directional control valves (power valves also includes the speed control valves Chapter 4) and compressed air lines which nect the actuators to the power valves.

That part of the circuit which controls the s ping or sequencing of the actuators is gene called the *sequential circuit*. It consists of me valves, "AND" function, "OR" function and delay valves (figs. 8–20 to 8–39).

The *fringe condition* circuits, which preferably are arranged in modules, affect the sequential circuit at its fringe and generally affect its start or stop characteristics (start permitted or not, emergency stop, etc.). These fringe condition modules are added in the final part of circuit design and are designed separately (for a detailed description of fringe conditions see Chapters 8 and 10).

Combinational circuits are network-type control circuits and their output signals depend solely on the momentary state of the input signals. Combinational circuits do not consider past actions which would require memory valves. For a detailed description of combinational controls see Chapter 10 and Chapter 11.

Fig. 7-6



METHODS OF CIRCUIT DESIGN	
COMBINATIONAL CIRCUIT	INTUITIVELY
	KARNAUGH
	BOOLEAN
SEQUENTIAL CIRCUIT	CASCADE
	KARNAUGH
	BOOLEAN
STEP COUNTER	BOOLEAN

EMERGENCY STOP MODULE	SEQUENTIAL CIRCUIT • INTUITIVE • KARNAUGH-VEITCH • STEP-COUNTER • COMPUTER • CASCADE
CYCLE SELECTION MODULE	
START RESTRICTION MODULE	
COUNTING MODULE	COMBINATORIAL CIRCUIT

Fig. 7-8

8 Pneumatic Step-Counter Circuit Design

The science or art of designing asynchronous sequential circuits for controlling automation systems has come a long way during the past thirty years. At one time circuits were "put together" more or less intuitively without applying a proper and logical design method. This approach was based on trial and error, although graphical aids such as traverse-time diagrams and step-motion diagrams were often employed to make the search for a viable solution more systematic.

The two methods presented in this book are based on systematic and logic design and are the result of extensive research work undertaken by system design engineers such as D.A. Huffman—The Franklin Institute U.S.A.; Prof. D.W. Pessen—Technion Haifa Israel; Dr. W. Huebl—Martonair Germany; Prof. E.C. Fitch—Oklahoma State University U.S.A.; H. Schwaar—Festo Switzerland and P. Rohner—Royal Melbourne Institute of Technology Australia. Both design methods are well proven and numerous control circuits based on these methods are installed in machines all over the world.

It must also be noted that both methods can be used to program electronic programmable controllers (PLC), and particularly the step-counter method is ideally suited and simple to program electronic controllers as applied for sequential machine control. A separate chapter in this book explains and illustrates how this may be achieved (see Chapter 11).

Traverse-time diagram (step-motion diagram)

The traverse-time diagram is a simple, effective and easily understood graphic representation of the motion sequence (step sequence) at which linear fluid power actuators operate. The machine designer defines the motion sequence and draws the corresponding traverse-time diagram, thus establishing a communication and design basis for all parties involved in the design, implementation and commissioning of the total control system. The following points are to be observed when setting up a traverse-time diagram (see fig. 8-1):

- Step commands are represented by vertical lines ("time lines"). The direction and speed rate of the actuator movements are shown by inclined lines.
- Sequence steps are numbered above the time lines. The beginning of time delay periods are labelled T (fig. 8-19), and stroke length and stroke speed are regarded as equal since these have no bearing on the sequencing of the machine.
- Horizontal lines represent stroke limits and are labelled according to the name given to the position sensing valves (limit valves) located at the stroke end.
- Circuit and signal labelling is based on the binary system whereby actuator extension is denoted with the binary logic 1 and retraction with the binary logic 0. For example, signal command A1 causes actuator A to extend. Limit valve a_1 confirms this extension. Signal command A0 causes actuator retraction and limit valve a_0 (feedback signal) confirms the completion of the retraction motion.

Below the traverse-time diagram is the "key". The *key* contains important information which later becomes the basis for circuit design. The key shows which limit valves are actuated at any particular sequence step during the machine cycle. For example in fig. 8-1 the key indicates that at the end of sequence step 2, the limit valves a_1 and $b_$ are actuated.

The key may also be used to register an impor tant confirmation signal, or combinations signals, which are essential to trigger the ne sequence step. For example in fig. 8-1 sequenc step 3 can only be triggered if the previous step completed. This completion is signalled by lir valve b_1. Hence limit valve b_1 in the key is circle This process is called "circling of essential co firmation signals". If these circled essent confirmation signals are now used as the basis implementing sequence steps, then no action sequence can ever occur unless the previc sequence step is completed.

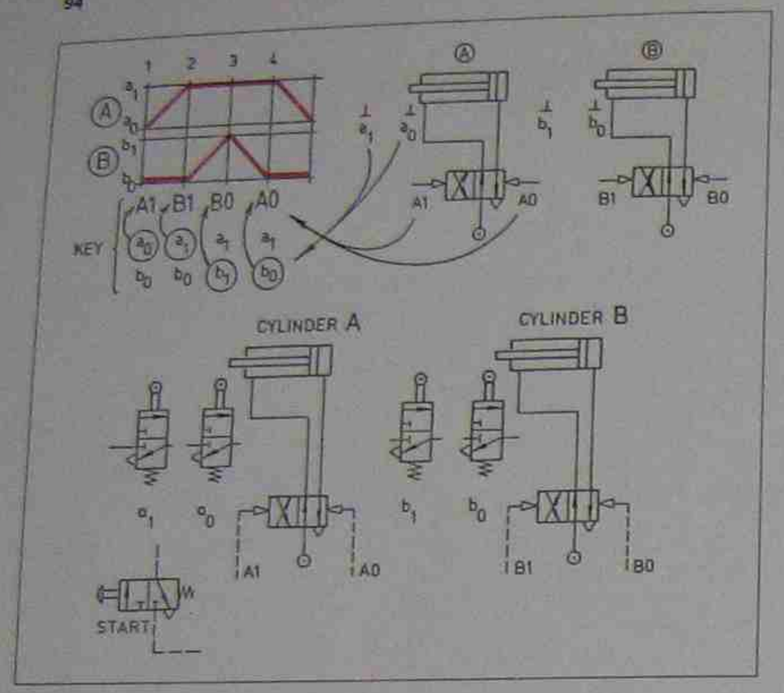


Fig. 8-1 Traverse-time diagram

Opposing signals

In the design and construction of sequential circuits involving a number of actuators (cylinders) following a given sequence, it is frequently found that circuit design is complicated by the presence of disturbing pilot signals (confirmation signals). Such disturbing pilot signals result from earlier actuator movements and oppose the later arriving pilot signals on the power valve (fig. 8-2). Hence the power valve can't be reversed unless the opposing (disturbing) signal is eliminated. A simple illustration of this problem is given in fig. 8-2. Here again, all essential confirmation signals are circled in the key and the arrows show how these pilot valves are connected to the power valves (compare also with a circuit given for this sequence in fig. 8-3). A close investigation reveals that the essential confirmation signal a_1 is used to switch sequence step 2 by producing command B1 on the power valve. This means that signal a_1 is used as the signal source to "SET" power valve B and thus cause its actuator to extend.

One step later, however, this pilot signal (a_1) is still "ON" since its actuator has not moved during

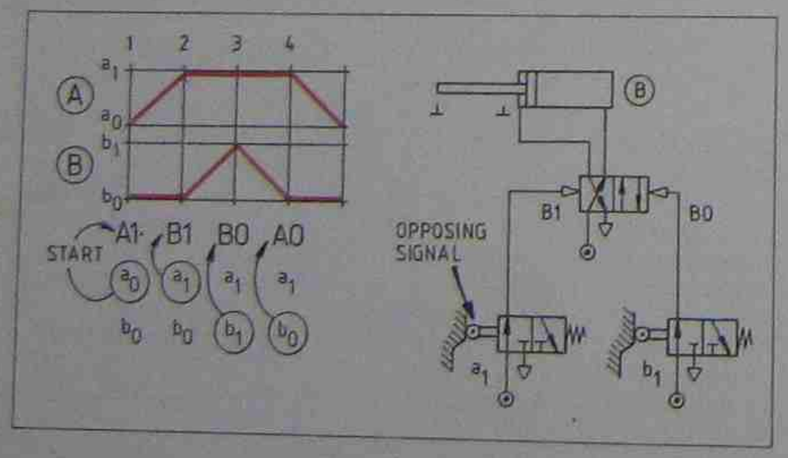


Fig. 8-2 The opposing signal is a_1

the second time phase of the sequence (see traverse-time diagram in fig. 8-2). Thus when pilot signal b_1 must "RESET" the power valve B to cause actuator retraction, it cannot, because of the opposing signal on the opposite side.

A simple method often applied to rid the circuit of such opposing signals is to use one-way trip valves instead of roller or plunger valves. Such one-way trip valves create only a short pulse while being overtravelled and no pulse when the actuator returns (figs. 8-3 and 6-1). However, the many negative aspects of these valves are discussed in detail in Chapter 6. Another possible solution is to feed the opposing signal through an impulse valve and thus cause the pilot signal to appear for a short time only. This method is shown in Chapter 2, figs. 2-45, 2-47 and 2-52.

The following two circuit design methods automatically eliminate the occurrence of opposing signals, and are therefore highly recommended for use when designing sequential control circuits. These methods are:

1. Step-counter design method (or: step sequencer).
2. Cascade design method (simple version).

Step-counter circuit design method

The step-counter circuit is a modular circuit design concept consisting of a chain of integrated circuit blocks or modules, whereby each sequence step (depicted in the traverse-time diagram) is allocated a module. The simplicity of the step-counter (sometimes called step-sequencer or sequence controller) stems from the construction of its modules and the unique integration of these modules into a sequence chain (fig. 8-4). Each

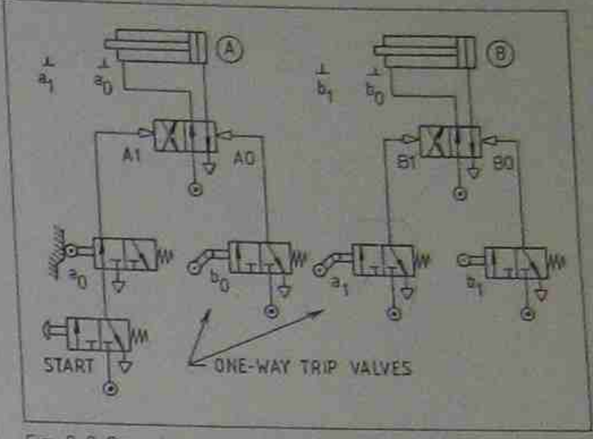


Fig. 8-3 Opposing signals are removed with one-way trip valves

module is built from a "MEMORY" valve and a pre-switched "AND" function valve. The two signals required to make the "AND" function are the essential feedback signal, confirming the completion of the previous sequence step, and the preparation signal from the memory valve of the previous step-counter module (compare figs. 8-4 and 8-5). The "AND" function sets the memory into the "ON" position. The memory must accomplish three functions: it provides the power valves (D.C.V.) with a signal command to extend or retract an actuator; it re-sets the memory valve in the previous step-counter module; and it provides the next step-counter module in the chain with a preparation signal (on the "AND" valve).

Opposing signals thus cannot occur since the

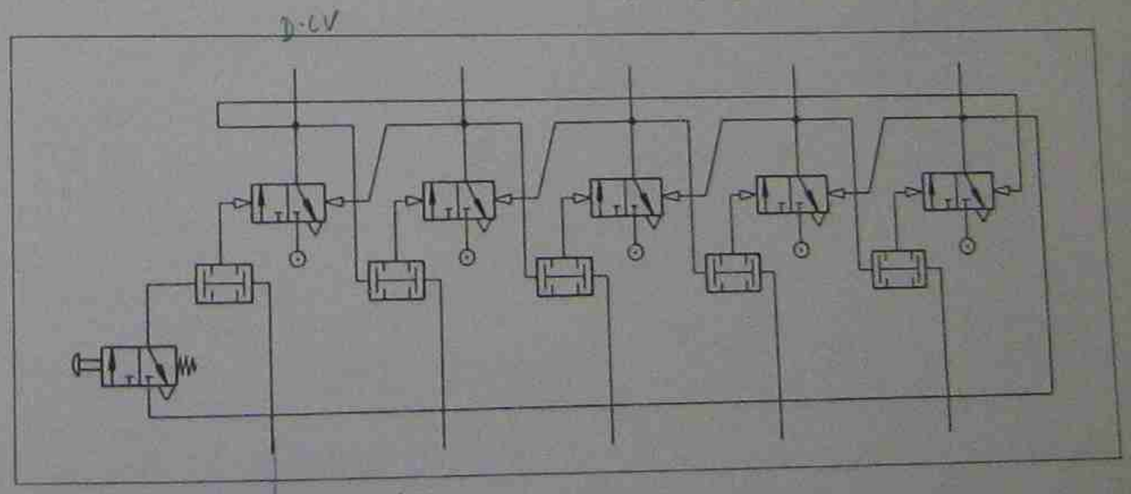


Fig. 8-4 Step-counter for five sequence steps

previously used confirmation signal (feedback signal) is automatically rendered inactive when the memory, which is "AND" connected to it, is being reset (see fig. 8-4).

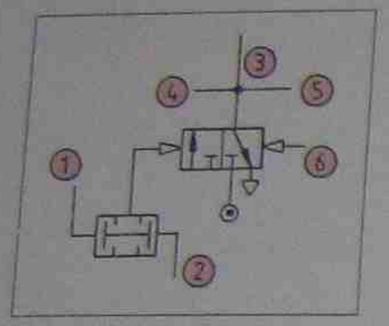


Fig. 8-5 Step-counter module
(1) Preparation signal from previous module
(2) Feedback signal from previous step
(3) Switching signal to power valve
(4) Reset signal to previous module
(5) Preparation signal to next module
(6) Reset signal from next module

When the sequence program is completed, the last module in the circuit chain remains set until the first module after the start signal has been given, resets it (fig. 8-6). The preparation signal for the "AND" function in module 1 is fed through the start valve (fig. 8-4). Alternatively, one may also place the start valve into the confirmation signal line prior to the "AND" valve in module 1 (see fig. 8-6). Thus the START valve interrupts continuous cycling and a new cycle cannot commence until the START command is given. A circuit for a clamp and drill application is given in fig. 8-6.

Logic switching equations for step-counter circuit design

Logic switching functions, and this applies to all sorts of control whether this be mechanical, pneumatic, hydraulic, electrical or electronic, can be expressed in equation form. The fundamental principles of logic switching expression use the notations of Boolean algebra, which was discovered and published by George Boole, Professor of Mathematics at Queens College, County Cork, Ireland in 1854. His laws and theorems are still valid today and are the foundation of logic switching from telephones to computers. The five most important logic functions (YES, NOT, AND, OR, INHIBITION) are shown in fig. 8-7. Further logic functions and the use of truth tables and corresponding Karnaugh-Veitch maps are illustrated and explained in Chapter 10. Figure 8-7 shows the name of the logic function in the left hand column, then the pneumatic symbol in the middle and in the right hand column the Boolean switching equation. "A" is signal input 1, "B" is signal input 2 and "S" is the output signal. A dash above the signal means "not on" or signal "not present". The "AND" function is denoted by a dot (•), the "OR" function by a plus sign (+).

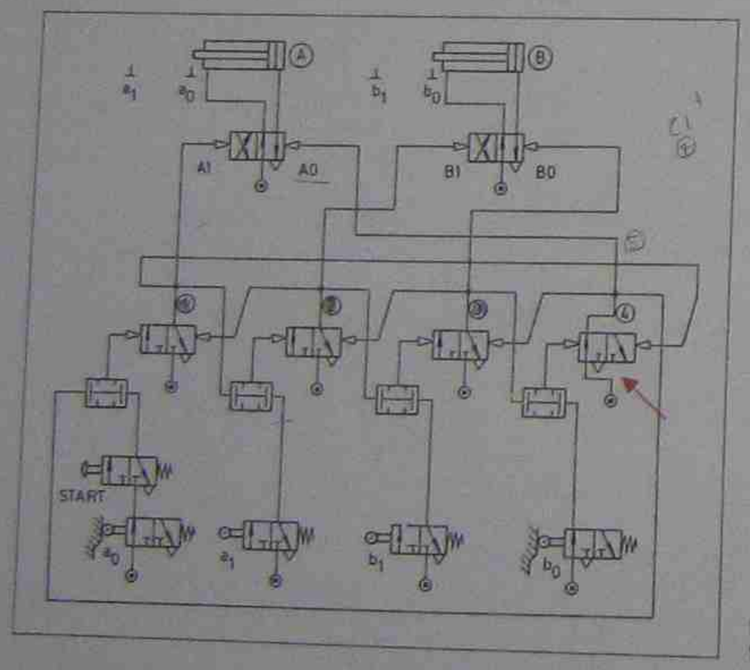


Fig. 8-6 Step-counter circuit for sequence given in fig. 7-1.

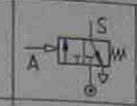
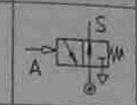
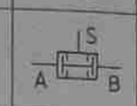
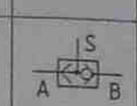
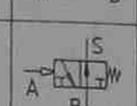
YES		A=S
NOT		$\overline{A}$=S
AND		A•B=S
OR		A+B=S
INHIBITION		$\overline{A}$•B=S

Fig. 8-7 Basic logic switching functions

Switching equations may be used directly to build a control circuit, thus making a circuit diagram obsolete. But not everybody can read and understand Boolean switching equations, so circuit diagrams are still frequently used in industry. To derive such switching equations one separates the circuit into power valve input signals and step-counter input signals (also called D.C.V. inputs, step-counter inputs). The step-counter is regarded as a chain consisting of individual step-counter modules and each module is given a number according to the step it switches (fig. 8-6).

Switching equations for the circuit shown in fig. 8-6 are:

D.C.V. inputs:

A1 = Step 1 (Module1)
A0 = Step 4
B1 = Step 2
B0 = Step 3

Step-counter inputs:

Stepping module 1 = a_0 • Start
Stepping module 2 = a_1
Stepping module 3 = b_1
Stepping module 4 = b_0

Switching equations for the circuit shown in fig. 8-11 are:

D.C.V. inputs:

A1 = Step 6
A0 = Step 1
B1 = Step 2 + Step 4
B0 = Step 3 + Step 6
C1 = Step 4
C0 = Step 5

Step-counter inputs:

Stepping module 1 = a_1 • b_0 • Start
Stepping module 2 = a_0
Stepping module 3 = b_1
Stepping module 4 = b_0
Stepping module 5 = b_1 • c_1
Stepping module 6 = c_0

Repeated actuator movements

Where an actuator must extend and retract more than once during a control cycle, the appropriate output signals from the step-counter chain must be connected with "OR" function valves before being connected to the signal port of the power valve. Thus an actuator may extend and retract several times during a machine cycle but each extension and retraction command must be signalled with a new step-counter module (figs. 8-8 and 8-10).

When pilot signals are to be *gathered*, T-connectors do not substitute for "OR" function valves, since the pilot signal from the step-counter chain would exhaust through the valve on the other end of the T-connection! This is illustrated in figs. 8-8, 8-9, 8-10 and 8-11.

Switching equations for the circuit shown in fig. 8-10 are:

D.C.V. inputs:

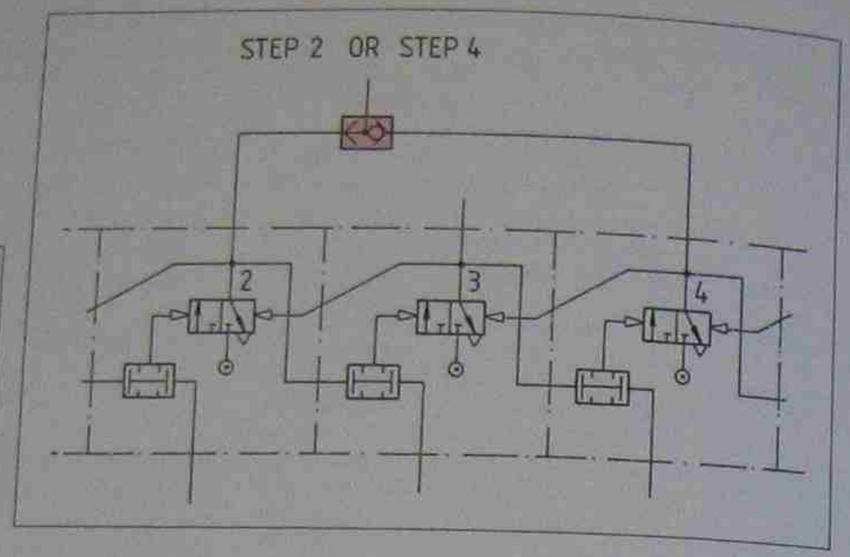
A1 = Step 1
A0 = Step 8
B1 = Step 2 + Step 4 + Step 6
B0 = Step 3 + Step 5 + Step 7

Step-counter inputs:

Stepping module 1 = a_0 • Start
Stepping module 2 = a_1
Stepping module 3 = b_1
Stepping module 4 = b_0
Stepping module 5 = b_1
Stepping module 6 = b_0
Stepping module 7 = b_1
Stepping module 8 = b_0

Note: the Start is series connected to the essential confirmation signal of sequence step 8 (a_0 • Start)

Fig. 8-8 *Right.* Gathering of signals requires an "OR" function valve.



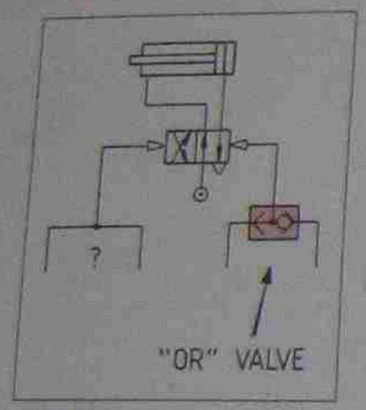


Fig. 8-9 T-connector must not be used to gather signals.

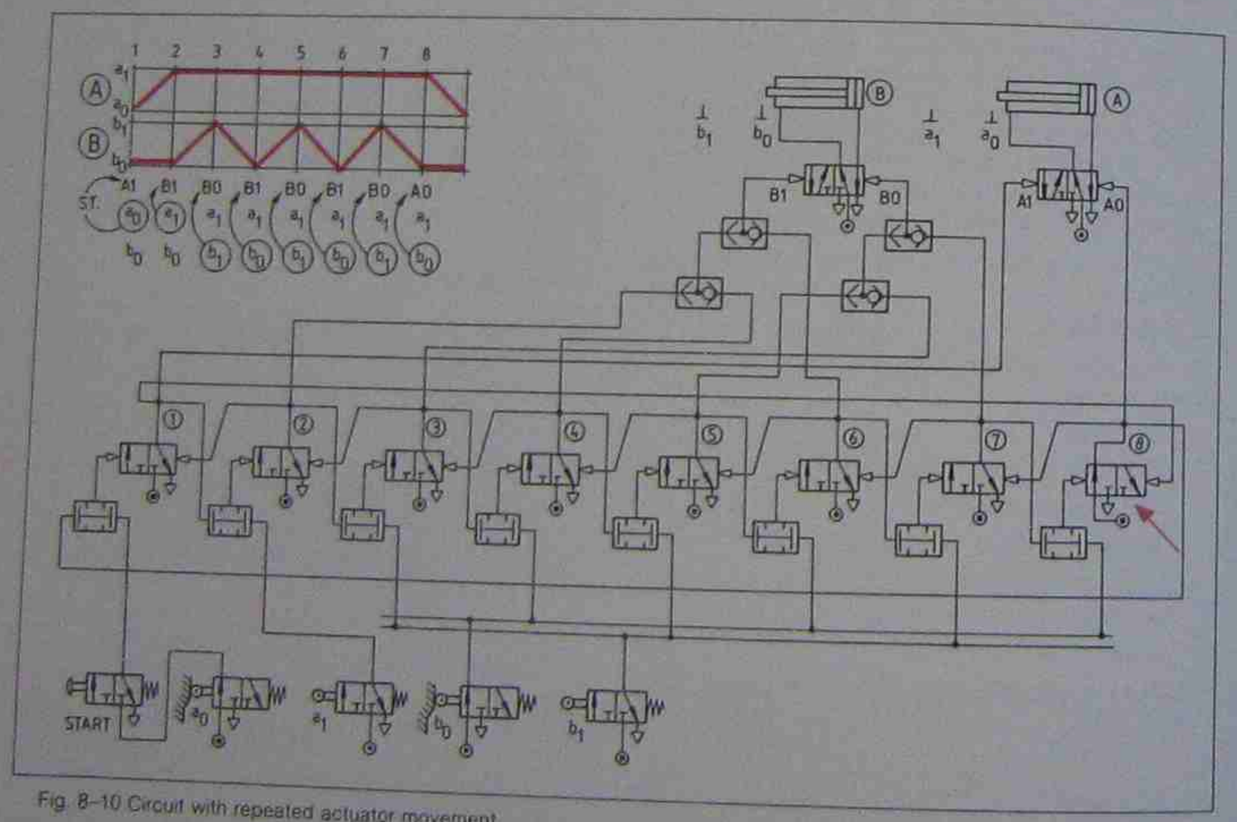


Fig. 8-10 Circuit with repeated actuator movement.

Simultaneous actuator movements

Where a step-counter module actuates more than one actuator (that is, two or more actuators traverse simultaneously), the output signal from the appropriate step-counter module is simply branched out (see arrow in fig. 8-11), and connected to the signal ports of the power valves involved in the simultaneous movements.

The next sequence step which precedes the step with simultaneous actuator movements must not switch, until all these movements are confirmed. Premature switching is prevented by "AND" function valves or where possible by connecting the appropriate limit valves in series order. Fig. 8-11 illustrates such an application where multiple confirmation signals are series connected. This is indicated by arrows on the lower edge of the circuit. Fig. 8-12 shows how additional "AND" valves can be attached where a series connection of multiple confirmation signals is not possible.

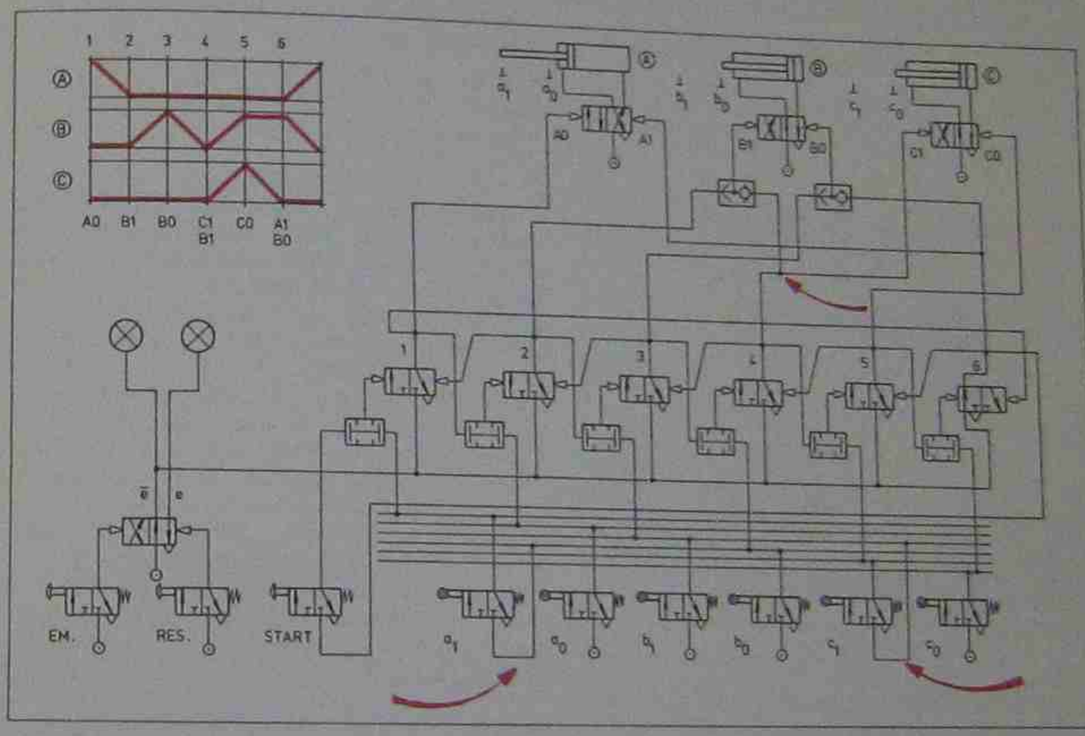


Fig. 8-11 *Above.* Sequential control with simultaneous actuator movements at steps 4 and 5.

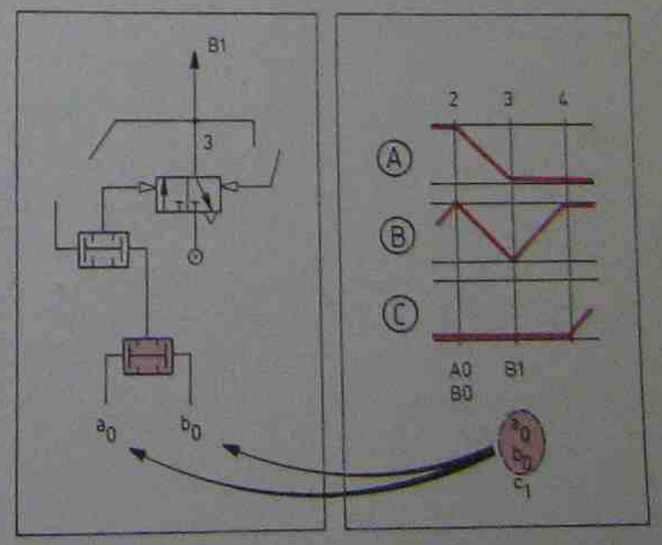


Fig. 8-12 Multiple confirmation of essential limit valve signals after simultaneous actuator movement. The key below the traverse-time diagram shows that the signals a_0 and b_0 are required to confirm the double movement of the actuators A and B.

Series connection of "AND" functions

In cases where a limit valve signal, start valve signal or timer signal is "AND" connected to another such signal, one may use a series connection to combine these signals (see also Chapter 2 fig. 2–34). With a series connection the "AND" valve becomes superfluous (fig. 8–12).

However, a series connection is only permitted if the valve which is downstream in the series connection appears only once in the switching equations for this circuit. The reason for this rule is the fact that any upstream valve "contaminates" the "name" of its downstream valves and thus the "name" of the downstream valves is no longer "pure" and can no longer be used on its own.

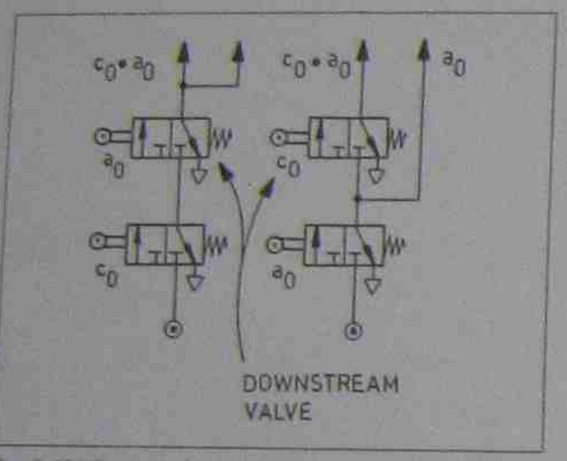


Fig. 8–13 "Contamination" rule for series function. In the left hand circuit the signal a_0 is no longer pure, but if it must stay pure, and still be "AND" connected as shown in fig. 8–14, then the right hand circuit solution must be used.

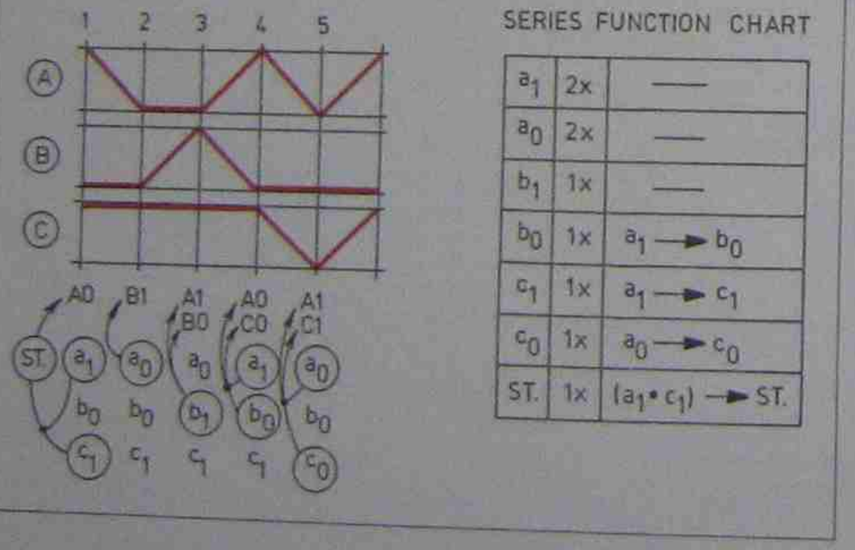
To demonstrate this rule a traverse-time diagram for three actuators is given in fig. 8–14. All essential confirmation signals are circled in the key and a series function chart is drawn. A series connection may only be envisaged for signals which appear only once in the switching equations (see switching equations and columns 1 and 2 of the series function chart) and are "AND" connected to another signal.

Switching equations for circuit shown in fig. 8–14 are:

Step-counter inputs:

Stepping module 1 = $c_1 \cdot a_1 \cdot$ Start
Stepping module 2 = a_0
Stepping module 3 = b_1
Stepping module 4 = $a_1 \cdot b_0$
Stepping module 5 = $a_0 \cdot c_0$

Connecting the step-counter input circuit from the switching equations and the series function chart is not complicated, if one follows the information established in the key of the traverse-time diagram and the connection column of the series function chart (compare figs. 8–13, 8–14, 8–15 and step-counter input equations). Fig. 8–15 shows only the step-counter input. All other circuit parts such as step-counter and power circuits are not shown.



SERIES FUNCTION CHART

a_1	2x	——
a_0	2x	——
b_1	1x	——
b_0	1x	$a_1 \rightarrow b_0$
c_1	1x	$a_1 \rightarrow c_1$
c_0	1x	$a_0 \rightarrow c_0$
ST.	1x	$(a_1 \cdot c_1) \rightarrow$ ST.

Fig. 8–14 Traverse-time diagram and series function chart.

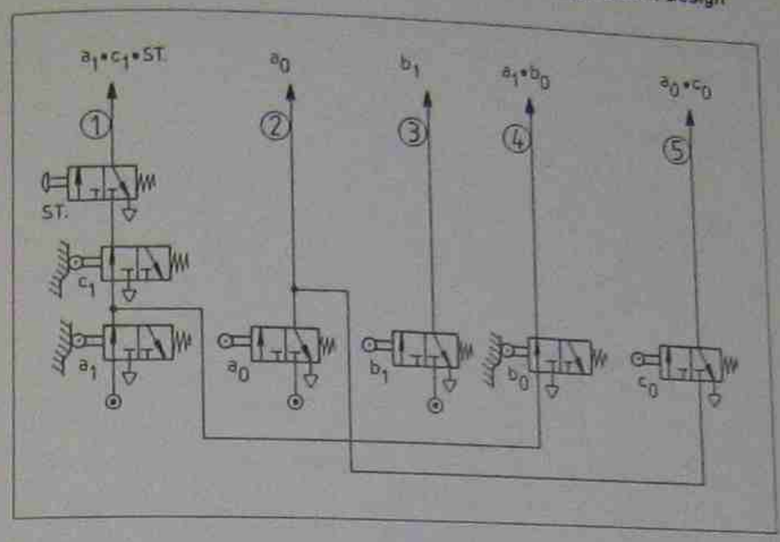


Fig. 8–15 Step-counter input circuit for machine sequence shown in fig. 8–14.

Identical "AND" function

A further reduction of circuit hardware may be achieved when the switching equations contain *identical* "AND" *functions*. To demonstrate this a circuit segment is given in fig. 8–16. Here the identical "AND" function $c_1 \cdot a_1$ is used by itself in the left hand signal branch and is "AND" connected to signal b_1 for the right hand branch. Even though the signal a_1 seems to appear twice in the series function chart, the fact that it can be grouped into an identical "AND" function (together with c_1) means it need only appear once (see fig. 8–16). Hence it can be further series connected to signal b_1. It is therefore wise to investigate the equations for identical "AND" functions before establishing the series function chart.

You may discover that further series functions may be formed. To demonstrate this, a typical cir-

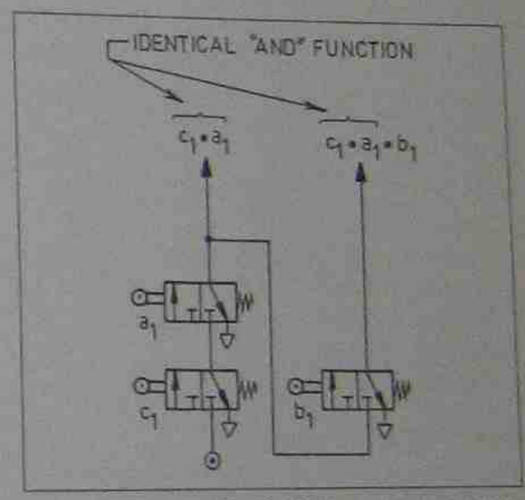


Fig. 8–16 Above: Identical "AND" functions need only be connected once and may then be distributed wherever they are required in the circuit.

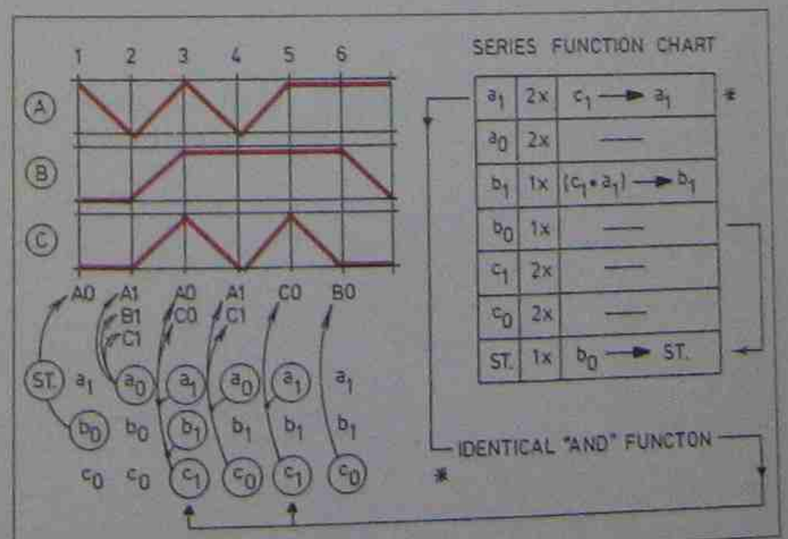


Fig. 8–17 Control with identical "AND" function for $c_1 \cdot a_1$.

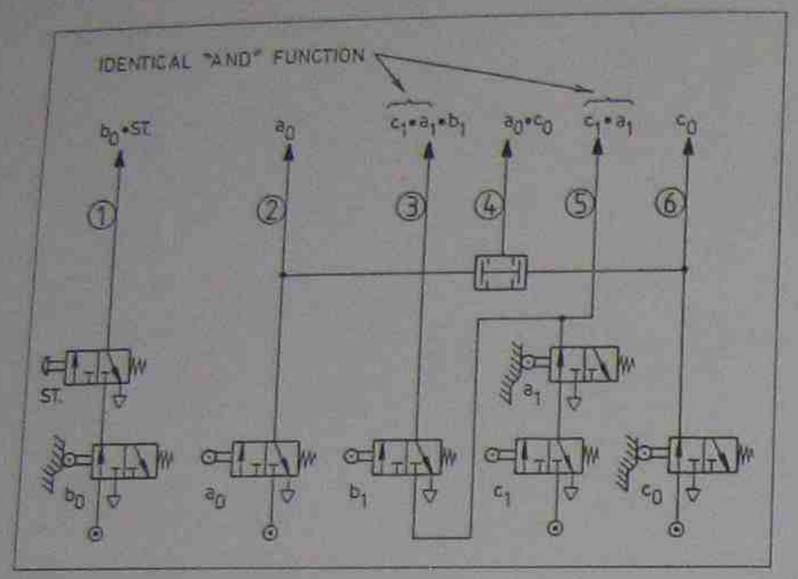


Fig. 8-18 Step-counter input circuit for control shown in fig. 8-17.

cuit sequence is depicted in fig. 8-17 together with the series function chart. The step-counter input circuit for this sequence is also given in fig. 8-18.

Step-counter inputs for fig. 8-17:

Stepping module 1 = b_0 • Start
Stepping module 2 = a_0
Stepping module 3 = $c_1 \cdot a_1 \cdot b_1$
Stepping module 4 = $a_0 \cdot c_0$
Stepping module 5 = $c_1 \cdot a_1$
Stepping module 6 = c_0

Time delayed sequencing

Time delayed sequencing is often encountered in industrial machine control circuits. The pneumatic timer may either be built into the confirmation signal line leading to the step-counter module or into the switching signal line leading to the power valve (see figs. 8-19 and 8-5). Timer placement in the switching signal line delays only the switching of the power valve. Resetting of the previous step-counter module is not delayed. With the timer in the confirmation signal line, both the power valve switching function and the resetting and setting of the step-counter modules is delayed. Circuit designers therefore have to evaluate both timer positions for their merits and select the correct timer position.

A typical time delay circuit where timer placement is important is shown in fig. 8-20. If the pneumatic timer were wrongly placed (in the position indicated by the arrow), then actuator B would overshoot the limit valve b_1 at the completion of sequence step 3.

All circuits with non-memory type power valves (spring centered, three position valves and spring reset four or five port power valves) need therefore careful consideration in the placement of the timer.

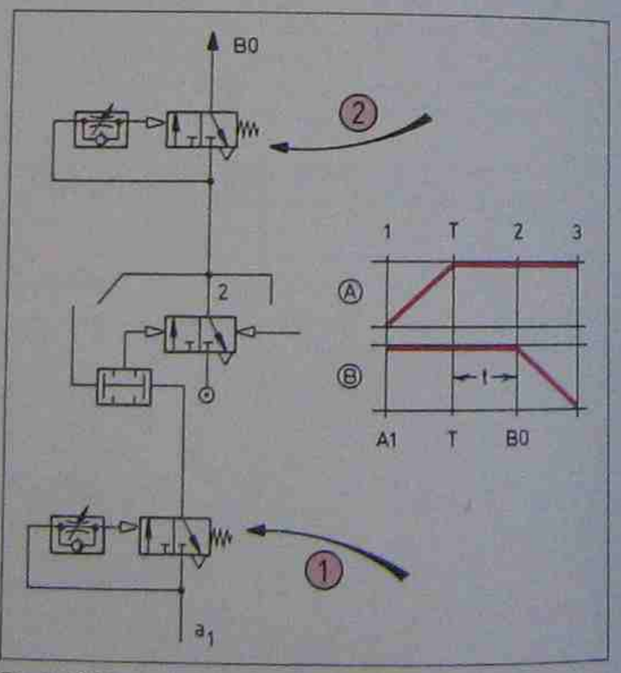


Fig. 8-19 Timer placement options.

Switching equations for circuit shown in fig. 8-20 are:

D.C.V. inputs:

A1 = Step 1
A0 = Step 5
B1 = Step 2 + (Step 3 • Timer)
B0 = Step 4

Step-counter inputs:

Stepping module 1 = a_0 • Start
Stepping module 2 = a_1
Stepping module 3 = b_1
Stepping module 4 = b_2
Stepping module 5 = b_0

Woodpecker motion control

Woodpecker motion control may easily be accomplished with the step-counter design concept (see fig. 8-21). Woodpecker motion control is also closely related to the repeated actuator movement control outlined in figs. 8-8 and 8-10. Here again each extension and retraction command shown in the key of the traverse-time diagram requires a separate step-counter module (fig. 8-21).

Switching equations for circuit shown in fig. 8-21 are:

D.C.V. inputs:

A1 = Step 1
A0 = Step 8
B1 = Step 2 + Step 4 + Step 6
B0 = Step 3 + Step 5 + Step 7

Step-counter inputs:

Stepping module 1 = a_0 • Start
Stepping module 2 = a_1
Stepping module 3 = b_2
Stepping module 4 = b_1
Stepping module 5 = b_3
Stepping module 6 = b_1
Stepping module 7 = b_4
Stepping module 8 = b_0

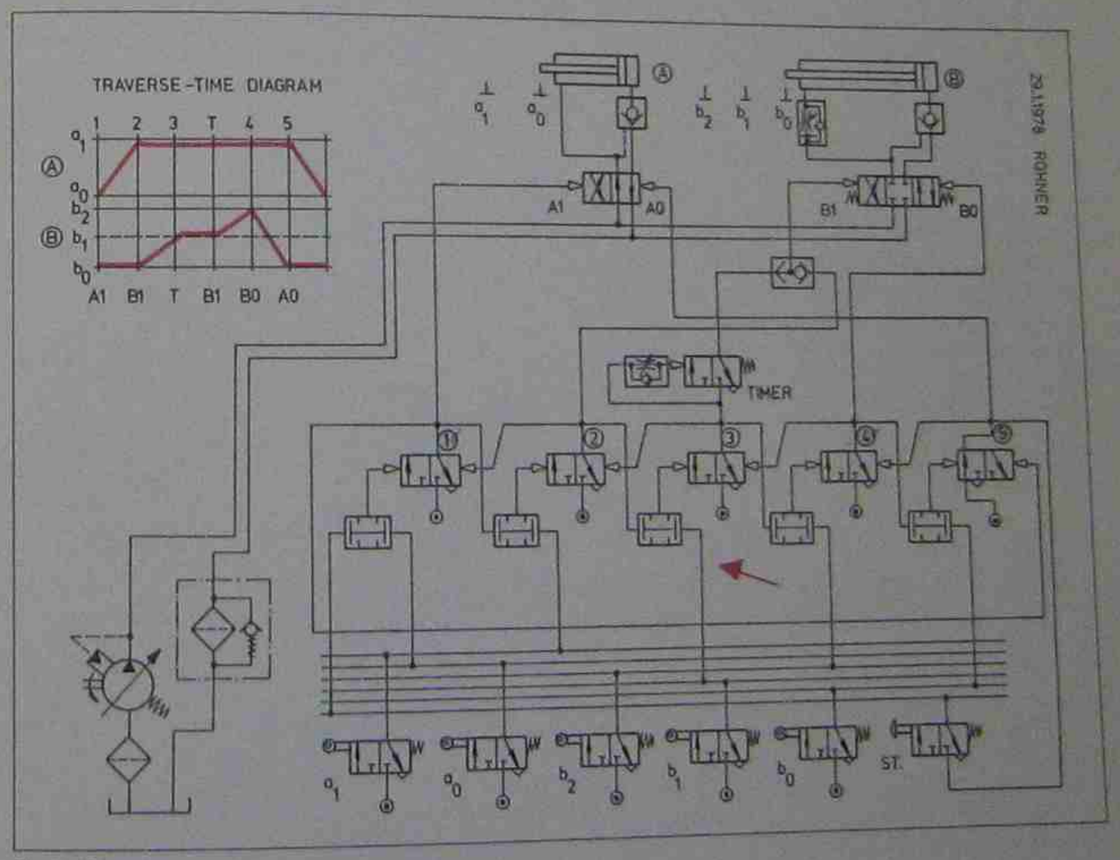


Fig. 8-20

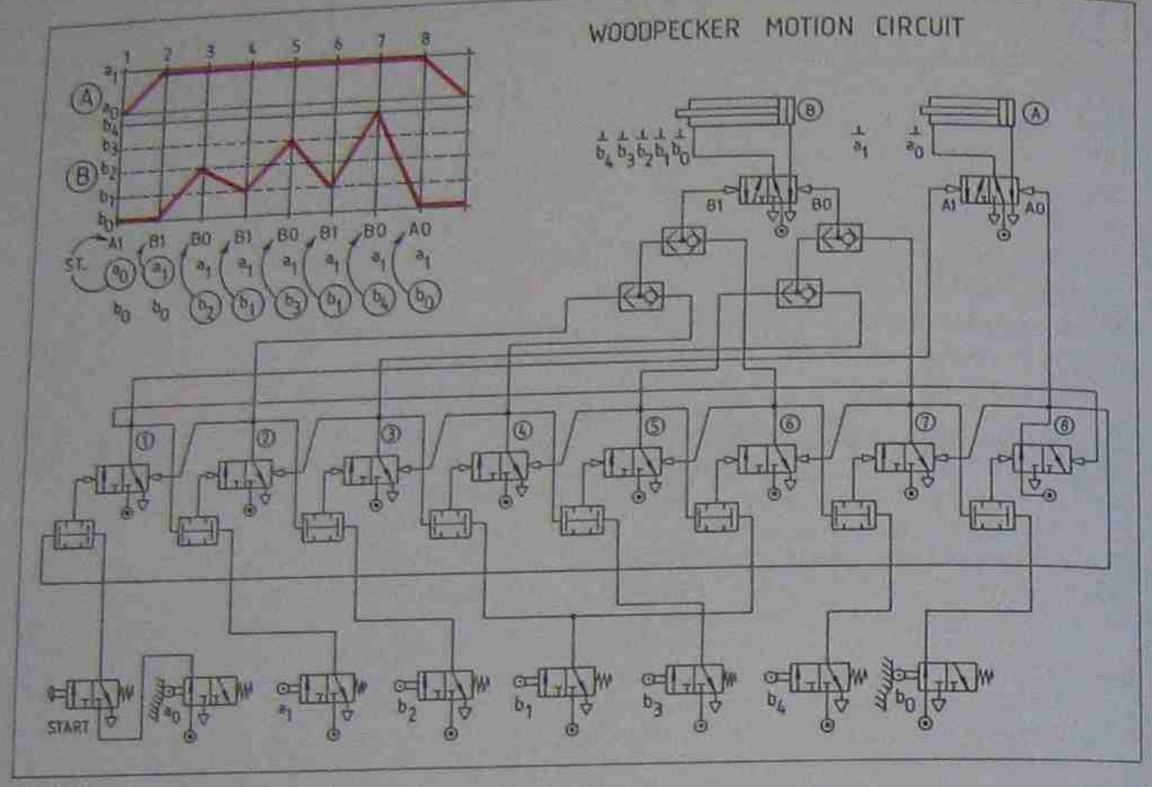


Fig. 8-21

Emergency stop with step-counter

The majority of automated machines operate according to a programmed sequence. Due to mishaps such as a damaged tooling, a misaligned workpiece in an assembly line, an empty workpiece magazine, a sudden drop in supply pressure or an endangered operator, the sequence must be interrupted or the start of a new cycle prevented if automatic cycling was selected.

The nature of such an interruption varies with the anticipated degree of danger and the inherent safety equipment already built into the machine (safety guards, remote control, intermittent operation, various and unskilled operators, etc.). The distinction is basically between the following three emergency stopping modes:

1. Stop instantaneously (use piston rod brakes if necessary).
2. Stop at end of commenced sequence step.
3. Stop at end of sequence cycle (if machine cycles automatically).

Once the machine cycle is interrupted and actuators have stopped, one has several options to choose further sequence or machine action. It is, therefore, the circuit designer's responsibility to decide what this action is to be. His choice is crucial, since it can prevent serious harm to the machine operator or avoid costly damage to workpieces, tooling and machinery. To illustrate: in a machine tool, one has to stop the drilling head and retract it completely before the workpiece may be unclamped and finally the automatic workpiece ejector is permitted to clear the machine (fig. 8-36). It would be disastrous if all these movements would happen simultaneously! However, in another machine, all actuators may quite safely act in unison and move into the position required for them to start a new cycle, once the emergency situation is cleared. In a third application, the machine cycle is brought to a halt with either stop-condition 1 or 2, as enumerated previously (fig. 8-22), and when the emergency situation is cleared the sequence is permitted to continue to the end of cycle (figs. 8-31 and 8-32). Such machine applications are quite common. They

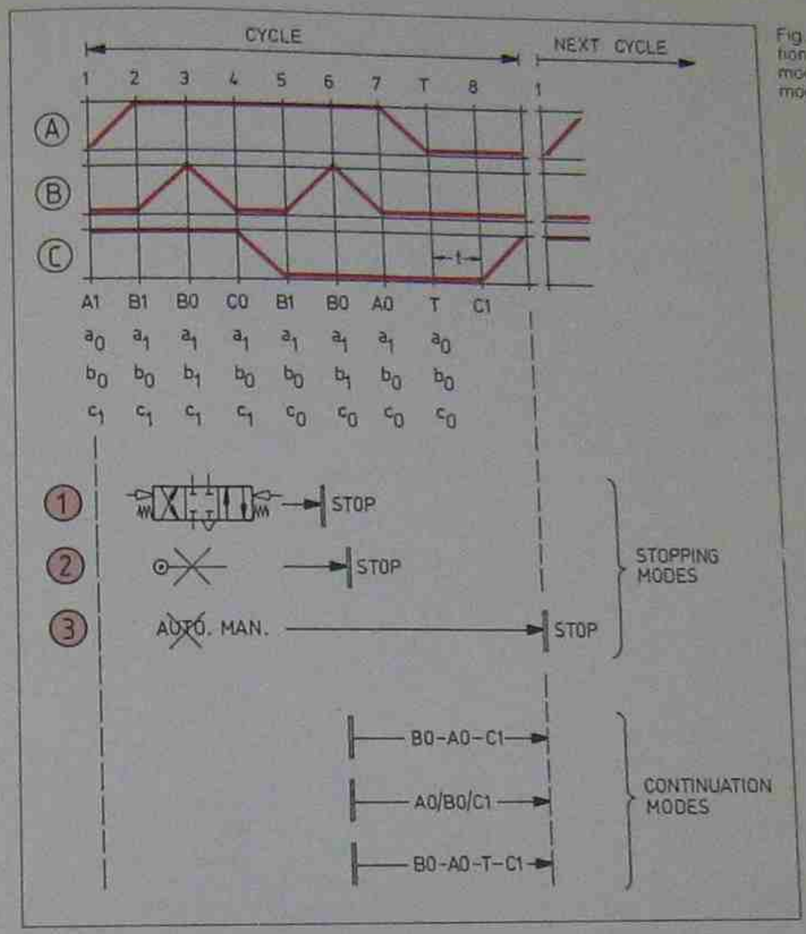


Fig. 8-22 Emergency stop variations showing the three stopping modes and some continuation modes.

may be regarded as classical "continuation modes" for machine sequence behaviour after emergency stop was signalled (see fig. 8-22). A fourth and not so common continuation mode is to reverse only those actuators which are in motion when the emergency stop is signalled. This emergency stop module is explained later and illustrated in fig. 8-30.

Basic emergency stop module

For maximum operator and machine safety, all emergency signals should be stored in a memory type valve. It is recommended that the emergency reset valve be placed inside the control cabinet, or if possible, that a key operated valve be used, which is only accessible to authorised personnel.

To make the emergency stop functional at all times, its memory valve must never be "AND" connected to any other signal and must therefore have its own air supply (see fig. 8-23)! For a circuit integration of this module see figs. 8-31 and 8-32.

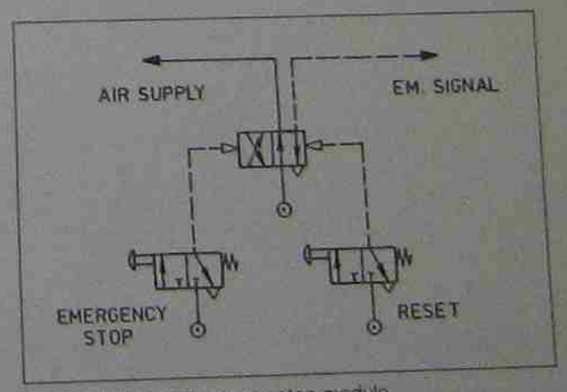


Fig. 8-23 Basic emergency stop module.

Detent-type push button emergency valves are sometimes used but have an inherent danger: the valve can simply be reset by operators unaware of an emergency situation. This could lead to machine damage or, more seriously, cause harm to the operator! The emergency stop memory may be a four port or five port valve and must never be a spring reset type valve.

Emergency stop module with multiple input

Where machinery is operated from several locations, it is imperative to provide an emergency stop valve for all such locations – particularly on large machines, or machines where operators are exposed to dangers, one should use an emergency stop module with multiple emergency inputs (fig. 8-24A).

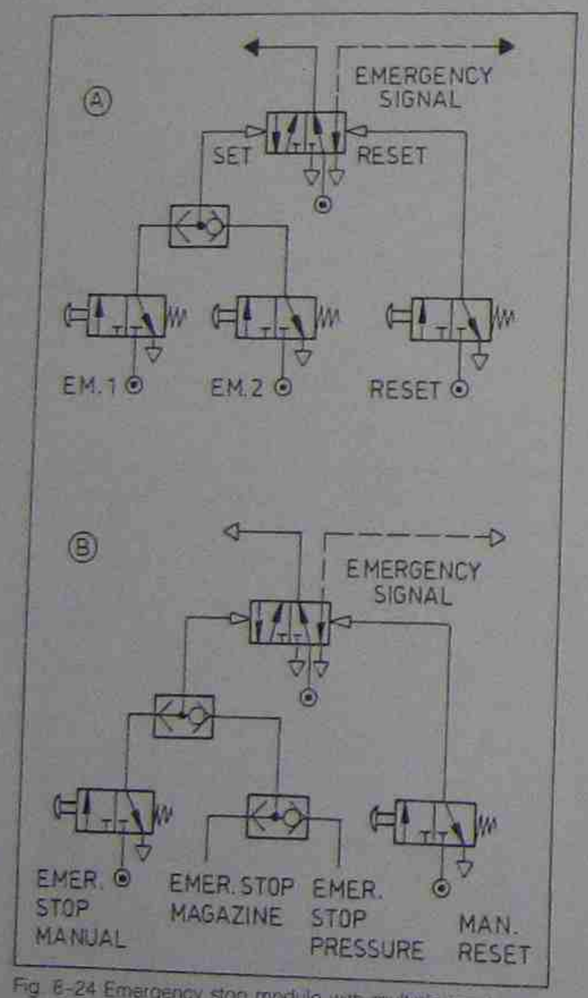


Fig. 8-24 Emergency stop module with multiple input.

Emergency stop module with manual and automatic input

Where the emergency signal must be triggered either by an operator or by an external machine operation, such as "PRESSURE INADEQUATE", "MAGAZINE EMPTY", "GUARD OPENED" or a similar stop-demanding signal, the emergency stop module shown in fig. 8-24B is used.

Simple cycle selection module

Although not directly an emergency stop module, the simple cycle selection module may be used to stop a continuous machine cycle (automatic cycling). This module is illustrated in fig. 8-26 (see also fig. 8-22, stopping mode 3).

The simple cycle selection module (see fig. 8-26) provides an inexpensive solution to furnish "low danger" rated machines with automatic

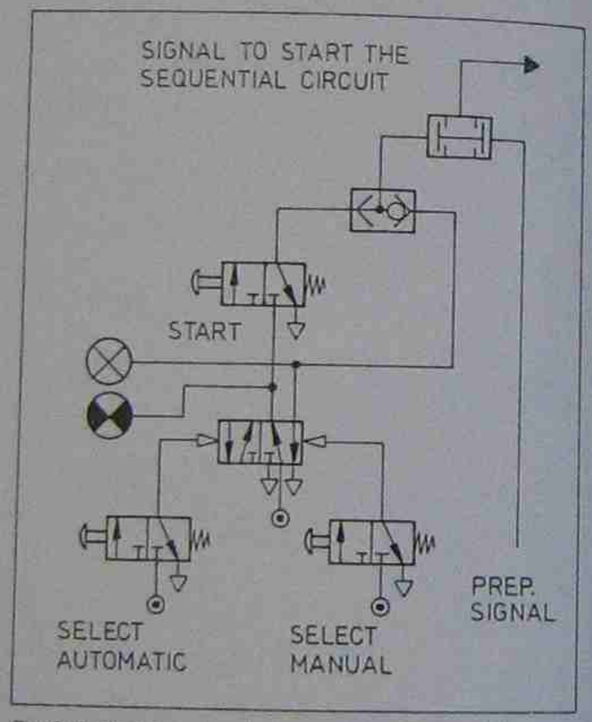


Fig. 8-25 Simple cycle selection module with visual indicators for automatic and manual start selection. Since the preparation or confirmation signal is only momentary (but display is required as permanent) one cannot use series function as in fig. 8-26. An "AND" valve is required to connect the start signal to the preparation signal.

cycling or manual cycling (single cycling). The disadvantage of this module is its combination of auto-selection and auto-start in the same push-button valve, which causes the machine to operate as soon as the "AUTO" selection is made (see fig. 8-26). For the integration of this module see fig. 8-33 where the cycle selection module is enclosed by a frame.

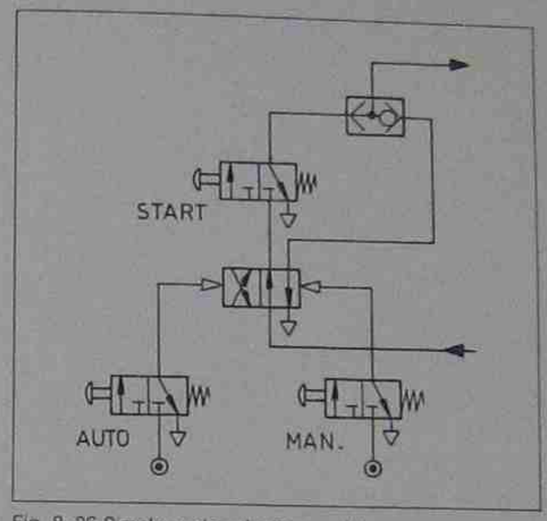


Fig. 8-26 Simple cycle selection module.

Extended cycle selection module

This module is an extension to the simple cycle selection module. It eliminates the disadvantage of the simple cycle selection module by providing separate selection as well as separate start for both cycling modes. The additional cost for the extra push button valves and one more memory valve is easily justified for the additional safety feature of this module (see fig. 8-27).

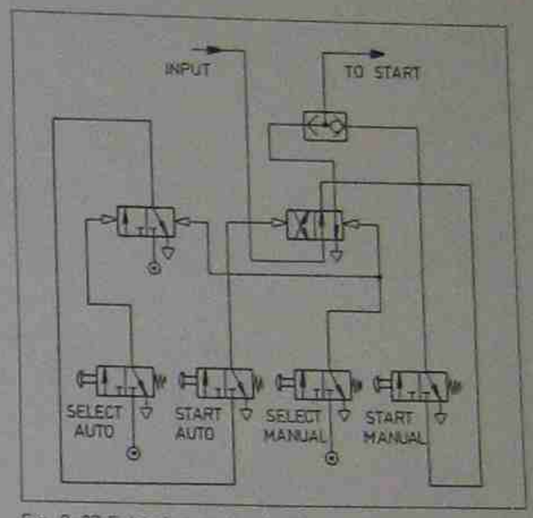


Fig. 8-27 Extended cycle selection module.

Cycle selection module combined with emergency stop module

In order to avoid the cycle starting unexpectedly after the emergency reset valve is actuated, while the cycle selection is in the automatic mode, this combination is furnished with a "LINK" which kicks the cycle selector into manual cycling mode (see fig. 8-28).

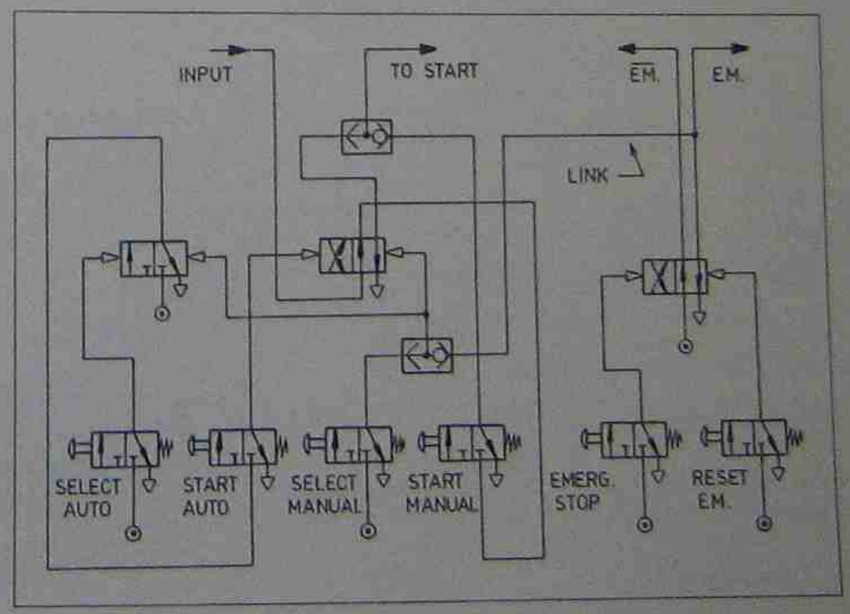


Fig. 8-28 Extended cycle selection module with emergency stop link.

Cycle selection with automatic manual selection

This cycle selection module provides the following switching functions. *Automatic selection* is only possible if the push button selector valve is actuated and other fringe conditions are also met. These fringe conditions may entail such inputs as: magazine full, guard closed, system pressure above basic limit etc. *Manual selection* is achieved when the push button selector valve is actuated or when one or more of the fringe conditions are no longer met. This module is similar to the module combination shown in fig. 8–28 where manual selection may be triggered if emergency is signalled.

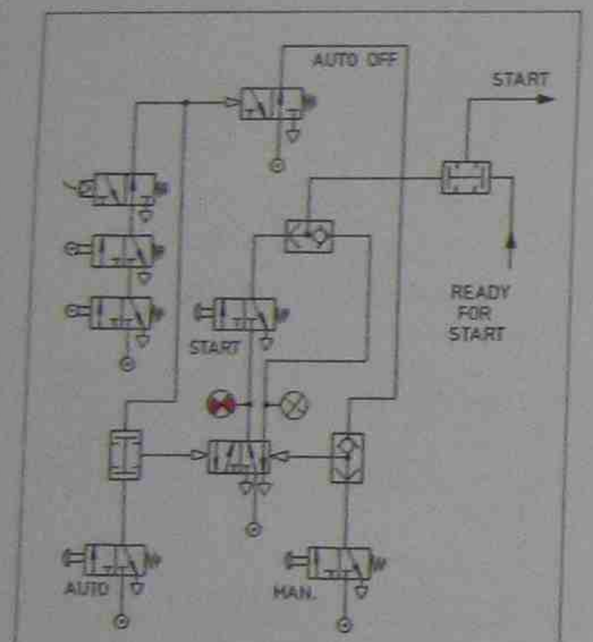


Fig. 8–29 Cycle selection with automatic manual selection.

The "READY FOR START" signal may be series connected through the memory valve. However, permanent auto- or manual indication on the visual indicators would then not be possible. Integration of this module is identical to the two cycle selection modules depicted in figs. 8–26 and 8–27 The fringe conditions may include several inputs.

Reverse actuators while in motion

The "REVERSE ACTUATORS WHILE IN MOTION" module is expensive and complicated and should, therefore, only be used for actuators which absolutely have to be reversed when an emergency is signalled (fig. 8–30). On actuation of the emergency stop, the cylinder which is in motion reverses to its previous position (should it be at rest in an end-position, it remains stationary).

This emergency stop module is very useful, since it is often the actual cylinder in motion which is causing the emergency, and therefore its motion must be reversed.

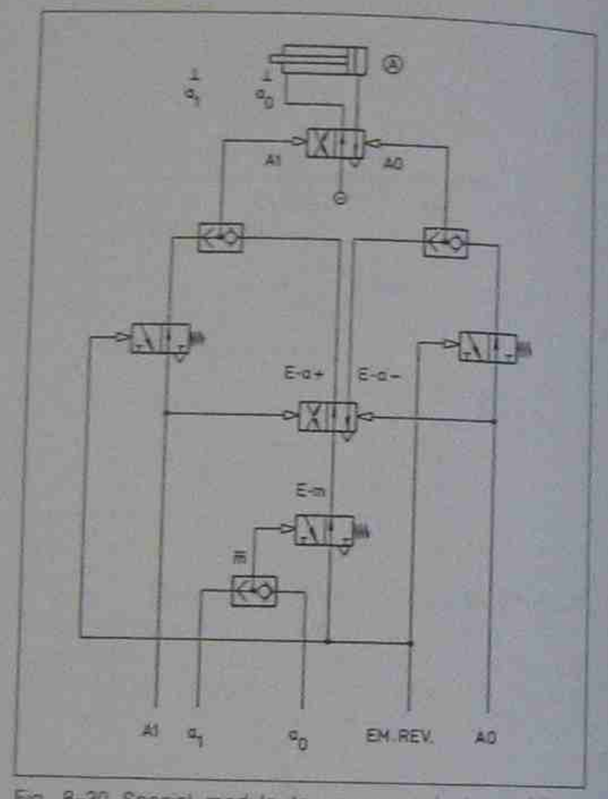


Fig. 8–30 Special module to reverse actuators while in motion.

Stop instantaneously (stopping mode no. 1)

The sequence in this circuit will stop instantaneously when an emergency is signalled. This is achieved by the three-position type power valves which centre automatically when the signals from the step-counter cease. Once the emergency is cancelled (reset), the circuit will continue with the interrupted sequence to the end of the cycle. Since the emergency stop memory valve has its own air supply, one of the two visual indicators will always be "ON". Pneumatic piston rod brakes must be used if rigid position holding is required during the emergency stop (see figs. 3–19 and 8-31).

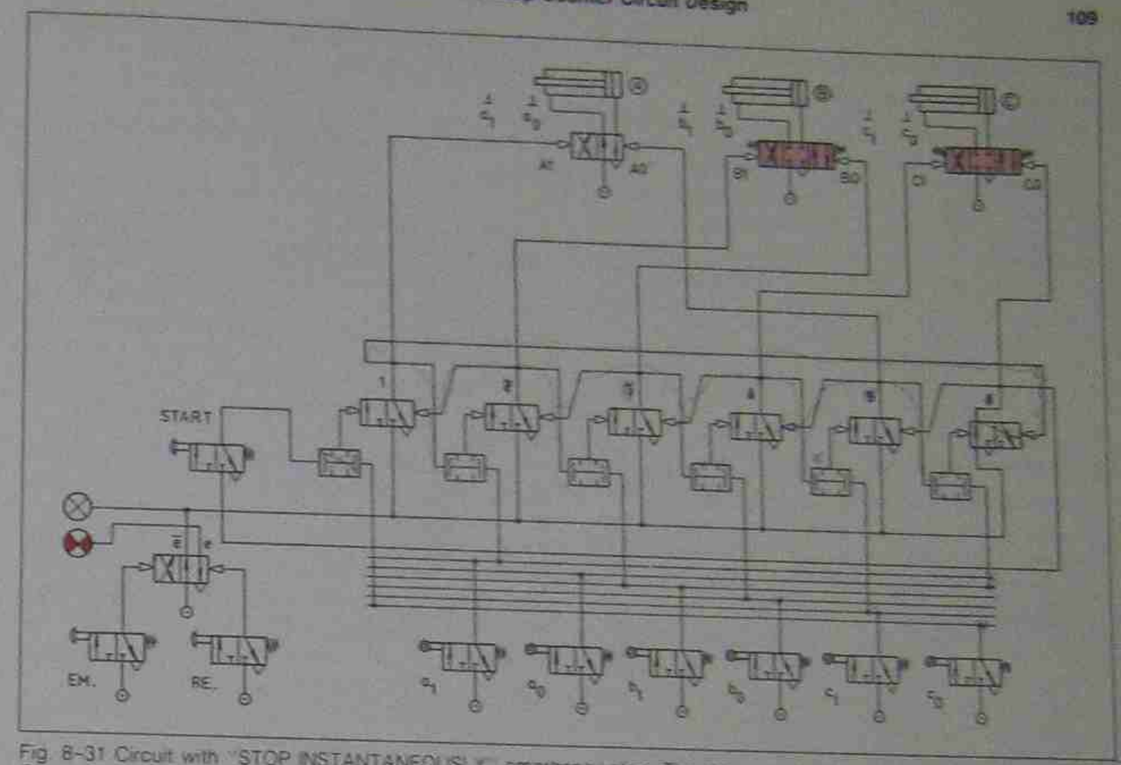
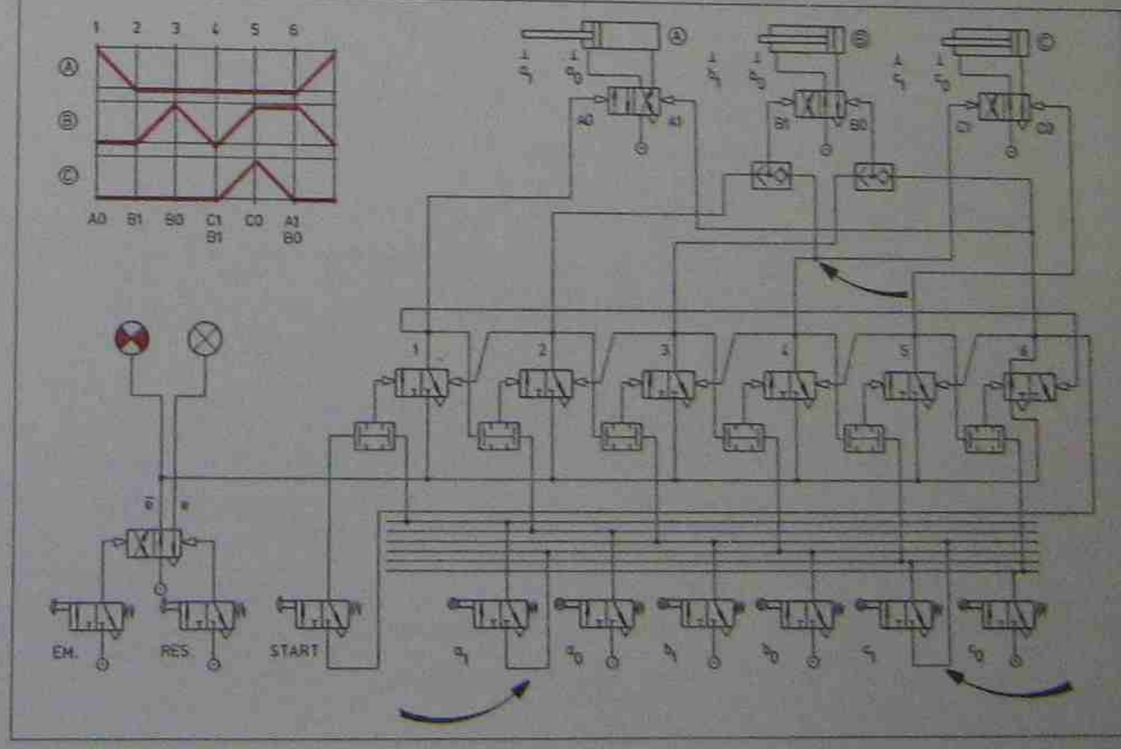


Fig. 8–31 Circuit with "STOP INSTANTANEOUSLY" emergency stop. The sequence for this control is A1-B1-B0-C1-A0-C0.

Fig. 8–32 Circuit with "STOP AT END OF COMMENCED STEP" emergency stop. Once the air supply to the step-counter is denied, the commenced step will be completed but no further steps can occur until the air supply is restored. After the restoration of the air supply the program continues along its normal sequence.



Stop at end of commenced step (stopping mode no. 2)

The normal sequence in this circuit will stop when an emergency is signalled and the current sequence step (emergency) is completed. This is taken care of by memory type power valves which maintain their position even when the pilot signals from the step-counter cease. Thus although the commenced step is completed further sequence steps cannot commence until the air supply to the stepping modules is restored. When the air supply is restored the interrupted sequence will continue to the end of cycle (see fig. 8–32 and compare with figs. 8–22 and 8–31).

Stop at end of cycle (stopping mode no. 3)

Athough not directly an emergency stop circuit, this control does bring about a stop of the ongoing sequencing. Automatic cycling ceases when the manual selection is made. The circuit will always finish a commenced cycle, but no *new* cycle is permitted to commence until the start command is given (see fig. 8–33).

Continuation modes deviating from the normal sequence

The three circuits depicted in figs. 8–31, 8–32 and 8–33 have a continuation mode which follows the normal sequence once the emergency module is reset (see fig. 8–22, continuation mode 3). However where the continuation mode must deviate from the normal sequence (as shown in the traverse-time diagram of fig. 8–36) one can no longer use the step-counter to sequence the actuators, and therefore the step-counter must be reset to "ZERO".

Resetting the step-counter to "ZERO" while the machine-sequence cycle is not yet fully completed, requires an "OR" function valve attached to every step-counter module, except the last one (see fig. 8–34). The last step-counter module logically needs no "OR" function valve since an emergency rarely occurs during the last sequence step. However, should there still be a possibility of an emergency, an "OR" valve may be simply added to that module.

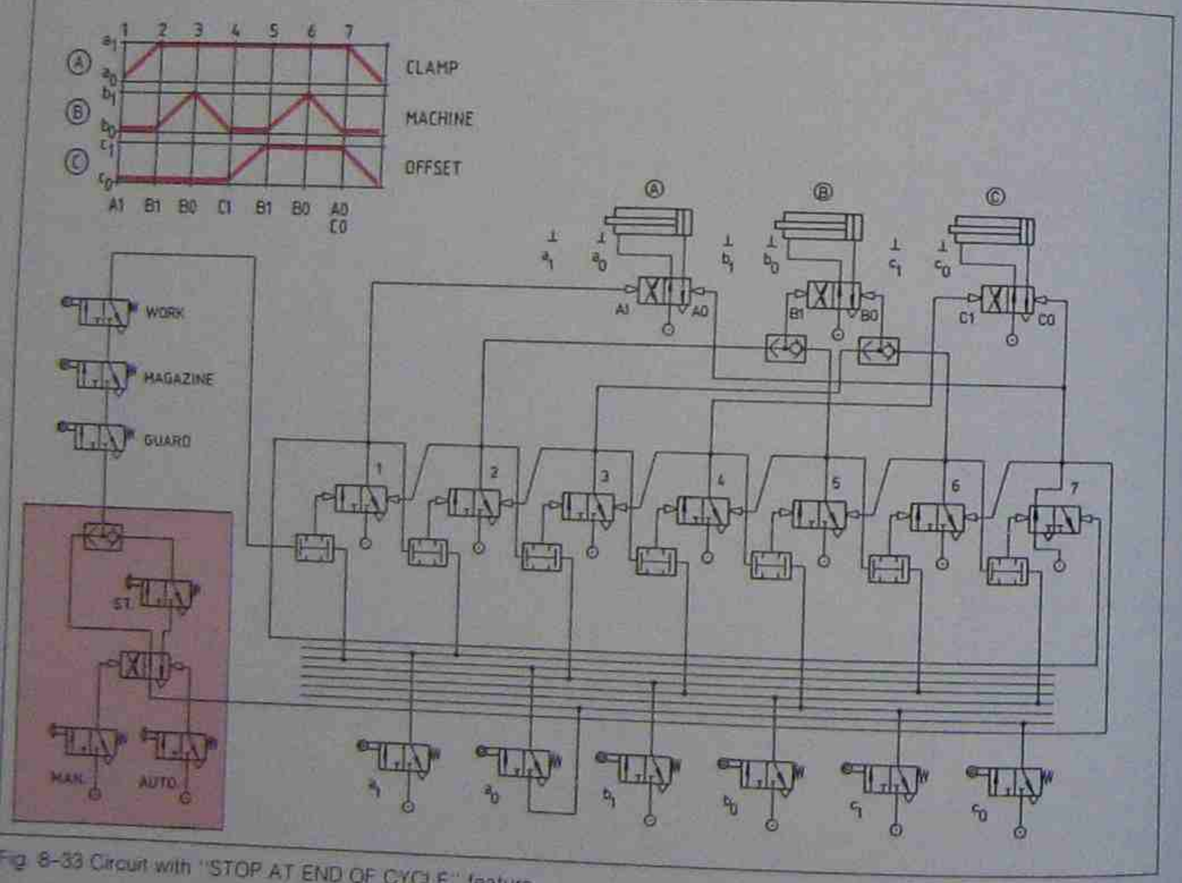


Fig. 8–33 Circuit with "STOP AT END OF CYCLE" feature.

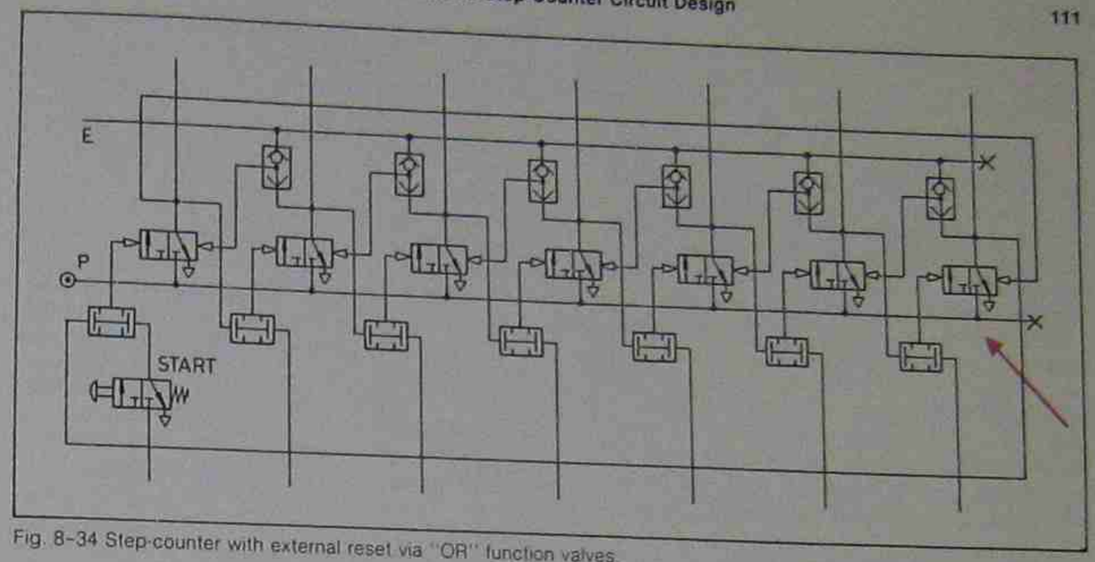


Fig. 8–34 Step-counter with external reset via "OR" function valves.

Under normal cycling conditions the preparation signal for the first step-counter module is provided by the last step-counter module in the chain (fig. 8–34). However, under emergency conditions, the circuit could stop anywhere between the first and the last module in the step-counter chain. The sequence would therefore never reach the last step-counter module in the chain, which means its memory could not send the essential preparation signal to module 1!! Under these circumstances one could no longer start a new cycle after the emergency has been reset. To overcome this problem, a special circuit modification may be placed between the emergency stop memory and the "AND" valve of the first step-counter module in the chain (see fig. 8–35).

Emergency stop modification module

This modification provides the circuit with a

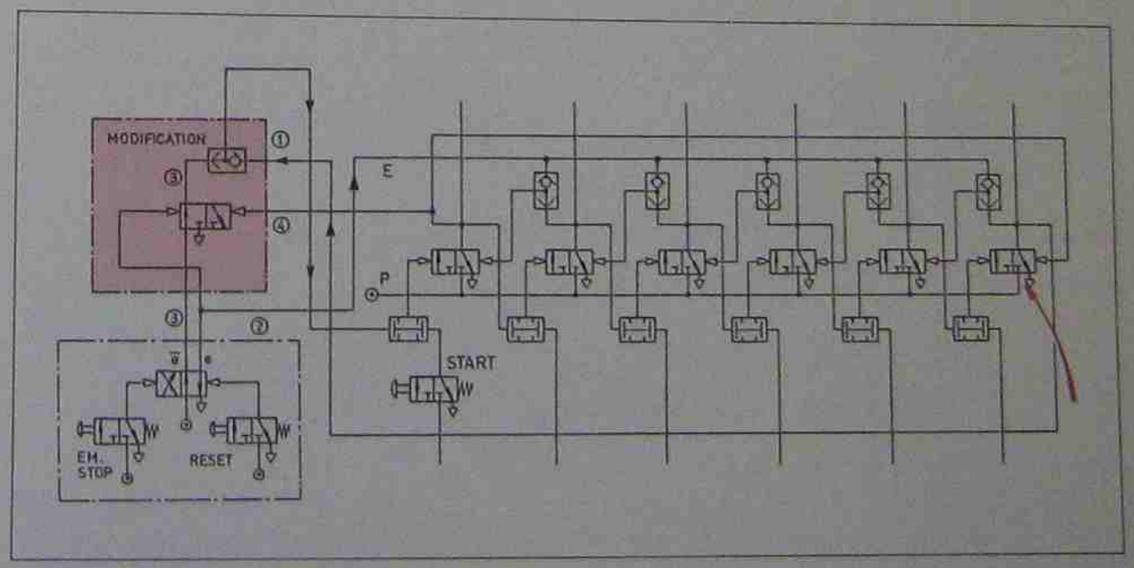


Fig. 8–35 Step-counter with emergency stop modification.

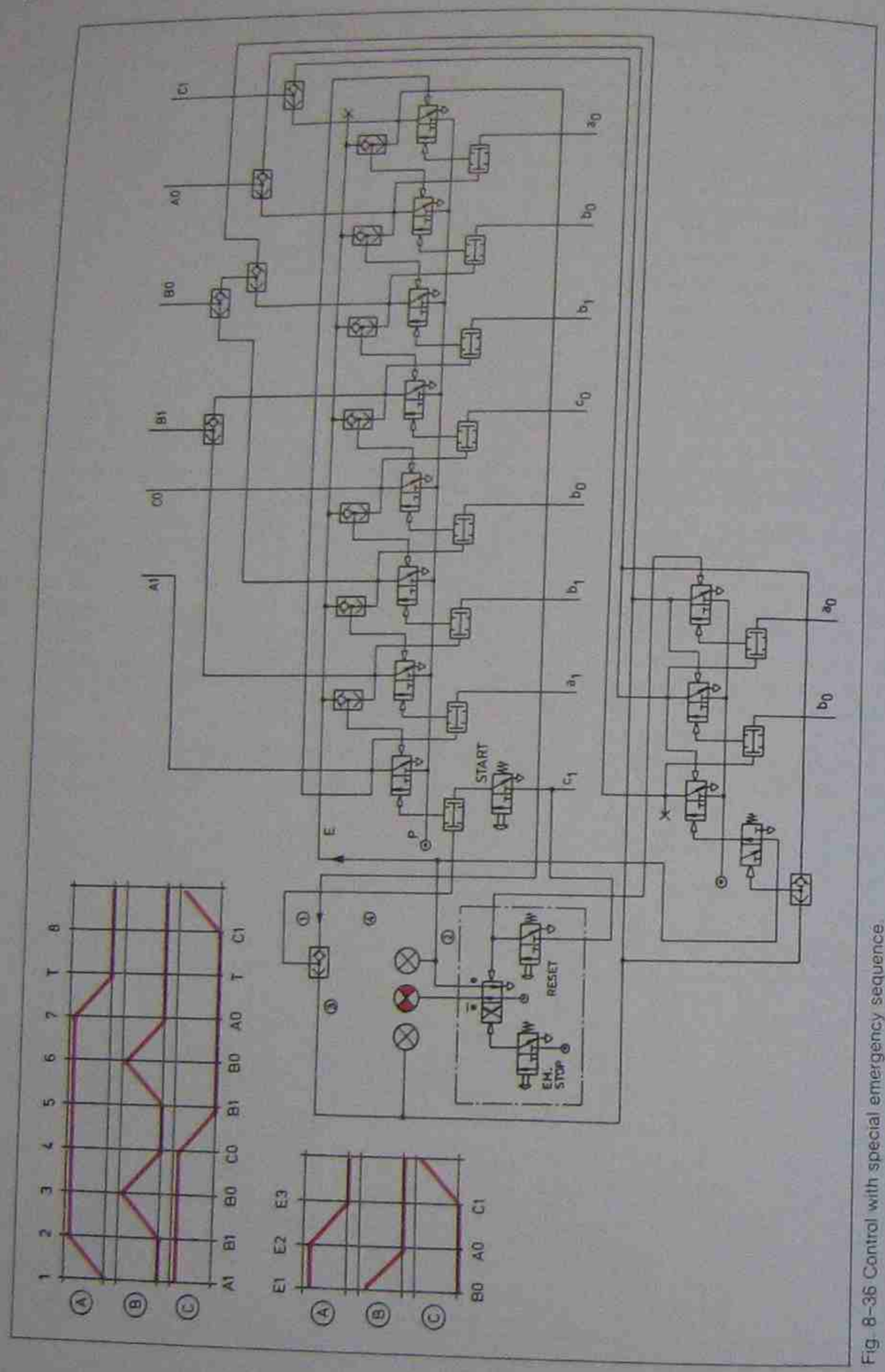


Fig. 8-36 Control with special emergency sequence.

"SUBSTITUTE PREPARATION" signal. The first step-counter module cancels this substitute preparation signal as soon as the first sequence step is being set, thus any interference by accidental actuation of the start valve during cycling is avoided (fig. 8-35).

Once the step-counter is reset to zero by the emergency stop signal "E", the same signal will also reset the actuators to their end-of-cycle position (continuation mode).

Where the continuation mode must follow a special emergency program (fig. 8-22 continuation mode (1)), one may also use step-counter modules to sequence this program (fig. 8-36). However, in this case, the modification as shown in fig. 8-35 is not required, as the preparation signal from the emergency program can be used (in "OR" connection) to provide the necessary preparation signal. The circuit depicted in fig. 8-36 is designed to achieve the sequence shown in fig. 8-22. When an emergency stop is signalled the normal program must stop and the emergency program must take over, with the sequence B0-A0-C1. This emergency program brings the actuators into the condition required to start a normal sequence program (compare figs. 8-22 and 8-36).

Commercial step-counter modules

In recent years complete step-counter modules, consisting of a memory valve, an attached "AND" function valve and an "OR" function valve for emergency reset, have appeared on the market. These step-counter modules are simply pushed together on a mounting bar and thus interconnections for preparation and reset signals, as well as air supply connections, are made automatically by means of air ducts sealed by O-rings on the connection faces (fig. 8-37). To merge the step-counter with the power valves and the limit valves, one simply has to connect the output ports of the step-counter modules to the appropnate pilots on the power valves, and the step-counter input ports to the appropriate limit valves. End plates connect the reset and preparation signal from the last step-counter module to the first step-counter module via external air tubes (figs. 8-37 and 8-38). These end plates are essential since the modules themselves have no provision to attach fittings and plastic tubing. However, on the outlet ports leading to the power valves, and inlet ports to accept the pilot signal from the limit valves, one finds push-in fittings or barbed sleeves to connect plastic tubing, and also the outer faces of the endplates are provided with fittings.

German design concepts for commercial step-counters

Amongst the many different brands of commercial step-counters one can clearly differentiate two separate design concepts. With the German designs, the last stepping module remains in the

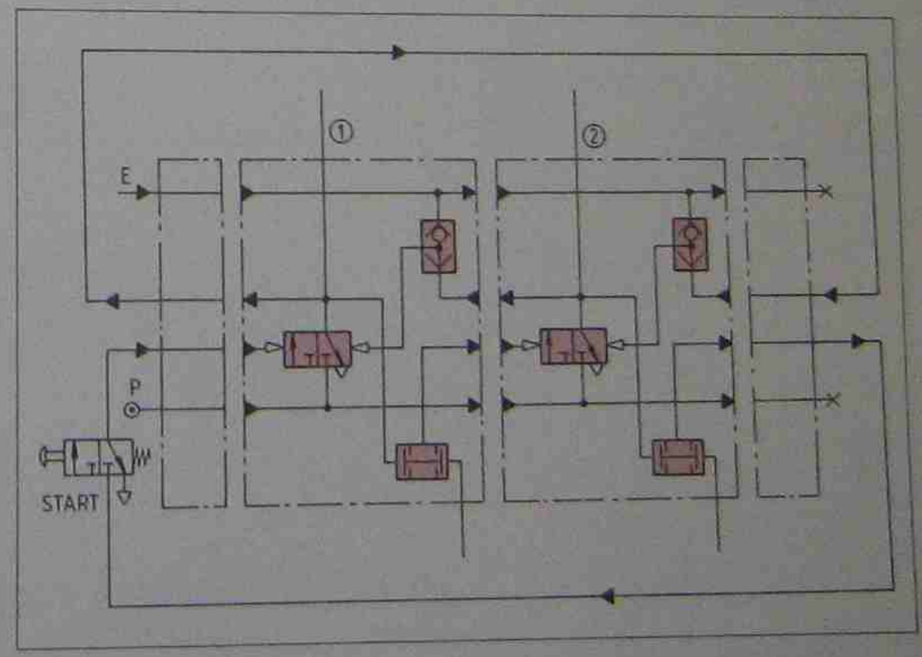


Fig. 8-37 Commercial step-counter modules.

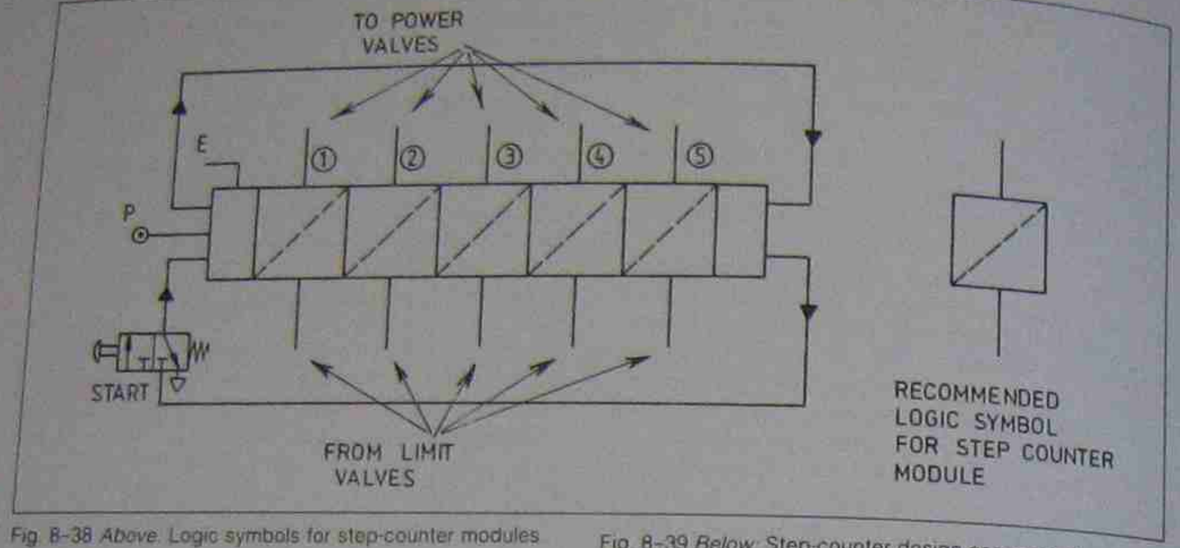
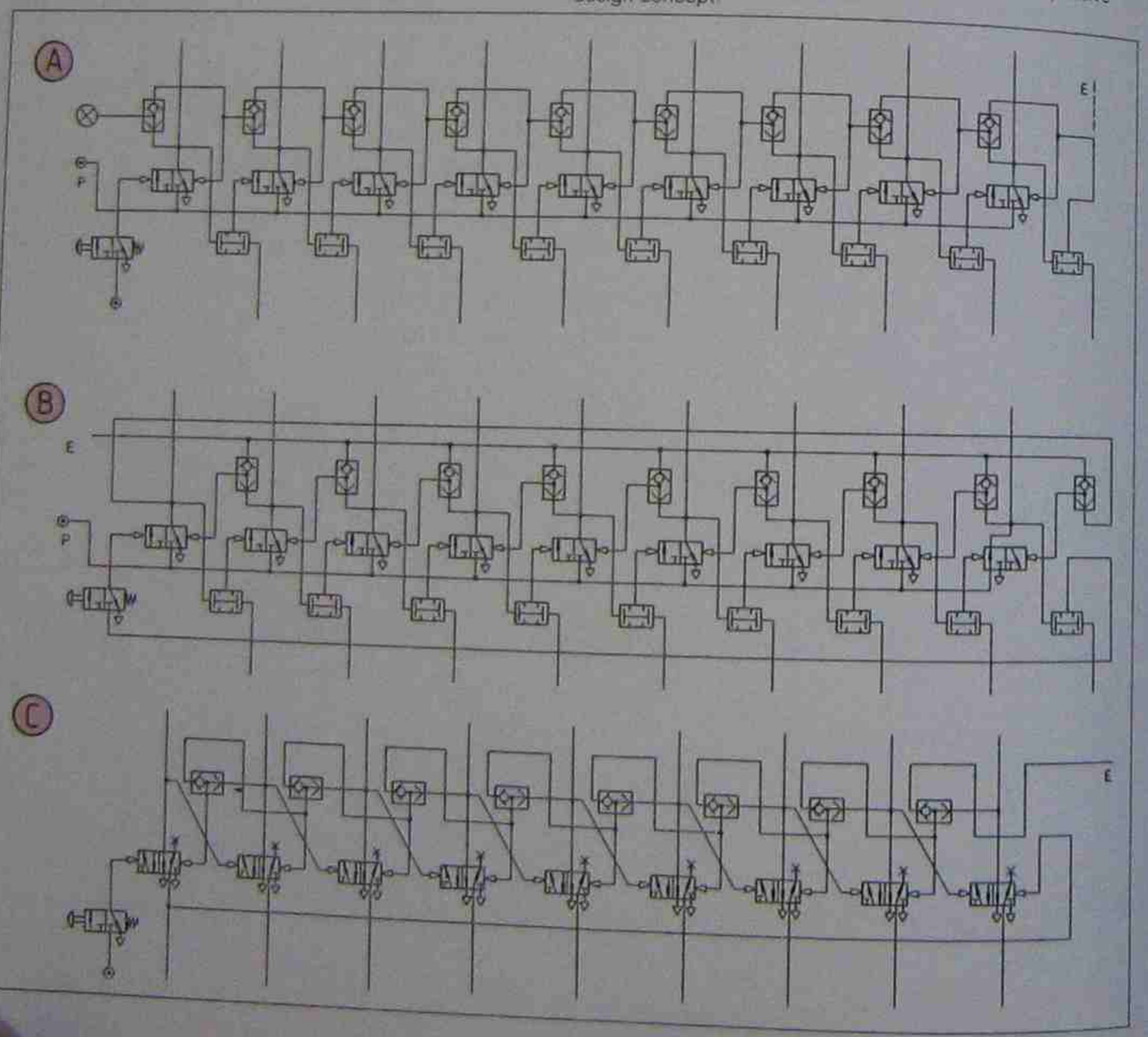


Fig. 8-38 *Above*. Logic symbols for step-counter modules

Fig. 8-39 *Below*. Step-counter design concepts; A = French design concept. B = German design concept. C = passive design concept.



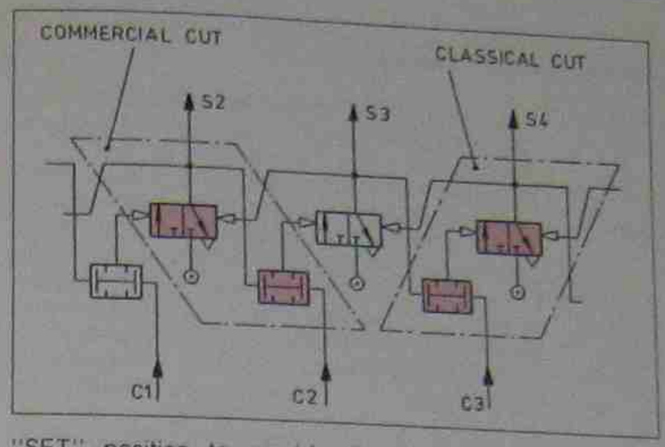


Fig. 8-40 Classical versus commercial step-counter

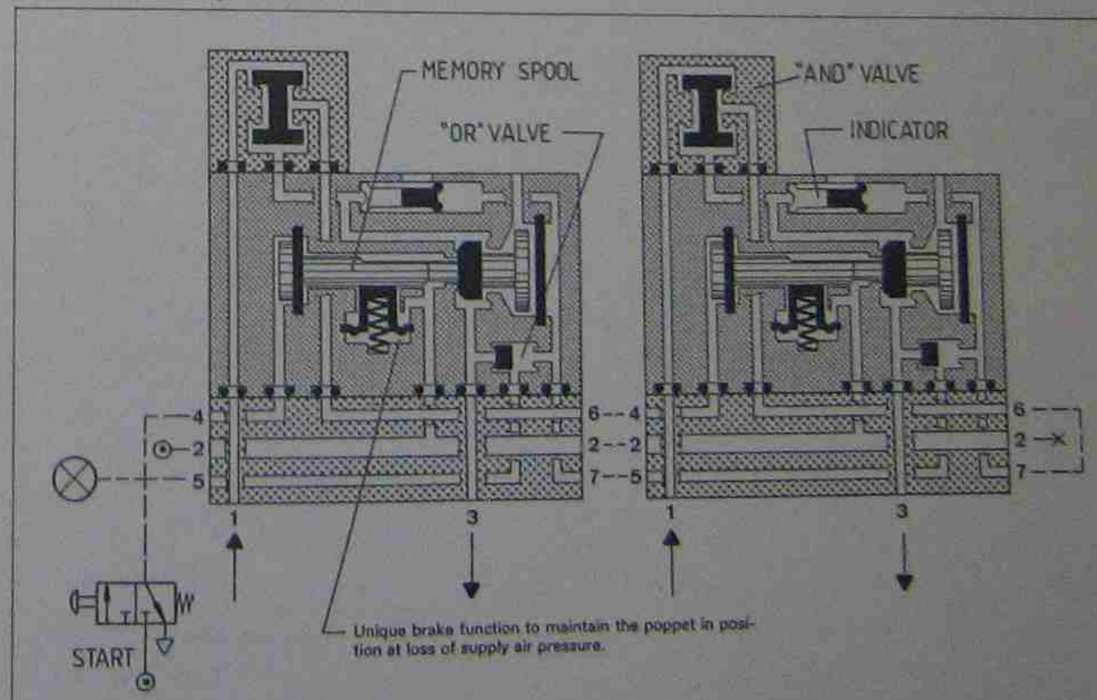
"SET" position to provide the first stepping module in the chain with a preparation signal (see figs. 8-31 to 8-36 and 8-39B). However, with the French design concept, the last step-counter module is reset as soon as the last confirmation signal arrives, and a unique interlinkage of the "OR" function valves constantly holds the first memory valve (in module 1) reset, as long as the step-counter chain is in progress of sequencing. Thus any interference from the start valve during cycling is prevented (fig. 8-39A). A third concept is the passive step-counter where the confirmation signal is fed through the step-counter memory valve and so becomes the switching signal for the power valves (fig. 8-39C).

The first two step-counter design concepts have, however, one common design characteristic. They both switch and confirm such switching in the same module block. This means step 2, for example, is switched by block 2 (signal S2) and the confirmation signal from the completion of that actuator movement (signal C2) is also connected to block 2 (compare figs. 8-36, 8-37, 8-39 and 8-40). The philosophy behind this arrangement is to make it easier for the inexperienced circuit designer to remember that each block switches an actuator function and that the confirmation signal of that function is connected to the same block.

French step-counter design concept

With the French step-counter design concept the last module in the chain is reset as soon as the last confirmation signal arrives; this happens when the last sequence step is completed. That is, prior to start no step-counter module is set at all! This concept has several advantages. The most important

Fig. 8-41 Crouzet step-counter modules.



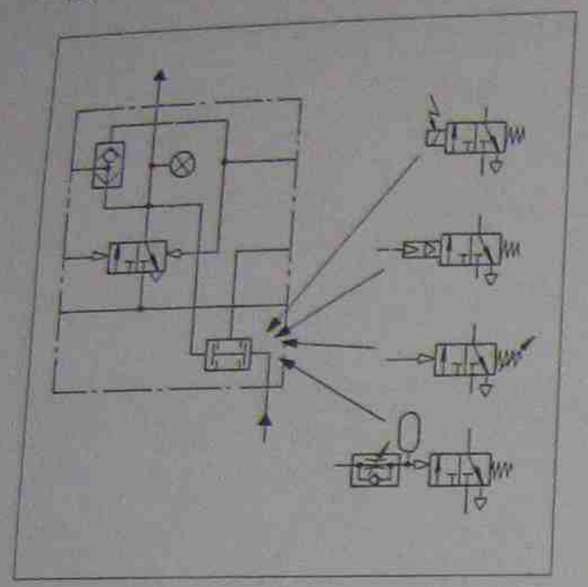


Fig. 8–42 French design step-counter module with detachable "AND" valve. The "AND" valve may be replaced with the valves shown on the side.

advantage is that the emergency stop modification shown in fig. 8–35 is *not required* with the French design. The unique interlinkage of its "OR" function valves holds the first memory valve in module 1 reset as long as the machine sequence is in progress. One may also attach a visual indicator to the "OR" function valve output of module 1 (fig. 8–39). This indicator is in the "ON" position as long as the sequence is in progress. A cross-section through a "CROUZET" step-counter module is shown in fig. 8–41. Another advantage with the French design is that the "AND" function valve is detachable and thus can be replaced with a timer, a pressure sequence valve, a signal amplifier valve, or even with a solenoid valve to interface with an electrical input. All these valves are thus used to render the "AND" function and are designed in such a way that they fit exactly into the position of the "AND" valve.

Step counter with interim start

Interim start may be used where the normal cycle program is divided into two or more cycle phases. Once the first cycle phase is completed the sequencing stops, and is then only permitted to

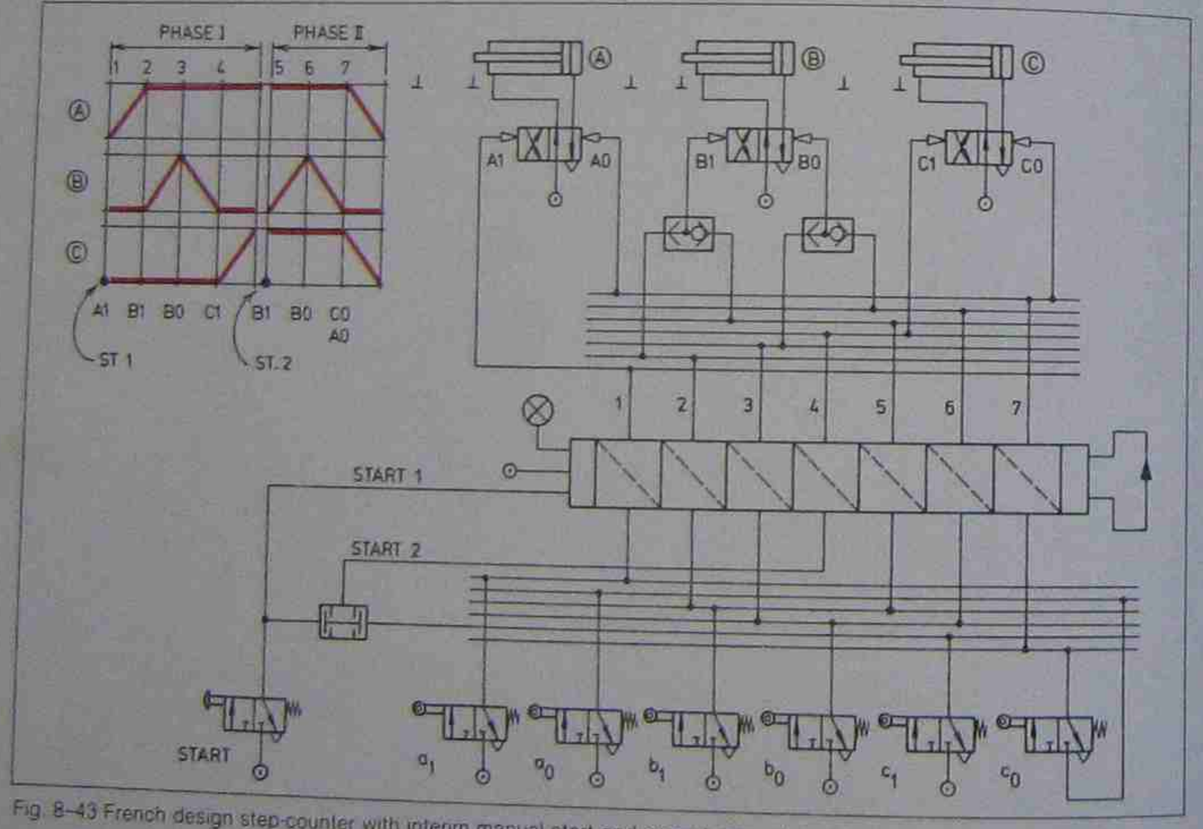


Fig. 8–43 French design step-counter with interim manual start and normal manual start from the same start valve.

continue when an external continuation signal is given from the interim phase being completed (fig. 7–43).

The interim phase can be a foreign machine function such as a forging press, a machining station, or a robot. In a forging machine for example the first few steps of phase 1 load the component into the machine, and the remaining steps of phase 2, which unloads the component out of the forging press, must only occur when the forging process (interim phase) is completed. Thus the forging machine provides the continuation signal.

Step-counter with undefined skipping

Skipping of certain sequence steps may be required if a machine malfunctions. In such a case the beginning of the skipping motion may or may not be previously defined or predictable. The skipping signal, if present, causes the step-counter to omit (skip-over) certain sequence steps, and after the skipping is completed, the program follows its normal sequence. A typical application for a drilling machine, where skipping would be required, is given in fig. 8–44. The machine follows the sequence depicted in fig. 8–36. Here a timer is used to make the skipping signal. Should the drilling signal B1, due to a broken or blunt drill, exceed the predetermined time of the timer, the skipping motion will automatically start and advance the program to the end of step 5. Thus the sequence steps 3, 4 and 5 in case 1 will be rapidly advanced (skipped) to the beginning of step 6. In case 2 the malfunction could occur during step 5. The skipping signal would then also advance the step-counter to the beginning of step 6. The remaining sequence steps 6, 7 and 8 will then follow the normal sequence controlled by the step-counter.

In order to skip sequence steps, one simply "OR" connects the skipping signal to the confirmation signal of these step-counter modules which must be skipped-over. The skipped modules are

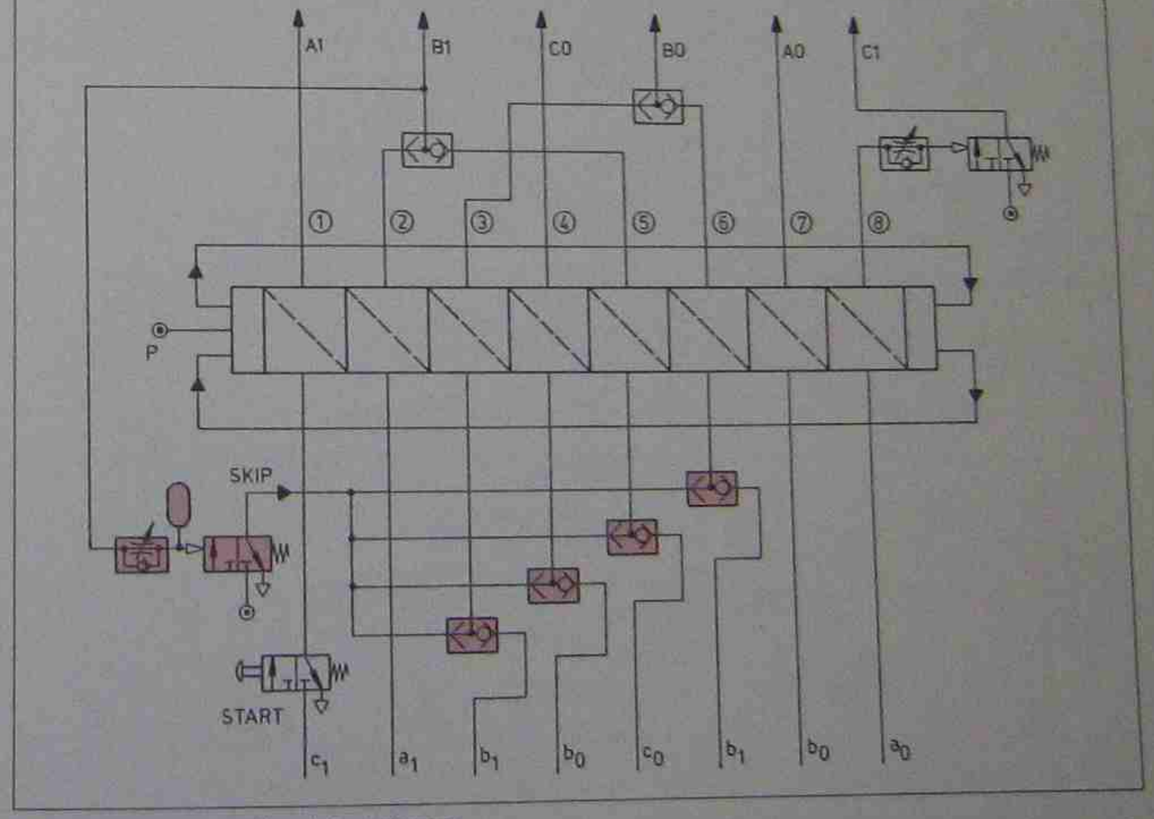


Fig. 8–44 Step-counter with undefined skipping.

then switched in extremely rapid succession, but the output signals (switching signals) of the skipped modules are too short to cause its connected power valves to switch.

Step-counter with defined skipping

Skipping of certain sequence steps may provide a simple solution if two machine programs have some sequence steps in common and are almost identical apart from the sequence steps which can be skipped. To illustrate, the traverse-time diagram of fig. 8–36 may again be used. Program I follows the sequence depicted in fig. 8–36. Program II, however, must only drill one hole into the workpiece and therefore sequence steps 4, 5 and 6 must be skipped (see also fig. 8–45). Since Actuator C never moves in program II, and therefore signal c_1 is constantly given, the sequence step 8 for C to extend is also skipped and therefore needs no extra "OR" valve. Thus the start of a new cycle can begin as soon as step 7 is completed and the timer phase is also skipped.

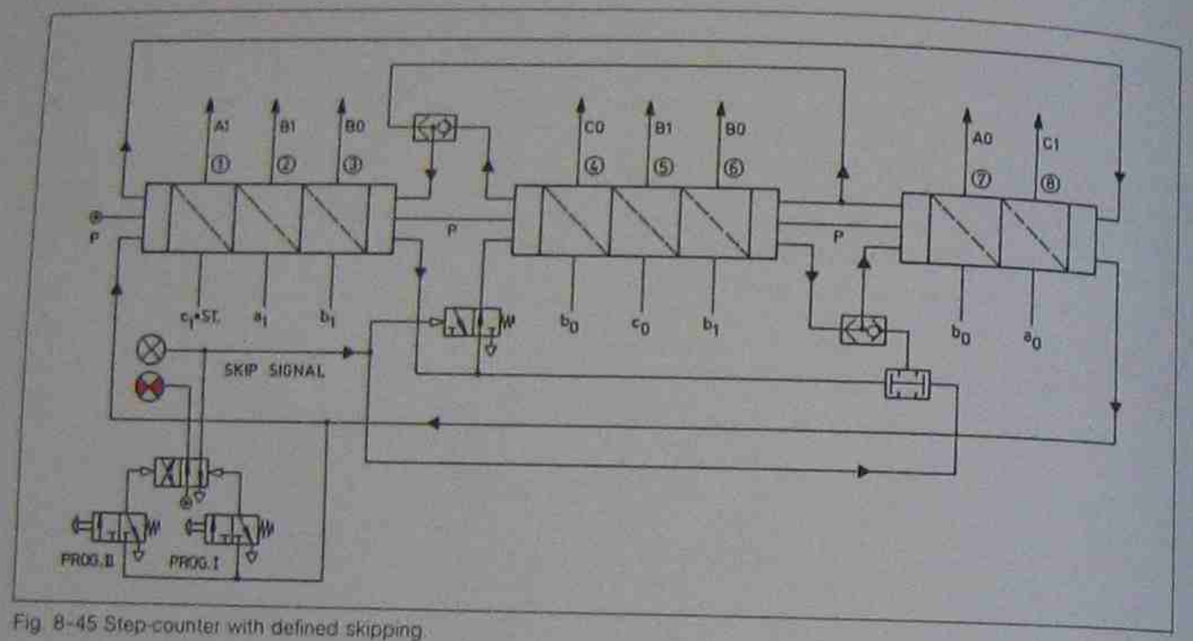
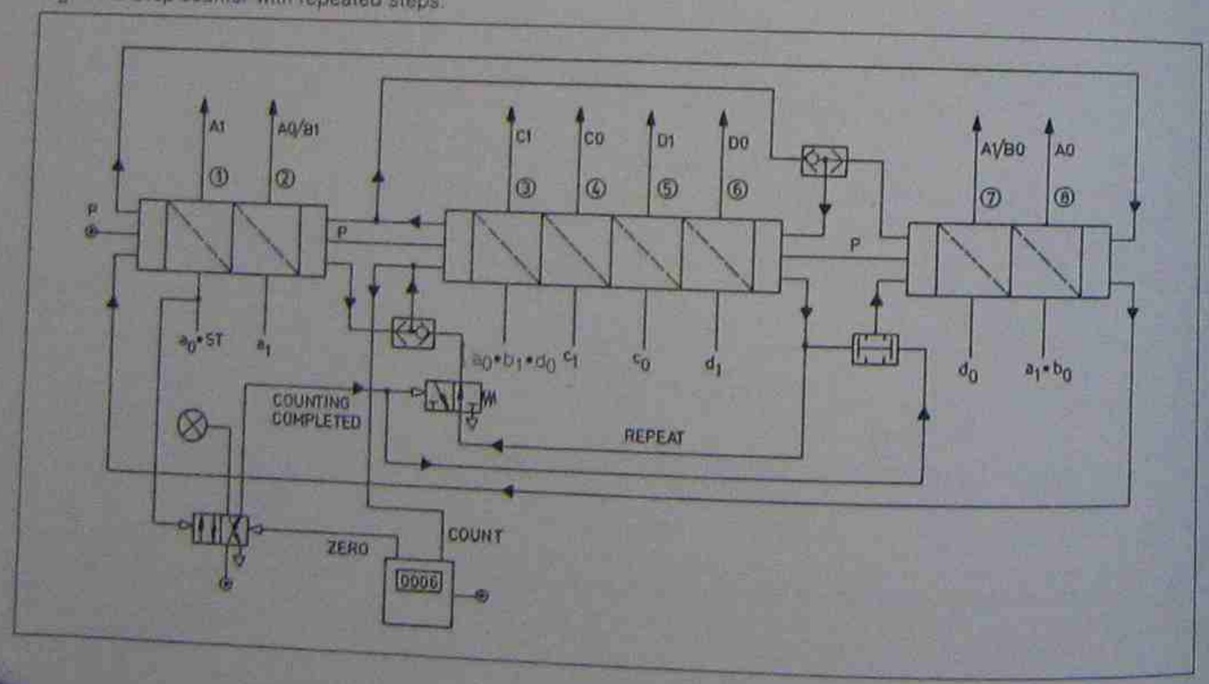


Fig. 8–45 Step-counter with defined skipping.

Fig. 8–46 Step-counter with repeated steps.



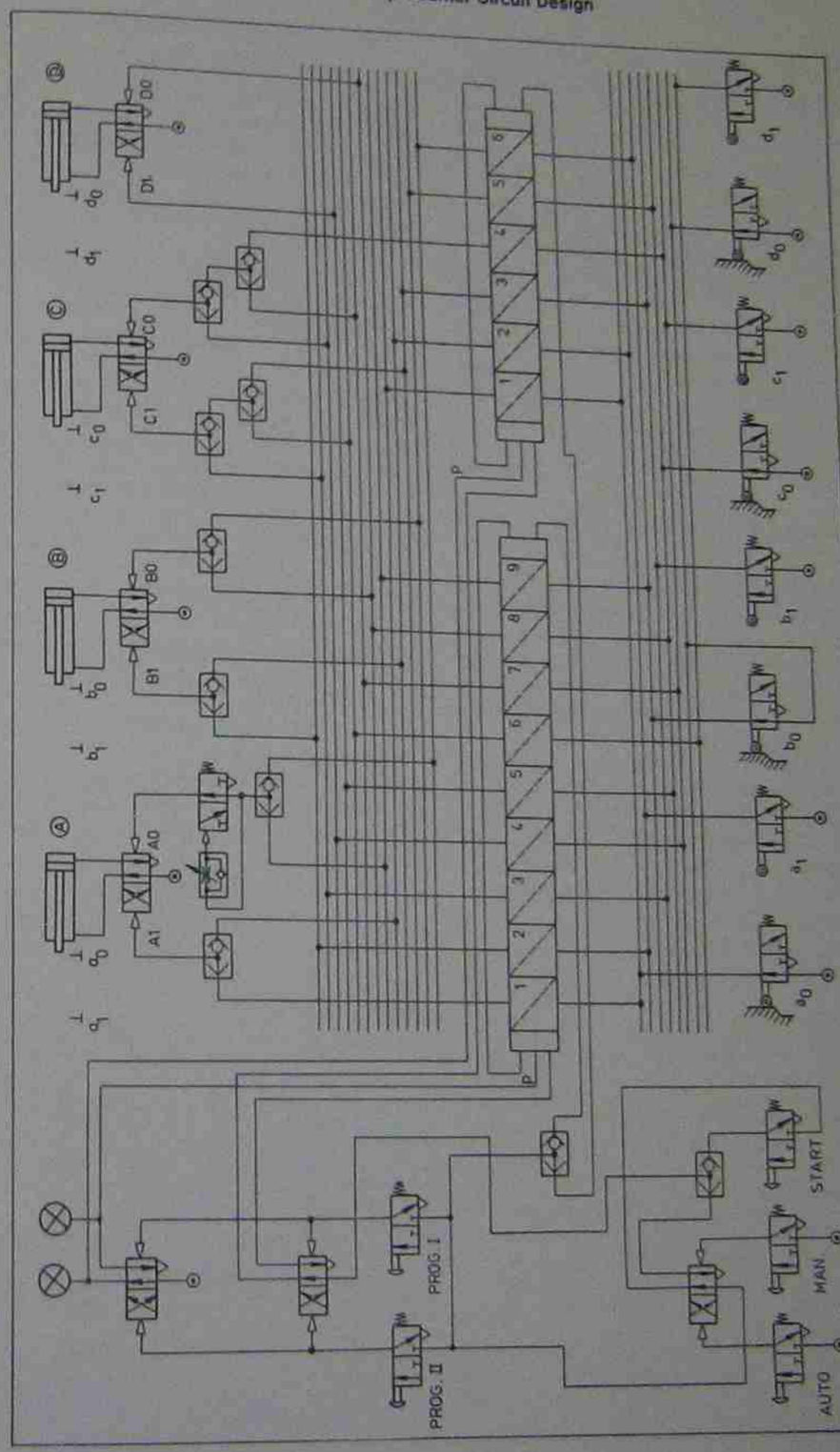


Fig. 8–47 Selective parallel program circuit.

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Step-counter with repeated steps

Step repetition is an extremely versatile and frequently used control method, which may simplify the control circuit considerably and thus save step-counter modules. To illustrate this control design concept, a sequence program is given for a disc to be machined. The disc is loaded automatically onto an indexing table by actuator A. The disc is then clamped by actuator B and the first drilling operation is accomplished with the drill actuator C. Indexing (with actuator D) and repeated drilling then must occur five times, thus drilling a hole every 60°. When the last indexing motion is completed, the workpiece must be unclamped with actuator B and automatically removed with actuator A. After the start command is given, a new sequence program may begin (see fig. 8–46).

Step-counter for selective parallel programs

Machine controls with several programs are frequently encountered on machine tools and multipurpose machines. Program selection and program start is made with a "program selector circuit", which may be designed either with the binary or with the cascade method (figs. 8–51 to 8–53).

With parallel selective control, each individual program consists of an independent circuit which may or may not have anything in common with its sister circuits. The sequence used to illustrate this control method in fig. 8–47 is as follows:

Prog. I → A1–B1–C1–C0–B0–A0

Prog. II → A1–B1–C1–C0–D1–C1–C0–B0/D0–A0

Since the last step of either program is maintained until reset by step 1, and therefore the signal A0 issued by this step is also maintained, an impulse valve must be used in line A0 to avoid an opposing signal when signal A1 of the alternative program appears (see fig. 8–47 and figs. 8–2, 8–3, 2–45 and 2–47).

The selective parallel program circuit depicted in fig. 8–47 is also furnished with a simple cycle selection module which replaces the start valve, and two visual indicators display the program in selection.

An other way of achieving selective parallel programs is depicted in fig. 8–48. Here the common steps A1–B1–C1–C0 are grouped together from both programs. Then a program selector shunts the preparation signal through the uncommon group consisting of the signals D1–C1–C0. Leaving this group, the preparation signal merges via an "OR" valve with the other preparation signal branch and actuates the final group consisting of the signals B0/D0–A0 which may again be regarded as common for both parallel programs. Although the signal D0 is not required for program I, its presence at step 8 causes no harm, as the actuator D is already retracted and was anyhow not used in program I.

Although somewhat more complex than the control method used in fig. 8–47, this kind of control is definitely less expensive as it requires only 9 step-counter modules.

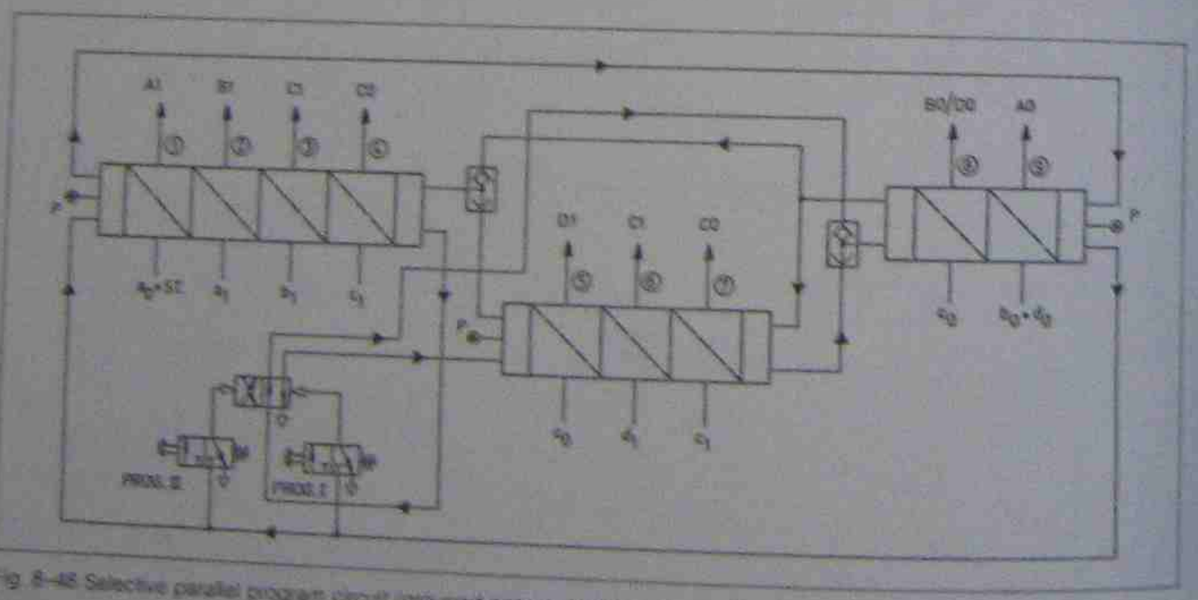


Fig. 8–48 Selective parallel program circuit (grouped approach with common steps).

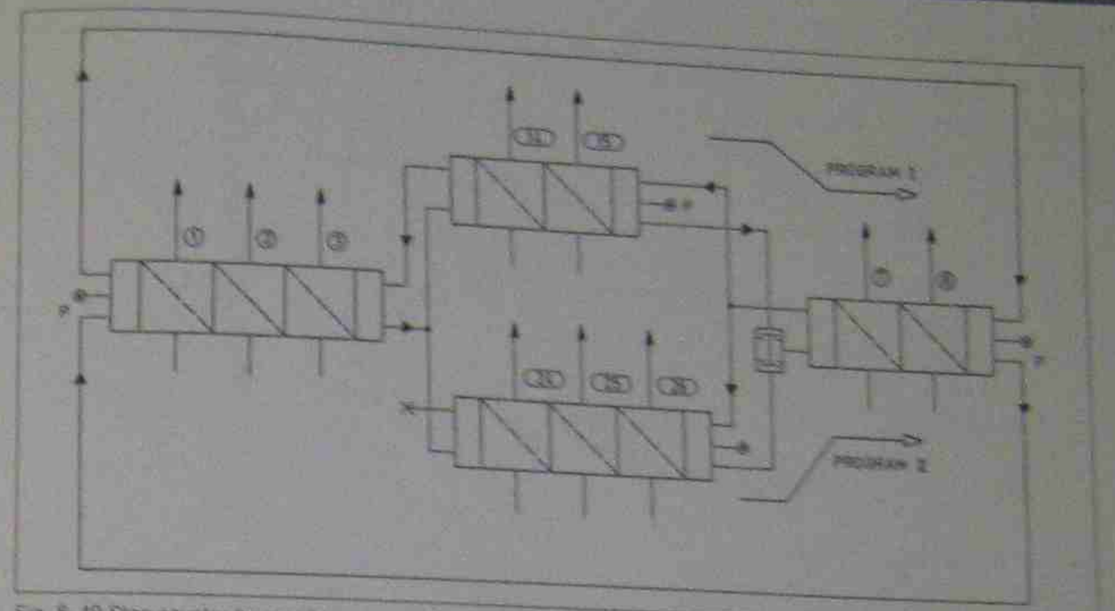


Fig. 8–49 Step-counter for simultaneous parallel programs.

Step-counter for simultaneous parallel programs

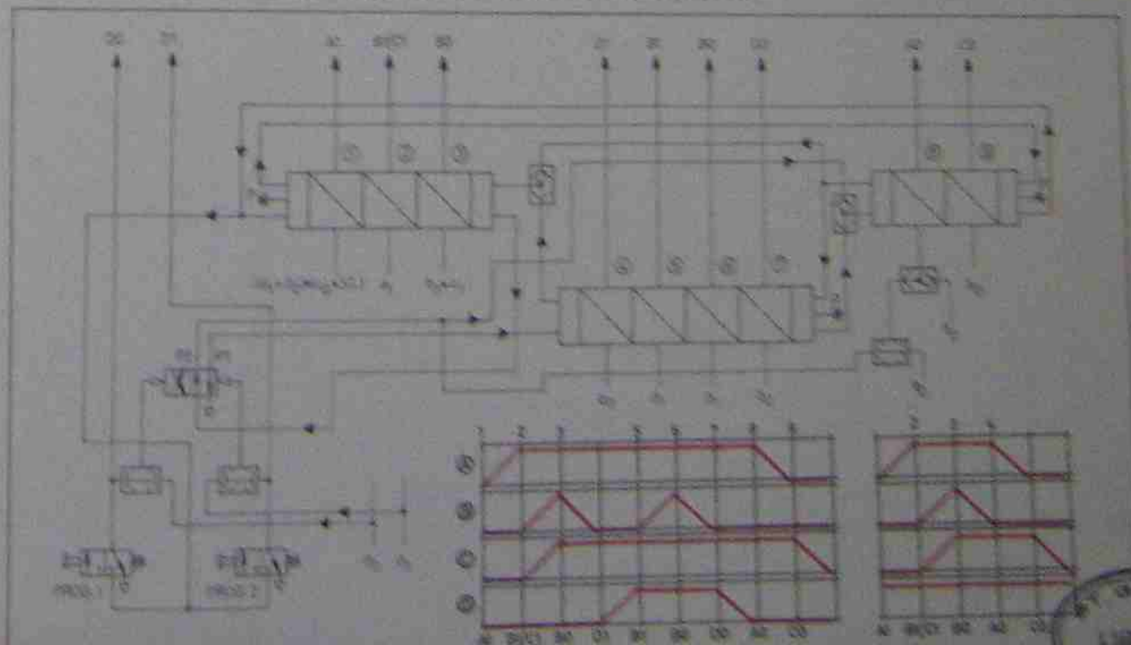
Simultaneous parallel controls are often found on transfer and indexing table machines, where each machining station has its own individual program, but the feed-in, transporting, indexing and clamping as well as loading of the work-pieces (components) is a common program. For such application one may select a control as shown by the circuit in fig. 8–49 and a real application for such a control is given in figs. 8–55 to 8–58.

Simultaneous parallel programs may consist of several branches, not just two as shown in fig. 8–49, and may or may not have a common program at the head-end or tail-end of the total cycle. But in each case the preparation signal of all the branches must be collected with "AND" functions and only one reset signal is required to reset the head-end common line. The reset signals from the other branches must be blocked (fig. 8–49).

Step-counter for parallel programs but different actuator start positions

Control circuits of this nature are almost identical to the controls shown in figs. 8–47 and 8–48. The

Fig. 8–50 Step-counter for parallel programs but different actuator start positions.



start position for actuator D differs, however, and actuator D in program 2 does not move at all.

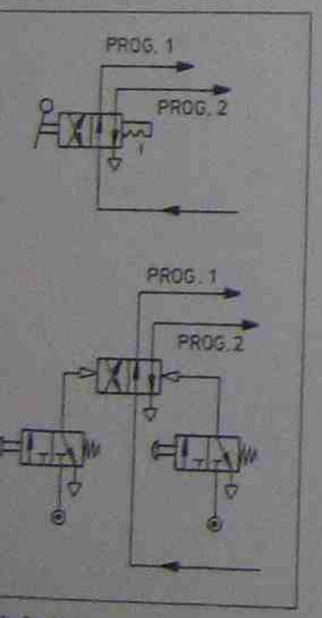
It remains extended throughout the entire cycle (fig. 8–50). To accomplish the rectification of actuator D into its new start position, the program selector circuit must be modified as shown in fig. 8–50. When program change is signalled, actuator D will receive a rectification command. This rectification is then confirmed with the "AND" valve and, together with the program change signal, causes the program selector memory to shift. The program selector push button pilot valves are series connected to the preparation signal for step-counter module 1. Thus a program change can only be signalled if the cycle is completed.

Program selector circuits

Program selector circuits are closely related to the cycle selection module shown in fig. 8–27. The ole purpose of the program selector circuit is to hunt the start signal to the selected line of step-ounter modules in the parallel program (fig. 8–47) nd maintain that program selection until another election is made.

If a step-counter with defined skipping is used to rovide alternative programs, then the program elector circuit is used to make or cancel the skip-ng signal (fig. 8–45).

Program selector circuits may range from a mple hand lever operated memory valve to ultiple input and remotely controlled selector bcircuits which may be designed either with the



8–51 Program selector circuits for two programs.

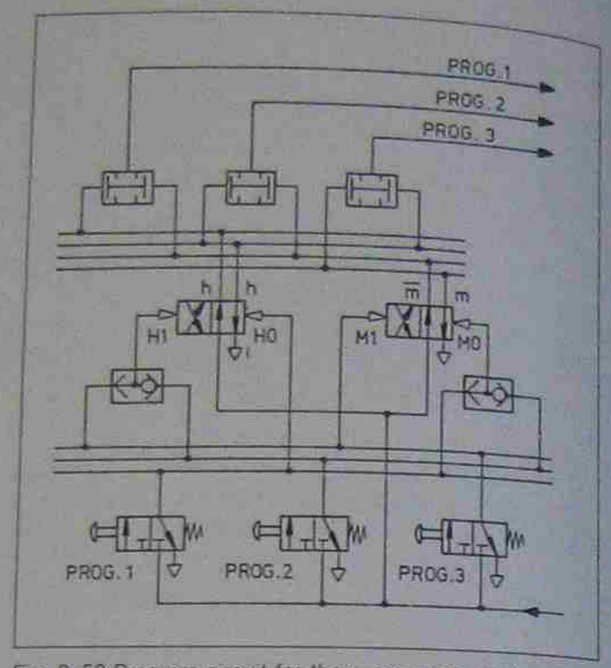


Fig. 8–52 Program circuit for three programs designed with binary methods.

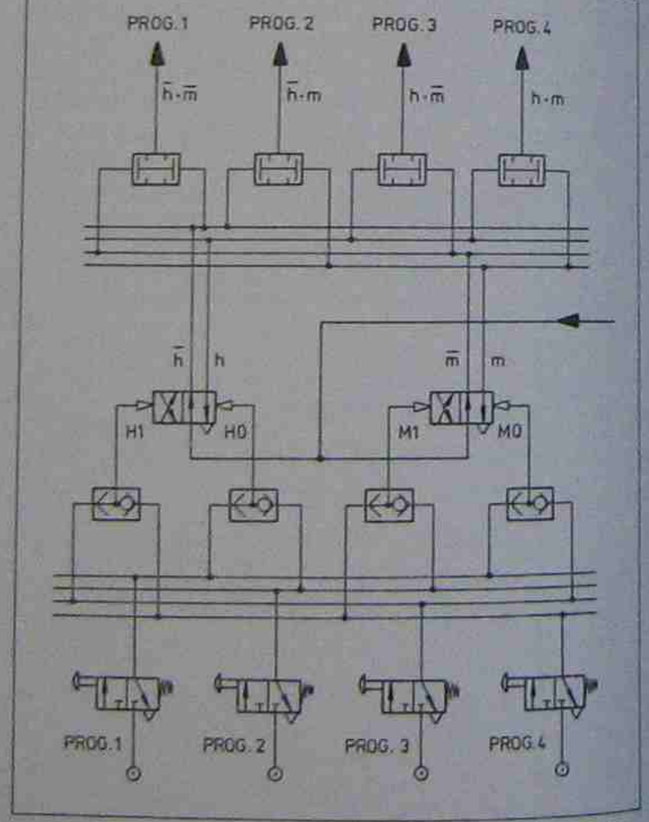


Fig. 8–53 Program selector circuit for four individual control programs.

binary logic or the cascade method (fig. 8–51 to 8–54).

The program selector circuit in fig. 8–51A uses a hand lever valve with detent to shunt the program selection signal to the selected line of the step-counter program. The program selector circuit in fig. 8–51B is remotely controlled, with two pneumatic pilot signals acting alternatively onto the memory shunt valve.

The program selector circuit in fig. 8–52 is designed with the binary method (see Chapter 10, fig. 10–30) and can shunt the selector signal to either of three step-counter lines. A binary program selector circuit for four program choices is shown in fig. 8–53.

Step-counter with stepping module

For non-stepping operation, the stepping selector module provides a permanent signal to all stepping "And" function valves. For stepping operation the select step valve provides the operator-dependent stepping signal to be given for each step. This module and circuit arrangement is mandatory when toolsetters are preparing a machine after changing tools or after necessary maintenance work.

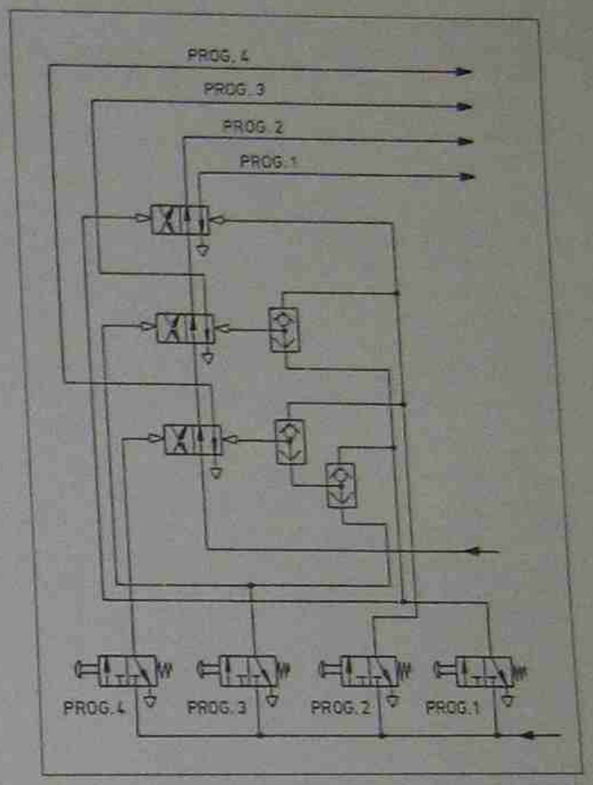


Fig. 8–54 Program selector circuit designed with cascade concept.

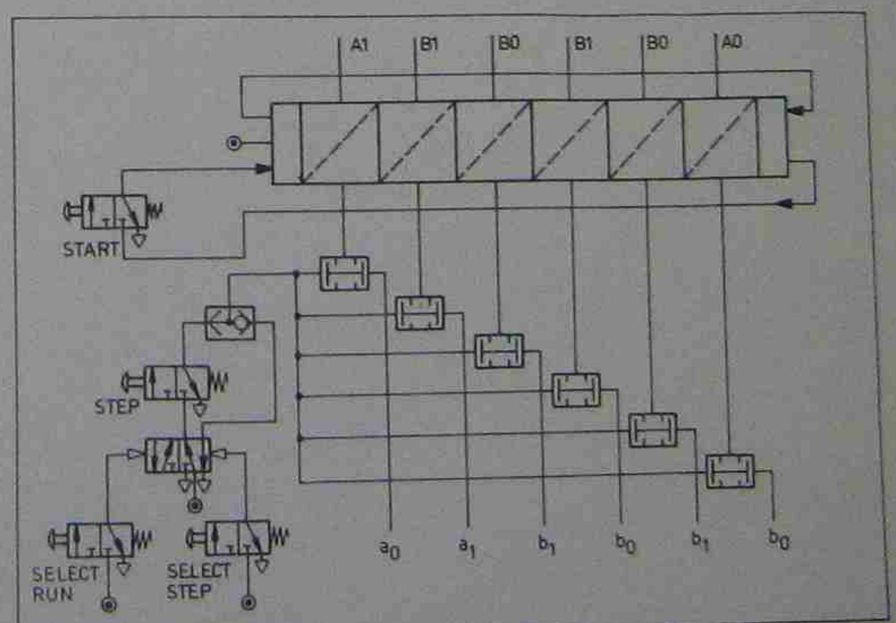


Fig. 8–55 Step-counter with choice of manual stepping or normal cycling (running).

9 The Cascade System of Pneumatic Sequential Control

In Chapter 8 the problem of opposing signals has been discussed, and how the step-counter circuit design method overcomes such opposing signals is outlined on page 96. The cascade method is also designed to remove opposing signals and its structure is closely related to the step-counter method.

The first cascade method was invented and introduced to the field of pneumatic sequential control by Arthur M. Salek, a mechanical engineering graduate of Canterbury University, New Zealand. His paper "Pneumatic Mechanisation for Industry", was published in *New Zealand Engineering* October 15, 1954. Mr. Salek's circuit design method became widely used in New Zealand, U.S.A. and Great Britain and was updated in a later paper in 1961. The cascade method has since been modified many times, and four popular versions (including Mr. Salek's version) are given in this chapter.

The step-counter circuit design method as outlined in the previous chapter allocates a memory valve to *each* sequence step. Thus opposing signals can never occur, since each step-counter module resets the memory valve in the previous step-counter module. The essential confirmation signal relayed through that memory valve is thus automatically cancelled and can no longer cause an opposing signal.

The cascade circuit design method uses fewer memory valves than the step-counter method, and opposing signals are eliminated when the cascade in operation resets the previous cascade. A detailed design and operation procedure for the cascade is given through the following pages.

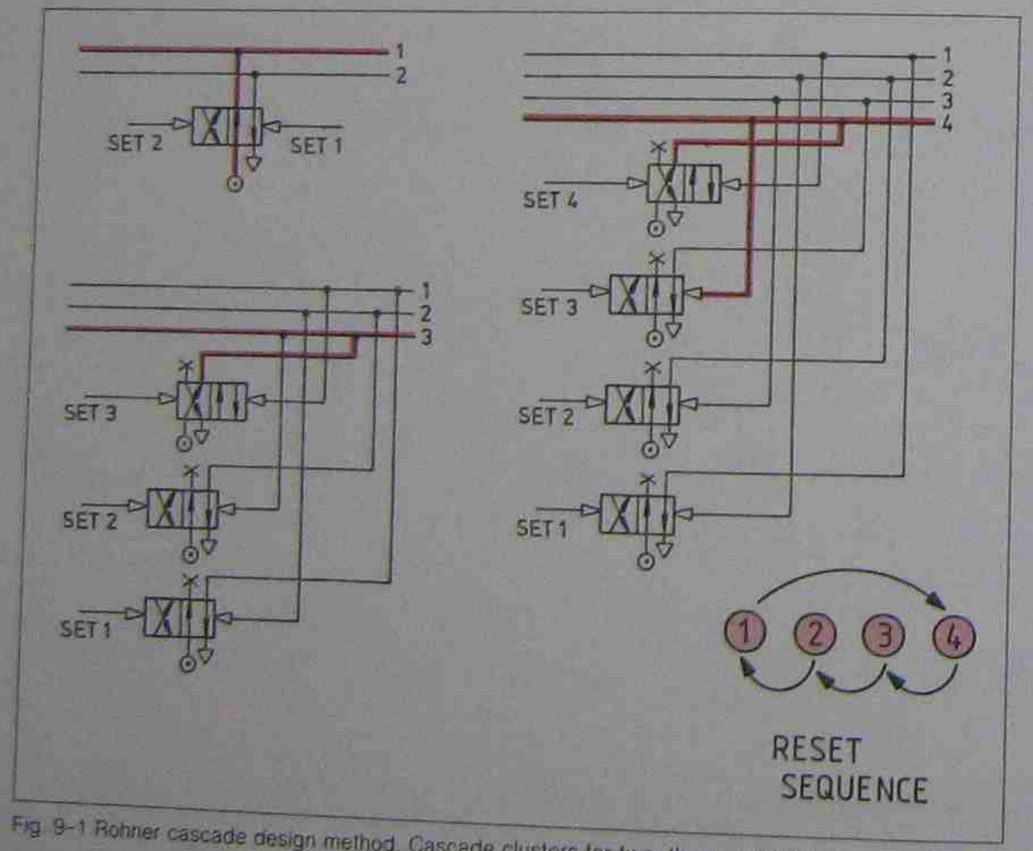


Fig. 9–1 Rohner cascade design method. Cascade clusters for two, three and four cascade groups are shown.

Rohner cascade design method

The "Rohner" cascade design method (design by Peter Rohner) uses one cascade memory valve (Group memory, or GM) for a two cascade group sequence program and thereafter one cascade memory for every cascade group (fig. 9–1). The "Rohner" design method is extremely simple but requires above two cascade groups one more cascade memory than the "MARTONAIR" method (fig. 9–5) or "FESTO" method (fig. 9–4). This, however, is well compensated for by the increased safety aspects of the "Rohner" method (no series and no series-parallel connection to the other cascade memories). The "Rohner" method is also simpler for cluster design and connection to other circuit parts, and because it is not series connected it is easier to faultfind and include emergency stop control.

Figure 9–2 shows how the cascade cluster can also be arranged horizontally, which then proves its remarkable similarity to the step-counter method. With the cascade design method, each cascade memory valve (group memory) performs three main functions (fig. 9–3).

- Function 1 is to switch the power valves either directly from the cascade group output signal or to switch them in "AND" connection with an essential confirmation signal (limit valve signal, see fig. 9–10).
- Function 2 is to reset the previous cascade memory valve. This then automatically cancels all opposing signals arising from that cascade group.
- Function 3 is to prepare the next cascade group set-signal which is "AND" connected to the last essential confirmation signal of the present cascade group. Thus one may conclude that these cascade valves function similarly to the step-counter modules explained and illustrated in Chapter 8, fig. 8–5. A detailed construction algorithm is given through the following pages.

Alternative cascade design methods

Both the "Salek" and "MARTONAIR" cascade design methods are based on the use of five port memory valves and utilize the exhaust flow ports R and S as input ports. Therefore these two methods require spool type valves rather than flat slide valves (figs. 2-4, 9–5 and 9–6).

The "Rohner" and "FESTO" methods can be built from four or five port valves, and both flat slide

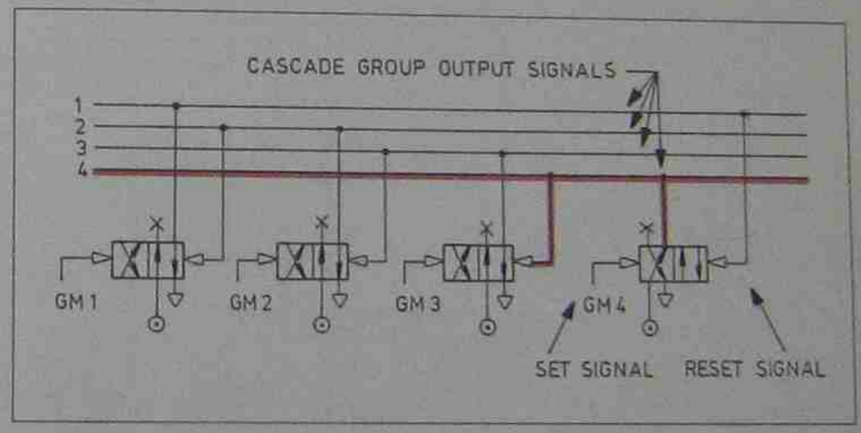


Fig. 9–2 The simple cascade (Rohner method) has only parallel connection and is shown here in horizontal arrangement.

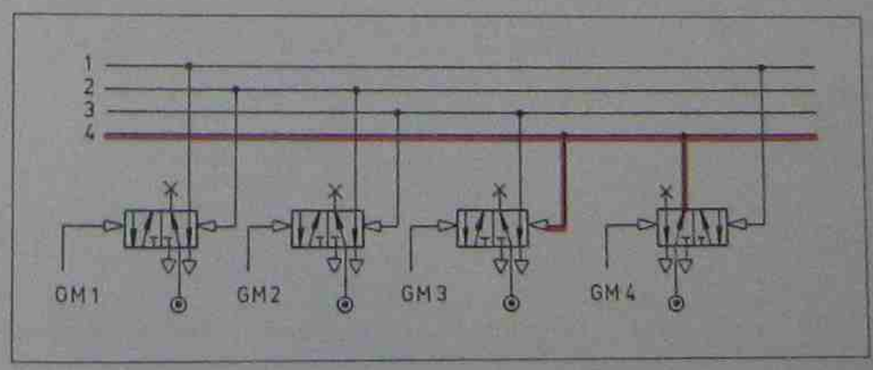


Fig. 9–3 Cascade cluster (Rohner method) built with five port group memory valves.

or spool type valves may be used (figs. 9–2, 9–3 and 9–4).

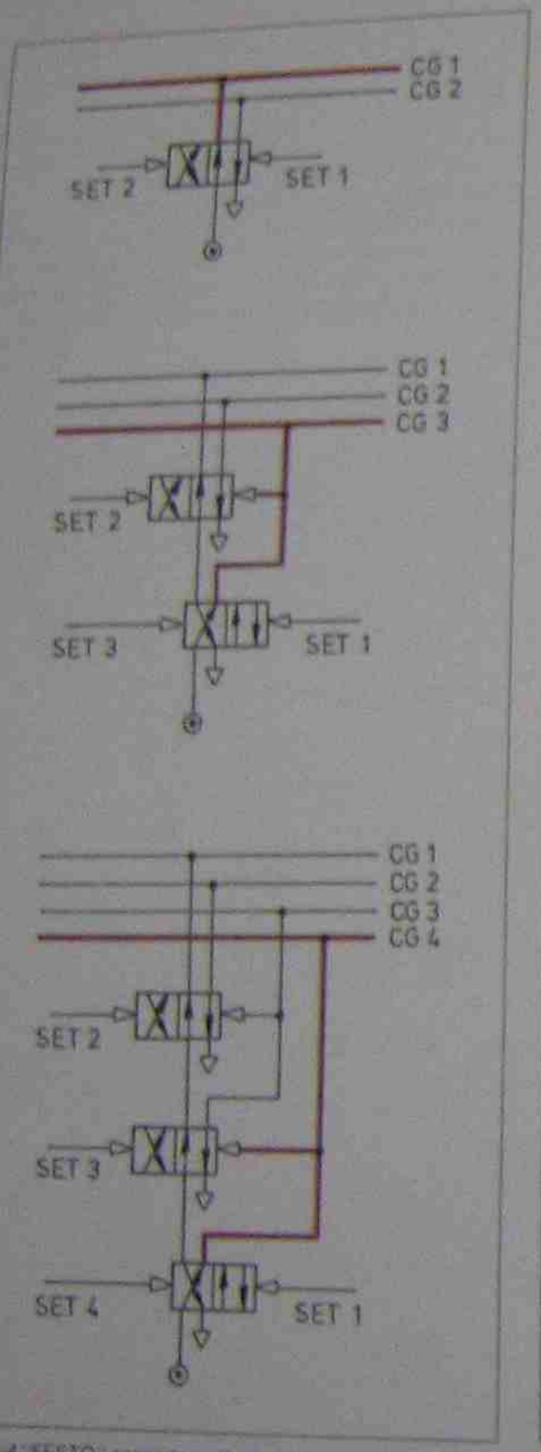


Fig. 9–4 "FESTO" cascade method with long series and parallel connection (four- or five-port valves may be used).

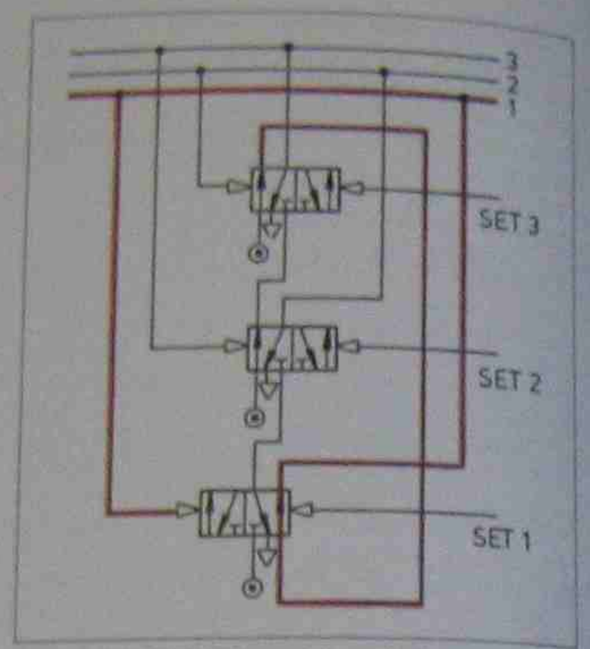


Fig. 9–5 "MARTONAIR" cascade method with short series and parallel connection similar to the "Salek" and "FESTO" methods (see figs. 9–4 and 9–6).

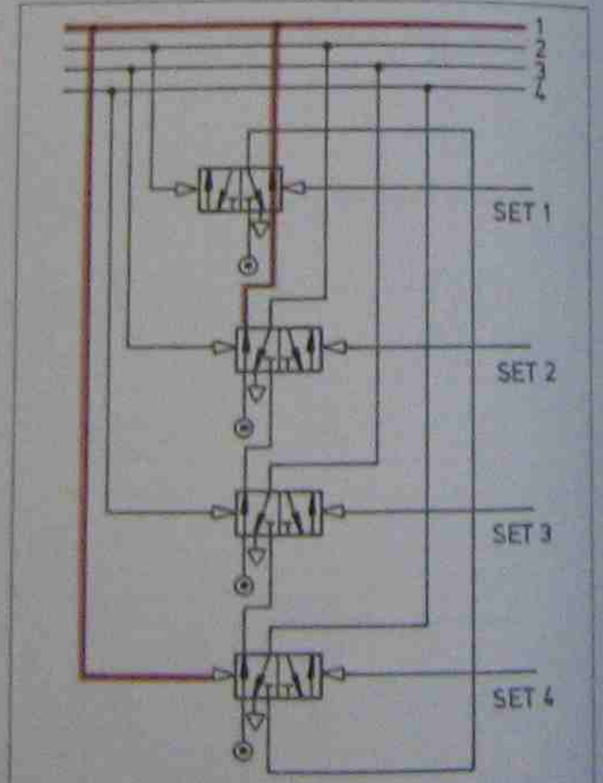


Fig. 9–6 "Salek" cascade method with short series and parallel connection.

Grouping procedure for cascade groups

With the cascade circuit design method the sequence program is divided into cascade groups. These groups are formed in such a way that no group contains an opposite switching signal (for example: A0, A1). When dividing the sequence program into cascade groups, the dividing should always be attempted from both sides (left to right, and thereafter right to left). Sometimes one approach produces less groups than the other, and thus less cascade valves have to be used. One must also remember that a cycle borders onto the beginning of the next cycle. When considering continuous cycling, cycle interruption is only made possible because of the start valve being placed into the switching command line for sequence step 1. Hence, a cycle should be regarded as a part of a continuous production program and therefore a cascade group running to the end of the sequence cycle may continue into the next cycle (over and beyond the start of the next cycle). To illustrate this, the following sequence is investigated:

A1–B1–C1–B0–D1–D0–A0–E1–E0–C0

Dividing the cycle from the front, one obtains:

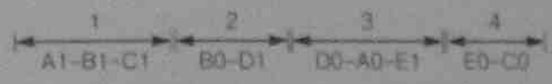


Fig. 9–7 Drilling machine.

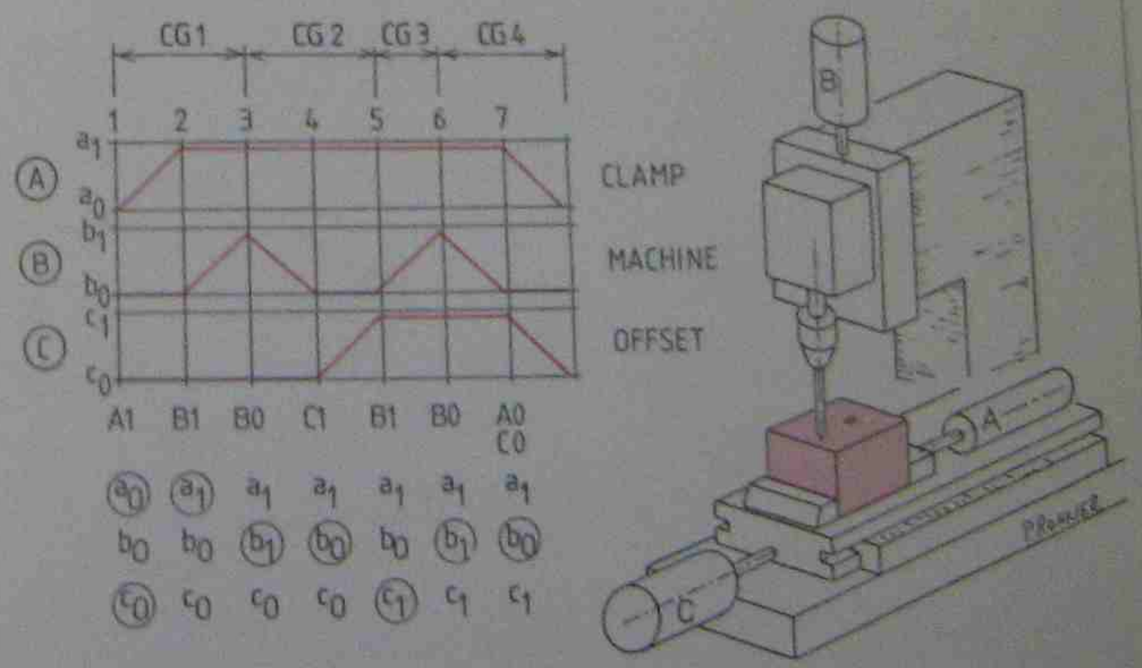
Note: The final group out of these four cascade groups cannot be joined to the first group in the program, since there would be a C0 command and its opposite C1 command in the same group! By splitting the cycle from the rear, one obtains:



With the grouping pattern above one can join the last two signal commands in the cycle to the first two commands without having opposite commands within one group. Thus dividing from the rear, for this program, produced a simpler result—only three cascade groups instead of four with the first dividing approach!

Cascade circuit construction

Once the grouping procedure is completed and the minimum number of required cascade groups is determined, one can draw the cascade valve cluster as shown in figs. 9–1, 9–2 or 9–3. To illustrate we assume a program sequence as shown in the traverse-time diagram given in fig. 9–7, for which four cascade groups have been formed. The first signal command in each cascade group is now directly attached to the cascade group output.



signal. Consecutive signal commands of the *same* group are constructed as an "AND" function. The source signals of this "AND" function are:

(a) The *essential* confirmation signal which confirms the completion of the previous sequence step (see transverse-time diagram).
(b) The *cascade group signal* which ensures that the essential confirmation signal is only active at the correct sequence step (fig. 9-9). Signal command C1 for example is switched by b_0 and so are the signals A0/C0. Signal C1 can only be switched by b_0 if cascade group 2 in "ON" and signals A0/C0 can only be switched by b_0, if cascade group 4 is "ON" (see switching equations and fig. 9-10).

To illustrate: Signal command A1 at step 1 is *directly* attached to cascade group signal CG1, but the next signal command in the sequence (B1) consists of the cascade group signal CG1 *and* the essential confirmation signal a_1 (see figs. 9-7 to 9-9 and equations). Similarly the first signal command in cascade group two (CG2), which is the command B0, is again *directly* attached to its cascade group output signal (CG2). The sources of the next signal command in group two are again "AND" connected and consist of the signals CG2 *and* b_0 (see also switching equations for this program sequence).

Cascade Memory Set Commands:

$GM1 = CG4 \cdot a_0 \cdot c_0 \cdot Start$
$GM2 = CG1 \cdot b_1$
$GM3 = CG2 \cdot c_1$
$GM4 = CG3 \cdot b_1$

D.C.V. Pilot Signals:

$A1 = CG1$
$A0 = CG4 \cdot b_0$
$B1 = CG3 + CG1 \cdot a_1$
$B0 = CG2 + CG4$
$C1 = CG2 \cdot b_0$
$C0 = CG4 \cdot b_0$

Identical "AND" function*

a_1	1x	$CG1 \rightarrow a_1$
a_0	1x	$CG4 \rightarrow a_0$
b_1	2x	—
b_0	3x	$CG4 \rightarrow b_0$*
c_1	1x	$CG2 \rightarrow C_1$
c_0	1x	$CG4 \cdot a_0 \rightarrow c_0$
ST.	1x	$CG4 \cdot a_0 \cdot c_0 \rightarrow$ Start

Fig. 9-8 Series function chart.

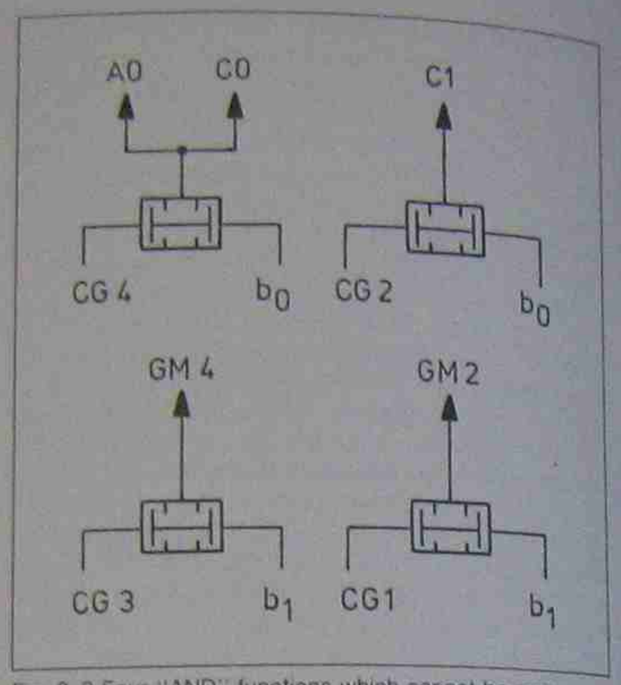


Fig. 9-9 Four "AND" functions which cannot be series connected (see equations).

The cascade memory valves in the cascade cluster are "SET" at the beginning of each cascade group and their "SET" commands may be compared to step-counter module "SET" commands (see fig. 8-6).

Hence, these set commands consist of the previous cascade group signal which may be regarded as the preparation signal. This preparation signal is then "AND" connected to the last essential confirmation signal of the previous cascade group (that sequence step which ends when the new cascade group begins). To illustrate: the cascade set command for the cascade group memory 2 requires signal CG1 *and* the essential confirmation signal b_1. To set cascade group memory 1, the preparation signal CG4 of the previous cascade group and the double confirmation signal of the successful completion of the previous sequence step is required. These signals must also be "AND" connected to the start valve (see switching equations and fig. 9-10).

"Series" functions and identical "AND" functions

The same principles and procedural steps outlined in Chapter 7 for the formation of identical "AND" functions as well as "Series" functions may also be used for the cascade circuit design method. In figures 9-7, 9-8 and 9-9 and their corresponding switching equations, provision is made for a typical application, where the circuit hardware may drastically be reduced if "Series" and identical "AND" functions can be formed. Thus a circuit such as fig. 9-10 can be built with four instead of ten "AND" valves (as shown in the switching equations for this sequence).

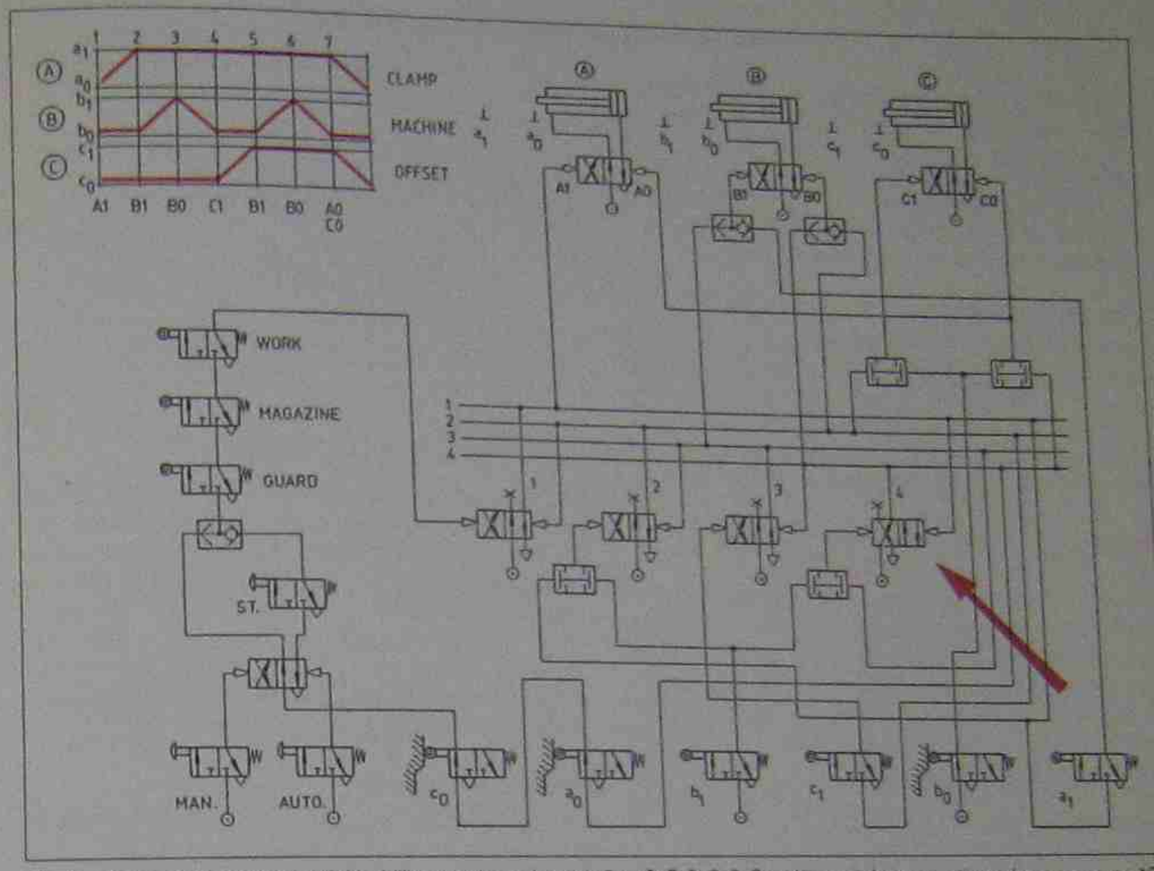


Fig. 9-10 Cascade control circuit for drilling machine shown in figs. 9-7, 9-9, 9-8 and its switching equations shown on page 12... The circuit is also equipped with a cycle selection module and some fringe starting conditions. Note: Group memory 4 remains ... until being reset by group memory 1.

Emergency stop for cascade circuits

Emergency stop integration for control circuits designed with the cascade circuit design method is often far more complex and difficult than for the step-counter design method discussed and illustrated in Chapter 8.

Limit valves frequently must be "AND" or "Series" connected to output signals from the cascade memory valves (fig. 9-10, in particular limit valves a_0, c_1 and a_1). Furthermore, cascade memory valves require extra "OR" function valves if the cascade cluster must be reset to "ZERO" (see figs. 8-22, 8-34, 8-35, 8-36 and 8-39 of the previous chapter). These "OR" function valves are already integrated into the step-counter modules if one decides to use commercial modules, but for cascade design such modules are not available.

In control problems where an emergency p... gram is required to sequence the actuators to ... end-of-cycle position, one requires limit valve ... nals to confirm the emergency steps (see ... 8-36). If these limit valves are series connected ... the cascade valves (see fig. 9-10), they are u... less, since resetting the cascade valves wo... render them without air supply. Thus one can... connect limit valves in series; "AND" func... valves must be used (see fig. 9-9).

With all these extra "OR" and "AND" func... valves, the hardware cost difference for s... counter versus cascade designed control p... lems becomes negligible. Step-counter contr... preferable overall, due to its simplicity of c... design, ease of faultfinding and ready applic... for the programming of PLC electronic contro... (see Chapter 11).

Should the decision still be made to use the ... cade circuit design method in conjunction wi... emergency stop provision, then the principle... cussed and illustrated in the previous ch... would also apply here (see figs. 8-22 to 8... These limitations of cascade circuits of cours...

hold true for control problems with emergency stop integration! For other problems, cascade circuits, although more complex than step-counter circuits, often prove to be less expensive. Three totally different control problems are presented below, to demonstrate the different advantages of step-counter and cascade methods.

Control problem 1

The control problem given here is based on a machine sequence already discussed in the previous chapter (fig. 8–32). The sequence for this control problem is: A0–B1–B0–C1/B1–C0–A1/B0. Dividing this sequence into cascade groups is not complicated and produces the following pattern:



If one chooses to use either the "Rohner" or the "MARTONAIR" cascade design method, then four cascade memories will be required for these four cascade groups, and the following equations may be derived from the traverse-time diagram (fig. 8–32):

Cascade Memory Set Commands

$GM2 = CG4 \cdot a_1 \cdot b_0 \cdot Start$
$GM2 = CG1 \cdot b_1$
$GM3 = CG2 \cdot b_0$
$GM4 = CG3 \cdot c_1 \cdot b_1$

D.C.V. Pilot Signals

$A1 = CG4 \cdot c_0$
$A0 = CG1$
$B1 = CG1 \cdot a_0 + CG3$
$B0 = CG2 + CG4 \cdot c_0$
$C1 = CG3$
$C0 = CG4$

Identical "AND" function*

a_1	1x	$b_0 \rightarrow a_1$
a_0	1x	$CG1 \rightarrow a_0$
b_1	2x	—
b_0	2x	—
c_1	1x	$b_1 \rightarrow c_1$
c_0	2x	$CG4 \rightarrow c_0$*
ST.	1x	$(b_0 \cdot a_1) \rightarrow$ Start

Fig. 9–11 Series function chart. Although limit valve c_0 appears twice it can be series connected, since its signal is used in an identical "AND" function (see fig. 9–12).

The step-counter control circuit designed for the same sequence requires six step-counter modules

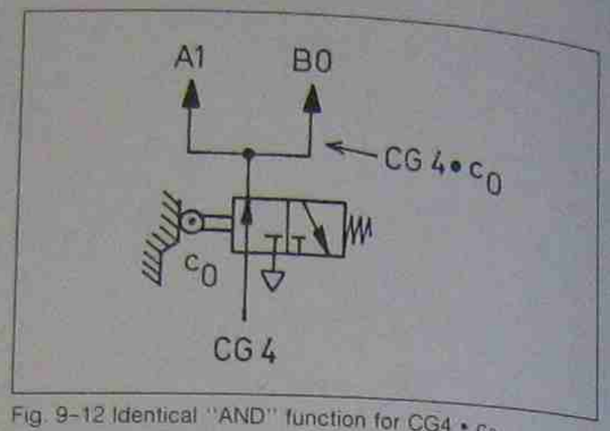


Fig. 9–12 Identical "AND" function for CG4 • c_0.

and a "Series" function can be formed for all "AND" functions found in the switching equations. Hardware cost calculations based on commercial step-counter modules, when compared to the four cascade memories and four "AND" function valves for the cascade design, show equal total costs for both designs. The circuit construction costs, however, would be slightly less for the step-counter circuit (see figs. 9–13 and 9–14).

Control problem 2

A circuit is to be designed for a machine which punches holes into aluminium window frames. Two different types of frames must be manufactured with the same machine. The window frames are manually loaded and unloaded to and from the machine.

Type 2 frame requires six holes to be punched, but type 1 frame requires every second hole to be punched—that is, 3 holes. Actuator A clamps the window frame and holes are punched by actuators B1 to B6. A program selector circuit is used to select the punching type (all six, or every second hole, see figs. 9–15 to 9–17).

All actuator end positions must be *sensed* for complete motion confirmation prior to consecutive actuator movements. Control circuits must be designed and drawn using the cascade and the step-counter design methods to permit evaluation of the most suitable method.

Cascade Memory Set Commands:

$GM1 = GM2 \cdot a_0 \cdot Start$
$GM2 = GM1 \cdot b_{1(ODD)} + GM1 \cdot b_{1(ALL)}$

D.C.V. Pilot Signals:

$A1 = GM1$
$A0 = GM2 \cdot b_0$
$B1 = CG1 \cdot a_1 \cdot PROG.\ 1\ (ACT.\ 1,3,5)$
$B1 = CG1 \cdot a_1 \cdot PROG.\ 2\ (ACT.\ 2,4,6)$
$B0 = CG2$

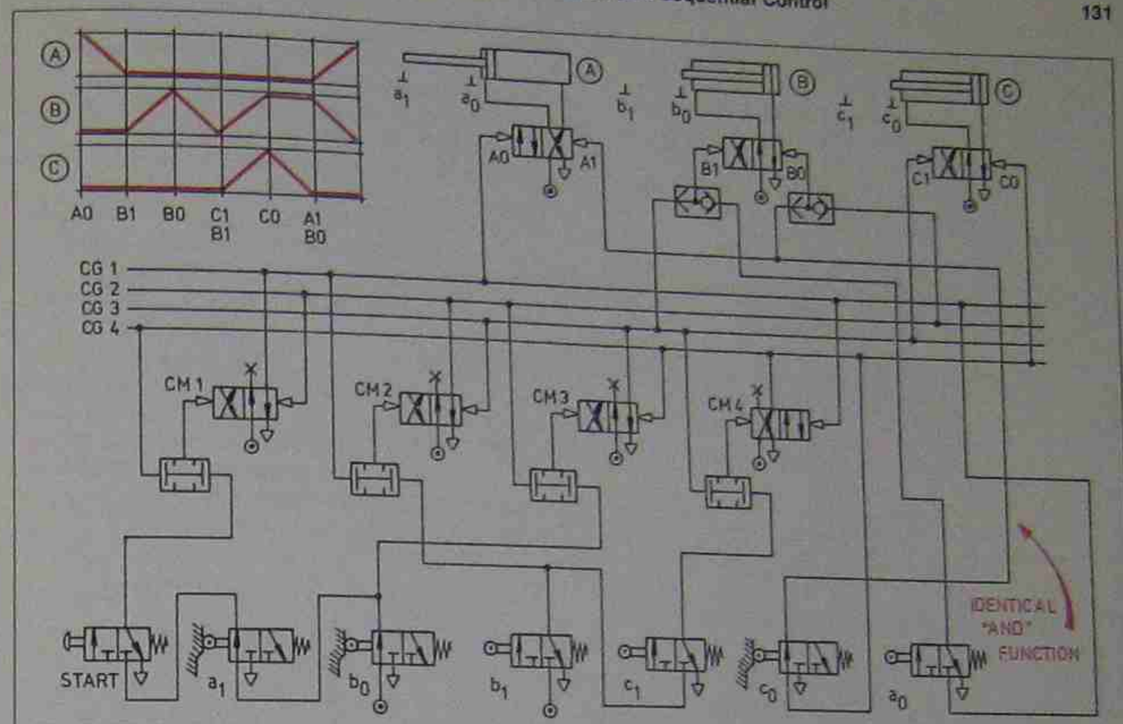


Fig. 9–13 Cascade control circuit to control problem 1.

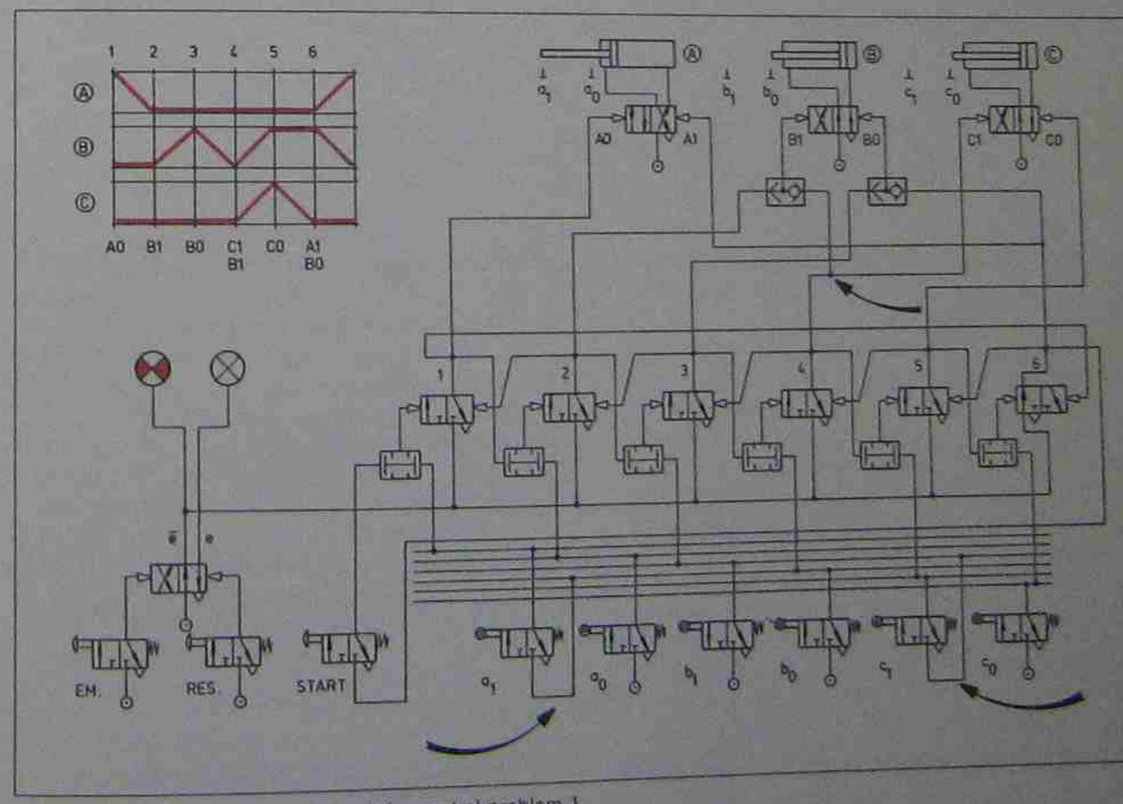


Fig. 9–14 Step-counter control circuit for control problem 1.

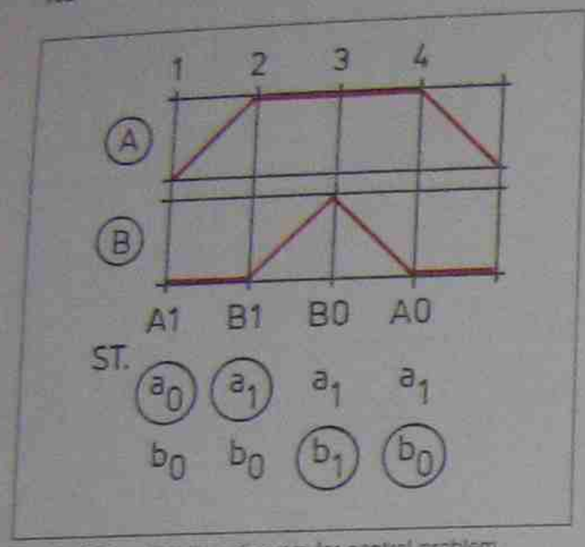


Fig. 9–15 Traverse-time diagram for control problem.

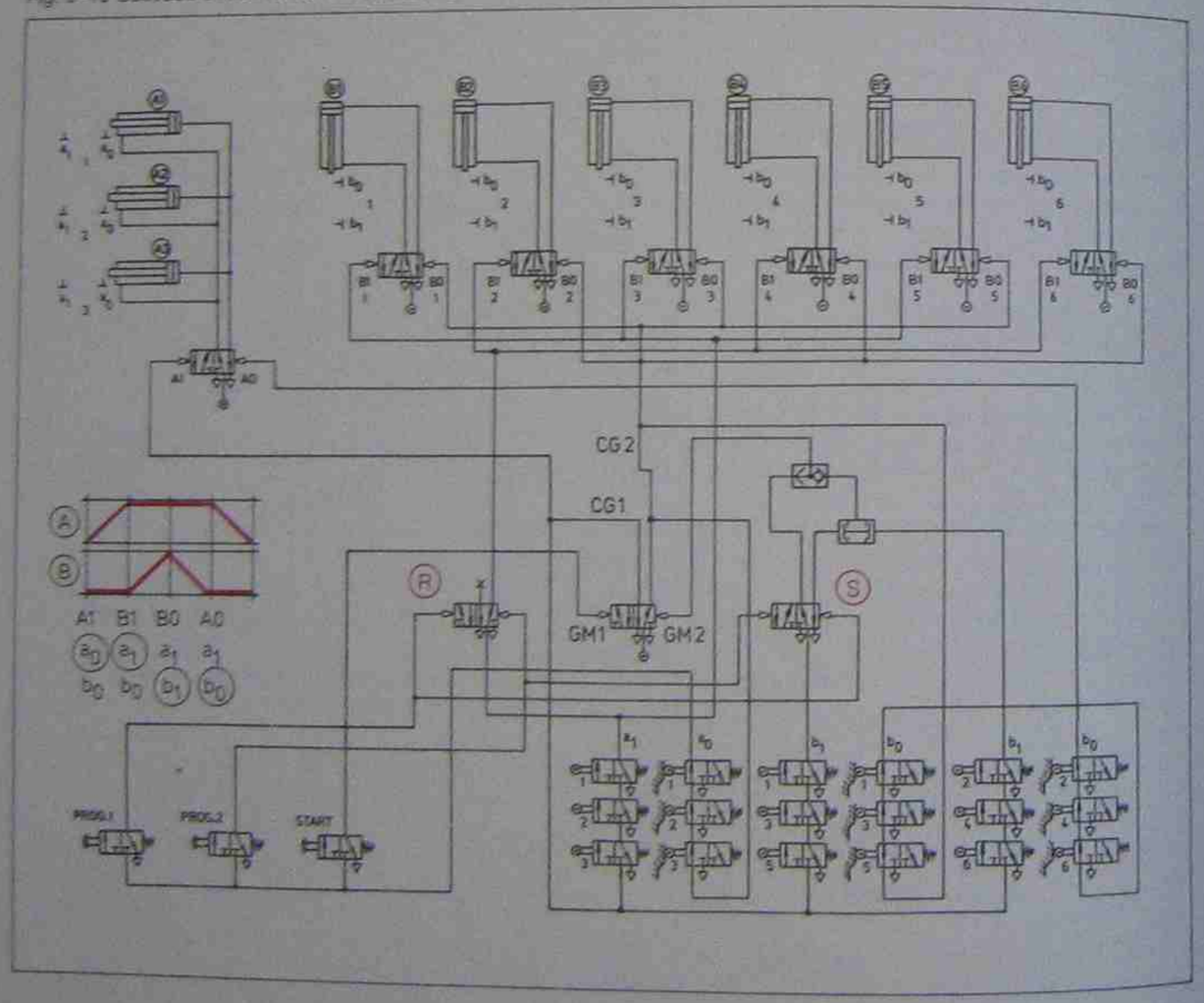
Design Concepts

The use of a restrictor memory Ⓡ, when program 1 is selected, inhibits the B1 signal command from reaching the power memories for the punching actuators B2, B4 and B6 to extend, and thus number 2, 4 and 6 holes are not punched with program 1.

The use of a shunting memory Ⓢ, when program 1 is selected, directs the combined b_1 signals of the actuators B1, B3 and B5 to GM2 without being "AND" connected to the other b_1 confirmation signal from the actuators B2, B4 and B6.

When program 2 is selected, the shunting memory directs the combined b_1 signals of the actuators B1, B3 and B5 to the "AND" function valve to be "AND" connected to the combined b_1 signals from the other B actuators, so that *all* six B actuators must be fully extended before they are permitted to retract.

Fig. 9–16 Cascade circuit for control problem 2.



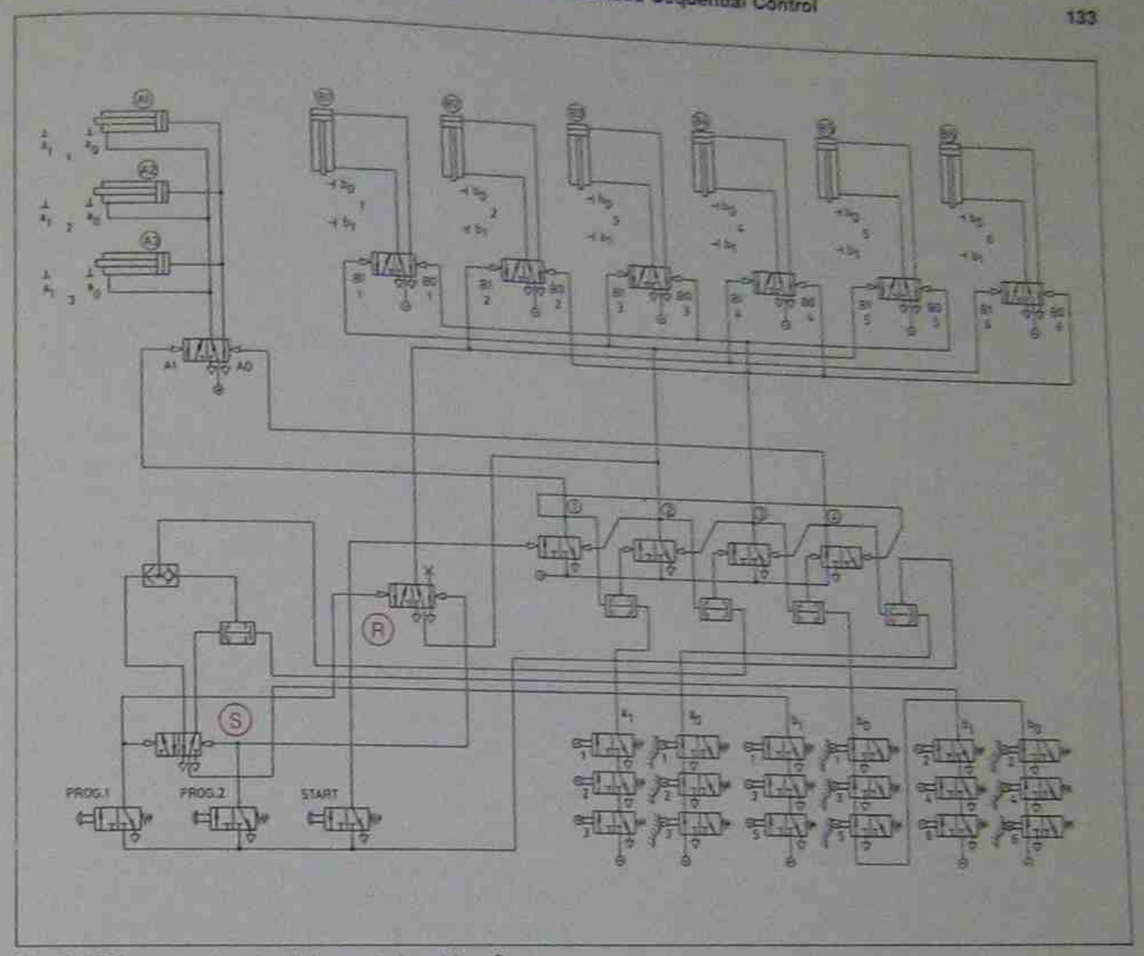


Fig. 9–17 Step-counter circuit for control problem 2.

Review and Comparison of design concepts for control problem 2

Both design concepts employ a shunting memory to direct the essential confirmation signals $b_{1\,(ODD)}$ directly to the "OR" function valve. However, if program 2 is selected, these $b_{1\,(ODD)}$ signals are shunted to the "AND" function valve where they must be "AND" connected to the $b_{1\,(EVEN)}$ signals. Thereafter these b_1 signals are also gathered by the "OR" function valve and are also directed to their destination to command the B actuators to retract. The restrictor memory is also used for both design concepts for the same purpose as explained previously.

The step-counter method uses 4 step-counter modules, whereas the cascade method gets by with only one cascade memory to cater for the two cascade groups. Hence, the cascade method is less expensive than the step-counter method for this particular control.

Control problem 3

A circuit is to be designed for the control of a silk-screen printing machine which prints and cuts paper labels from paper reels. The paper transport actuator Ⓒ pulls the paper off the reel and feeds it through the printing machine. The paper is gripped by vacuum suction cups. The venturi vacuum generator Ⓥ produces the vacuum for the suction cups. Actuator Ⓐ moves the ink-spreader and actuator Ⓑ operates the guillotine.

There are two machine cycles within the same control program. That is, two labels are produced during the 12 sequence steps of this program. Actuator Ⓐ (the ink-spreader) makes only one stroke per label (cycle), but a full extension and

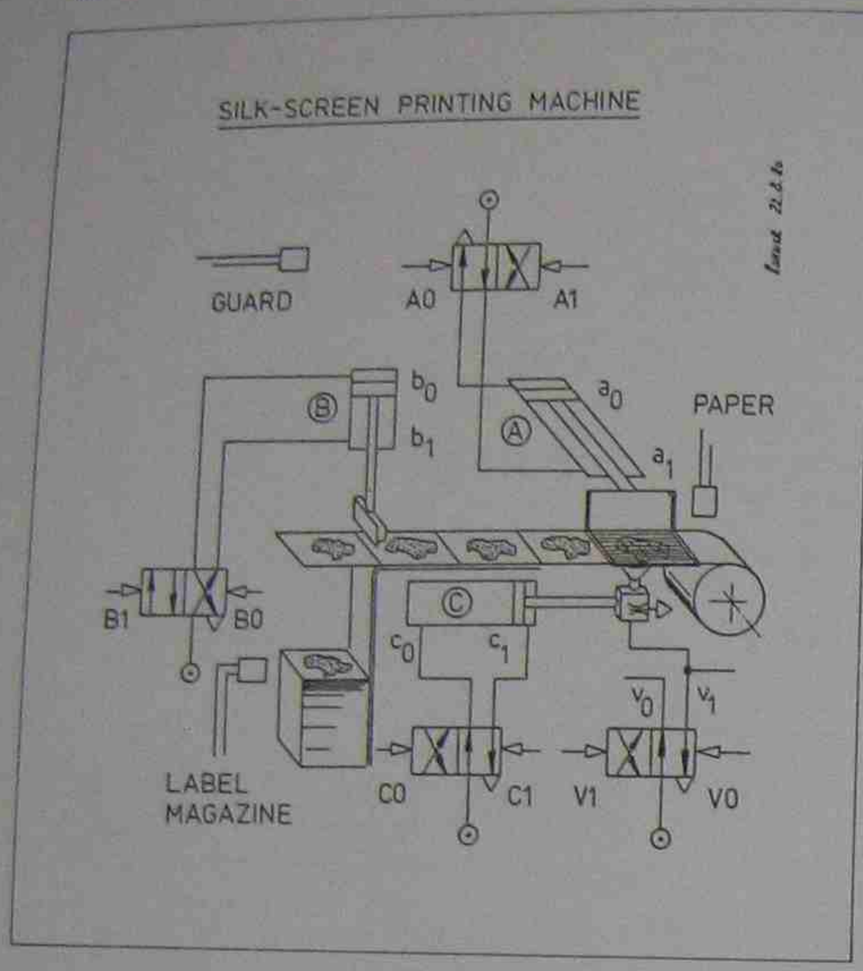


Fig. 9-18 Machine layout for silk-screen printing machine (see also traverse-time diagram Fig. 9-19)

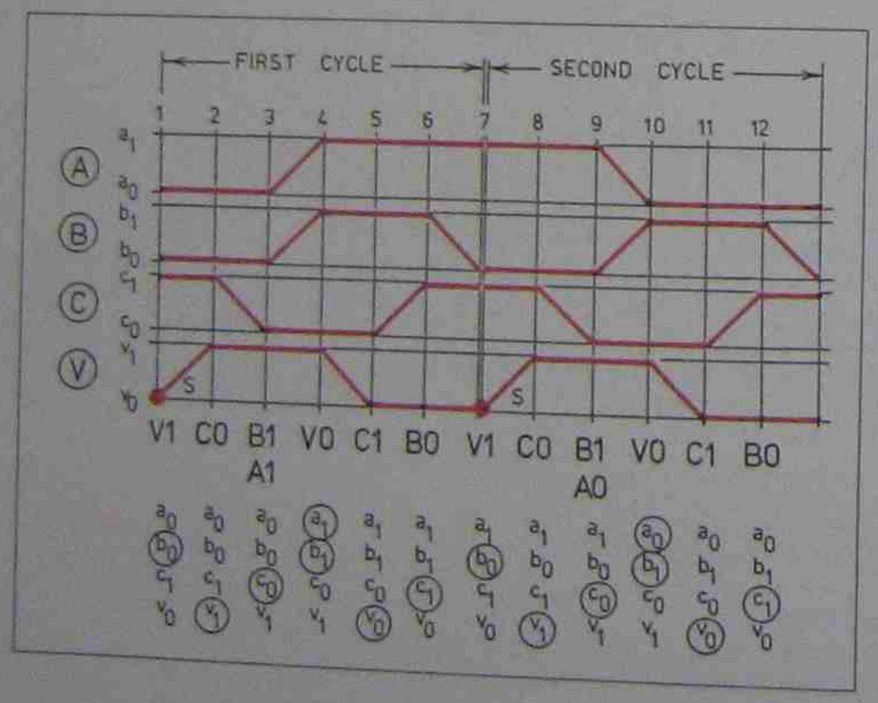


Fig. 9-19 Traverse-time diagram for silk-screen printing machine

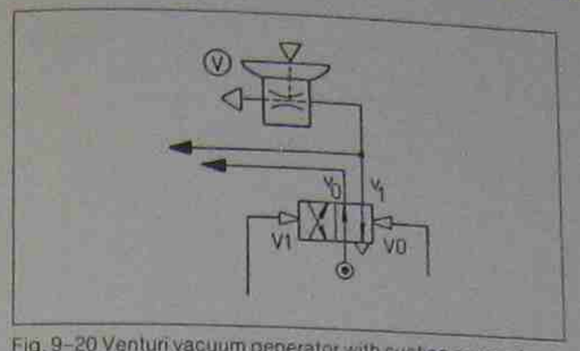


Fig. 9-20 Venturi vacuum generator with suction cup and control valve

retraction movement for two labels (see traverse-time diagram fig. 9-19 and its associated machine layout fig. 9-18). Designation V in the traverse-time diagram represents the vacuum which must be switched "ON" for the retraction of actuator © and again be switched "OFF" prior to its extension. Figure 9-20 shows how confirmation signals can be achieved from the vacuum control memory. Signal v_0 indicates vacuum "OFF" and signal v_1 vacuum "ON". One may use these signals in the same manner as limit valve signals actuated by the pneumatic cylinders.

The sequence control circuit must include a start restriction control circuit to provide selection and start of the following sequencing modes:

- Push-button selection for sequencing through a complete program: consisting of all twelve sequence steps, and producing two labels (see traverse-time diagram fig. 9-19). The program selector valve selects the program mode, and then the common start valve must be actuated to initiate the program (see figs. 9-21 and 9-22).
- Push-button selection for sequencing through one cycle only (one label only). The cycle selector valve selects the single cycle mode (first or second cycle), then the common start valve must be actuated for each cycle initiation.
- Push-button selection for automatic and continuous sequencing through all twelve sequence steps, with automatic initiation of further programs. To start the first program after automatic cycling has been actuated, the common start valve must be simultaneously actuated.
- Upon actuation of the cycle selector push-button or the program selector push-button, the memorised automatic sequencing selection must be cancelled (fig. 9-21).

Design Concepts

The "MARTONAIR" cascade method has be chosen to design this control circuit. Dividing t sequence into cascade groups produces following pattern:

1 2 3 4
V1-C0-B1/A1 V0-C1-B0 V1-C0-B1/A0 V0-C1-

With the "MARTONAIR" cascade method cascade memories must be used and the follow equation may be derived from the traverse-t diagram given in fig. 9-19.

Cascade Memory Set Commands:

$GM1 = CG4 \cdot b_0 \cdot Start$
$GM2 = CG1 \cdot b_1 \cdot a_1$
$GM3 = CG2 \cdot b_0 \cdot Start$
$GM4 = CG3 \cdot b_1 \cdot a_0$

Identical "AND" function*

Identical "AND" functions may be found for th following functions:

$b_0 \cdot Start$
$CG1 \cdot c_0$
$CG3 \cdot c_0$

D.C.V. Pilot Signals:

$A1 = CG1 \cdot c_0$
$A0 = CG3 \cdot c_0$
$B1 = CG1 \cdot c_0 + CG3 \cdot c_0$
$B0 = CG2 \cdot c_1 + CG4 \cdot c_1$
$C1 = CG2 \cdot v_0 + CG4 \cdot v_0$
$C0 = CG1 \cdot v_1 + CG3 \cdot v_1$
$V1 = CG1 + CG3$
$V0 = CG2 + CG4$

Identical "AND" function*

Series functions may be formed for:
$b_1 \rightarrow a_1$; $b_1 \rightarrow a_0$; $b_0 \rightarrow$ Start

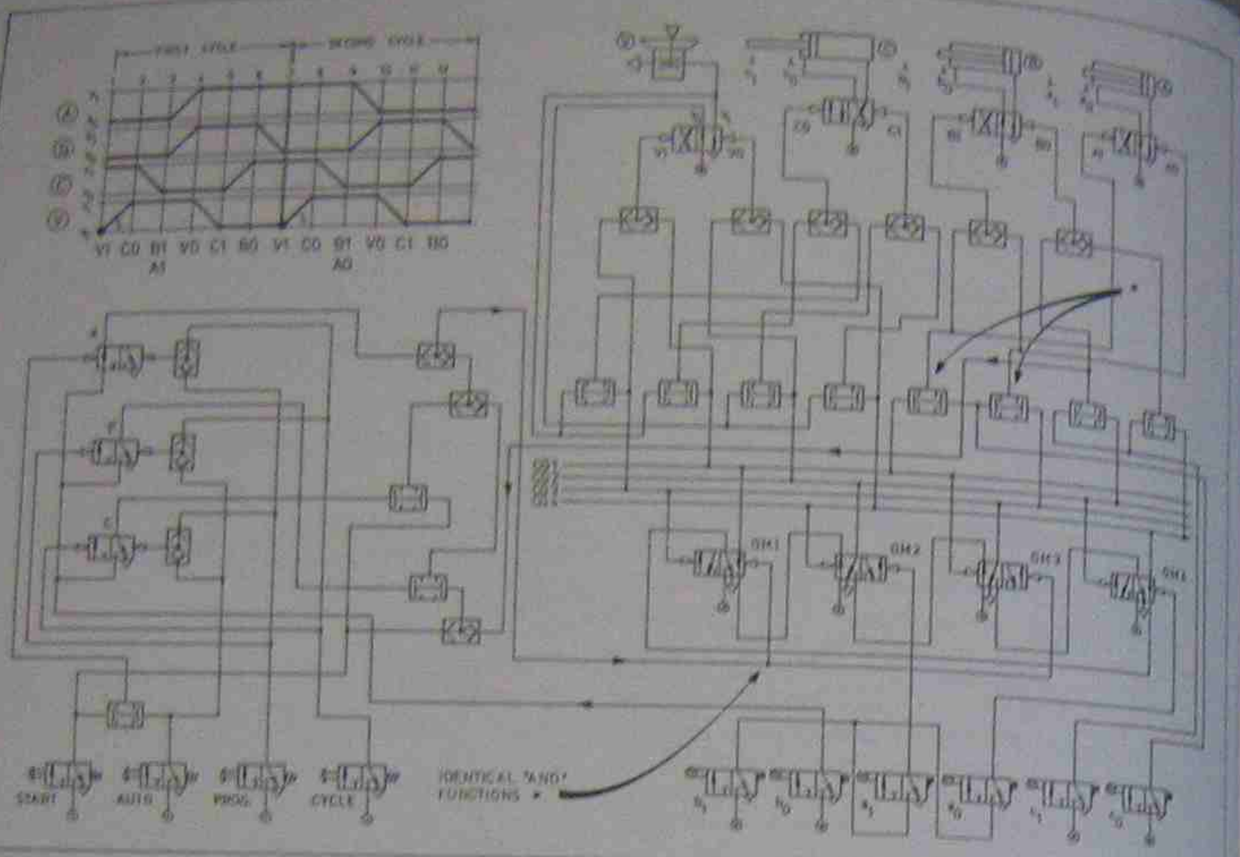


Fig. 9-21 Circuit for control problem 3 designed with cascade method.

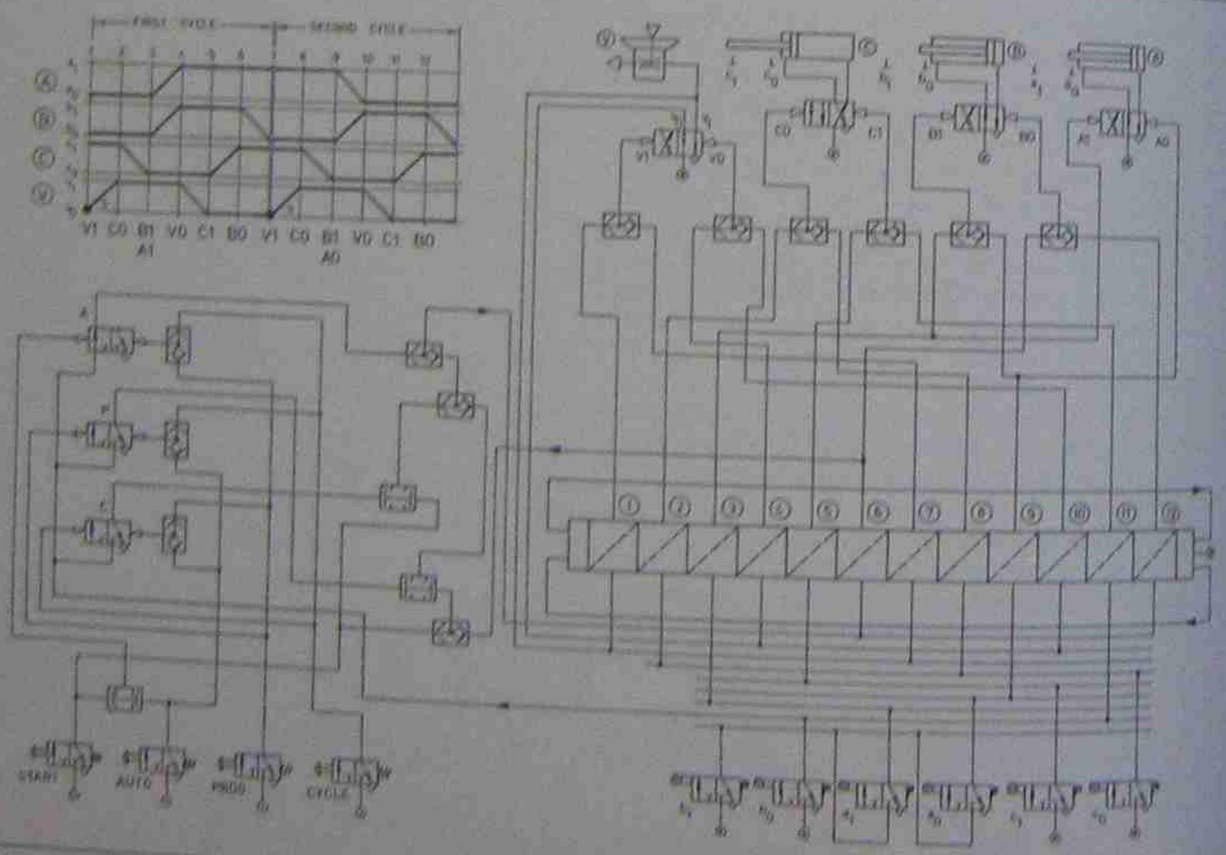


Fig. 9-22 Circuit for control problem 3 designed with step counter method.

10 Combinational Circuit Design

Combinational circuit output signals depend solely on the momentary state of their input signals or input variables. Time-delay and signal memorisation are not taken into consideration in combinational circuits. This fact makes combinational circuits relatively simple to design. The tools used to design them are:

- Boolean algebra (see page 96 and fig. 8-7)
- Truth tables (see page 139 and fig. 10-4)
- Karnaugh-Veitch maps (see page 142 and fig. 10-9)

Each of these design tools is explained and applied separately and in detail, and application exercises are presented. Combinational circuits are best designed using the following eight logic construction steps:

1. Analyse *all* input signal sources (valves) and determine all output signal destinations (signal commands) and allocate appropriate letters to these signals.
2. Construct and draw a truth table with columns for all input signals and a column for the required output signal (S).
3. Analyse *all* input combinations for those which must provide an output signal. All the remaining combinations must inhibit the output signal.
4. Construct and draw a Karnaugh-Veitch map, then plot all logic 1 outputs from the truth table into the fields of the Karnaugh-Veitch map and label them.
5. Loop all labelled entries in the Karnaugh-Veitch map and closely adhere to the looping rules listed on page 143.
6. Extract the minimised switching equations from the loops in the Karnaugh-Veitch map, and combine them (by "OR" connection) into a collective equation.
7. Knowledge and application of Boolean algebra, particularly the Distributive Law, may bring a further minimisation of the extracted equations obtained in logic step 6.
8. Find where possible series function formations (see Chapter 8, figs. 8-13 and 8-15) which may render a further hardware reduction and draw the graphic symbol circuit.

Boolean logic concepts

To understand the peculiarities of logic switching, whether this be applied to pneumatic or electric or electronic control makes no difference, one must understand some basic rules of Boolean algebra.

These rules are now presented in simple and abbreviated form and no attempts have been made to prove their origin or consecutive logic development.

Boolean postulates

$1 = 0$	$\bar{0} = 1$
$0 \cdot 0 = 0$	$0 + 0 = 0$
$0 \cdot 1 = 0$	$0 + 1 = 1$
$1 \cdot 0 = 0$	$1 + 0 = 1$
$1 \cdot 1 = 1$	$0 + 0 = 0$

Boolean theorems (for one input signal)

$A \cdot 0 = 0$	$A + 1 = 1$
$A \cdot 1 = A$	$A + 0 = A$
$A \cdot A = A$	$A + A = A$
$A \cdot \bar{A} = 0$	$A + \bar{A} = 1$

Theorems for more than one input signal

Commutative laws

$A \cdot B = B \cdot A$ $\qquad$ $A + B = B + A$

Associative laws

$(A \cdot B) \cdot C = A \cdot (B \cdot C) = A \cdot B \cdot C$

$(A + B) + C = A + (B + C) = A + B + C$

Distributive law

$(A \cdot B) + (C \cdot B) = B \cdot (A + C)$ or $(A + C) \cdot B$

$(A + B) \cdot (C + B) = B + (A \cdot C)$ or $(A \cdot C) + B$

Absorption law

$A + A \cdot B = A$

De Morgan's theorem

$\overline{A \cdot B \cdot C} = \bar{A} + \bar{B} + \bar{C}$ $\qquad$ $\overline{A + B + C} = \bar{A} \cdot \bar{B} \cdot \bar{C}$

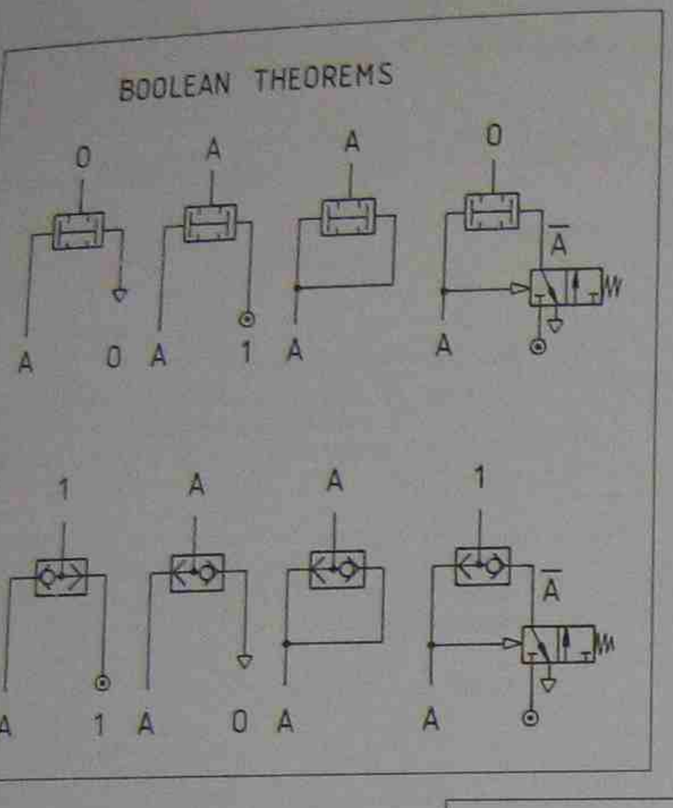


Fig. 10-1 Boolean theorems as applied to Boolean algebra for logic combinational and sequential circuit design.

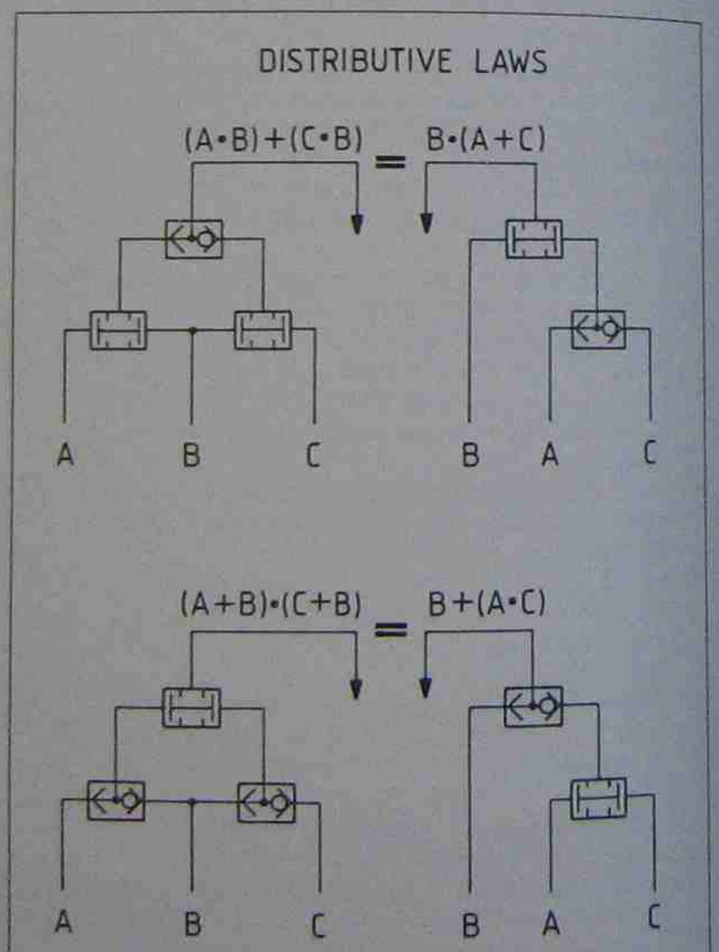


Fig. 10-2 The distributive law is one of the most important laws in Boolean algebra since it lends itself ideally to minimise pneumatic "AND" and "OR" valves (see also Chapters 8 and 9). This law is an absolute "MUST" for the pneumatic circuit designer and control engineer.

To illustrate some of these laws and theorems it may be best to apply them to simple pneumatic valves and subcircuits, such as figs. 10-1, 10-2 and 10-3.

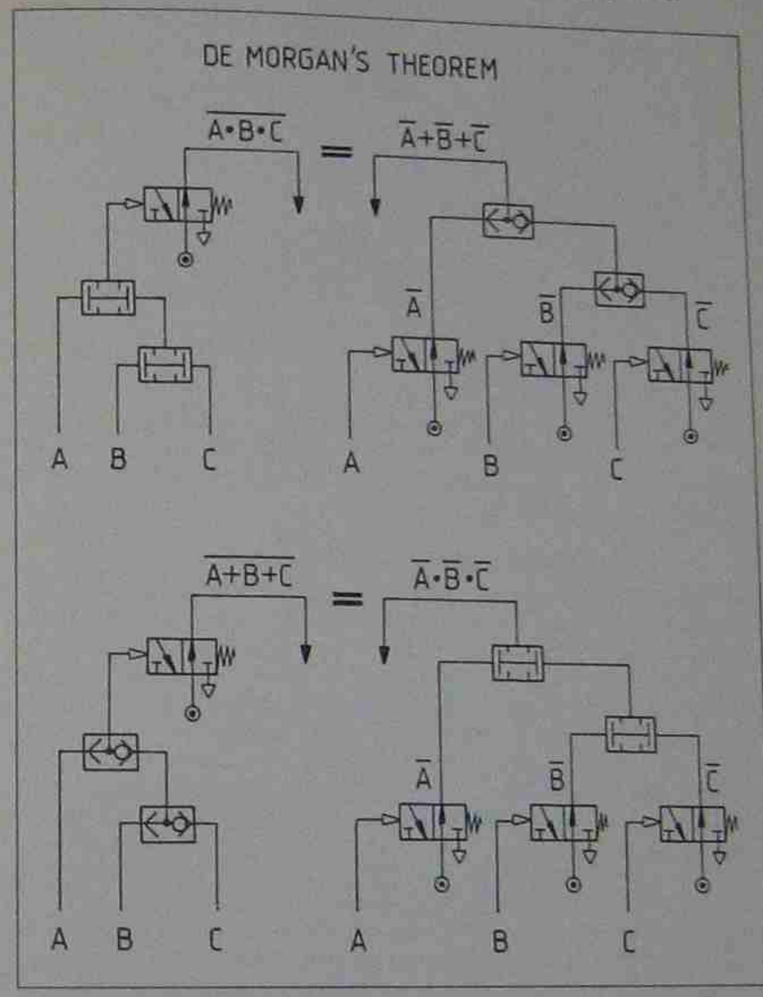


Fig. 10-3 De Morgan's theorem is also an ideal tool for circuit simplification. It may also be used on some programmable logic electronic controllers with limited "AND" input functions but multiple "OR" input instead (use inversion function and De Morgan's theorem).

Truth table construction and usage

To achieve a better understanding of the problem of combinational input relationships, links of the input signals should be tabulated. The table used for such tabulation or grouping is called a value table or, more commonly, a truth table (fig. 10-4).

A truth table consists of columns (vertical) and rows (horizontal). Columns hold input signals which may be labelled x_1, x_2, x_3 and the extreme right hand column shows the resulting output signal for these "AND" connections. Input signals may of course also be labelled with whatever letter is best suited for these signals. Therefore, if a logic function (which is in fact a small combinational circuit, see figs. 10-8 and 10-14) has two input signals, then its truth table will show three columns and four rows. The number of rows is determined by the number of "binary" combination possibilities achieved for its input signals. This number is given the letter K and is calculated with the following formula:

$K = 2^n$ (n = input signals, K = rows)

Each input signal in the "binary" system can only have two distinct values. It can either be in the "ON" state (which means a signal is produced by the valve or switch), or in the "OFF" state (which means that no signal is produced by the valve or switch—see figs. 10-5 to 10-6).

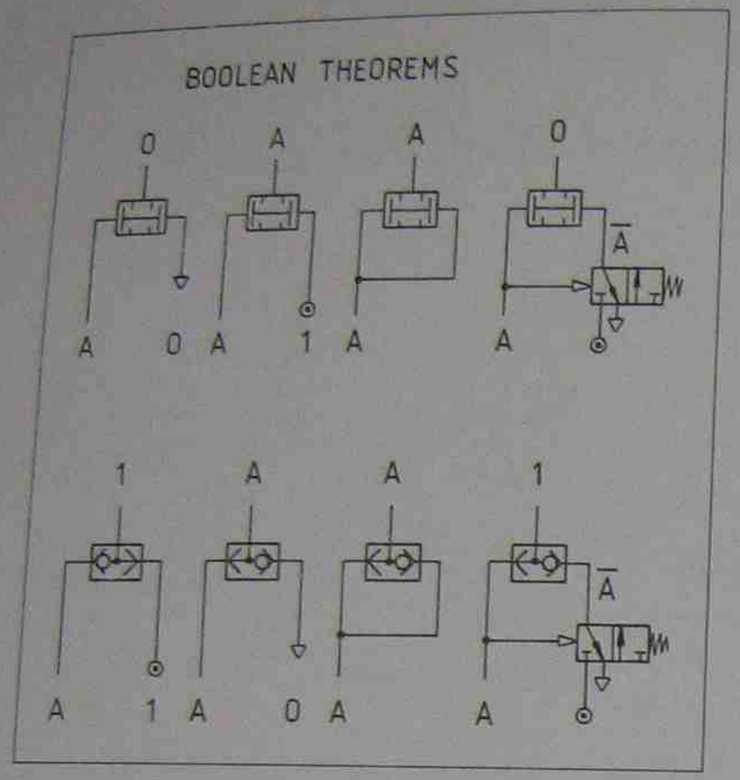
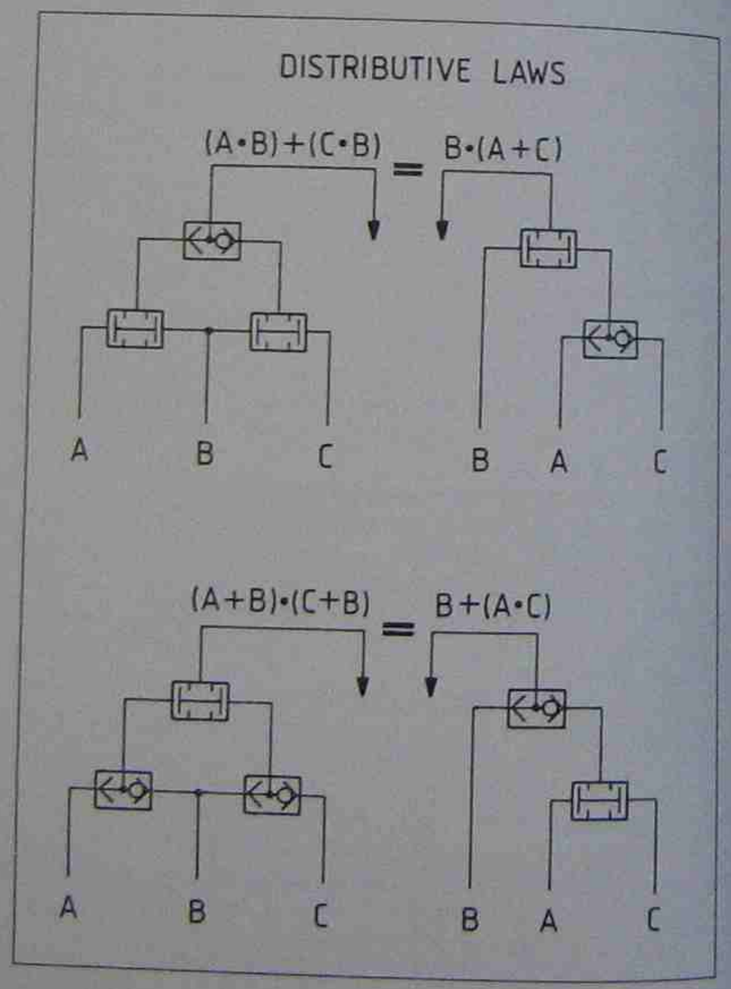


Fig. 10-1 Boolean theorems as applied to Boolean algebra for logic combinational and sequential circuit design.



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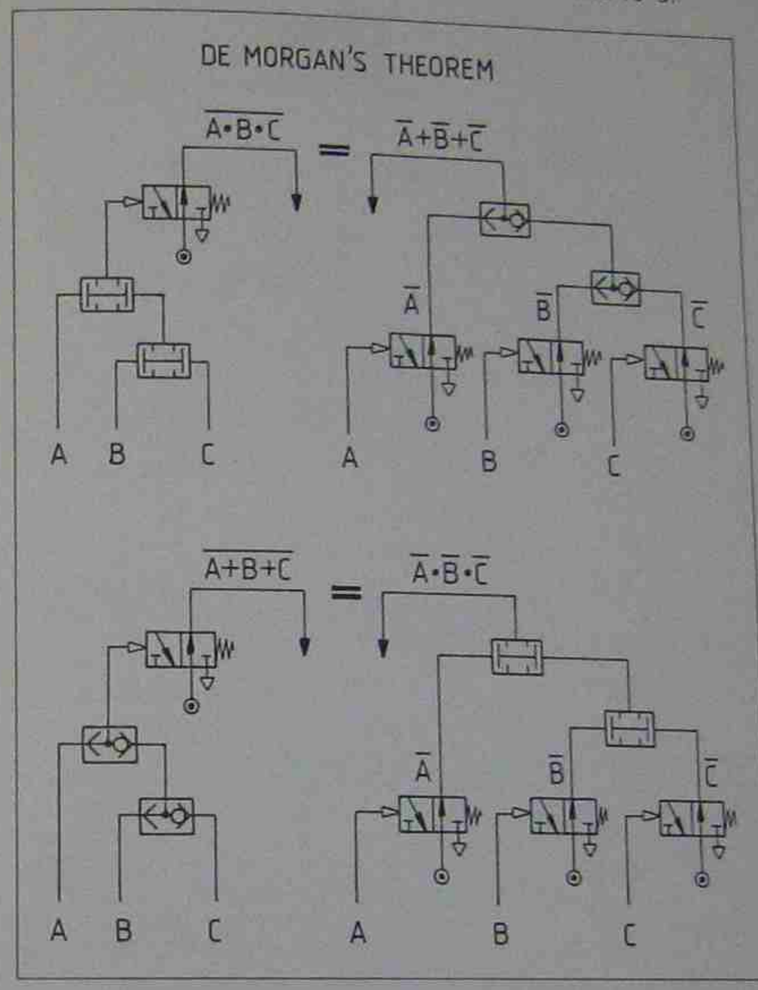

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TRUTH TABLE

a	b	c	A1
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Fig. 10-4 Truth table for three input signals.

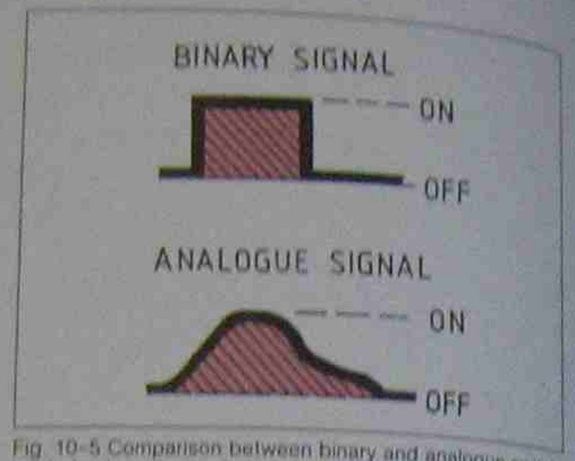

Fig. 10-5 Comparison between binary and analogue switching behaviour.

Pneumatic and electric switchgear have predominantly binary switching characteristics. A valve is said to have "analogue" switching characteristics when it can be selected into any position ranging from fully closed to fully open and/or any in between position. An adjustable orifice or flow control valve is a typical analogue valve and so is a water tap which is slowly opened or closed. A push-button or roller valve, however, which is rapidly actuated into its "ON" or "OFF" position, is effectively a binary valve.

Valves which are used for extremely fast acting combinational logic functions must possess positive overlap for their crossover movement (see Chapter 2 and fig. 10-6). Should for example a valve with negative overlap be used in an inhibition function then the input signal A could still reach the output (S) despite the presence of the inhibition signal B (see fig. 10-8).

Dual coding of truth tables

To bring order and method into the truth table we list all input signals with the binary "DUAL" code. The dual code is also used for tabulation of decimal indications in binary counting systems (see fig. 10-7). Output signals (values) in the far right column of the truth table may be called true (logic 1) or false (logic 0), or optional, as shown in fig. 10-22. Sometimes the degree of trueness is grouped into true 1, true 2, etc., as shown in fig. 10-30. Truth tables can be constructed for any combination of letters, numbers or symbols that pertain to a given control problem.

Only designers familiar with the peculiarities of a particular control problem should fill in the output column of a truth table, since for every row the

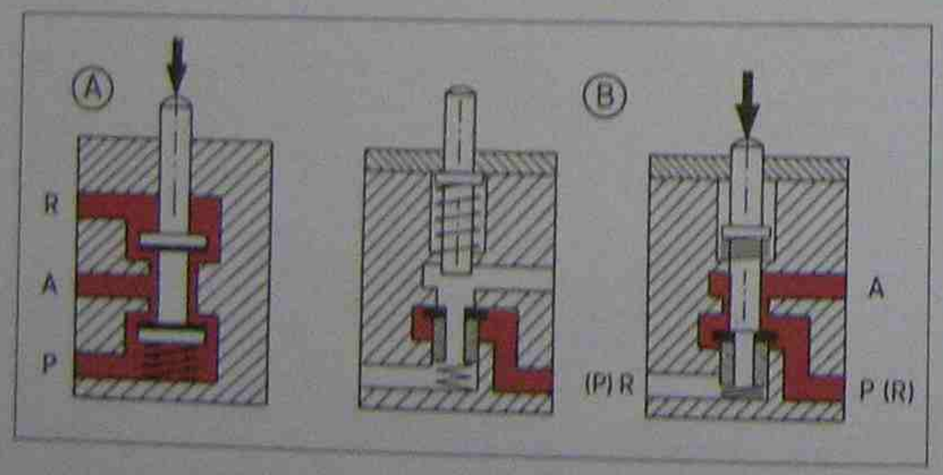

Fig. 10-6A Is a valve with negative overlap. Fig. 10-6B Shows a spool-poppet valve with positive overlap where A – R closes before P – A opens.

0	0	0	0															
0	0	0	1															
0	0	1	0															
0	0	1	1															
0	1	0	0															
0	1	0	1															
0	1	1	0															
0	1	1	1															
1	0	0	0															
1	0	0	1															
1	0	1	0															
1	0	1	1															
1	1	0	0															
1	1	0	1															
1	1	1	0															
1	1	1	1															
2^3 8	2^2 4	2^1 2	2^0 1															

BINARY EXPRESSION FOR VALUE 13

8 • 4 • 0 • 1 = 13

Fig. 10-7 "DUAL" code applied to a truth table with four input signals.

Fig. 10-8 Logic functions matched with their truth table, logic symbol, pneumatic symbol and Boolean expression.

YES	A | S 0 | 0 1 | 1	A = S	A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
NOT	A | S 0 | 1 1 | 0	A = S	$\overline{A}$ = S	A = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
AND	A | B | S 0 | 0 | 0 0 | 1 | 0 1 | 0 | 0 1 | 1 | 1	A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
OR	A | B | S 0 | 0 | 0 0 | 1 | 1 1 | 0 | 1 1 | 1 | 1	A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
NAND	A | B | S 0 | 0 | 1 0 | 1 | 1 1 | 0 | 1 1 | 1 | 0	A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
NOR	A | B | S 0 | 0 | 1 0 | 1 | 0 1 | 0 | 0 1 | 1 | 0	A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
INHIBITION	A | B | S 0 | 0 | 0 0 | 1 | 0 1 | 0 | 1 1 | 1 | 0	A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1
MEMORY		A = S	$\overline{A}$ = S	A • B = S	A + B = S	$\overline{A \cdot B}$ = S	$\overline{A + B}$ = S	A • $\overline{B}$ = S	A = S_0 B = S_1

question must be asked: "Must this combination produce an output signal, and would such an output signal make the machine work correctly and also be safe for the person operating the machine?" Control problem 2 demonstrates this (see figs. 10–16 to 10–19).

Truth tables for basic logic functions

Figure 10–8 illustrates the use of truth tables for all basic logic functions. This figure shows the association of logic functions with their respective truth tables, logic symbols, pneumatic symbols and Boolean algebra switching expressions.

For example, the basic logic "AND" function (see truth table, fig. 10–8) shows the input signals A and B in the two left hand columns. These two input signals render, according to the previously given formula, four distinct combinations ($K = 2^2 = 4$). Therefore, the truth table must show four rows. The output column now indicates an output signal (with the binary value 1) only for the input combination $1 \cdot 1 = 1$, which means that the "AND" function will only render an output signal S if both the input signals A and B show the binary value 1. Mixtures of 1 and 0 values, or both input signals 0, render no output and therefore are given a logic 0 in the output column (see truth tables in figs. 10–4 and 10–8).

Karnaugh-Veitch map

The Karnaugh-Veitch map is by far the fastest and simplest tool to minimise Boolean switching equations. Actually, the Karnaugh-Veitch map is but another graphical form of the truth table, as well as a graphical representation of a Boolean equation. Each field in the Karnaugh-Veitch map represents a row in the truth table and thus is also equivalent to a binary combination ("AND" combination or "AND" function). Furthermore, for each row found in the truth table, the Karnaugh-Veitch map will also show a field, and therefore the number of fields may again be determined by the formula:

$K = 2^n$ (n = input signals, K = fields)

Since the Karnaugh-Veitch diagram is used to minimise switching equations, it has been decided to designate its fields with the "GRAY" code. When moving from one field to the next, the "GRAY" coded fields change only one of their compounded designations (from logic 1 to logic 0 or the reverse). For example the compounded designation for the bottom right-hand field in fig. 10–9 reads:

$a \cdot \bar{b} \cdot c$; which would be equivalent to a = logic 1, and b = logic 0, and c = logic 1.

This unique property of the Gray code enables the user, when minimising with the Karnaugh-Veitch map, to eliminate unnecessary "AND" functions with ease.

The Gray code is sometimes also called "MIRROR CODE". The mirror lines can be regarded as adjacent lines, indicating that the signals divided by them are adjacent (mirror 2 divides signal b but not signal a).

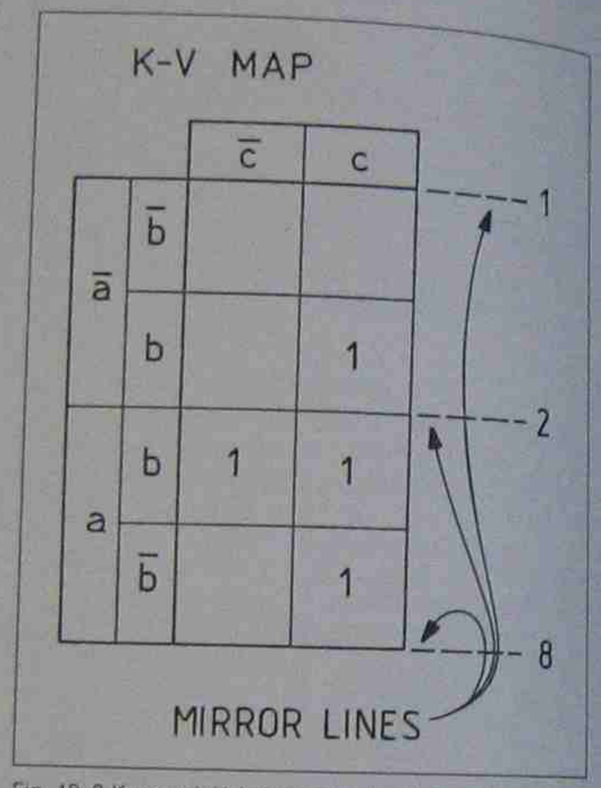

Fig. 10–9 Karnaugh-Veitch map for the truth table shown in Fig. 10–4. The logic 1 output signals from the truth table have been transferred as "ENTRIES" into the map.

This adjacency rule makes the Karnaugh-Veitch map, when rolled together so that mirror line 1 touches mirror line 3, three dimensional (fig. 10–10). Larger Karnaugh-Veitch maps with more than one signal listed on top of the map can also be rolled together in the horizontal direction so that its vertical mirrors 1 and 3 can be joined (figs. 10–9 and 10–10).

Although the map may be regarded as three-dimensional, it must always be drawn as a flat diagram or map with only two dimensions. This assists the process of looping (equation minimisation) and renders the Karnaugh-Veitch map an ideal and highly esteemed design tool for the system design engineer.

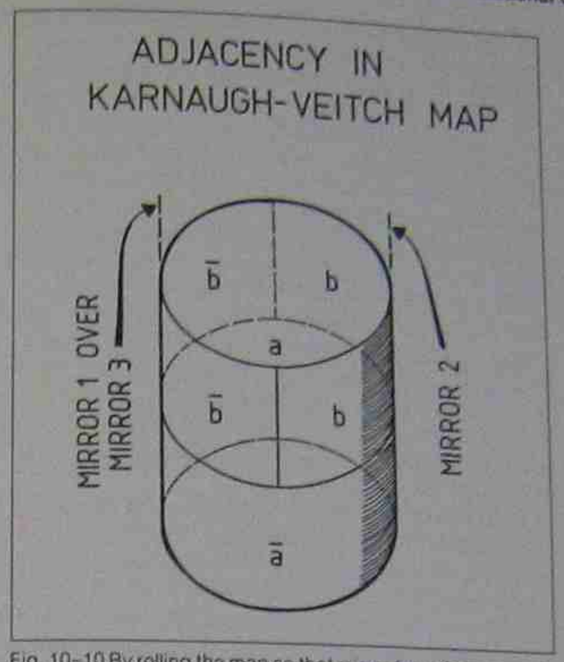

Fig. 10–10 By rolling the map so that mirror 1 overlaps mirror 3, input signal 5 becomes also adjacent (see also fig. 10–9).

Rules for looping the Karnaugh-Veitch map

Once all these "AND" combinations rendering a logic 1 output signal in the truth table have been transferred (plotted) into the Karnaugh-Veitch map, the looping process can be started. Seven basic looping rules however must be carefully followed to ensure a complete and correct minimisation of the plotted equation. These fundamental rules are:

1. Loops should encompass as many plotted entries as possible to produce maximum minimisation of the final equation (less "AND" functions and "OR" functions). The map in fig. 10–9 shows these entries.
2. Fields not containing a plotted entry must not be included into the loops, since these fields show clearly that their combination will not give an output signal (see truth table fig. 10–4 and compare with fig. 10–11). (Exceptions to this rule are the "don't care" combinations explained in control problems 3, 4 and 5.)
3. The looped entries in a single loop must always be a power of two (for example 1, 2, 4, 8, 16 etc. entries), thus a loop with six entries would be wrong.
4. Entries which are already looped may be looped again to form other loops (fig. 10–13). The number of times an entry may be used for looping is unlimited.
5. Loops which extend beyond a mirror line must always be symmetrical about this mirror line (for mirror lines and loop symmetry see fig. 10–13).
6. Part-loops which extend beyond an edge of the map (edge mirror line) join the part loop on the opposite end of the map and form one loop (figs. 10–17 and 10–31).
7. Part or full loops, which precisely and fully overlap when the map is folded about one or more of its mirror lines, may be regarded as one single loop. A typical example for this rule is presented in fig. 10–31 in the Karnaugh-Veitch maps on the left (1–6).

Extraction of minimised equations after looping

Input signals which are represented with both binary values (logic 1 opposed by logic 0) in the same loop cancel each other out and thus disappear from the name of this loop. Examples: the horizontal loop in the Karnaugh-Veitch map of fig. 10–11 encompasses two fields and therefore the unminimised equation for this loop reads:

$\bigcirc = a \cdot b \cdot \bar{c} + a \cdot b \cdot c$

With the signal cancellation principle applied, one can without difficulty see that signal c in this loop changes its binary logic value from c to $\bar{c}$ (logic 1 to logic 0), and thus is represented with both binary states in the same loop! Therefore, the signal c is cancelled and the remaining equation for this loop reads:

$\bigcirc = a \cdot b$

Individual loops are now linked with "OR" functions and are then grouped into the collective equation. Thus each individual loop represents only a part of the collective equation (this part is an "AND" expression), and in the final circuit these loops must be "OR" connected with "OR" function valves to form the collective combinational circuit (fig. 10–14).

To let the reader make personal observations and gain confidence and practice five typical control problems for combinational circuits or sub-circuits are presented and solved. Some of these control problems are exclusively combinational, others which also include memories and timers are

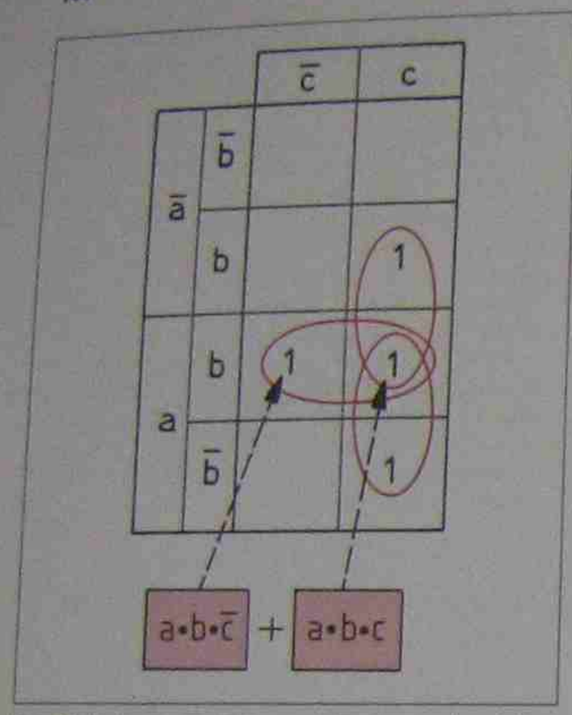

Fig. 10-11 Loops are being used to minimise the plotted entries. Individual loops must be "OR" connected to form the collective equation.

mixed controls which means they become an integral part of a sequential circuit.

Control problem 1

A sorting machine attached to a packaging machine requires an automatic start-stop control.

It was found that under part-load conditions the sorting machine runs very uneconomically. "START" must therefore only occur, when at least two of the three feeding conveyors are running, and automatic "STOP" must always be signalled when less than two conveyors are running. This implies that the "START" command must then automatically disappear.

- First logic step: The signal designations which signal the running of the three conveyors are: conveyor one = a, conveyor two = b, conveyor three = c. The signal which must start the sorting machine is designated A1.
- Second logic step: The truth table, according to the construction rules given before, will show eight rows, three input signal columns and one output signal column ($2^3 = 8$ rows, for truth table see fig. 10-12).
- Third logic step: Row 1, according to the given logic switching specifications, must not start the machine since none of the three conveyors are running. For rows 2, 3 and 5 where only one conveyor is running, the output signal column must also be filled with a zero (logic 0). In rows 4, 6 and 7 two conveyors are running and in row 8 all three conveyors are in operation. Hence, the output columns for the rows 4, 6, 7 and 8 must be given a logic 1 which renders an A1 signal for the sorting machine to start.
- Fourth logic step: The bottom right hand field in the Karnaugh-Veitch map previously prepared, carries the name of its coordinate signals and therefore is called field $a \cdot \bar{b} \cdot c$. This field represents row 6 of the truth table and must therefore be plotted with a logic 1. In that sense, only

a	b	c	A1
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Fig. 10-12 *Left:* Truth table for control problem 1.

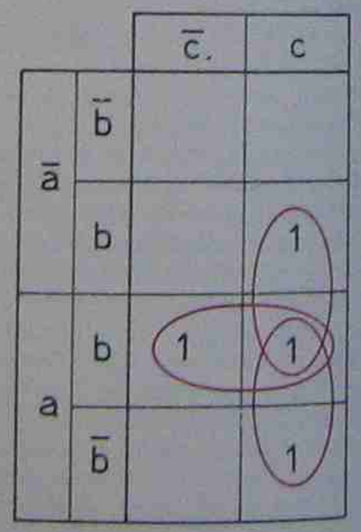

Fig. 10-13 *Right:* Karnaugh-Veitch map for control problem 1.

these combinations with a logic 1 output must be transferred from the truth table into their corresponding Karnaugh-Veitch map fields (fig. 10-13).

- Fifth logic step: The Karnaugh-Veitch map illustrated in fig. 10-13 shows the best possible looping of the four plotted logic 1 entries. The entry in field $a \cdot b \cdot c$ (Row 8 of the truth table) serves all three loops (see looping rule no. 4).
- Sixth logic step: The looping method has now produced a minimized equation which consists of loop 1 "OR" connected to loop 2 "OR" connected to loop 3.

$$A1 = \square + \square + \bigcirc$$

With logic values inserted this equation reads:

$$A1 = b \cdot c + a \cdot c + a \cdot b$$

- Seventh logic step: Knowledge of Boolean algebra will bring a further minimisation and reduction of switching hardware (valves). Fully minimized with the so called distributive law of Boolean algebra, the equation now reads:

$$A1 = a \cdot (b + c) + b \cdot c$$

- Eighth logic step: Input signal a appears only once in the afore presented equation; it can therefore be series connected to the "OR" expression (b + c). This brings a further hardware reduction in the circuit (see fig. 8-13).

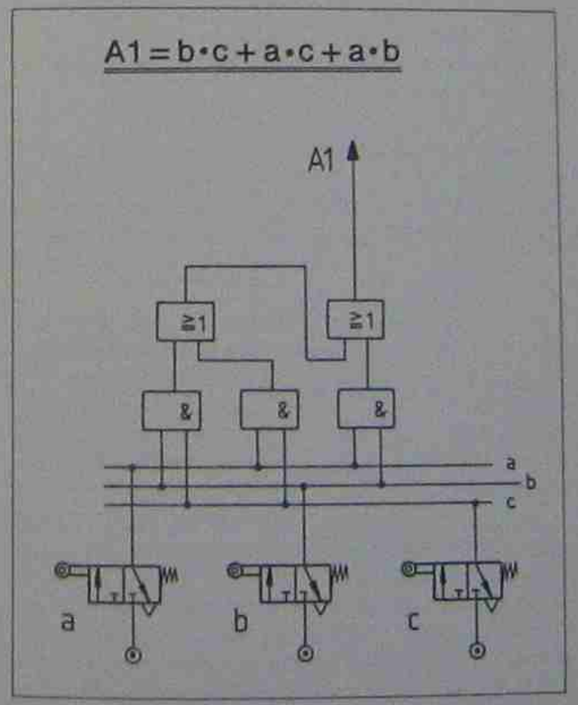

Fig. 10-14 Circuit for equation obtained in sixth logic step without algebraic reduction.

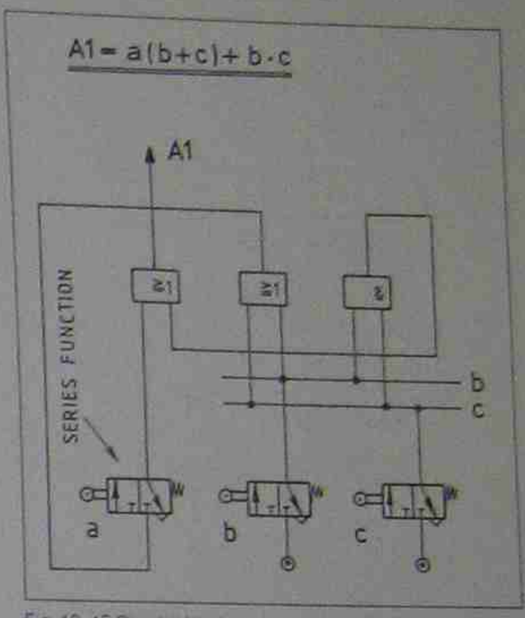

Fig. 10-15 Circuit with algebraic reduction and series connection for signal a.

Control problem 2

A special purpose milling machine (machine tool) must only be permitted to start if certain safety and machine loading conditions are met (fringe conditions).

Two permanent visual indicators must be built into the signal output of the combinational circuit to indicate either "START PERMITTED" or "START NOT PERMITTED". Should the machine fail to start, such visual indicators would then narrow faultfinding procedures to either the combinational circuit or to the sequential circuit or to the external start prerequisites giving the "start permitted" output signal.

- First logic step: The signal designations which render a start signal are: G for the guard on the machine, T for the tool setter and W for the work piece correctly placed into the machining station.
- Second logic step: The truth table according to the three required input signals must show four columns and eight rows (see fig. 10-16).
- Third logic step: The tool setter signal input which is a key operated push-button valve, mus

Fig. 10-16 Truth table

T	G	W	S
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

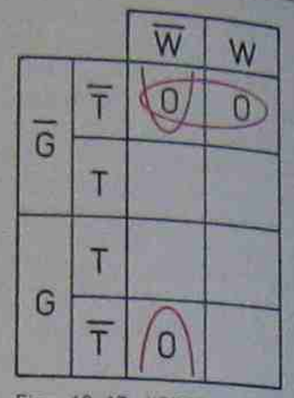

Fig. 10-17 "START NOT PERMITTED" entries.

$S = T + G \cdot W$

$\overline{S} = \overline{G} \cdot \overline{T} + \overline{W} \cdot \overline{T} \rightarrow \overline{T} \cdot (\overline{G} + \overline{W})$

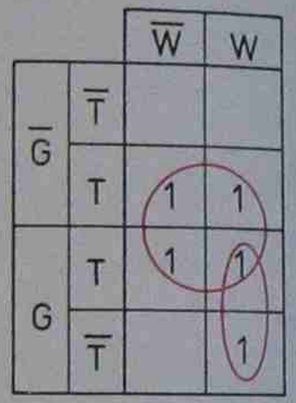

Fig. 10-18 "START PERMITTED" entries.

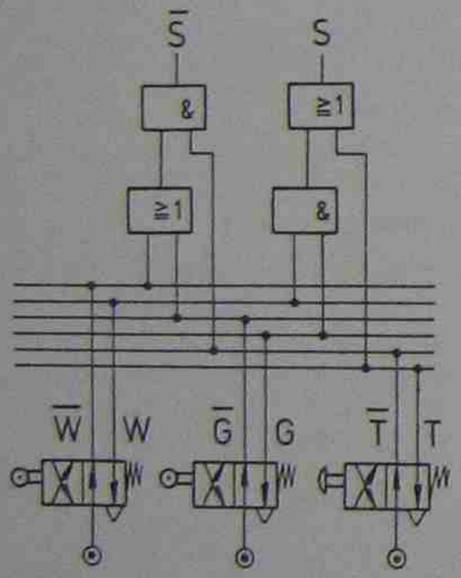

Fig. 10-19 Independent combinational logic circuits built from minimised Boolean equations above.

always start the machine regardless of presence or absence of the other two input signals. With the absence of signal T, a workpiece must be properly located in the machine (signal W to be logic 1) and the guard must be fully closed (signal G to be logic 1) to cause "start".

- Fourth logic step: All logic 1 output signals from the truth table must now be transferred and plotted into the prepared Karnaugh-Veitch map, and these entries are given the logic 1 designation (fig. 10-18).
- Fifth logic step: All logic 1 entries are now being looped to obtain minimised equations for each loop. These equations may then be used for further minimisation if possible (see Karnaugh-Veitch map fig. 10-18).

- Sixth logic step: Extracting the minimised logic equation renders the following result:

  $S = T + (G \cdot W) \longrightarrow$ START PERMITTED

  This equation can be no further minimised with Boolean algebra and thus remains in this state.
- Special logic steps: The specification for this control states that the "START NOT PERMITTED" condition must also be displayed. Looping all logic 0 entries will now render the minimised equation for "START NOT PERMITTED", since all logic 0 entries correspond to the logic 0 output rows in the truth table (fig. 10-17). Extracting the minimised logic equation for the looped logic 0 entries in the Karnaugh-Veitch map renders the following result:

  $\overline{S} = (\overline{G} \cdot \overline{T}) + (\overline{W} \cdot \overline{T}) \longrightarrow$
  START NOT PERMITTED

  Applying Boolean algebra rules to this equation renders the following result:

  $\overline{S} = \overline{T} \cdot (\overline{G} + \overline{W}) \longrightarrow$
  START NOT PERMITTED

  This equation can now be no further minimised with Boolean algebra rules or series function (fig. 10-17).
- This "START NOT PERMITTED" signal is the so called "FALSE OUTPUT FORM" of a truth table or Karnaugh-Veitch map. The false output form may also be obtained through the application of "DE MORGAN'S" theorem which is explained later in this chapter.
- Final logic steps: Each circuit obtained from the equations extracted in figs. 10-17 and 10-18 represents an independent combinational circuit. These two circuits are depicted in fig. 10-19.

Since this control problem requires input signals to be in their binary 1 state as well as in their binary 0 state, one may use valves which render a signal for both of these logic states (a signal for "ON" and a signal for "OFF", see fig. 10-19). If such valves are not available one may obtain the same result using two valves (fig. 10-24). This solution would obviously be much more expensive.

Valves which render a signal for their logic "ON" state as well as their logic "OFF" state are said to be *complementary valves* (see fig. 10-20. Such complementary valves may have four or five flow ports and may be manually, pneumatically, electrically or mechanically actuated.

Fig. 10-20 shows the complete combinational start-stop control circuit as described in the control specification to control problem 2. In this format the circuit is called a "START-STOP MODULE".

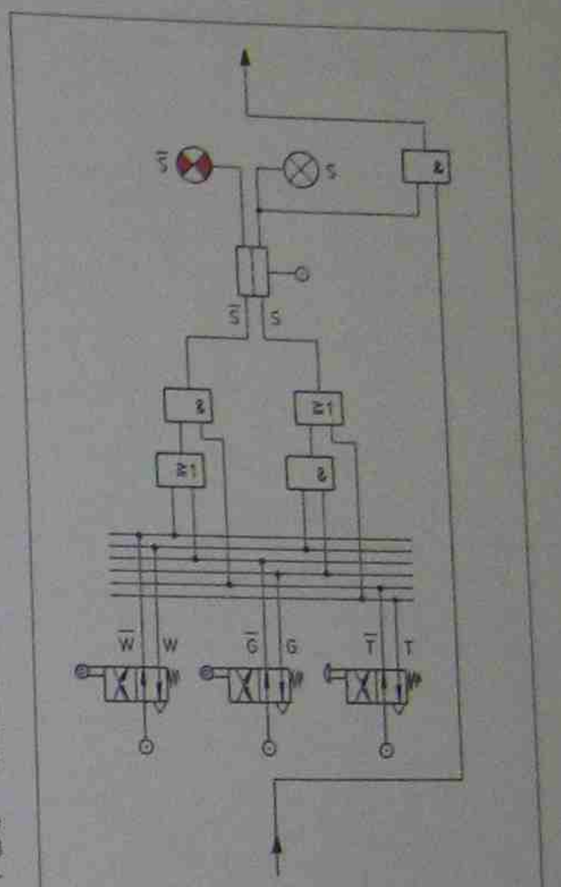

Fig. 10-20 Combinational "START-STOP MODULE" with permanent display (visual indicators) of the "START PERMITTED" and the "START NOT PERMITTED" output signals.

Control problem 3

A stamping press with a pneumatically operated clutch must only operate when safe input combinations exist and *must not start* if any other combination exists. The press and its input signal locations are depicted in fig. 10-21 and the truth table is shown in fig. 10-22.

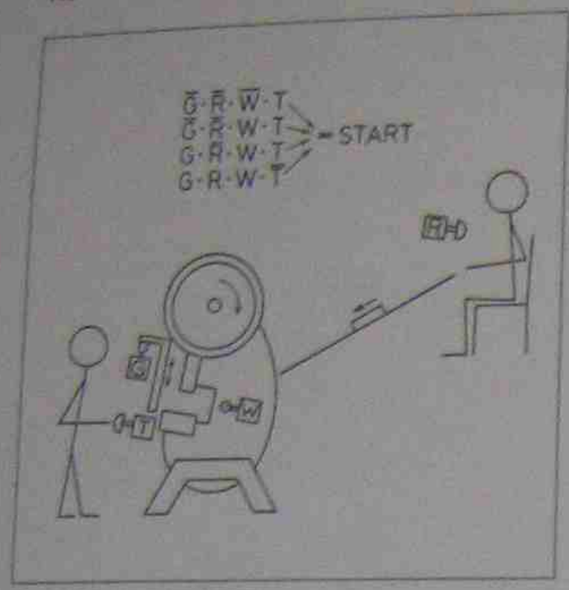

Fig. 10-21 Stamping press

Symbol explanation:

G = Signal from guard when fully closed.
T = Signal from toolsetter or operator valve.
W = Signal from workpiece in the machine.
R = Signal from remote start position.

G	R	W	T	ST.	
0	0	0	0	0	
0	0	0	1	1	→ START
0	0	1	0	0	
0	0	1	1	1	→ START
0	1	0	0	0	
0	1	0	1	0	
0	1	1	0	0	
0	1	1	1	0	
1	0	0	0	0	
1	0	0	1	0	→ OPTIONAL
1	0	1	0	0	
1	0	1	1	1	→ START
1	1	0	0	0	
1	1	0	1	0	→ OPTIONAL
1	1	1	0	1	→ START
1	1	1	1	0	→ OPTIONAL

Fig. 10-22 Truth table for control problem 3

The combinations rendering a logic 1 output in the truth table are as follows:

$$START = \overline{G} \cdot \overline{R} \cdot \overline{W} \cdot T + \overline{G} \cdot \overline{R} \cdot W \cdot T + G \cdot \overline{R} \cdot W \cdot T + G \cdot R \cdot W \cdot \overline{T}$$

The combinations called "OPTIONAL" in the truth table may be regarded as "relatively safe" combinations which could occur but would not be used for the operation of the press (fig. 10-22). Such optional combinations are also called "DON'T CARE" combinations, which means combinations causing no harm. To simplify the problem these combinations are not included in the valid start conditions but their inclusion would result in a much shorter collective equation!

To minimise the combinations with a logic 1 output signal in the truth table, a Karnaugh-Veitch map is constructed (fig. 10-23). This map is shown as a square but it could also be drawn as a single column map with sixteen fields in vertical direction or as a map with two columns and eight fields in vertical direction. The form of the map or its labelling order does not affect the minimisation process and will always render identical results.

For combinational circuit design all the plotting entries must be taken into consideration and this applies also to plotted entries which cannot be looped to other entries. The Karnaugh-Veitch map for control problem 3 (fig. 10-23) shows such a single entry. All individual loops and the single entry being circled are now linked with "OR" functions and grouped into the collective equation which reads:

START = ▯ + ⬭ + ○

$$START = \overline{G} \cdot \overline{R} \cdot T + W \cdot \overline{R} \cdot T + W \cdot G \cdot R \cdot \overline{T}$$

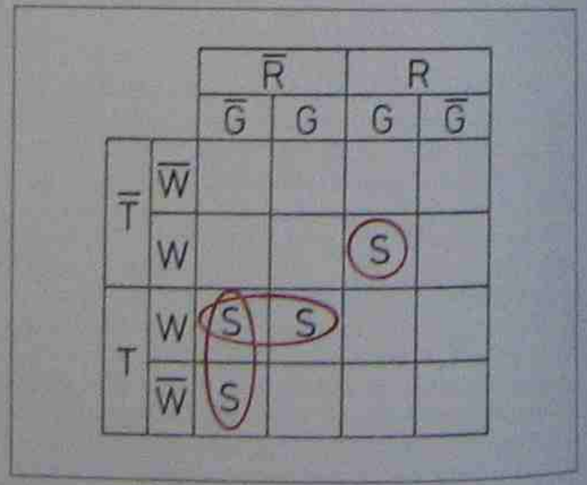

Fig. 10-23 Karnaugh-Veitch map for control problem 3

This collective equation minimised and extracted from the Karnaugh-Veitch map can now be further minimised with Boolean algebra. As a result the final equation now reads:

$$START = \overline{R} \cdot T \cdot (\overline{G} + W) + W \cdot G \cdot R \cdot T$$

This control problem also requires valves rendering complementary signals for the input signals R, T and G. But to illustrate the logic principle of "signal inversion" it has been decided that valves rendering only the "YES" function must be used (see control circuit fig. 10-23 for control problem 3).

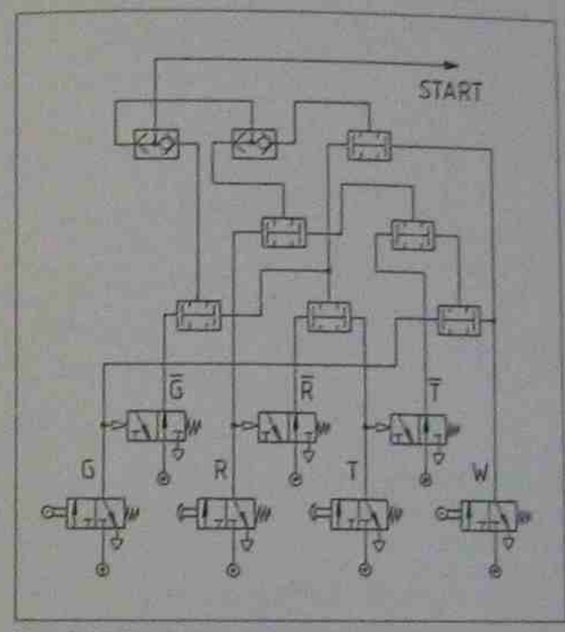

Fig. 10-24 Circuit diagram for control problem 3

Control problem 4

A bottle sorter must be pneumatically powered and controlled. Glass bottles of four different sizes are to be analysed and then according to size pushed on to separate conveyors for filling and packaging. Four pneumatic air barrier sensors are used to detect the size of the passing bottles. Air barrier sensors were described in Chapter 6. The passing bottles must be counted according to size.

A front view of the bottle size detector is given in fig. 10-25 and a plan view of the bottle sorting machine including attached conveyors is given in fig. 10-26.

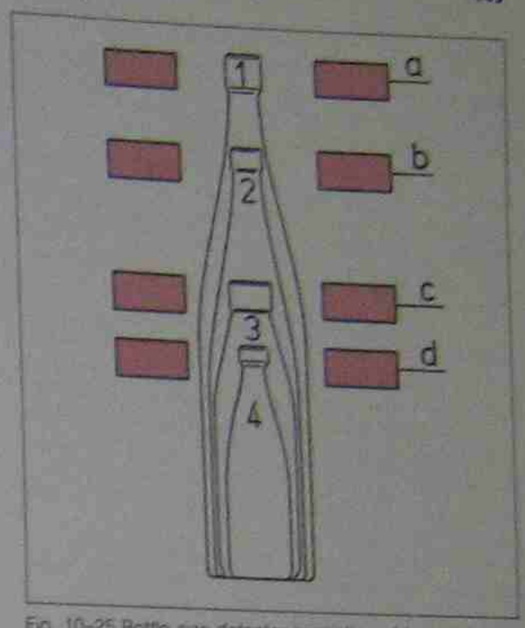

Fig. 10-25 Bottle size detector consisting of four air barrier sensors

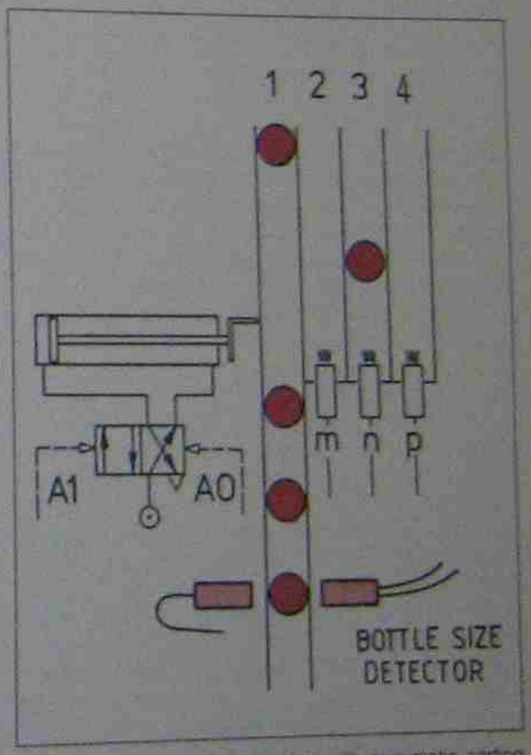

Fig. 10-26 Bottle sorting machine with pneumatic sorting actuator

Design considerations for bottle sorter

It is advisable to construct a Karnaugh-Veitch map and a truth table to assist in the problem analysis and equation minimisation. The uppermost combination of the truth table stands for "NO BOTTLE IN THE DETECTOR". This combination must not render an output signal. The same may be said for the lowermost combination, which stands for bottle size 1. Size 1 bottles continue on the feed conveyor and therefore require no sorting movement (see fig. 10-26).

All combinations with an A1 output are numbered according to their bottle size. All remaining combinations marked with an X may be used for looping, since they represent "DON'T CARE" combinations (fig. 10-27). So the actuator must only extend when a bottle of size 2, size 3 or size 4 is detected, and thus the minimisation equation consists of the three loops shown in the Karnaugh-Veitch map (fig. 10-28).

If bottles of sizes 2, 3 and 4 were only to give a counting pulse for separate counting, and then had to be shifted on to a common conveyor, the entries in the Karnaugh-Veitch map could be looped into a common loop rendering the equation $A1 = \bar{a} \cdot d$. The collective final equation extracted from the three loops in the Karnaugh-Veitch map reads:

$$A1 = b \cdot \bar{a} + \bar{b} \cdot c + d \cdot \bar{c}$$

d	c	b	a	A1	
0	0	0	0	0	→ NO A1
0	0	0	1	X	
0	0	1	0	X	
0	0	1	1	X	
0	1	0	0	X	
0	1	0	1	X	
0	1	1	0	X	
0	1	1	1	X	
1	0	0	0	4	→ A1
1	0	0	1	X	
1	0	1	0	X	
1	0	1	1	X	
1	1	0	0	3	→ A1
1	1	0	1	X	
1	1	1	0	2	→ A1
1	1	1	1	1	→ NO A1

Fig. 10-27 Truth table for bottle sorter.

The bottles pass very rapidly through the size detector gate and therefore signal combinations obtained from these detectors disappear just as rapidly. It is therefore imperative that such combinations are stored in a memory valve to make them available for actuator extension limitation.

Such extension limitation is essential for the correct sorting of the various bottle sizes. Bottles of size 4 may be moved over the full actuator extension stroke but bottles of size 3 must only be pushed to limit sensor n and bottles of size 2 only to limit sensor m. Hence, the retraction signal for bottle size 2 consists of the memorised (stored) bottle size combination $\bar{a} \cdot b$ and the limit sensor signal m. The retraction signal for bottle size 3 consists of the bottle size combination $\bar{b} \cdot c$ and the limit sensor signal n.

The memory valves are reset as soon as the power valve (D.C.V.) causes actuator retraction and since the reset signal is a continuous signal which would cause memory blockage an impulse valve is used to transform it into a momentary signal (pulse). For circuit construction and Karnaugh-Veitch map see fig. 10-28.

Control problem 5

A packaging machine for washing powder packets is to be automated. Five filling machines, filling the packets with washing powder, feed onto a common conveyor. This conveyor then transports the packets to the packaging machine where they are wrapped into parcels of 4 kg. Four out of the five filling machines process washing powder packets of 1 kg. Machine A, however, produces 2 kg packets and feeds these always into line A of the conveyor. The other four filling machines (B, C, D and E) feed also into their allocated lines (fig. 10-29). All five filling machines are synchronised and push their washing powder packets simultaneously onto the conveyor, but not all filling machines may operate at any one time.

A weight detector station controlled by a combinational logic signal evaluation system evaluates the weight units of the passing washing powder packets and permits only clusters of a total weight of four kilograms to move on into the wrapping machine.

Powder packet clusters with less or more than four kilograms are ejected into separate chutes

PROBLEM ANALYSIS

$a \cdot b \cdot c \cdot d = 1$
$\bar{a} \cdot b \cdot c \cdot d = 2 \rightarrow A1$
$\bar{a} \cdot \bar{b} \cdot c \cdot d = 3 \rightarrow A1$
$\bar{a} \cdot \bar{b} \cdot \bar{c} \cdot d = 4 \rightarrow A1$
$\bar{a} \cdot \bar{b} \cdot \bar{c} \cdot \bar{d} = 0$

$A1 = b \cdot \bar{a} + \bar{b} \cdot c + d \cdot \bar{c}$

		$\bar{d}$		d	
		$\bar{c}$	c	c	$\bar{c}$
$\bar{b}$	$\bar{a}$	0		3	4
	a				
b	a			0	
	$\bar{a}$			2	

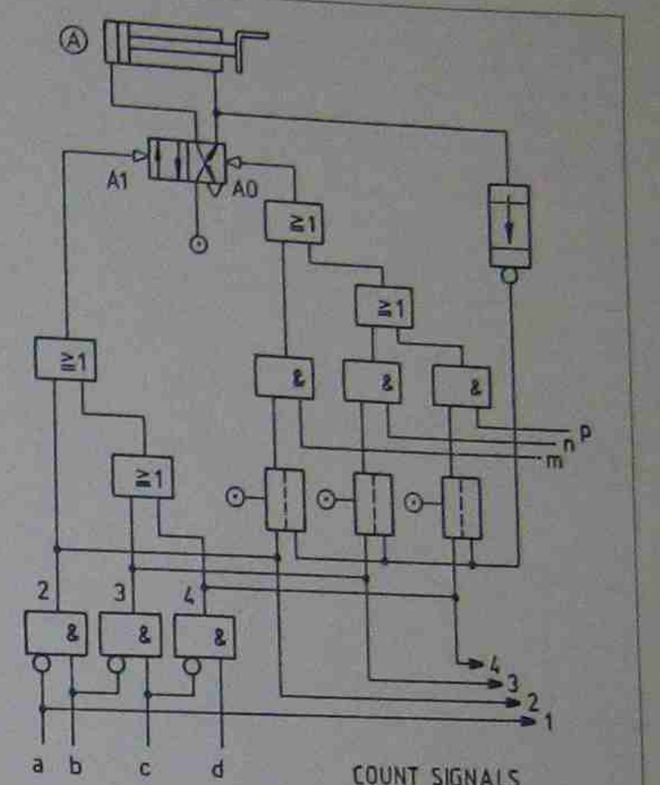

Fig. 10-28 Circuit diagram and Karnaugh-Veitch map for bottle sorter. Inhibition functions may be used for the collection A1 equation (the sensors are not shown).

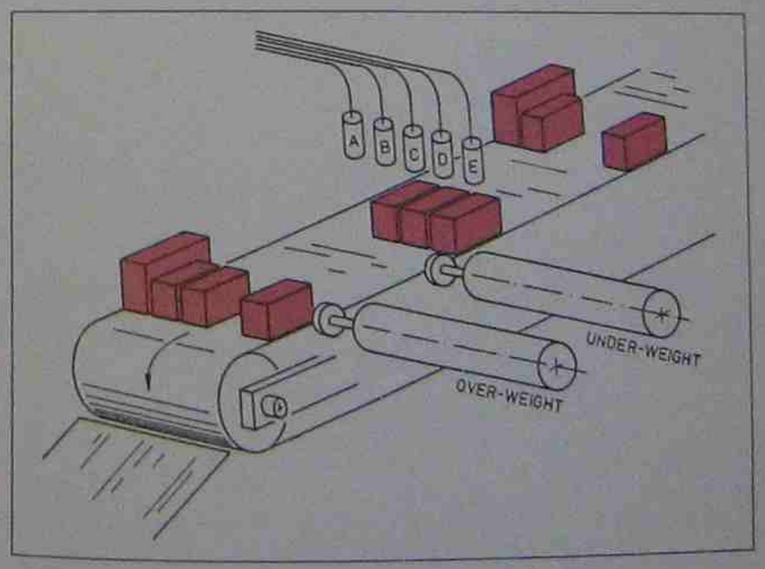

Fig. 10-29 Weight detector station with ejector actuators.

(underweight clusters separately and overweight clusters separately, see fig. 10–29). Ejector actuators must only be extended when a rejected cluster has arrived at its respective eject position. Overweight or underweight commands must therefore be memorised (similarly to control problem 4) and then "AND" connected to their respective eject position signals.

Design considerations

The truth table for this control problem must differentiate between underweight, overweight and correct weight signal combinations; hence, this truth table is to be furnished with three output columns; one for each weight cluster group. Underweight is designated "U", overweight "O", and correct weight "W". Washing powder packets detected in line A of the conveyor weigh 2 kg and are therefore given two columns in the truth table.

A	B	C	D	E	W	U	O
0	0	0	0	0	0	X	
0	0	0	0	0	1	1	
0	0	0	0	1	0	1	
0	0	0	0	1	1	1	
0	0	0	1	0	0	1	
0	0	0	1	0	1	1	
0	0	0	1	1	0	1	
0	0	0	1	1	1	1	
0	0	1	0	0	0	1	
0	0	1	0	0	1	1	
0	0	1	0	1	0	1	
0	0	1	0	1	1	1	
0	0	1	1	0	0	1	
0	0	1	1	0	1	1	
0	0	1	1	1	0	1	
0	0	1	1	1	1		
1	1	0	0	0	0	1	
1	1	0	0	0	1	1	
1	1	0	0	1	0	1	
1	1	0	0	1	1		
1	1	0	1	0	0	1	
1	1	0	1	0	1		
1	1	0	1	1	0		
1	1	0	1	1	1		1
1	1	1	0	0	0	1	
1	1	1	0	0	1		
1	1	1	0	1	0		
1	1	1	0	1	1		1
1	1	1	1	0	0		
1	1	1	1	0	1		1
1	1	1	1	1	0		1
1	1	1	1	1	1		1

Fig. 10–30 Truth table for control problem 5.

The top row in the truth table represents a combination where there are no clusters under the detector station. Since ejector signals must be "AND" connected to an eject position signal rendered by a passing cluster, this combination cannot cause an ejector to extend. Therefore this combination may be called a "DON'T CARE" combination which can be used for the minimisation of any loop and as many times over as required (see looping rule 4 and figs. 10–11, 10–29, 10–30 and 10–31).

To establish the logic values in the output columns of the truth table, one simply adds all the logic 1 entries in each row. If the sum of these entries is precisely four, then the "W" output gets the logic 1. If the sum is more than four, this would denote an overweight cluster which therefore produces a logic 1 entry in the "O" column of this row. If the sum is less than four, the underweight column gets the logic output 1 (see fig. 10–30).

Because of the large number of underweight combinations in the truth table, it may be wise to draw three Karnaugh-Veitch maps for the underweight entries, and a separate Karnaugh-Veitch map for overweight and correct weight (see fig. 10–31). Looping of large Karnaugh-Veitch maps with more than two or three input signals is of course somewhat more complex and requires skill, but if the looping rules are correctly applied one can always count on a satisfactory and optimal minimisation result. The control circuit is bound to work even with extracted equations based on less than optimal looping!

The minimised equations extracted from the loops in the Karnaugh-Veitch maps for the output signal "U" (underweight) read as follows:

$$U = \overline{A} \cdot \overline{B} + \overline{A} \cdot \overline{C} + \overline{A} \cdot \overline{D} + \overline{C} \cdot \overline{D} \cdot \overline{E} + \overline{A} \cdot \overline{E} + \overline{B} \cdot \overline{C} \cdot \overline{D} + \overline{C} \cdot \overline{B} \cdot \overline{E} + \overline{B} \cdot \overline{D} \cdot \overline{E}$$

Further minimised with the distributive law of Boolean algebra this equation reads as follows:

$$U = \overline{A} \cdot (\overline{B} + \overline{C} + \overline{D} + \overline{E}) + \overline{C} \cdot \overline{D} \cdot (\overline{E} + \overline{B}) + \overline{B} \cdot \overline{E} \cdot (\overline{C} + \overline{D})$$

The minimised equation extracted from the loops in the Karnaugh-Veitch map for the output signal "O" (overweight) reads as follows:

$$O = A \cdot B \cdot C \cdot D + A \cdot B \cdot C \cdot E + A \cdot C \cdot D \cdot E + A \cdot B \cdot D \cdot E$$

Further minimised with the distributive law of Boolean algebra this equation reads as follows:

$$O = A \cdot B \cdot C \cdot (D + E) + A \cdot D \cdot E \cdot (C + B)$$

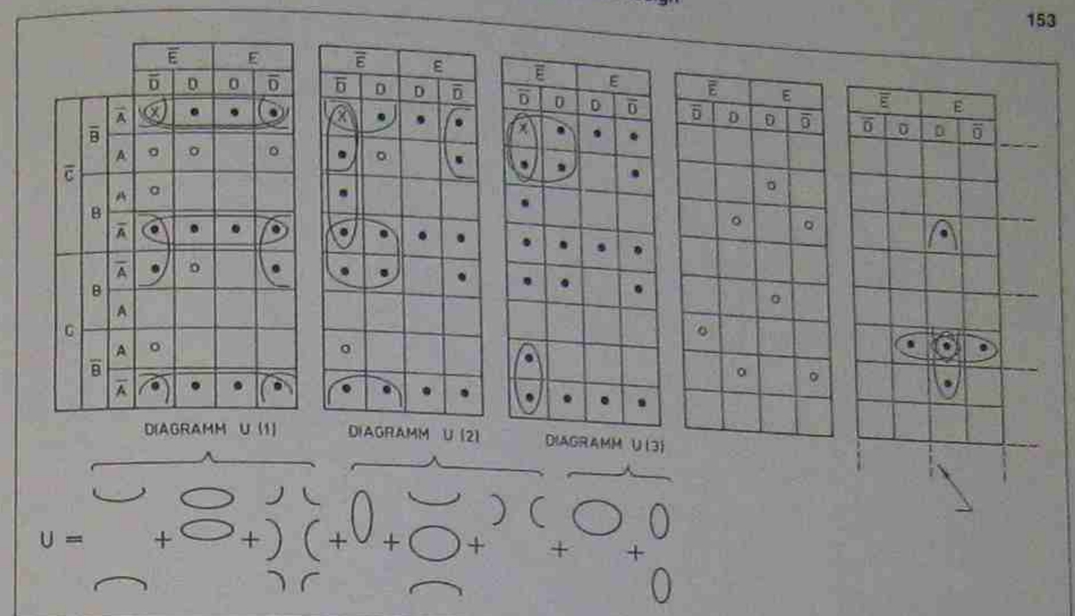

Fig. 10–31 Karnaugh-Veitch maps for control problem 5.

Since all output signals in the truth table are filled either with an output 1 or an X (DON'T CARE) and none of the three output signals share their output with a letter in another column of the same row, we can regard these output signals as overlap free and combinationally complete.

This implies that the minimised "O" and "U" output equations when connected with an "OR" function may be regarded as the "true output form" of the truth table (these must render an output or eject signal). The remaining output combinations represent the "false output form" of the truth table (these combinations must not render an eject signal). To achieve an output signal for the purpose of counting the clusters moved through the wrapping station, one now simply has to use the "NOR" function which renders an output when "U" or "O" are not present (see also fig. 10–8).

The weight detector renders an $\overline{A} \cdot \overline{B} \cdot \overline{C} \cdot \overline{D} \cdot \overline{E}$ signal as soon as a cluster has left the detectors. Such a combination would however set the underweight signal! To avoid such pseudo-underweight signals reaching the memory, a logic filter has been built into the signal line leading to the underweight memory (fig. 10–32).

Another precautionary measure has been taken to avoid spurious underweight signals reaching the underweight memory. If, for example, a washing powder packet is slightly in front of the other packets in a correct weight cluster, its presence signal would then send an underweight signal which would be evaluated as "ONE PACKET ONLY". This misleading signal would simulate line two of the truth table, although it was a correct weight cluster. To avoid such mishaps a timer is used which stops any spurious signals until the complete cluster is under the weight detector (see timer in circuit of fig. 10–32).

Review of control problems

Control problems 4 and 5 were mixed controls, consisting of a combinational control driving a sequential control. Pure combinational controls and pure sequential controls are seldom required in industry. It is therefore important that control designers and service personnel know how to design such controls and therefore understand the use of Boolean algebra (at least the theorems and laws presented in this chapter), truth tables, and Karnaugh-Veitch maps.

Combinational pattern circuits

To round this chapter off, some combinational pattern circuits are given. The circuit in fig. 10–34 is a previously introduced program selector circuit (see Chapter 8), designed with combinational logic principles.

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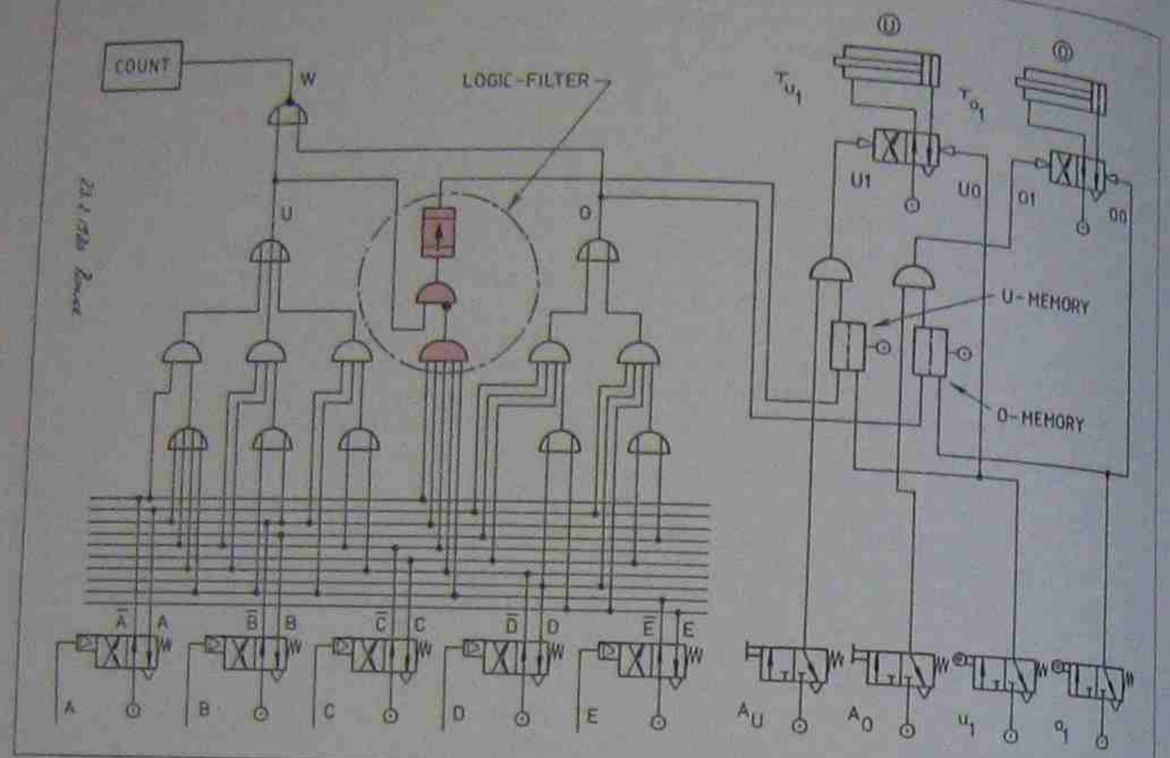
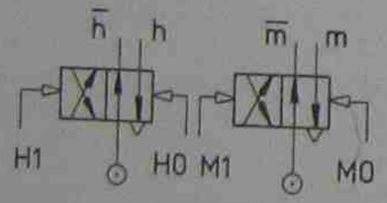


Fig. 10-32 Circuit diagram for control problem 5. The proximity sensors are not shown.

DESIGN OF BINARY PROGRAM SELECTOR

h	m	
0	0	PROG. 1
0	1	PROG. 2
1	0	PROG. 3
1	1	PROG. 4



PROG. 1 = $\bar{h} \cdot \bar{m}$ h = H1 = PROG. 3 + PROG. 4
PROG. 2 = $\bar{h} \cdot m$ $\bar{h}$ = H0 = PROG. 1 + PROG. 2
PROG. 3 = $h \cdot \bar{m}$ m = M1 = PROG. 2 + PROG. 4
PROG. 4 = $h \cdot m$ $\bar{m}$ = M0 = PROG. 1 + PROG. 3

Fig. 10-33 Combinational logic design for program selector.

If two memory valves with two output states are used, one can obtain four unique output combinations ($2^2 = 4$). The truth table shows these combination possibilities. The memory input signals are also taken from the truth table by connection with "OR" functions (see figs. 10-33 and 10-34).

T-Flip Flop

This type of memory is used for *binary counting* or binary reduction control. It may also be used to cause an actuator to extend and thereafter retract (or vice versa), but only one command valve is required since every "T input signal" changes the output of the memory on top ($\bar{A}$, A). Such valves are also commercially available in single block form.

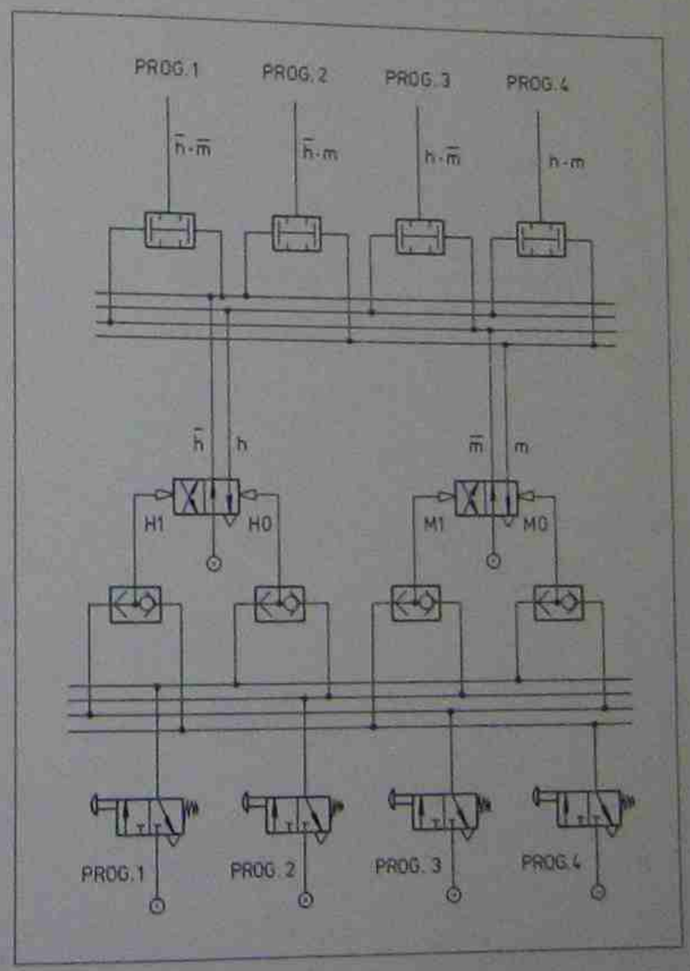


Fig. 10-34 Binary program selector circuit.

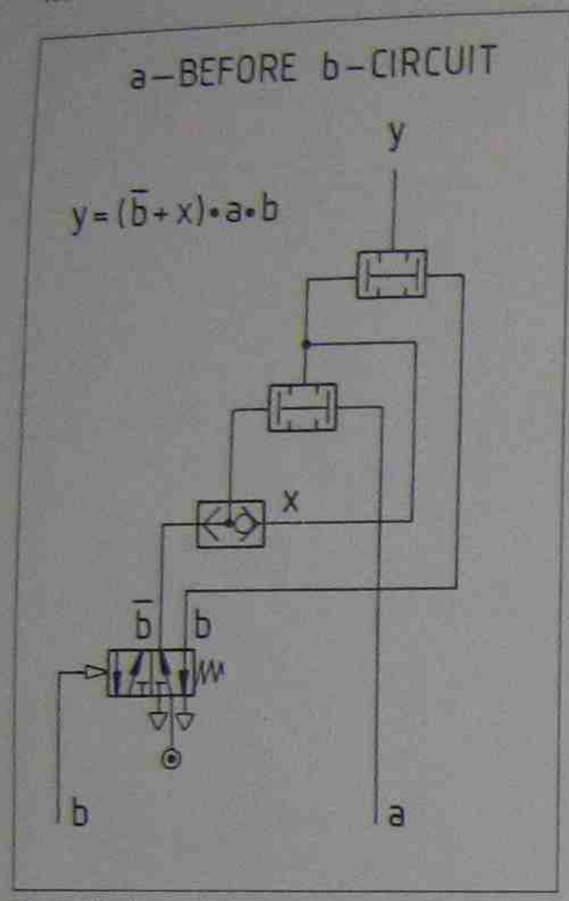


Fig. 10–35 a-before-b circuit.

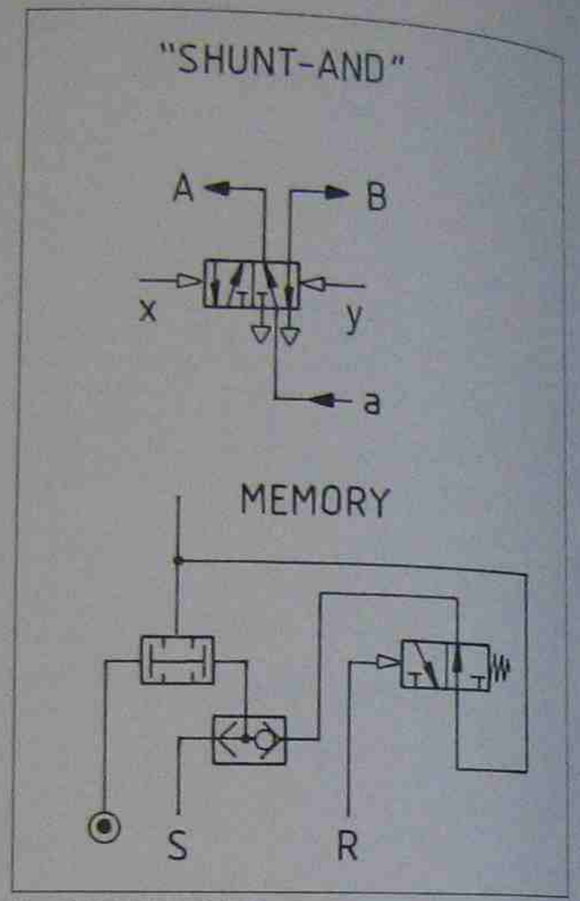


Fig. 10–36 "SHUNT-AND" circuit; memory circuit built with non-memory type valves.

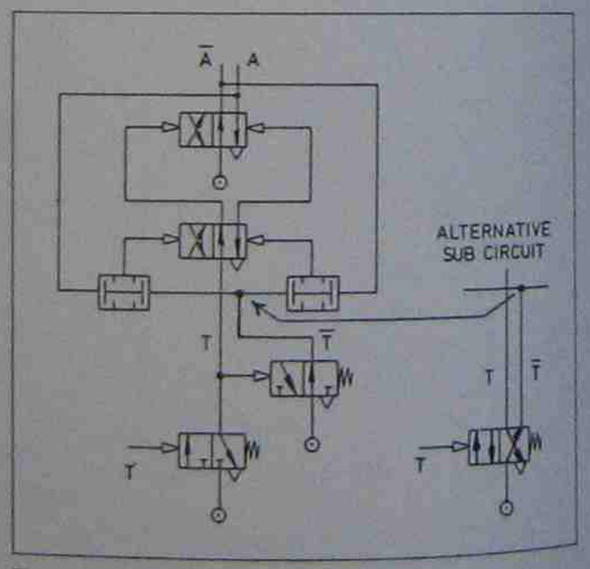


Fig. 10–37 T-flip flop (memory) circuit.

BOOLEAN IDENTITIES

1. (a) 0 is unique
   (b) 1 is unique
2. (a) $A + 0 = A$
   (b) $A \cdot 1 = A$
3. (a) $A + \overline{A} = 1$
   (b) $A \cdot \overline{A} = 0$
4. (a) $A + 1 = 1$
   (b) $A \cdot 0 = 0$
5. (a) $A + B = B + A$
   (b) $A \cdot B = B \cdot A$
6. (a) $A + (B \cdot C) = (A + B) \cdot (A + C)$
   (b) $A \cdot (B + C) = A \cdot B + A \cdot C$
7. $\overline{\overline{A}} = A$
8. (a) $A \cdot A = A$
   (b) $A + A = A$
9. (a) $0 + 0 = 0$
   (b) $1 \cdot 1 = 1$
   (c) $1 + 0 = 1$
   (d) $1 \cdot 0 = 0$
10. (a) $\overline{0} = 1$
    (b) $\overline{1} = 0$
11. (a) $A(A + B) = A$
    (b) $A + AB = A$
12. (a) $A(\overline{A} + B) = AB$
    (b) $A + \overline{A}B = A + B$
13. If $A = B$ then $\overline{A} = \overline{B}$
14. (a) $\overline{A}(A + B) = \overline{A}B$
    (b) $\overline{A} + AB = \overline{A} + B$
15. (a) $(A + B) \cdot (\overline{A} + C) = A \cdot C + \overline{A} \cdot B$
    (b) $(A + B) \cdot (C + D) = A \cdot C + A \cdot D + B \cdot C + B \cdot D$
    (c) $(AB + CD) = (A + C)(A + D)(B + C)(B + D)$
16. (a) $\overline{AB} = \overline{A} + \overline{B}$
    (b) $\overline{A + B} = \overline{A} \cdot \overline{B}$
    (c) $AB = \overline{\overline{A} + \overline{B}}$
    (d) $A + B = \overline{\overline{A} \cdot \overline{B}}$
17. (a) $\overline{AB + CD} = (\overline{A} + \overline{B})(\overline{C} + \overline{D})$
    (b) $\overline{(A + B)(C + D)} = \overline{A} \cdot \overline{B} + \overline{C} \cdot \overline{D}$
18. (a) $(A + B)(A + \overline{B}) = A$
    (b) $AB + A\overline{B} = A$
19. (a) $A + (B + C) = (A + B) + C = A + B + C$
    (b) $A(BC) = (AB)C = ABC$
20. (a) if $A = B$ then $A + C = B + C$
    (b) & $A \cdot C = B \cdot C$
21. (a) if $A + B = 0$ then $A = B = 0$
    (b) if $A \cdot B = 1$ then $A = B = 1$
22. (a) $(A + B)(C + D) = (A + B)C + (A + B)D$
    (b) $AB + CD = (AB + C)(AB + D)$

11 Electronic programmable controllers for fluid power

Over recent years electronic programmable logic controllers have sprung up like mushrooms, and over three hundred different types and brands are presently available. Electronic programmable logic controllers have undoubtedly become a very valuable and indispensable part of the ever advancing industrial automation.

These controllers evolved as industry sought more economical ways to automate their production lines, particularly those involved in the manufacturing of equipment, consumer goods and heavy industry products. Thus the electronic programmable controller has replaced relay based, hard wired electrical systems, and more recently it has also made significant inroads into the traditional domain of pneumatic logic circuitry. These inroads unfortunately have not gone unnoticed and have brought about some problems:

- programming difficulties caused through non-standardised and varying programming techniques;
- programming difficulties caused through the use of varied logic element names and element description for elements within the controller;
- demarcation problems in factories between electrical- and metal-worker unions when maintenance on machines with fluid power control and electronic control is required;
- extreme shortage of skilled personnel who can program and install such electronic controllers and interface them with fluid power circuitry.

What is an electronic programmable controller?

Electronic programmable logic controllers are often abbreviated with the letters P.C. This abbreviation is misleading, since the letters P.C. are also used for "personal computers". It is therefore suggested that the abbreviation P.L.C. (programmable logic controller) should be used instead.

Programmable logic controllers (P.L.C.) operate by monitoring input signals from such sources as push-button switches, proximity, heat or level sensors, limit switches and pressure sensors. When binary logic changes are detected from these input signals, the P.L.C. reacts through a user-programmed internal logic switching network and produces appropriate output signals. These output signals may then be used to operate external loads and switching functions of the attached fluid power control system (see figs. 11-1 and 11-17).

Programmable logic controllers eliminate much of the wiring and rewiring that was necessary with conventional relay-based systems. Instead the programmed "logic network" replaces the previously "hard wired" network. This logic network may be altered as required by simply programming or reprogramming the P.L.C. Thus, the automated processes of a production line or complex manufacturing machine can be controlled and modified at will for highly economical adaptability to a rapidly changing manufacturing environment.

How does an electronic programmable controller work?

A typical programmable electronic controller (P.L.C.) has four separate yet interlinked components; an input/output section, a central processing unit which is microprocessor based, a programming device (console), and a power supply.

The input section is often powered by a 24 volt power supply built into the controller. This supplies the limit switches, sensors and push-button switches with the necessary power. The P.L.C. also reads all the on/off conditions of all input terminals and memorises them in its input image memory before executing the program.

The central processing unit reads the stored information from the image memory and processes that information according to the control plan programmed into the central processing unit (C.P.U.). The C.P.U. is microprocessor based and may be regarded as the "BRAIN" of the controller. The main purpose of the C.P.U. is to continuously scan (monitor) the status of all input signals and thus direct the status of all output signals. Such an internal control plan may include numerous "MEMORY" functions, logic "AND", "OR", as well as "INHIBITION" functions, arithmetic computations, timers and counter functions. The program is entered with ladder diagram or other programming concepts and remains in the C.P.U. until deliberately changed by the user with one of the programming devices. Such execution results are then written internally (electronically) into the element image memory. The element image memory then drives the output relays of the P.L.C.

Upon completion of the internal functions the P.L.C. starts again and repeats these processes endlessly. The programming device may be a push-button console or a tape recorded program.

To summarise: A programmable controller is an aggregate control mechanism made up of multiple electronic relays, timers and counters used to execute the internal logical wiring by the programming panel. A conventional hard wired relay panel basically differs from a P.L.C. in the sequence execution method. Its sequences are executed in parallel while the P.L.C. executes its sequences in the order of the program and cyclically as the scanning reveals any input changes.

This book is not intended to teach any particular brand or type of programmable controller and, therefore, care has been taken to make the necessary information as unbiased as possible. To make the applications nevertheless meaningful some practical programming procedures are given, and have been based on the "OMROM C20" programmable controller which is basically identical to the "FESTO FPC 201" and closely related to the "MITSUBISHI Melsec F series". These are all in fact small type controllers, ideally suited for fluid power sequential and combinational control.

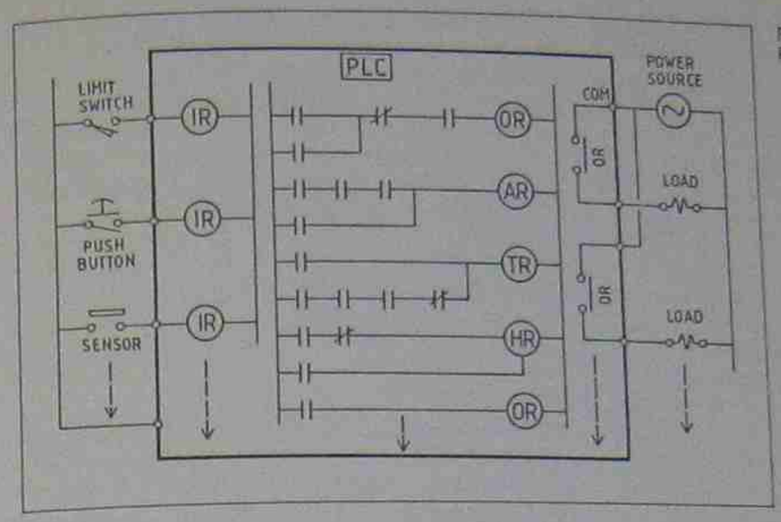


Fig. 11-1 Internal configuration of a P.L.C.

Programming the electronic controller (P.L.C.)

A most misleading impression for many control engineers and electricians when confronted with a programmable controller is that these machines (P.L.C.) can easily be programmed with the "ladder logic" method. Ladder logic *is not a method of circuit design*; it is a method of circuit presentation, like a pneumatic or hydraulic circuit. For this reason numerous "amateur" programmers had insurmountable difficulties and frustrations whilst programming their little electronic "wizard"; some to such an extent that they gave up before they ever saw their controller work!

The author of this chapter has therefore made attempts to present a programming and design method which works for most types and brands of P.L.C. This method is of course not new to the experienced circuit designer of pneumatic sequential controls. It is called the "step-counter design method" and is explained and applied in Chapter 8. In fact most principles outlined in Chapter 8 can be directly applied to P.L.C. programming.

Electronic switching peculiarities

Compared with pneumatic valves, the only electronic counterpart to a pneumatic memory valve is the "KEEP RELAY". The keep relay is sometimes also called "holding relay" or "retentive relay", and maintains its logic status (set or reset) even during power failure! For pneumatic memory valves, this memory or retentive behaviour is achieved with the mechanical friction between the

spool and the valve body. For electronic memories (relays) the latch-in must be maintained with a battery back-up when power fails. This demands that every logic switching function which in a pneumatic circuit would normally end up as a pneumatic pilot signal to a memory valve, when electronically achieved, also has to end up driving an electronic memory which is in fact a keep relay or holding relay (see figs. 11-8 and 11-9).

Another peculiarity is the terminology used for normally open and normally closed pneumatic valves compared to electronic contacts and switches. A normally closed pneumatic valve does not pass any flow in its non-actuated position. A normally closed contact, however, or a normally closed switch, does pass a signal in its normally closed state (see figs. 2-5 and 11-2).

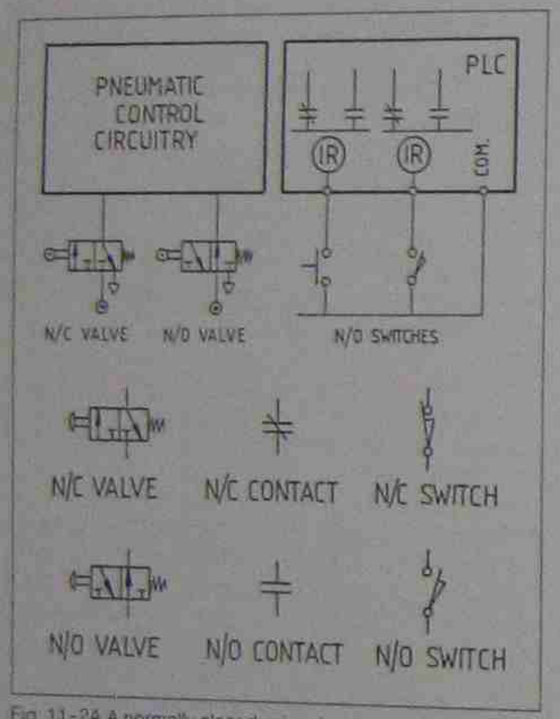


Fig. 11-2A A normally closed valve does not pass a signal but a normally closed contact does. Electronic controllers make all relay signals available in their logic 1 and also logic 0 form (normally closed and normally open contacts; see also fig. 11-9.)

The third peculiarity is related to series connection of pneumatic valves, as explained in Chapter 2, figs. 2-34 and 2-35 and also in Chapter 8, figs. 8-12 to 8-18. The electronic and electric ladder diagram presentation shows only series connection and no "AND" connection by means of "AND" gates. Electronic input relays as well as internal relays drive a vast number of normally closed and normally open contacts. Therefore, one never has to worry about reducing a complex logic input equation to its fully minimised form, as this would be necessary for a pneumatic control. Thus, when programming an electronic controller, one may safely assume that each relay has an unlimited number of contacts which can always be "AND" connected (see figs. 11-1 and 11-5). These contacts may be called upon at any time, as long as the relay driving them is set and these contacts are always freely available in the logic 1 form or logic 0 form (which means inversion of signals is no longer required – fig. 11-2).

Relay types

A Programmable Logic Controller (P.L.C.) has basically four different types of relays. Figure 11-22 lists these relays in conjunction with their channel allocation number. These relays can be grouped into the following four categories:

1. Input Relays [IR]
2. Output Relays [OR]
3. Internal Auxiliary Relays [AR]
4. Holding Relays [HR]

- Input relays (IR) are used to receive incoming signals and distribute them wherever these input signals are required. These relays may be compared to a limit valve or push-button start or stop valve in a pneumatic circuit. The signal emerging from such relays may be processed in normally open (N/O) or normally closed (N/C) form (see fig. 11-2 and 11-22). The "OMRON C 20" has 16 input relays and may be extended to 80.
- Output relays (OR) are the only relays which can be used to drive a load outside the P.L.C. (for example a solenoid, a siren, start a motor or turn on an oven). The "OMRON C 20" has only 12 output relays, but these may be expanded to 60 (fig. 11-5). Output relays are not memory retentive during power failure (fig. 11-3).
- Internal auxiliary relays (AR) are only used for internal logic signal processing and cannot be used to drive an outside load! The "OMRON C 20" has 136 internal auxiliary relays. Internal auxiliary relays are not memory retentive during power failure (fig. 11-3) and may be compared to an air pilot operated, spring reset pneumatic valve.
- Holding relays (HR) are also used for internal logic signal processing, much the same way as internal auxiliary relays. Holding relays are memory retentive during power failure if they are combined with the Fun. 11 instruction (see fig. 11-5). Holding relays are basically set-reset type relays. The

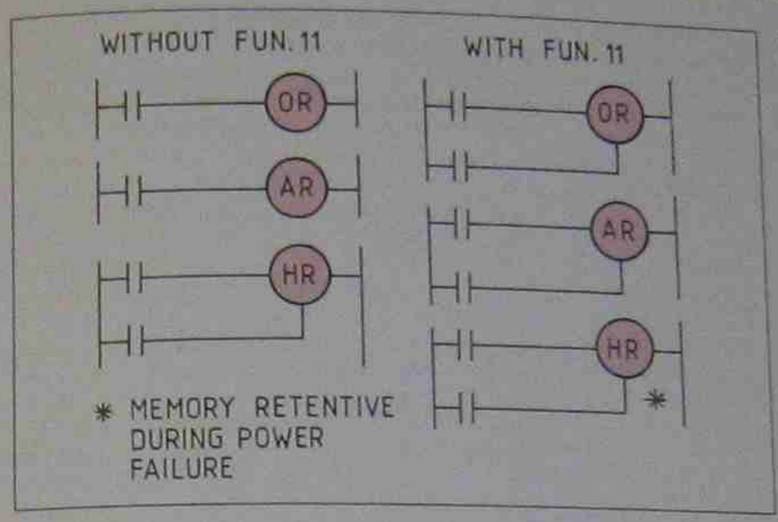
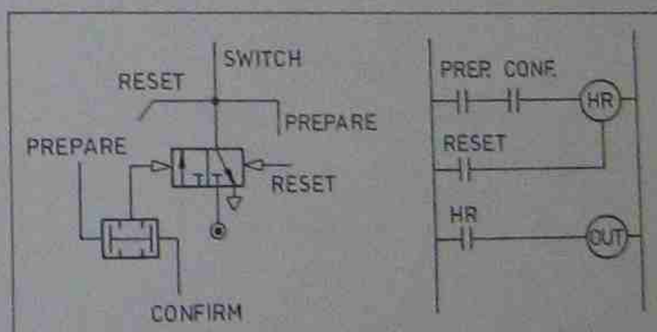


Fig. 11-3 Relay types and integration of "Fun 11"

Latching function (FUN. 11)

"OMRON C 20" has 160 holding relays (fig. 11-22). Only holding relays have true memory capacity which makes them memory retentive during power failure (see figs. 11-3 and 11-5). Such relays are also called "Keep Relays."

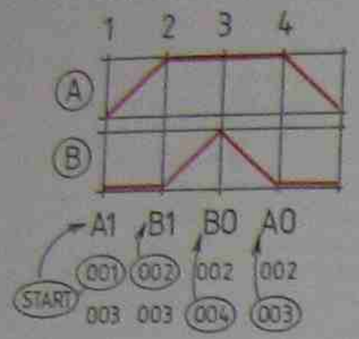
Output relays (OR), as well as internal auxiliary relays (AR) may also be combined with the latching function (Fun. 11) to turn them into set-reset relays with a separate set and reset input signal (see fig. 11-3). This, however, does not make them memory retentive during power failure!



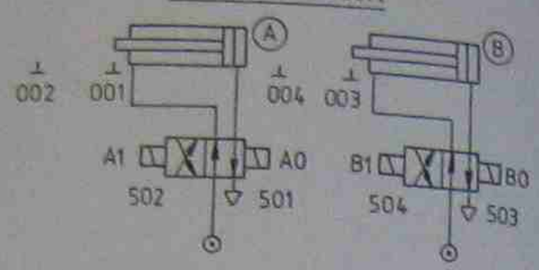
ADDRESS	INSTRUCTION	DATA	EXPLANATION
200	LD	(NO.)	PREPARATION SIGNAL
201	AND	(NO.)	CONFIRMATION SIGNAL
202	LD	(NO.)	RESET HOLDING RELAY
203	FUN 11	HR (NO.)	HOLDING RELAY ON
204	LD	HR (NO.)	HR DRIVES OR
205	OUT	(NO.)	OUTPUT RELAY ON

Fig. 11-4 Step-counter module comparison for P.L.C. programming, instruction ladder logic diagram and pneumatic circuit diagram. The designation HR stands for holding relay (keep relay) and "OUT" stands for the output relay which is not a memory retentive relay.

TRAVERSE-TIME DIAGRAM



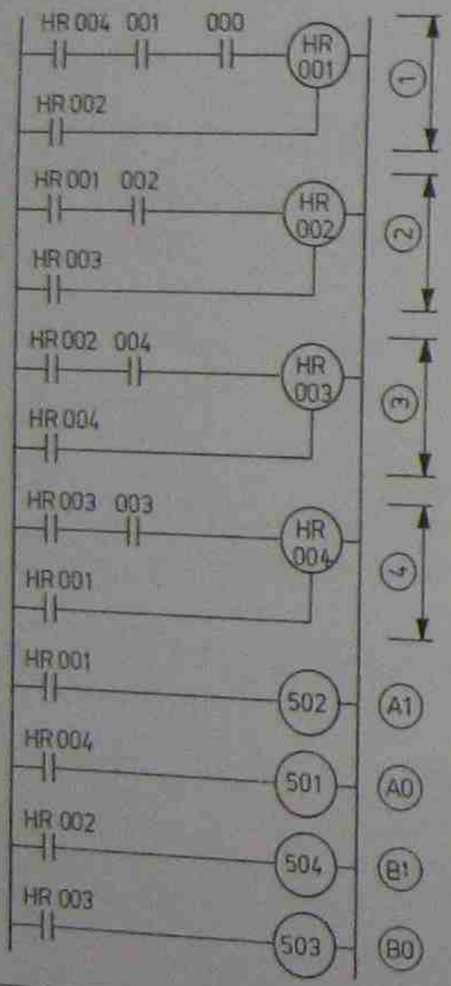
PNEUMATIC CIRCUIT



START = 000
A1 = 502
A0 = 501
B1 = 504
B0 = 503

a_1 = 002
a_0 = 001
b_1 = 004
b_0 = 003

LADDER DIAGRAM



CODING CHART

ADDRESS	INSTRUCTION	DATA
000	LD	HR 004
001	AND	001
002	AND	000
003	LD	HR 002
004	FUN 11	HR 001
005	LD	HR 001
006	AND	002
007	LD	HR 003
008	FUN 11	HR 002
009	LD	HR 002
010	AND	004
011	LD	HR 004
012	FUN 11	HR 003
013	LD	HR 003
014	AND	003
015	LD	HR 001
016	FUN 11	HR 004
017	LD	HR 001
018	OUT	502
019	LD	HR 004
020	OUT	501
021	LD	HR 002
022	OUT	504
023	LD	HR 003
024	OUT	503
025	FUN 01	

Fig. 11-5 Ladder diagram and coding chart for clamp and drill control sequences as depicted in the traverse-time diagram

Step-counter programming for a P.L.C.

The step-counter circuit design method may also be used to program a P.L.C. (see Chapter 8, figs. 8-4 and 8-5). Each step-counter module is "built" from a keep relay (HR) and a preswitched "AND" function. The two signals required to make the "AND" function are the essential confirmation signal, confirming the completion of the previous sequence motion, and the preparation signal rendered by the keep relay of the previous step-counter module (or sequence step).

The essential confirmation signal is of course only a contact which is driven by the input relay (IR). The input relay is actuated by the limit switch on the machine (see figs. 11-1 to 11-4). The preparation signal is also only a contact which is driven by the keep relay (HR) of the previous step-counter module (fig. 11-4).

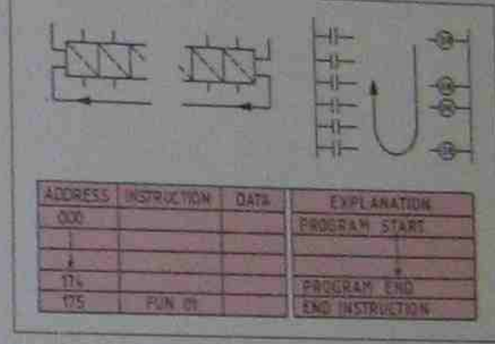
The P.L.C. integration of the individual step-counter modules into the step-counter chain follows the same pattern as established in pneumatic circuit design. The first rung in the ladder diagram includes the start switch or a contact from a cycle selection module (figs. 11-5 and 11-12).

To demonstrate the correlation and integration of the individual step-counter modules, a ladder diagram is now established for a clamp and drill machine with the sequence: A1-B1-B0-A0. The pneumatic power circuit is given and all necessary limit switches and solenoid signal commands from the output relays leading to the solenoids are allocated with their appropriate relay numbers.

It must be noted that the keep relay (HR) in a P.L.C. step-counter program performs the same functions as the memory valve in a pneumatic step-counter. These functions are:

1. To switch the output relay. The output relay then drives the solenoids on the power valves (figs. 11-4, 11-5 and 11-13).
2. To reset the keep relay (HR) of the previous electronic step-counter module.
3. To prepare the "AND" function which switches the keep relay of the next electronic step-counter module.

At this stage it may be appropriate to mention that immediately after the last sequential address (address 024 in the given exercise) an "END" instruction must also be programmed into the P.L.C. program. For the "OMROM C20" this instruction is function 01 (fig. 11-5). An error message would usually be displayed on the P.L.C. if this end instruction was omitted. The C.P.U. of the programmer scans the program data from address 0000 to the address with the end instruction in the sequence (fig. 11-6).

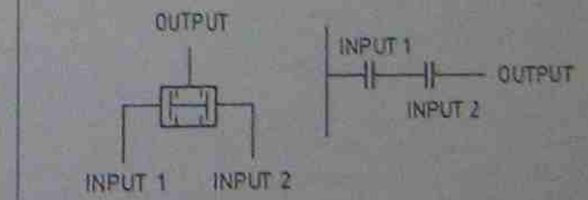


ADDRESS	INSTRUCTION	DATA	EXPLANATION
000			PROGRAM START
↓			↓
174			↓
175	FUN 01		PROGRAM END
			END INSTRUCTION

Fig. 11-6 At the end of each sequence program an end instruction must be given to the program. This end instruction brings the program back to step one.

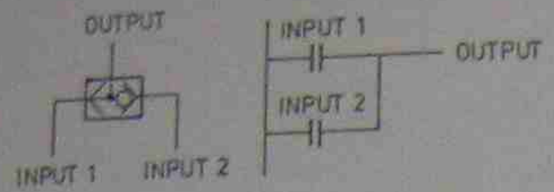
Logic function for P.L.C.

Figures 11-7, 11-8 and 11-9 depict a few logic functions which have not been explained in much detail previously. The structure of the output relay in fig. 11-9 is identical to the structure of all other internal auxiliary relays. These also have a multitude of N/C and N/O contacts to drive them.



ADDRESS	INSTRUCTION	DATA	EXPLANATION
200	LD	(NO.)	INPUT 1
201	AND	(NO.)	AND CONNECT INP. 2

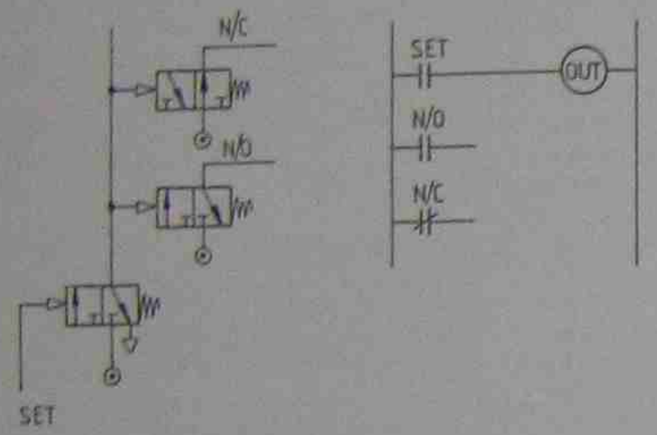
Fig. 11-7 Programming the electronic "AND" function. Although the "AND" function in the electronic ladder diagram is shown as a series function inside the P.L.C., these input signals are "AND" connected by electronic "AND" gates and not in series order!



ADDRESS	INSTRUCTION	DATA
200	LD	(NO.)
201	OR	(NO.)

EXPLANATION
INPUT 1
OR CONNECT INPUT 2

Fig. 11-8 Programming the electronic "OR" function



ADDRESS	INSTRUCTION	DATA
200	LD	(NO)
201	OUT	(NO)

EXPLANATION
SET SIGNAL
OUTPUT RELAY ON

Fig. 11-9 Programming the output relay. This is the same for internal auxilary relays

Timer functions

With timer functions one may again follow the structure given for internal auxiliary relays. A timer may be programmed for a set time ranging between 0 and 999.9 seconds. Timer number allocations for the "OMROM C20" are from 00 to 47. Timers and counters may not be allocated the same number.

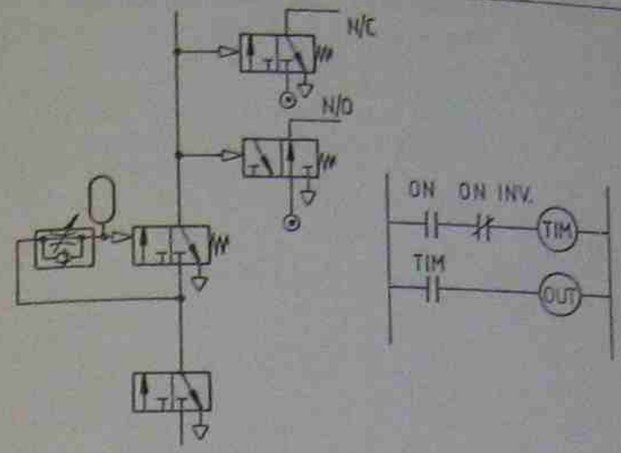
The timer works by decrementing and produces an output signal when the time has elapsed to 0000 sec. The timer starts when its timer "ON" signal is logic 1 and resets when its "ON" signal is cancelled. The timer output is transmitted externally through an output relay as shown in fig. 11-10.

The timer appears separately in the ladder diagram and its contact (or contacts if several times used) may be used in the ladder diagram wherever required (see figs. 11-10 and 11-13). Timer contacts may be normally open or normally closed (see fig. 11-10).

The timer is in reality a counter in which an internal clock pulses the timer from its "set value" to count down to zero. This internal clock works on a pulse rate of 0.1 per second. Thus a 10.6 second delay is programmed as # 106.

Shunt module (selector module)

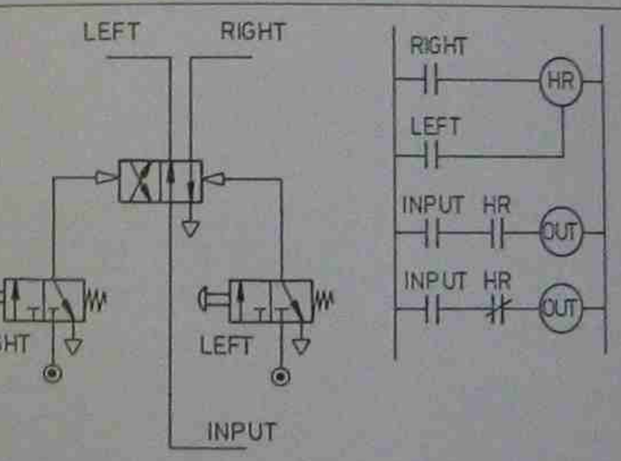
The shunt module may also be regarded as an independent module similar to the step-counter module discussed and illustrated in fig. 11-4. The shunt module can be used for program selection in selective parallel control applications, as illustrated in figs. 8-47 and 8-48.



ADDRESS	INSTRUCTION	DATA
200	LD	(NO.)
201	AND-NOT	(NO.)
202	TIM	(NO.)
———		#
203	LD	TIM (NO)
204	OUT	(NO.)

EXPLANATION
TIMER "ON" SIGNAL
AND CONNECT "ON" INV.
SET TIMER RELAY
SET TIME VALUE (sec)
TIM DRIVES OR
OUTPUT RELAY ON

Fig 11-10 On-delay timer. The timer requires an output relay when used externally to drive a load. Timer set value does not require an address. Timer values are set in increments of 0.1 seconds (pulse rate of the internal clock). Thus a 2 second time delay is programmed as value 20 (# 20).



ADDRESS	INSTRUCTION	DATA
200	LD	(NO.)
201	LD	(NO.)
202	FUN 11	HR (NO.)
203	LD	(NO.)
204	AND	HR (NO.)
205	OUT	(NO.)
206	LD	(NO.)
207	AND-NOT	HR (NO.)
208	OUT	(NO.)

EXPLANATION
SELECT RIGHT
SELECT LEFT
HOLDING RELAY ON
INPUT
AND CONNECT HR
OUTPUT RIGHT ON
INPUT
AND CONNECT $\overline{HR}$
OUTPUT LEFT ON

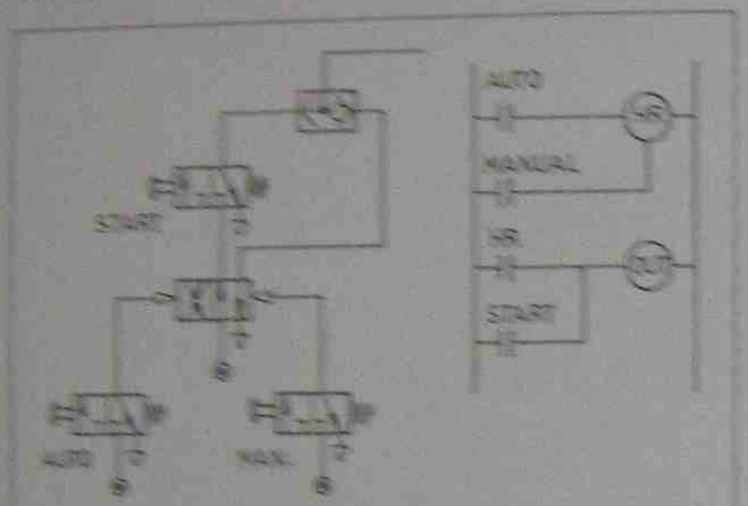
Fig. 11-11 Shunt module as used for program selection in multi-program control applications (see Chapters 8 and 9).

Simple cycle selection module

The simple cycle selection module has already been explained and applied in Chapter 6 (figs. 8-26 and 8-33). This module is used to furnish a sequentially controlled machine with a permanent start signal when "AUTO" cycling is selected. When "MANUAL" cycling start is selected, the operator is required to actuate the start valve each time a cycle is to begin (see figs. 11-12 and 11-13). An application circuit which includes a time-delay function and a cycle selection module is given in fig. 11-13.

Extended cycle selection module

The extended cycle selection module has also been explained and applied in Chapter 6 (fig. 8-27). This module provides separate selection as well as separate start for both cycling modes. It therefore requires two holding relays (keep relays), four push-button or key operated switches, and a number of logic functions (see fig. 11-14).



ADDRESS	INSTRUCTION	DATA	EXPLANATION
200	LD	(NO)	AUTOMATIC SIGNAL
201	LD	(NO)	MANUAL SIGNAL
202	FUN 11	HR (NO)	HOLDING RELAY ON
203	LD	HR (NO)	AUTOMATIC ON
204	OR	(NO)	OR MANUAL ON
205	OUT	(NO)	AUTO OR MAN. START

Fig. 11-13 Right: Circuit with time delay function and cycle selection module. The sequence for this control is A1-B1-B0-C1-B1-B0-T-A0/C0. The combination from sequence step T must be an "AND" function consisting of the signals a_0 and c_0 (001 = 005). Allocation of relay numbers is as follows:

A1	= 502	b_1	= 004
A0	= 501	b_0	= 003
B1	= 504	c_1	= 006
B0	= 503	c_0	= 005
C1	= 506	AUTO	= 013
C0	= 505	MAN.	= 014
a_1	= 002	START	= 015
a_0	= 001	START	= 1000

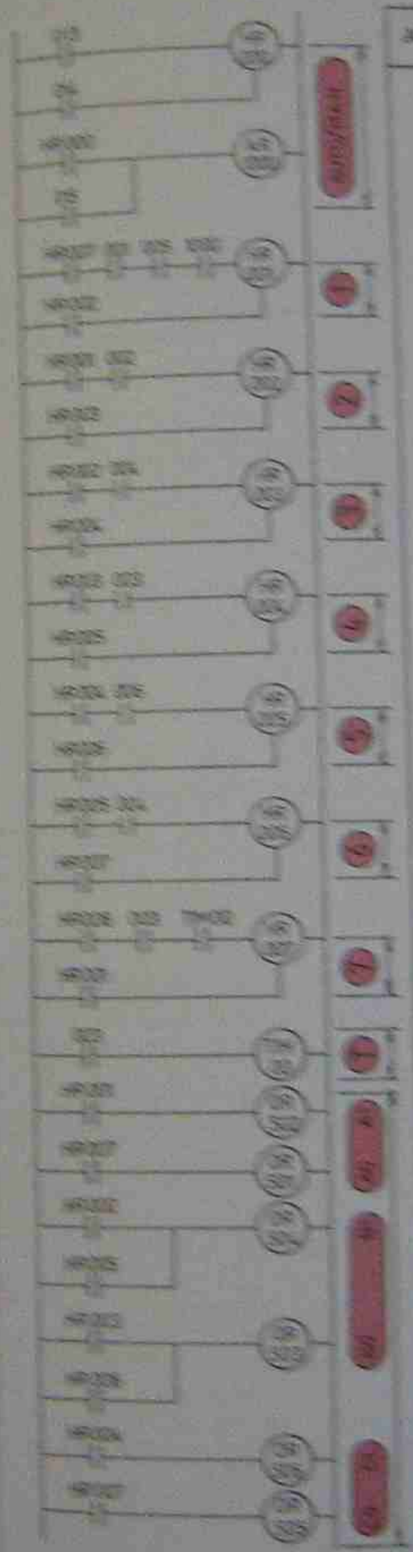
Fig. 11-12 Simple cycle selection module to provide either automatic cycling or manual cycling. To achieve a true memory function a holding relay must be used. The output relay (OR) is driven either by the contact of the holding relay (HR) or by the start switch (see also "OR" function depicted in fig. 11-8).



ADDRESS	INSTRUCTION	DATA
200	LD	012
201	LD	014
202	FUN 11	HR 200
203	LD	HR 200
204	AND	013
205	LD	014
206	FUN 11	HR 201
207	LD	HR 201
208	LD-NOT	HR 201
209	AND	015
210	OR-LD	
211	AND	HR 200
212	OUT	500

SELECT AUTO → 012 START AUTO → 013
SELECT MAN → 014 START MAN → 015

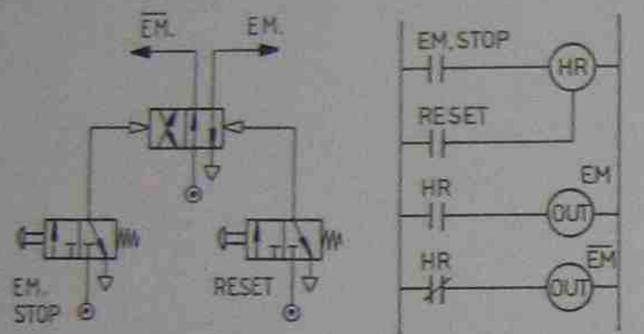
Fig. 11-14 Extended cycle selection module (see also figs. 8-27 and 11-17). This module provides separate selection and start for both cycling modes.



ADDRESS	INSTRUCTION	DATA
000	LD	013
001	LD	014
002	FUN 11	SR 000
003	LD	SR 000
004	OR	015
005	OUT	1000
006	LD	SR 007
007	AND	001
008	AND	005
009	AND	1000
010	LD	SR 002
011	FUN 11	SR 001
012	LD	SR 001
013	AND	002
014	LD	SR 003
015	FUN 11	SR 002
016	LD	SR 002
017	AND	004
018	LD	SR 004
019	FUN 11	SR 003
020	LD	SR 003
021	AND	003
022	LD	SR 005
023	FUN 11	SR 004
024	LD	SR 004
025	AND	006
026	LD	SR 006
027	FUN 11	SR 005
028	LD	SR 005
029	AND	004
030	LD	SR 007
031	FUN 11	SR 006
032	LD	SR 006
033	AND	003
034	AND	TIN 00
035	LD	SR 001
036	FUN 11	SR 007
037	LD	003
038	TIN	00
		4 30
039	LD	SR 001
040	OUT	502
041	LD	SR 007
042	OUT	501
043	LD	SR 002
044	OR	SR 005
045	OUT	504
046	LD	SR 003
047	OR	SR 006
048	OUT	503
049	LD	SR 004
050	OUT	506
051	LD	SR 007
052	OUT	505
053	FUN 01	-

Emergency stop for P.L.C. step-counter

The principles for emergency stop control explained and illustrated in Chapter 8 without exception also apply for P.L.C. programming. Figure 11-15 illustrates the concept and P.L.C. programming instructions used to obtain a basic emergency stop module (see also Chapter 8 fig. 8-23).



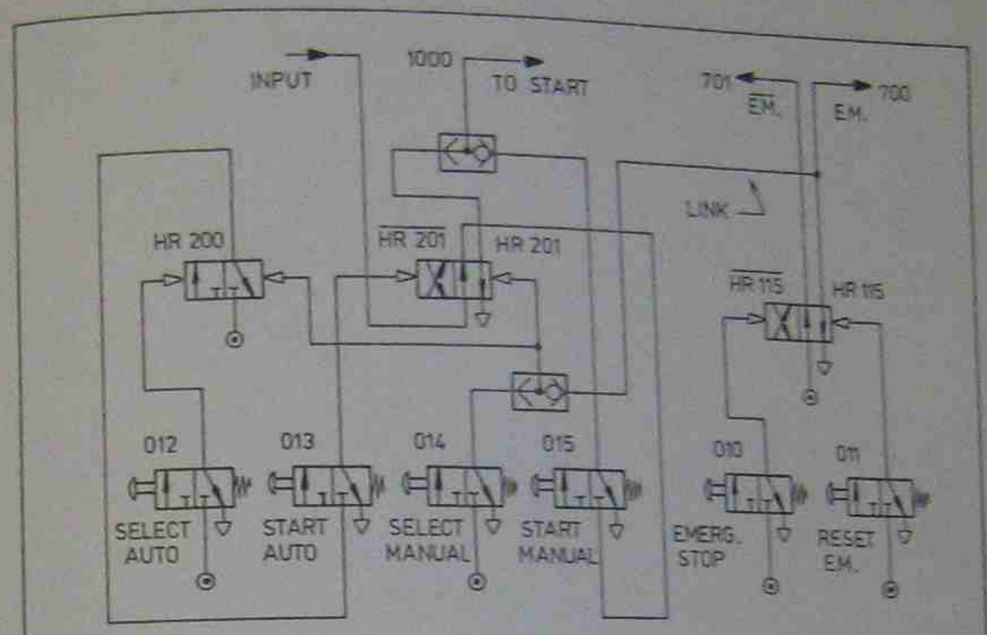
ADDRESS	INSTRUCTION	DATA	EXPLANATION
200	LD	(NO.)	SELECT EMERGENCY
201	LD	(NO.)	RESET EM.
202	FUN 11	HR (NO.)	HOLDING RELAY ON
203	LD	HR (NO.)	HR DRIVES OR EM
204	OUT	(NO.)	OUTPUT RELAY EM. ON
205	LD-NOT	HR (NO.)	$\overline{HR}$ DRIVES OR $\overline{EM}$.
206	OUT	(NO.)	OUTPUT RELAY $\overline{EM}$. ON

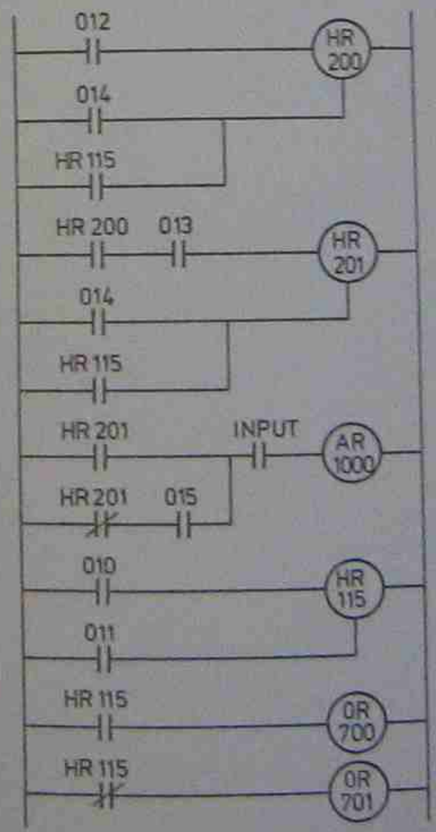
Fig. 11-15 Basic emergency stop module. This module is useful for all emergency stop modes except emergency stopping mode 3 which requires a cycle selection module (fig. 11-12).

Emergency stop and cycle selection

This module too may be linked to a cycle selection module to shift the cycle selector into manual cycling mode after emergency stopping was selected. The pneumatic version of this arrangement is shown in fig. 8-28 and the P.L.C. version in fig. 11-16.

To obtain stopping modes 1 and 2, which are called "STOP INSTANTANEOUSLY" and "STOP AT END OF COMMENCED SEQUENCE STEP", one must cancel all electrical signals leading to the solenoid valves of the fluid power circuit (see figs. 8-31 and 8-32). With the P.L.C. this may be achieved as is shown in figs. 11-15 and 11-17. Stopping mode 3 is illustrated in fig. 11-13, in conjunction with the basic cycle selection module. A detailed explanation of these stopping modes is given in Chapter 8.





ADDRESS	INSTRUCT.	DATA
000	LD	012
001	LD	014
002	OR	HR 115
003	FUN 11	HR 200
004	LD	HR 200
005	AND	013
006	LD	014
007	OR	HR 115
008	FUN 11	HR 201
009	LD	HR 201
010	LD-NOT	HR 201
011	AND	015
012	OR-LD	-
013	AND	HR 300
014	OUT	1000
015	LD	010
016	LD	011
017	FUN 11	HR 115
018	LD	HR 115
019	OUT	700
020	LD-NOT	HR 115
021	OUT	701

Fig. 11-16 Extended cycle selection module combined with emergency stop module.

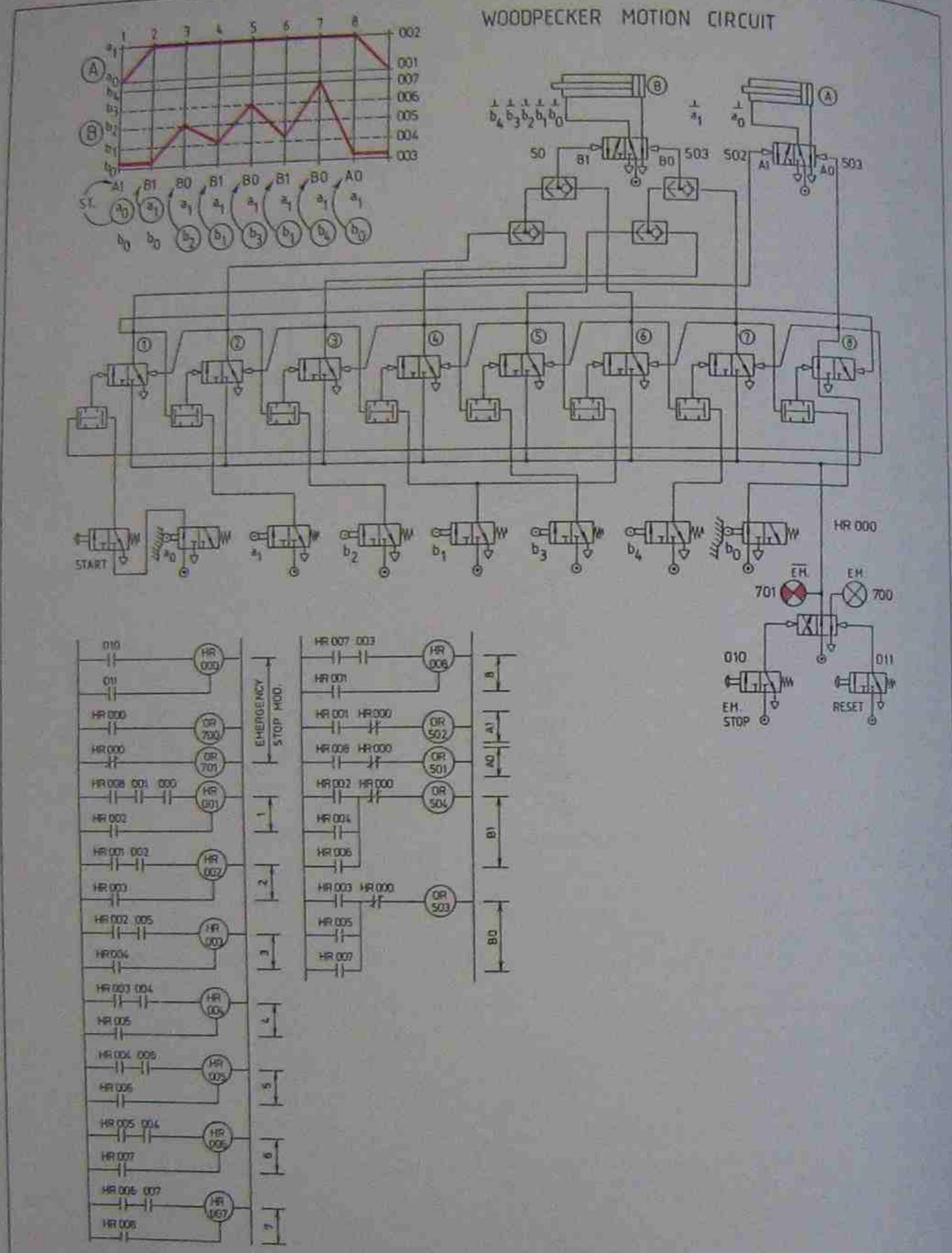


Fig. 11–17 P.L.C. programming instructions and emergency stop inclusion for a woodpecker control circuit (also shown in fig 8–21). Stopping mode no. 2 is used for this control example.

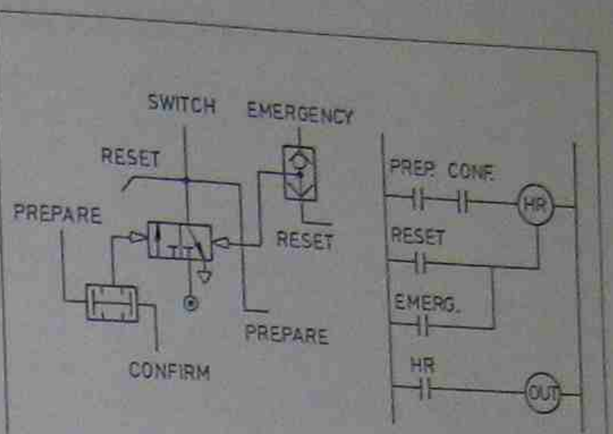
Continuation modes deviating from the normal sequence

Where the continuation mode (fig. 8–22) must deviate from the normal machine sequence, as shown in the traverse-time diagram, one can no longer use the step-counter to sequence the actuators, and therefore the step-counter must be reset to "ZERO".

To accomplish this, the stepping modules require an "OR" function on every reset rung in the ladder diagram leading to the keep relays (holding relays; see figs. 8-34 and 11–18). The last step-counter module logically needs no "OR" emergency reset-input, since there is hardly a possibility for an emergency to occur during the last sequence step.

Emergency-stop modification module for P.L.C.

For pneumatically controlled circuits it was recommended that a modification be used to produce a substitute for the missing preparation signal usually coming from the last keep relay in the sequence control. Because of the emer-

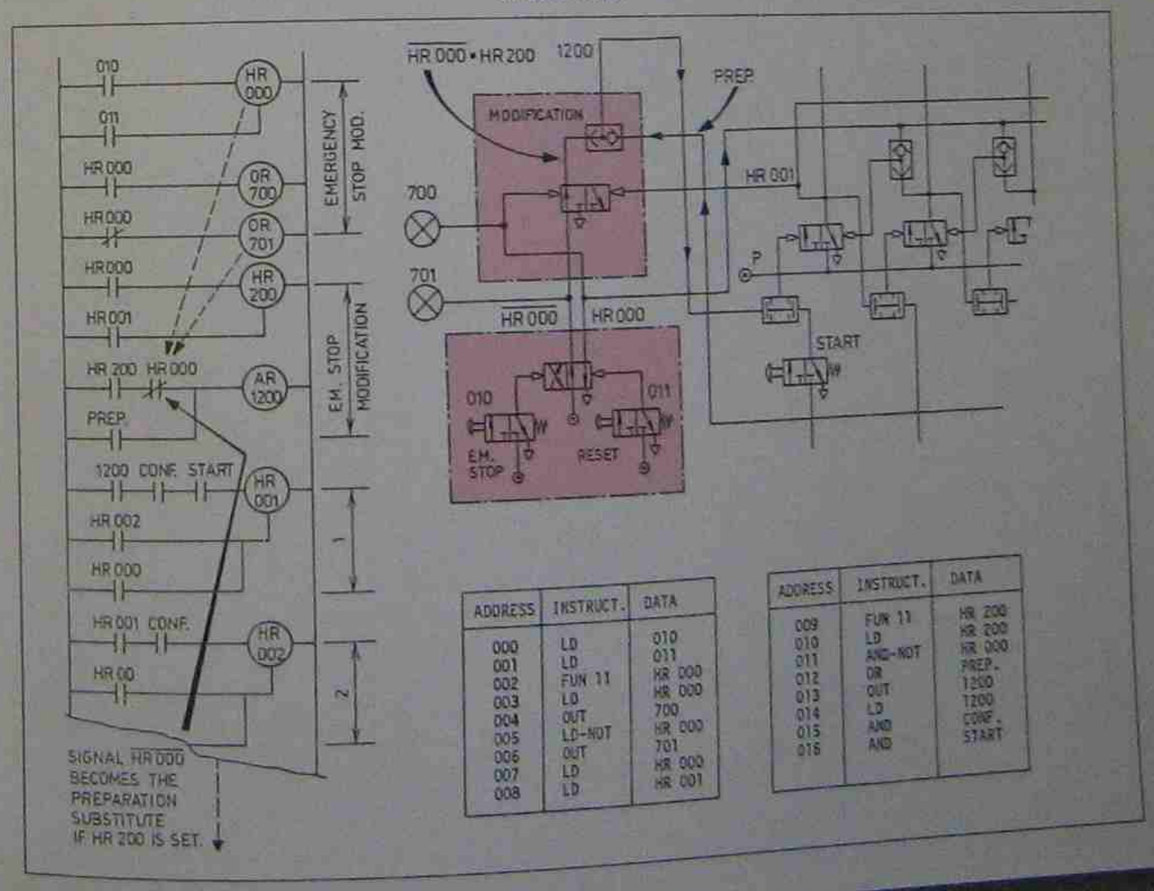


ADDRESS	INSTRUCTION	DATA
200	LD	(NO.)
201	AND	(NO.)
202	LD	(NO.)
203	OR	(NO.)
204	FUN 11	HR (NO.)
205	LD	HR (NO.)
206	OUT	(NO.)

EXPLANATION
PREPARATION SIGNAL
CONFIRMATION SIGNAL
RESET HOLDING RELAY
EMERGENCY SIGNAL
HOLDING RELAY ON
HR DRIVES OR
OUTPUT RELAY ON

Fig. 11–18 Step-counter module with emergency-reset provision.

Fig. 11–19 Emergency-stop module combined with preparation signal substitute module.



ADDRESS	INSTRUCT.	DATA
000	LD	010
001	LD	011
002	FUN 11	HR 000
003	LD	HR 000
004	OUT	700
005	LD-NOT	HR 000
006	OUT	701
007	LD	HR 000
008	LD	HR 001

ADDRESS	INSTRUCT.	DATA
009	FUN 11	HR 200
010	LD	HR 200
011	AND-NOT	HR 000
012	OR	PREP.
013	OUT	1200
014	LD	1200
015	AND	CONF.
016	AND	START

gency interruption, the last step counter module does not get set, and therefore no preparation signal is available to start a new cycle. It is, therefore, also necessary for P.L.C. programming to use this modification. For programming instruction see fig. 11-19.

Where the continuation mode demands that after the emergency command was given all actuators must return to their initial cycle position, one also has to use "OR" functions on the power valve signal inputs to achieve such emergency return. A typical control example including this continuation mode is given in fig. 11-20.

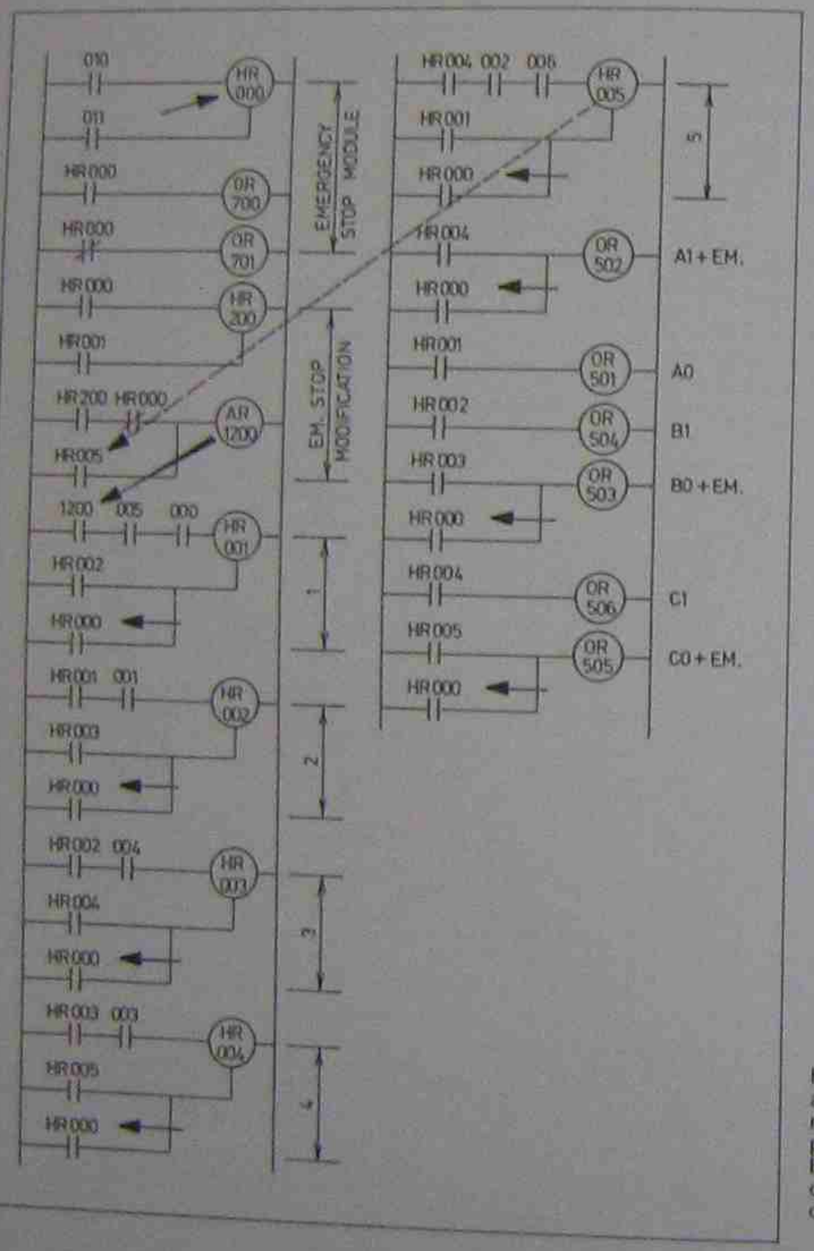


Fig. 11-20 Control example including an emergency stop module, a preparation substitute module, and a control program for the sequence: A0-B1-B0-C1/A1-C0. The emergency signal causes all actuators to return to their cycle start position at once.

Programming the P.L.C.

As previously explained, no commercially available electronic programmable controller can be programmed in exactly the same way as another brand.

The "OMROM C20", however, has many features in common with the more widely used brands for fluid power control. To give the reader a real recipe for the programming of a P.L.C. the following illustrations and procedural steps are based on the "OMROM C20". The "OMROM" manual suggests that the following seven basic programming steps should be used.

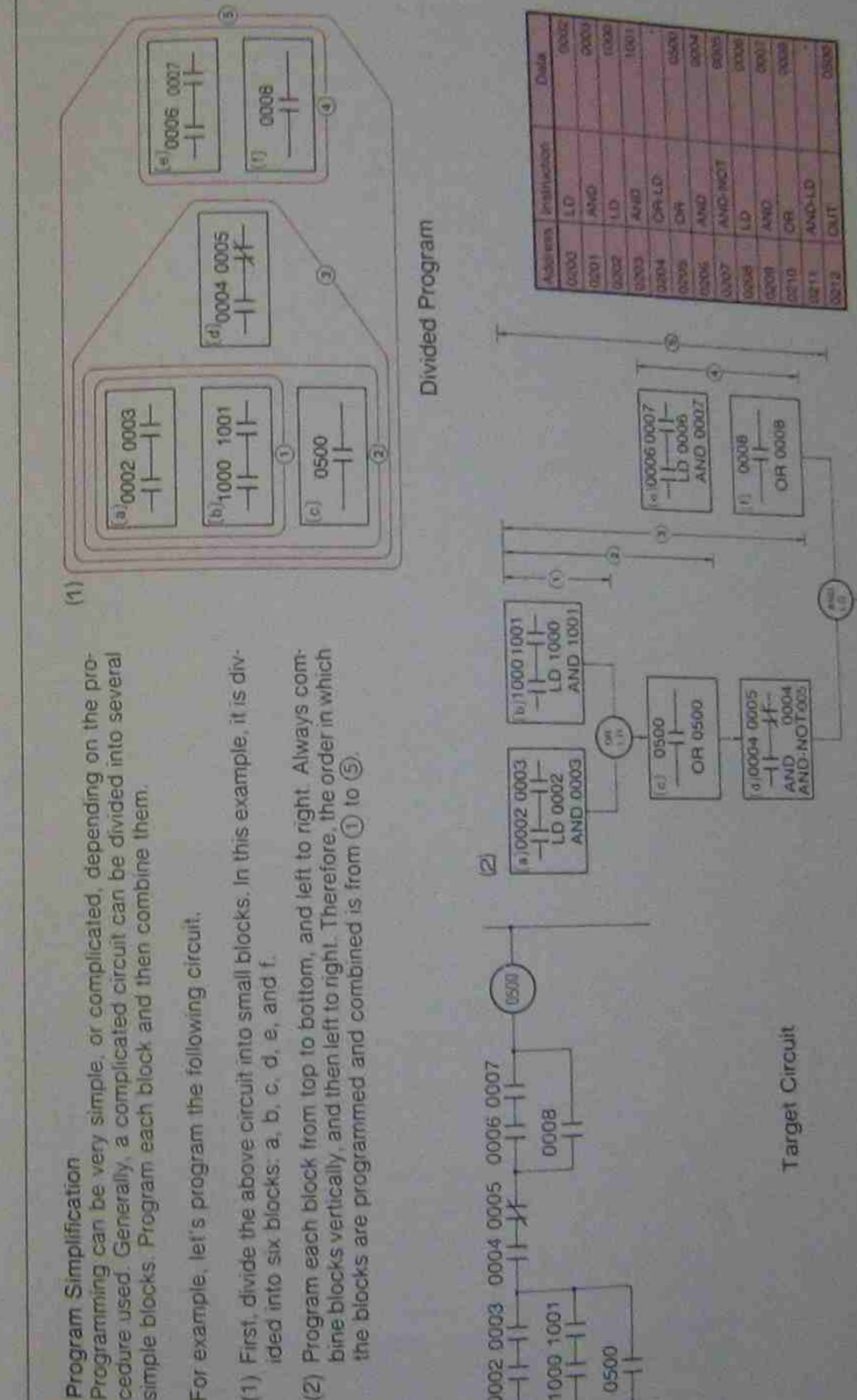


Fig. 11-21 Program simplification (target circuit — divided program — programming by blocks)

Program Simplification

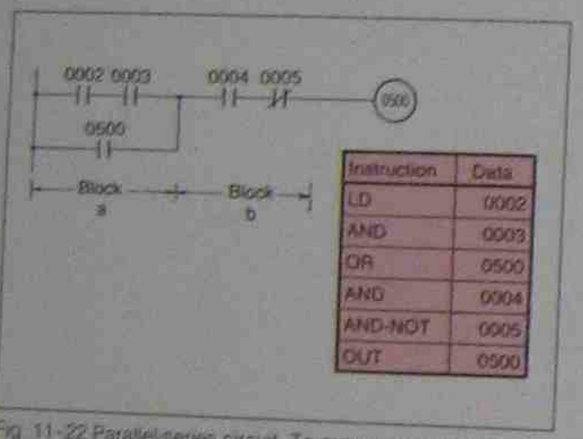
Programming can be very simple, or complicated, depending on the procedure used. Generally, a complicated circuit can be divided into several simple blocks. Program each block and then combine them.

For example, let's program the following circuit.

(1) First, divide the above circuit into small blocks. In this example, it is divided into six blocks: a, b, c, d, e, and f.

(2) Program each block from top to bottom, and left to right. Always combine blocks vertically, and then left to right. Therefore, the order in which the blocks are programmed and combined is from ① to ⑤.

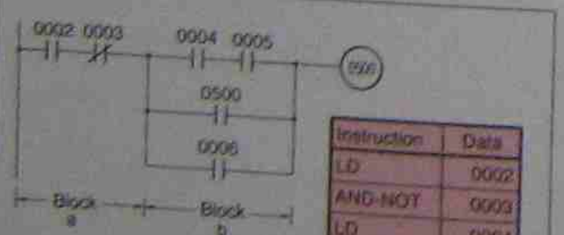
- Determine what the system to be controlled must do, and in what order the sequence steps must occur (draw a traverse-time diagram).
- Assign labels to all input and output devices. That is, designate name or number to all limit switches, start switches, or other input switches and also to all solenoid valve commands which cause these valves to redirect or pass flow (A1, B0, C1, a_0, b_0, START).
- Draw a ladder diagram using relay and contact symbols as shown in the previous illustrations. This diagram must represent the correct sequence at which the program is to execute its switchings.
- Code the ladder diagram with appropriate relay and contact numbers as shown in figs. 11-5 and 11-16. The C.P.U. of the controller does not accept any other instructions.
- By means of the programming console transfer these coded numbers and instructions into the C.P.U. of the controller.



Instruction	Data
LD	0002
AND	0003
OR	0500
AND	0004
AND-NOT	0005
OUT	0500

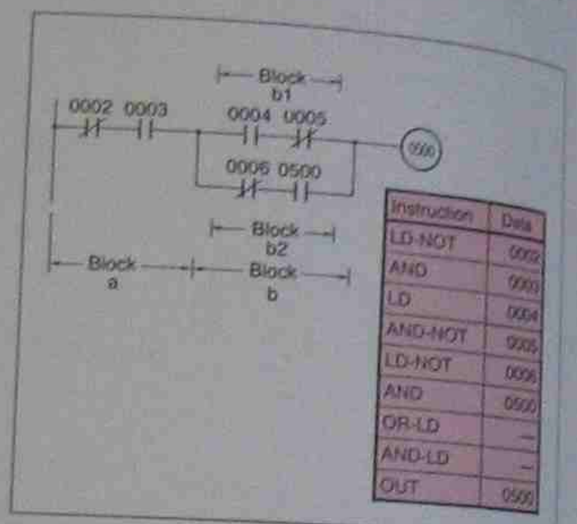
Fig. 11-22 Parallel-series circuit. To program a parallel-series circuit, simply program the parallel circuit blocks first, and then the series circuit blocks. In the following example, first program block a and then block b.

Fig. 11-23 Series-parallel circuit. To program a series-parallel circuit, divide the circuit into the series circuit blocks, and parallel circuit blocks. Program each block and then combine the blocks into one circuit. In the following example, divide the circuit into blocks a and b, and program each block. Then combine blocks a and b with AND-LD.



Instruction	Data
LD	0002
AND-NOT	0003
LD	0004
AND	0005
OR	0500
OR	0006
AND-LD	—
OUT	0500

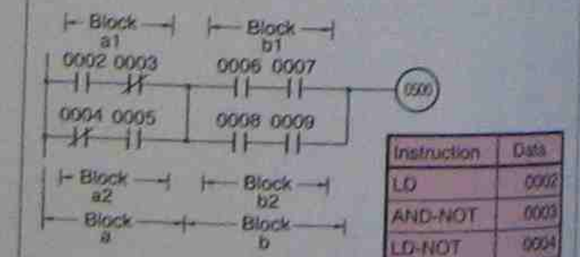
- Edit the program, and test the program for errors. These functions are accomplished with inbuilt "SEARCH" facilities which enable the programmer to locate, insert, delete and rectify any parts of the program before it is permanently saved onto a cassette tape.
- Save the program, after it has been tested, onto a cassette tape. The same tape may also be used to program other compatible P.L.C. controllers.



Instruction	Data
LD-NOT	0002
AND	0003
LD	0004
AND-NOT	0005
LD-NOT	0006
AND	0500
OR-LD	—
AND-LD	—
OUT	0500

Fig. 11-24 The parallel circuit block of the series-parallel circuit shown below can also be divided into two branches. In this case, program block a, and then blocks b1 and b2, in this order. Then combine blocks b1 and b2 with OR-LD. Finally combine block a and block b with AND-LD.

Fig. 11-25 Connecting parallel circuits in series. To program two or more parallel circuit blocks in series, first divide the entire circuit into the parallel circuit blocks. Then subdivide each parallel circuit block into the individual blocks. Program each of the parallel circuit blocks, and then combine them in series.



Instruction	Data
LD	0002
AND-NOT	0003
LD-NOT	0004
AND	0005
OR-LD	—
LD	0006
AND	0007
LD	0008
AND	0009
OR-LD	—
AND-LD	—
OUT	0500

Name	No. of points	Relay number
Input relay	80	000CH to 004CH
Output relay	80	005CH to 009CH
Internal auxiliary relay	136	010CH to 018CH
Holding relay (retentive relay)	160	HR00 to HR15: 00CH to 04CH; 05CH to 09CH

Name	No. of points	Timer/counter number
Timer/counter	48	TIM/CNT00 to 47

Fig. 11-26 Assignment of input/output channels and relay numbers for an "OMRON C20" programmable electronic controller.

Allocation of I/O channels and relay numbers

The C20 comes in two versions, a basic unit and an expandable unit.

The capabilities of the basic unit include up to 1194 program statements, 28 I/O points, and 136 internal auxiliary relays. The expandable unit is functionally identical to the basic unit except that it can be expanded using expansion I/O units to include up to 140 I/O points.

The C20 offers the flexibility of either RAM- or EPROM-based operation. When a RAM chip is installed as the memory, programs written by the user can be modified and rewritten. EPROM provides a semi-permanent storage for complete programs.

The programming console can be detached and is upwardly compatible with the full line of SYSMAC C-Series programmable controllers.

Due to its compact design, the C20 incorporates the detachable I/O terminals and microprocessor functions in a single housing called the CPU. The detachable programming console functions as the programming device. Additionally, various optional peripheral devices are available to support system expansion.

The input channel of the CPU is fixed at channel 00 while the output channel is fixed at channel 05.

When an expansion I/O unit, I/O link unit, or both are connected to the CPU, the I/O channel of the connected units are automatically assigned and registered in the CPU.

For example, when a 28-point expansion I/O unit is connected, input channel 01 is automatically assigned to the expansion I/O unit and registered in the CPU. As the output channel number of the expansion unit, 06 is automatically assigned and registered.

The input/output signals (devices) are connected to the input/output terminals on the CPU. Because the CPU uses the numbers assigned to the input/output terminals when executing the program, assignment and management of the input/output terminal numbers are required and must be correctly performed.

The numbers assigned to each relay are listed in the following tables. Use these to keep a record of which relays have been used.

Input relays

The CPU has 16 input relay points (one input channel). The number of input points can be increased to a maximum of 80 by the addition of expansion I/O units. Because one channel equals 16 points, this means that a maximum of five channels (from channel 00 to 04) are available.

The data from the SYSBUS are received by the input channel relays assigned to the I/O link unit.

Output relays

As with the input relays, the CPU has one output channel consisting of 16 relay points. However, of these 16 points, numbers 12 to 15 are internal auxiliary relays used to carry out CPU internal processes. For this reason, the number of output relays the CPU actually possesses is 12.

When expansion I/O units are connected to the CPU, a maximum of 60 output relays are available for a total of five channels, 05 to 09. The statuses of all the output channel relays assigned to the I/O link unit are transferred to the SYSBUS when an I/O link unit is employed.

Internal auxiliary relays

The CPU has 136 internal auxiliary relays (No. 1000 to 1807) that constitute channels 10 to 18.

Holding relays (retentive relays)

The CPU has 160 holding relays (No. HR000 to 915) that constitute holding relay channels 0 to 9. The holding relay retains data during power failure.

Timers/counters

The CPU has 48 points of timers/counters, TIM/CNT00 to 47, that can be used for either timers or counters. Timers and counters cannot be assigned the same number.

Temporary memory relays

The CPU has eight temporary memory relay points (TR0 to 7).

Special auxiliary relays

The CPU has 16 special auxiliary relays, some of which operate or release according to internal conditions controlled by the hardware irrespective of the statuses of the I/O devices. Each of these special auxiliary relays functions as follows:

Relay 1808
This relay operates when a battery failure occurs. An alarm signal indicating a battery failure can be output to an external device by programming a circuit incorporating the contact of this relay.

Relay 1809
Normally OFF

Relay 1810
Normally OFF

Relay 1811
Normally OFF

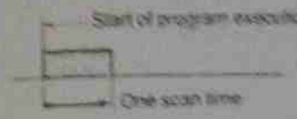
Relay 1812
Normally OFF

Relay 1813
Normally ON

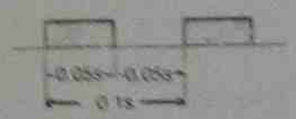
Relay 1814
Normally OFF

Relay 1815
This relay is turned ON for one scan time at the start of program execution.

A *scan time* is the time required for the PC to execute the user program once starting from address 0000 to the program's end instruction.

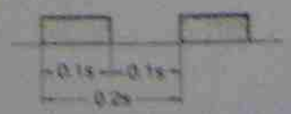


Relay 1900
This relay is used to generate a 0.1 s clock. When used in conjunction with a counter, it functions as a long-time timer that can retain its present value during power failure.



Note: The ON time of a 0.1 s clock is 50 ms. If a longer time is required for program execution, the CPU may fail to read the clock.

Relay 1901
This relay is used to generate a 0.2 s clock. When used in conjunction with a counter, it functions as a long-time timer that can retain its present value during power failure.



Relay 1902
This relay is used to generate a 1 s clock. When used in conjunction with a counter, it functions as a long-time timer that can retain its present value during power failure. The relay output can be also used as a flicker signal.



Relay 1903
This relay turns ON when the result of an arithmetic operation is not output in BCD form.

Relay 1904
This relay serves as a carry flag and operates or releases according to the result of an arithmetic operation. It can be forcibly turned ON by the SET CARRY (STC) instruction and turned OFF by the CLEAR CARRY (CLR) instruction.

Relay 1905
This relay turns ON if the result of the COMPARE (CMP) instruction is ">" (more than).

Relay 1906
This relay turns ON if the result of the compare operation is "=" (equal to). It may also turn ON if the result of an arithmetic operation is 0.

Relay 1907
This relay turns ON if the result of the compare operation is "<" (less than).

Relays TR0 to 7
These are temporary memory relays and may not necessarily be assigned in sequence. The same coil number of these relays must not be used in duplicate within the same block of a program. However, the same coil number can be used in a different block. When using a temporary memory relay, the letters "TR" must be prefixed to the relay number (e.g., TR0).

Assigning I/Os

Points and channels

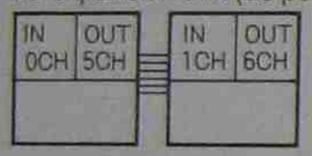
The programmable controllers of the SYSMAC C-Series all use the concept of I/O channels to identify individual I/O terminals, or points. Each of these channels consists of 16 points.

CPU (28 points)



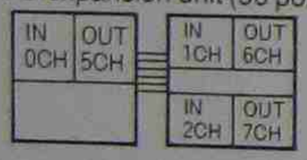
The four-digit number used to identify an I/O point therefore can be broken down into the left-hand two digits, which identify the channel, and the right-hand two digits, which identify the point within the channel.

CPU (28 points)
+ I/O expansion unit (28 points)



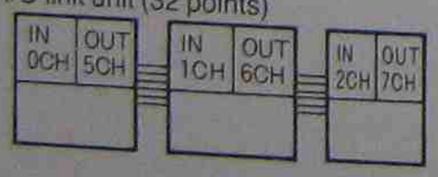
For example, "0000" identifies the first point of the first channel and "0104" identifies the fifth point of the second channel. In the C20, the first five channels (00 to 04) are used for input and the next five (05 to 09) for output.

CPU (28 points)
+ I/O expansion unit (56 points)



Note: for simplicity reasons the author has omitted the first digit on all input relay numbers. Thus number 0002 appears as 002, etc.

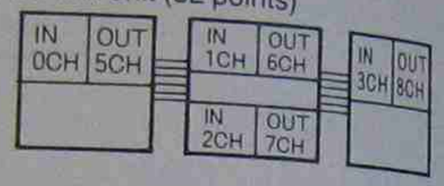
CPU (28 points)
+ I/O expansion unit (28 points)
+ I/O link unit (32 points)



The actual number of points used by the basic C20 is 16 inputs and 12 outputs.

Remember that the C20 can be expanded by adding expansion I/O units. Up to four new channels can be added for a total of 80 (5 × 16) input and 60 (5 × 12) output points.

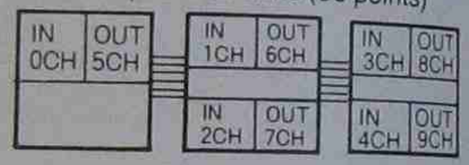
CPU (28 points)
+ I/O expansion unit (56 points)
+ I/O link unit (32 points)



I/O channel assignment

The assignment of I/O channels is as shown on the left.

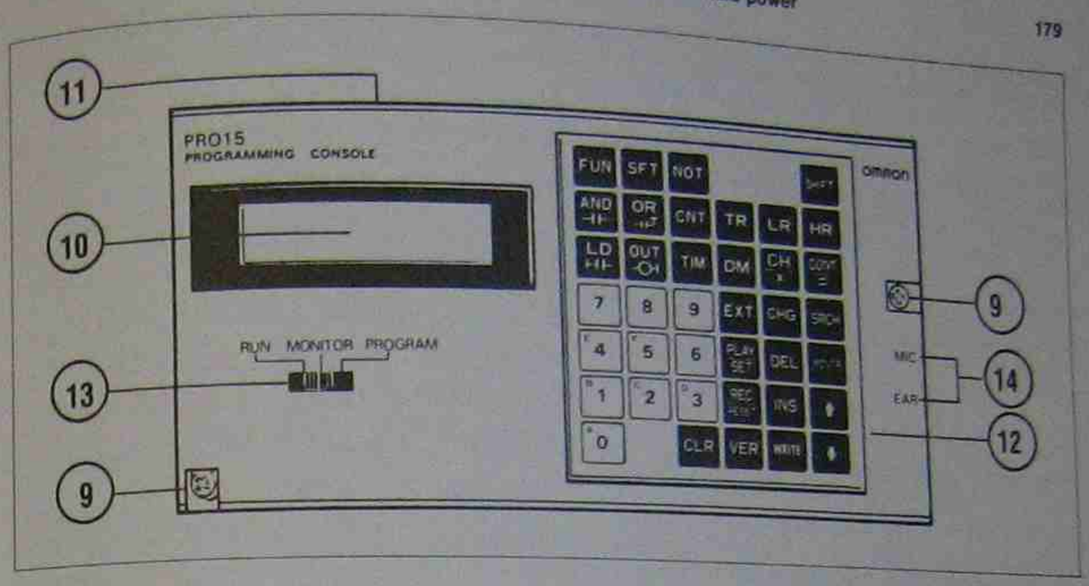
CPU (28 points)
+ two I/O expansion units (56 points)



Note: The total number of I/O points, including those of an I/O link unit, cannot exceed 140.

Programming console

This is the standard programming device used with the C20. The control programs written by the programming console are stored and run in the CPU.



9 Mounting screws

These two screws secure the detachable programming console to the CPU.

10 LCD

This displays the program as it is being written and is used for checking and monitoring program operation. It also displays error messages.

11 Display light switch/contrast switch

This display switch controls the light that illuminates the LCD for use at night or in poorly lit environments. The contrast switch adjusts contrast level of display.

12 Keypad

The color-coded keypad is functionally divided into the following areas:

White 10 keys used to input program addresses, timing values, and other types of numeric entry

Red One key used to clear the display

Yellow 12 keys used to provide editing functions while writing and correcting the control program

Grey 16 keys used to input instruction words used in the program

The function of each key is detailed later in this chapter.

13 Mode selector switch

This three-position switch selects one of three operation modes of the PC: program, monitor, and run. These modes are explained in detail in Chapters 4, and 5.

14 Jacks for connecting cassette tape recorder

Programs may be saved to a standard cassette tape recorder connected to the output (MIC) jack. Previously written programs can also be supplied to the CPU via the input (EAR) jack.

The keyboard

Numeric keys

These are the white keys numbered 0 to 9.



These keys are used to input numeric values used for program data. For instance, in a program as shown in figs. 11-13 and 11-21, these keys would be used to input the input/output numbers and timer/counter numbers and values.

These keys are also used in combination with

the function key (FUN) for special instructions such as FUN 11 (keep relay or holding relay).

CLR key
This red key is used to clear the display. It is also a key used when keying in the "password", which is used to foil unauthorized access to the PLC's program. Rather than using an actual password, though, one gains access using this two-keystroke entry:



When this is done, on the console display one will see written either PROGRAM, MONITOR, or RUN. Pressing the CLR key again makes the word disappear and prepares the PLC for the operation selected with the three-position mode switch.

Operation keys
These yellow keys are the ones used to carry out the editing functions of the programming console. These functions will be explained in more detail later but at this point it's important to know how three of these keys in particular are used.

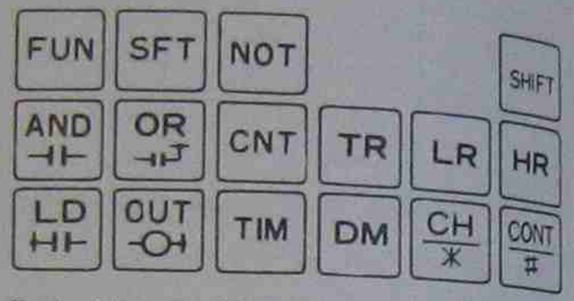


The first two are the arrow keys. To move through the program a step at a time, press the bottom (down) arrow key. The displayed address of the program will increment once for each press. To go in the opposite direction, press the other (up) key. The program will then decrement one step at a time until it reaches its beginning.

The arrow keys are normally used for moving only a small number of steps in the program. Later several ways are given to move right to the program step you want.

The third key important in the yellow group is the WRITE key. During programming when one has written an instruction and its data, this key is used to register the instruction in the PLC memory at the address desired.

Instruction keys
Except for the SHIFT key on the upper right, these grey keys are the ones used to place instructions in the program. The SHIFT key is similar to the shift key of a typewriter, and is used to obtain the second function of those keys which have two functions.

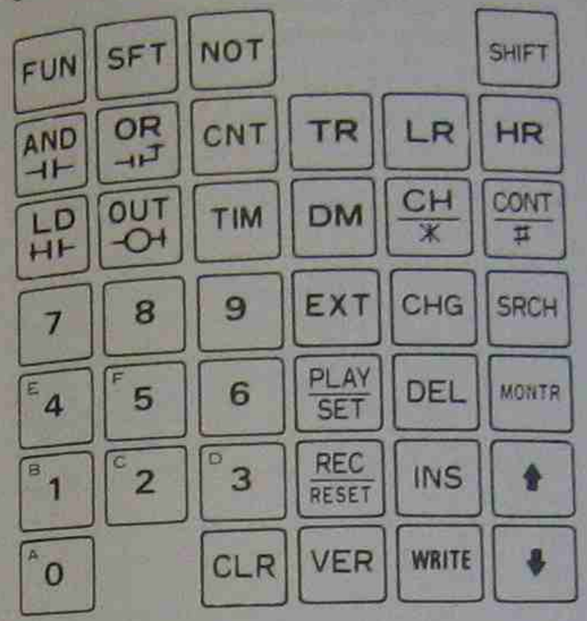


Each of the remaining grey keys has its function indicated by an abbreviation. The abbreviations mean:

FUN Selects a special function. Used to key in special instructions. These special instructions are realized by pressing FUN and then the appropriate numerical values. The special instructions are listed in Appendix B.
SFT Enters SHIFT REGISTER instruction.
NOT Forms NC contact.
AND Enters AND instruction used for ANDing two contacts.
OR Enters OR instruction used for ORing two contacts.
CNT Enters counter instruction. Must be followed by counter data.
LD Enters LOAD instruction used for loading a specified input.
OUT Enters OUTPUT instruction for outputting to a specified output point.
TIM Enters timer instruction. Must be followed by timer data.
TR Enters temporary memory relay instruction.
LR* Enters link relay instruction.
HR Enters holding relay instruction.
DM* Enters data memory instruction.
CH* Specifies a channel.
CONT Used to search for a contact.

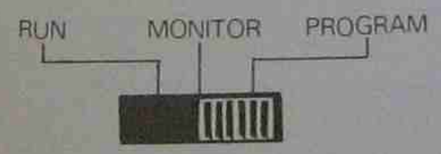
* Although these functions are not available on the C20, these keys are provided to ensure programming console compatibility with other SYSMAC C-Series PLCs.

A complete overview of all the keys on the programming console is given below.



Mode switch
Now let's turn to the three-position mode switch one will use to select the operating mode of the PLC. Three modes can be selected.

The RUN mode is the one used to begin PLC operation. When this mode is turned on the PLC begins controlling the equipment using the program written into the PLC memory.



The MONITOR mode allows visual monitoring of the operation in progress. For instance, if one wants to check that a particular relay is in the correct state (either ON or OFF) at the proper time, one can move to the address (or step) which references that relay.

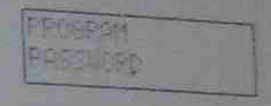
Using the PLC in the RUN and MONITOR modes is explained later.

The PROGRAM mode, which is fully explained below, is used during the programming operation.

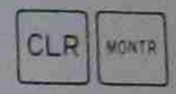
Console display
The easy-to-read display is a practical window to look into the workings of the PLC. The display format changes depending on the mode selected. Let's first examine the PROGRAM mode.



PROGRAM mode
If the mode selector switch is turned to PROGRAM, this is what you'll see when you apply power to the PLC.



This is your electronic sentry that blocks unauthorized use of the PLC. To gain access, an actual password isn't necessary—just this key sequence:



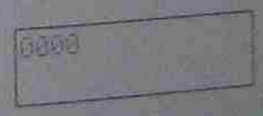
The PLC responds with a beep each time you depress a key. This is what you now will see, informing you of the mode you are in.



To clear this, press



At this point you are ready to begin entering your program step-by-step using the code you wrote from your ladder diagram. The display you see is the starting address of the memory. This location is used in connection with the quick-search editing functions.



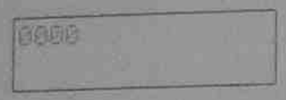
Let's skip this for now because we won't need to use it until after we have input our program.

Although it is possible to overwrite an old program with a new one, this is not recommended because it may cause confusion and lead to program-writing errors.

If the programming console has been used before and an old program currently exists in the memory, carry out the procedure given next.

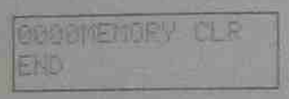
To erase existing memory

Caution: The following procedure will entirely and permanently erase any program which currently exists in the CPU memory.



Anytime you want to erase the memory or start again when inputting your program, use this key sequence:

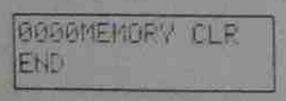




At this point, the display will be the one shown at left to allow you to reconsider. If you then press



you have finished the memory clearing operation and the display will change to this.



Now if you press

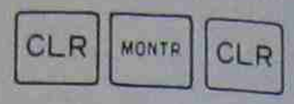


you can begin writing your program.

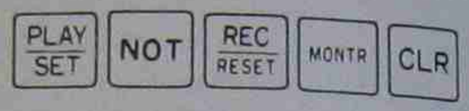
Summary

Putting all these steps together, here's a summary on what to do to begin programming the CPU:

1. Confirm whether a RAM chip is mounted and the DIP switches are set correctly.
2. Apply power to PLC
3. Turn mode selector switch to PROGRAM
4. Do these key sequences:



5. If you want to completely clear the old memory, press



Example program

For practice, let's key in the program code given below. This is the coding chart used as an example.

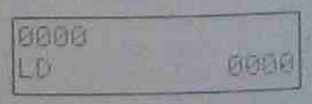
Address	Instruction	Data
0000	LD	0000
0001	LD	1000
0002	CNT	47
		#0005
0003	LD	CNT47
0004	OR	1000
0005	AND.NOT	TIM00
0006	OUT	1000
0007	LD	1000
0008	TIM	00
		#0020
0009	OUT	0500
0010	END(FUN01)	

Entering the program in the CPU

The first information to be keyed in is the LD instruction. To do this, press



and you see this display



The first set of four 0s at left is the beginning address position, and is where the LD instruction will be stored. The second set of four 0s at right is a

numeric value representing the input point. Currently the input point is 0000. Since this is the value you assigned to the input of Counter 47, you can leave it unchanged. Then, to WRITE this LD instruction to memory address 0000, press

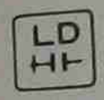


and this display appears.

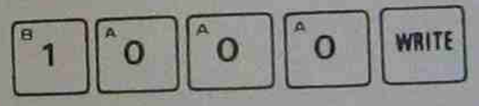


Here, 001 is the address number; READ means you are reading the program; and NOP (00) means that no operation has yet been assigned to this address.

Next enter



again to specify the reset input of the counter. READ disappears because you are now *writing* to address 0001 instead of only *reading* its contents. Now key in the relay number and write it to the address with



In the next address we want to input the counter. This is done by pressing



Now we have to specify the coil number of the counter we want, which is 47. Do this by keying in



This second counter display



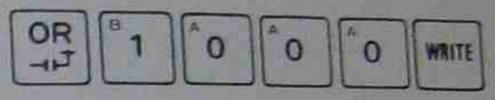
indicates the set value of the counter. Currently it is 0000. We want to change this to 5, the number of signals that must be input by the optical sensor. So key in



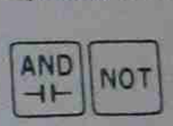
Now we have to enter the LD instruction to specify the contact of the counter that corresponds to the coil of Counter 47. Do this by pressing



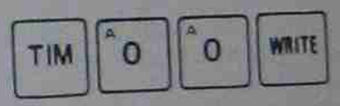
For address 0004, key in



to enter the OR instruction and specify the internal auxiliary relay number. So that the timer acts to turn on the solenoid only 2 seconds, for address 0005 key in

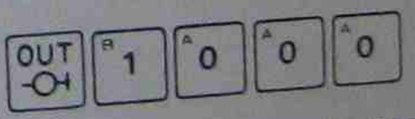


This causes the contact of the timer instruction to act as an NC (normally closed) contact. Key in

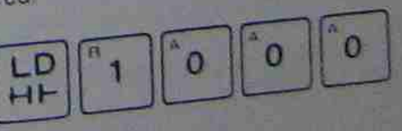


Now we have finished entering the timer contact. The timer coil for this contact must exist somewhere in the program for the timer instruction to be executed.

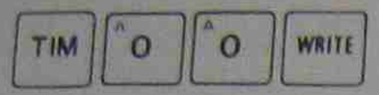
For address 0006 to designate the relay coil, key in



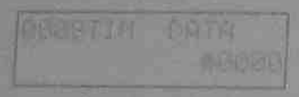
For address 0007, key in the contact corresponding to the internal auxiliary relay coil we have just entered.



Remember that the coil and the time value for the contact keyed in for address 0005 must still be specified. This is done by keying in



for address 0008.



This message is displayed asking for the timer data. Since the data includes a decimal point before the last digit, to set a value of 2 seconds, we enter

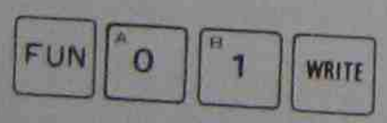


The only thing that remains is to complete the circuit by specifying the output. Do this by entering



The output relay number for this output is 0500, which is automatically selected by the PLC. (Remember that 05xx is the ouput channel designation, while 00xx is the input channel designation. The relay number is xx.)

The final instruction in our program is the END instruction, which tells the PC that the program is complete. Writing this requires the use of the FUN key and the value 01 which represents the END instruction. So key in



and you're finished.

Now check your program

To check whether the program has been correctly written, go back through it using the arrow keys to scan what you've done. If you see you need to make corrections, just overwrite the statements that are in error.

Deletion and insertion of instructions is explained next.

Deleting instructions

Let's return for a moment to Timer 00. For practice, let's delete it from the program using the following procedure.

First, go to address 0008. Then key in



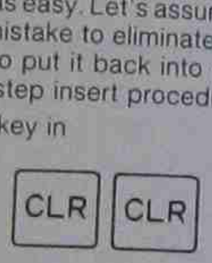
This eliminates the TIM instruction and moves the next instruction (LD, in this case) into the 0008 address location.

This function is useful when you wish to modify or correct an existing program.

Inserting instructions

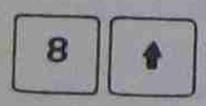
Inserting an instruction somewhere in a program is almost as easy. Let's assume that we now realize it was a mistake to eliminate Timer 00 from the program. To put it back into the program, we follow this six-step insert procedure:

1. First key in

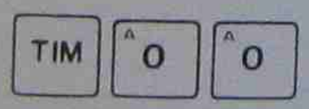


This takes you to the first address of the memory.

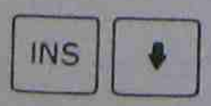
2. Then key in the number of the address where you wish to make the insertion.



3. Press

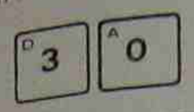


4. And then



to move the program down one step, reserving address 0008 for the TIM instruction.

5. Key in the TIM data





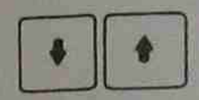
6. Then press



to complete the insertion.

Note: Steps 5 and 6 are necessary only to input the timer and counter data. These are not required for insertion of other types of instructions.

You can check that the insertion has been correctly done by moving the program using the arrow keys.



Spend some time becoming acquainted with these editing functions by inserting and deleting various instructions. In the next chapter you'll learn how to put these to use in debugging much larger programs.

Checking and running your program

Overview

The C20 has a number of helpful features to help you debug your program and fine-tune the operation before and after it is under way.

This instruction covers the final three steps for programming. We now explain how the quick-search editing functions make locating instructions quick and easy. Also explained is how to correct the program using the C20's debugging capabilities.

Once you're ready to begin a test run of the program, you'll learn how you can monitor the operation and make any necessary modifications based on the actual performance of the equipment.

Finally, we show you how to use a standard cassette tape recorder to save and load your program.

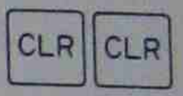
Editing the program

Quick-search editing functions

The C20 programming console has three features which greatly facilitate program editing and debugging. One allows you to go directly to specific program addresses. Another allows you to hunt for specific instructions. The last lets you speedily check each contact. These editing features eliminate the need for you to travel through the program a single step at a time—quite a tedious process when a large number of addresses are involved.

Going directly to a known address

This is a simple way of going straight to the address you want. Do this by first clearing the display by pressing



Then key in the number of the address you want.

Let's assume that we want to change the time value from 2.0 seconds to 3.0 seconds. We first key in its address



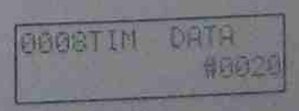
and follow that with



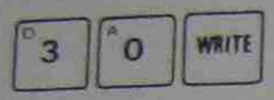
When you do this you will see that the display has gone directly to address 0008. Before you can change the time value, however, you must first go to the timer's data by pressing



to move the program down one step. This is the display.



At this point you can make the change to 3.0 seconds by keying in



Check the display. It should now look like this.

```
0008TIM  DATA
           #0030
```

When correcting or modifying a program, this method of address locating is particularly useful to go quickly to a new part of the program. Note, though, that you must always start at the first address in memory which is reached by pressing




```
0000
```

one or more times.

Searching for a specific instruction

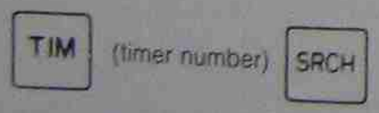
This second editing technique gives you a convenient way to locate a particular instruction for which you do not have to know the program address. Assume, for example, that you wished to go to an unknown address containing Timer 00. To do this, press



several times until you see the first address.

```
0000
```

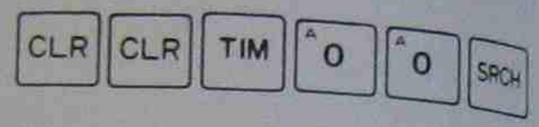
Then key in



This takes you to address 0008 which contains Timer 00.

This editing feature has a wide range of uses. For instance, in a long program you may wish to determine whether you have inadvertently used the same timer or counter number more than once. This normally would be an error, since a particular timer or counter should be used only once in a program.

Let's imagine for a moment that our program is actually quite large and that there's a possibility that Timer 00 has been duplicated somewhere. We would search for the first reference to this timer by using the approach we just learned. Do this by keying in



which moves us again to address 0008. To search for any illegal timers, simply press



again, which tells the PLC to scan the rest of the program for any other mention of a timer with the number 00. As you can see, there are no others in our program. (To test this further, go to any address, say 55, write in TIM00, and then repeat the search procedure.)

NO END INSTRUCTION message

In doing this you may have reached this display message.

```
1193NO END INSTR
END
```

The number 1193 here represents the total number of address locations available. Normally when you see this message, it means that you forgot to put an END instruction at the end of your program.

This is one time when you can ignore the error message, though. The search function has carried you into the unused region of the memory (address locations 0011 to 1193). No new END statement is actually required here.

Searching relay contacts

The quick-search operation can be performed still another way. If you wish to locate specific contacts, this can be accomplished easily in any of the three modes with this simple operation. Start from the first address of memory. Then press




```
0000CONT
LD          0000
```

If you still have our sample program in the CPU memory, this should be the display. Then, to go to the next contact with the same number, again press

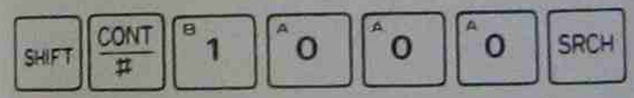


The display now changes to the next address containing an instruction with the same contact number (the four digits at the lower right of the display). This continues until the end of the program is reached.

If you want to search for a contact having a different contact number, follow the same steps as before. But this time, enter the numeric value of the contact you want to locate.

Using our sample program, if you enter 1000 and press the search key, the display will show the LD instruction in address 0001. This is how you would do it:

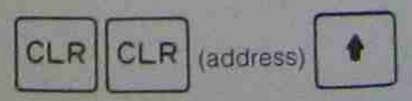
```
0001CONT SRCH
LD          1000
```



Search function summary

The C20 gives you three convenient ways to search through a long program for specific addresses, instructions, or contacts. The key entries for these are summarized here:

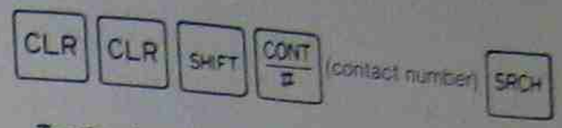
Address search



Specific instruction search



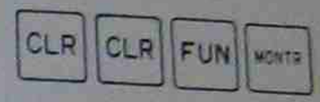
Specific contact search



Testing for errors

The C20's debugging features can be used to catch many types of programming errors. For this you use the FUN and MONTR keys in any of the three modes.

To see if the program you entered in the PLC has a programming error, press



This is the display if no error is found.

```
0000ERR CHK
OK
```

If an error is found in the program, the corresponding error message number will be displayed. Refer to Appendix E, Maintenance and troubleshooting, and carry out the corrective action listed there.

If more than one error exists, continue pressing



to display each error message one at a time.

There are basically two levels of errors—fatal and non-fatal. A fatal error, such as a memory error, prevents the PLC from operating. A non-fatal error, such as a battery failure, allows the operation to proceed but still must be corrected. In case both types of errors have occurred, the error messages for the fatal error take precedence over the other and must be corrected first.

Status check

At times you may want to scan the status (whether ON or OFF) of each relay contact before you start the control operation. This can be an effective troubleshooting technique and is available in both the RUN and MONITOR modes.

You would normally perform the status check after you have carried out the debugging step above. To begin, go to the first address and press



You'll see the address, the instruction, and the word OFF or ON displayed in the upper right hand corner of the LCD. OFF or ON indicates the current state of the relay contact. Continue pressing the DOWN arrow key to check the status of each of the relays that follow.



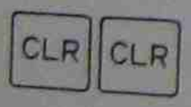
Forced set/reset

During the execution of the program, this operation is used to force set or reset (for one scan time) the operating status of each I/O relay, internal auxiliary relay, holding relay, timer, or counter. This operation is only meaningful while the PLC is in the MONITOR mode.

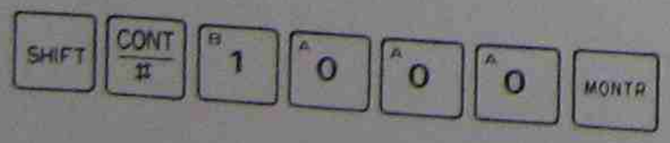
The most common use of this function is during a trial run of the controlled system. For instance, if a particular task (such as illuminating a heat lamp for drying) would normally take 30 minutes but you simply wish to test the contact, use this function to force reset the contact after a few moments of lamp operation. The program could then continue to the next task in the control sequence without delay.

Forced relay set

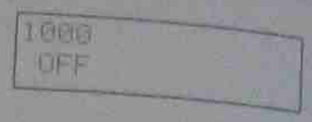
To do a forced set of a relay contact, first place the PLC in the MONITOR mode and press



Now specify the contact that you wish to force set. In this case, Relay 1000 is to be forced set. Press



The display shows the present status of the relay which in this case is OFF



Now, to force set the relay (to ON), press



This force sets the relay from OFF to ON.

Forced relay reset

To force reset a relay to the OFF state, press

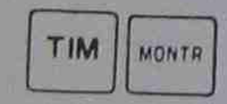


This turns the currently ON relay to OFF.

Forced timer set

To force set a timer, put the PLC in MONITOR mode and press





The display shows the first timer, Timer 00, and its preset time if the timer is not currently running. Then, to clear the set time for one scan time, press



Due to the short cycle period, however, you will not be able to see this clearing actually take place. If the timer is currently operating, depressing



displays the current value of the timer. If the timer has completely gone through its timing period, you will see this value.



Depressing



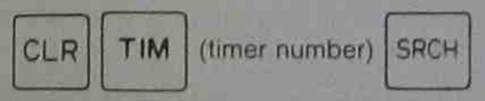
restarts the timing operation from the set time.

Note: Special auxiliary relays 1808 to 1907 cannot be forcibly set or reset. These relays serve as flags that are internally "raised" and "lowered" (set and reset) to enable monitoring of PLC operation. If an attempt is made to set or reset one of these relays, you'll hear a beep and no key input will be accepted by the programming console.

Changing set value of timer or counter

It's also possible to change the set value of a timer/counter during program execution. This is used for such purposes as slowing down or speeding up an assembly line operation without having to stop the program.

This operation can only be done in MONITOR mode. To reset the value of a timer, first key in



In our sample program, the timer number is 00.

Now press



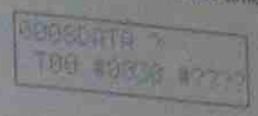
to move to the timer data display.

The timer currently is set for 3.0 seconds. To change this to 6.0 seconds, press

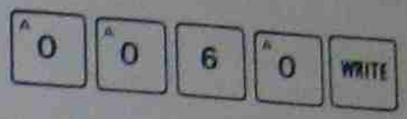


and the PLC display will query you about the new data.

0008DATA? informs you that the operation to be performed is the setting of a value for the instruction address 0008; T00 is the number of the timer; #0030 is the timer's present set time; and #???? asks what you want the new set time to be.



In response, key in your new set time and write it to the PLC memory.



Follow the same procedure to change the set value of a counter.

Input/output monitor

While the PLC automatically controls the equipment, you can keep a watchful eye over the operation using the PLC's monitoring capabilities.

You may, for instance, have a particular unit of equipment that you want to check for correct operation. Or you may want to keep a running check on the value of a down counter.

The C20 allows you to easily check the status of any device connected to it by this procedure.

Place the PLC in the MONITOR mode during operation.

Locate the device you wish to check. We could do this for Counter 47 in our practice program, for instance, by keying in



which gives this display



Press



and the display changes to this.



If the PLC were currently operating, we would be able to watch the counter as it is decremented. The same thing is also possible with timers.

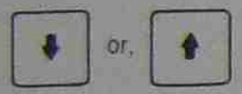
Rapid check of counter/timer values
For a fast way to visually scan the set value of all timers and counters in a program, go to an address where a timer or counter is located. Then press



and the set value of the timer/counter is displayed as a four-digit number.



Then, each time you press



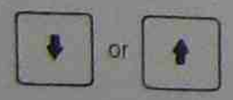
you will be able to see the set time of the next timer/counter.

Rapid check of relay status
You can check the status of relay contacts using the same technique. To do this, go to the address of a relay you want to check. Then press



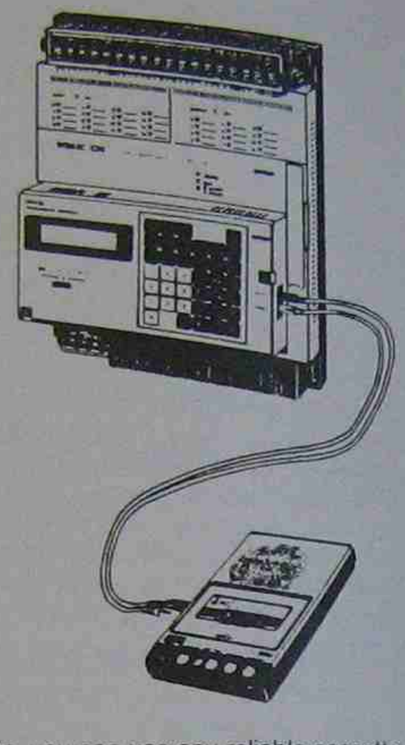
to display the current status (whether ON or OFF) of the relay. Then, to move to the next relay, press either





Saving your program to cassette tape

At this point it's assumed that you have completed program debugging and the trial run of the equipment and are satisfied with the operation. Now it's time to save the program to a cassette tape.



For this, you can use any reliable cassette tape recorder.

This provides a way to save your programs for later use. The same tape can also be used to program other C20s which control identical operations. Multiple copies of the tape can be made using a conventional tape copier, at either normal or high speed.

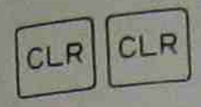
Store only one program to a tape (or side of a tape). The reason for this is that there is no way to identify individual programs if more than one have been stored on the same side of a cassette. The only requirement is that the tape be at least 7 minutes long. Either a standard or microcassette tape can be used.

First you'll learn how to save the program you have in the PLC's memory. Then you'll see how to load it back into the PLC and verify that it was loaded correctly.

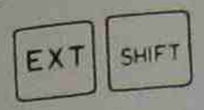
To save the program, carry out this procedure:

1. Plug one end of a Type SCY-PLG01 cable into the MIC jack of the PLC and the other into the MIC jack of the tape recorder.*
2. Plug a second cable into the EAR jacks of both devices.**
3. Turn the volume and tone controls of the tape recorder to their maximum levels.
4. Switch the PLC to the PROGRAM mode.

5. Press



6. Press



A message is displayed to ask you to start the save operation.

* On some tape recorders this may correspond to the LINE-IN jack.
** On some tape recorders this may correspond to the LINE-OUT jack.

7. Press the button or buttons on the tape recorder that begin the recording.
8. Then within 5 seconds press



on the programming console keyboard. A blinking rectangle appears in the right corner of the display. This means the program is being saved to the tape.

9. Wait about 7 minutes.

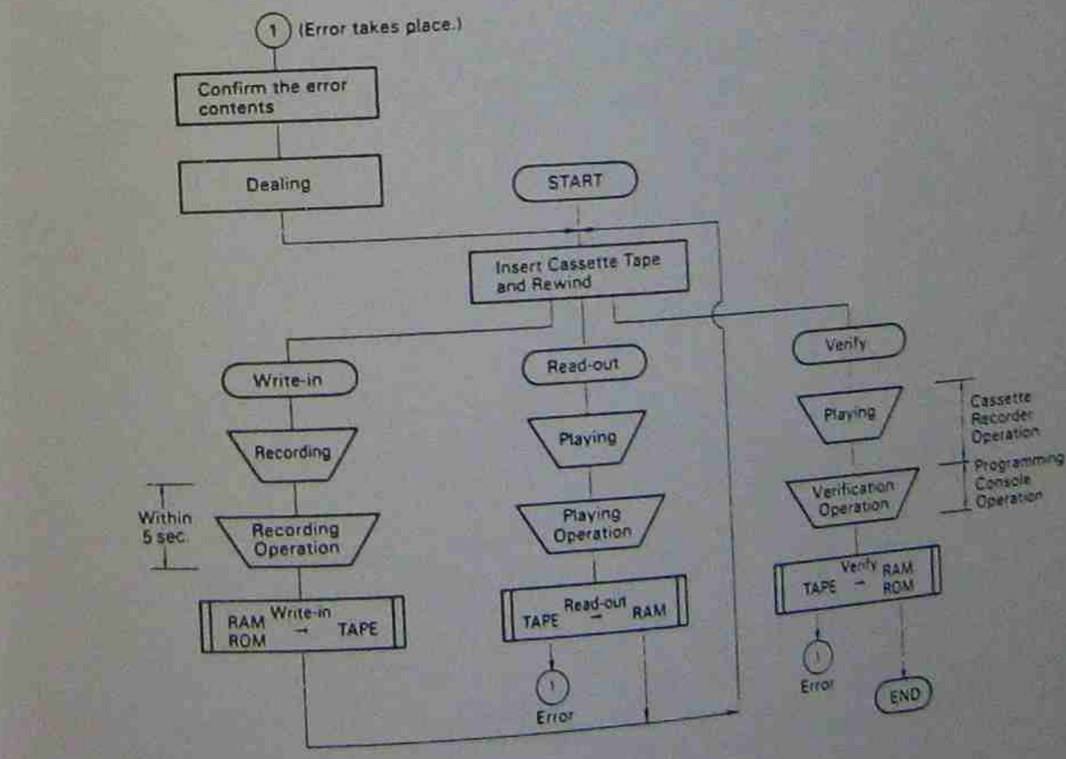
The program is being saved from the first program address to the end of the RAM/EPROM memory area. The PLC display increments as each address goes into the cassette recorder. During this period you can halt the save operation by pressing



10. When the program (plus vacant memory) has been completely recorded, the save operation stops with this message.



Refer to this flowchart for the correct procedure when saving your program to the cassette recorder.

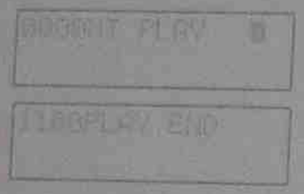


Loading and verifying the program

Before loading a program into the C20, determine that the tape is correctly positioned. The taped program should begin to load into the PLC within 5 seconds after the loading operation has been initiated. You can determine this by listening for the sound that marks the beginning of the program. Then rewind the tape slightly so a few seconds of blank tape precedes the beginning of the program. Then follow these steps:

1. Press PLAY on the tape recorder to start loading the tape into the PLC.
2. Press





on the PLC keyboard. When you do, this message appears and you'll see a blinking rectangle on the upper right portion of the display.

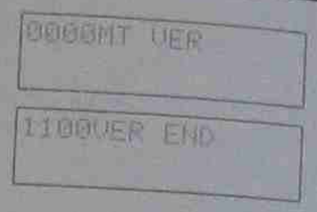
3. Wait about 7 minutes for the program to be completely loaded.
4. When the loading is complete, a message appears.

Verifying the program

It's always a good practice to check that the program was loaded correctly. This is done by performing the following procedure:

1. Rewind the tape until you reach the beginning. Provide about 5 seconds of blank tape leader before the taped program segment begins.
2. Turn on the PLAY button of the tape recorder.
3. On the C20 keyboard, press





When you do, a message appears and a blinking rectangle indicates that program verification is taking place.

4. Wait about 7 minutes. A message will appear when verification has been successful.
5. If a program loading error has occurred, one of the messages described in Appendix E will be displayed. In this case, repeat the tape load operation.

12 Compressed Air Servicing

The final stage of compressed air servicing or conditioning is a process carried out on the air supply, directly before its point of usage. This process is accomplished by three devices, collectively called the *air service unit*, sometimes abbreviated F.R.L. or A.S.U. The air service unit consists of a filter, a pressure regulator, and in most cases also a lubricator. To read off the adjusted system pressure, a pressure gauge should also be attached to the pressure regulator (fig. 12-1). One of the three aims of the air service unit is to provide the air consuming equipment (actuators, motors, air tools and control circuits) with compressed air of suitable cleanliness: that is, without contaminants such as dirt and water. This aim is accomplished with the air filter.

The air service unit should also provide pressure stabilised air at no more than the required maximum pressure, which is normally about 50 kPa below the cut-in pressure of the air compressor capacity controller, but may be adjusted to less if required.

Lastly, it provides an air supply (flow), which carries lubricating oil in the correct adjusted quantities to lubricate the various components, such as valves, cylinders and motors.

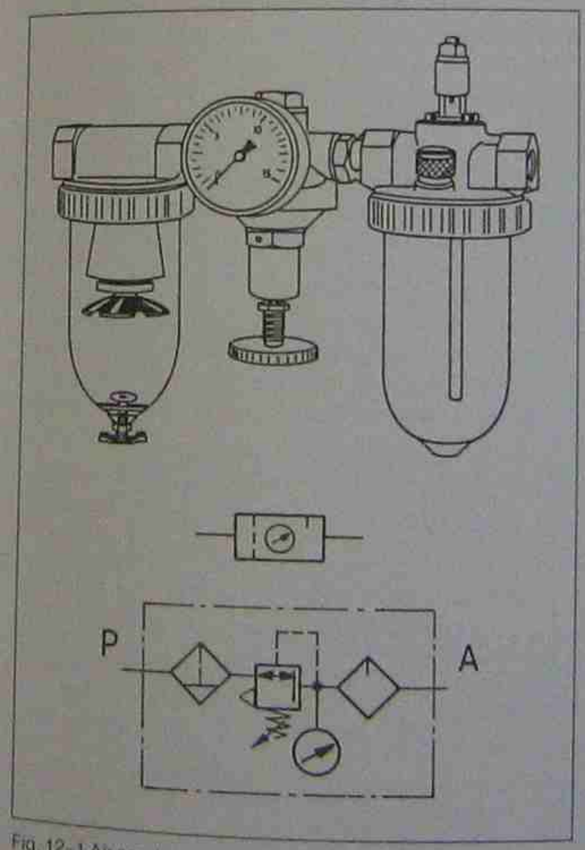


Fig. 12-1 Air service unit consisting of filter, pressure reducing valve and lubricator

Air line filter (separator)

The air line filter is in fact more than just a filter, since it serves a twofold purpose. It is designed to filter out contaminant particles, but it also

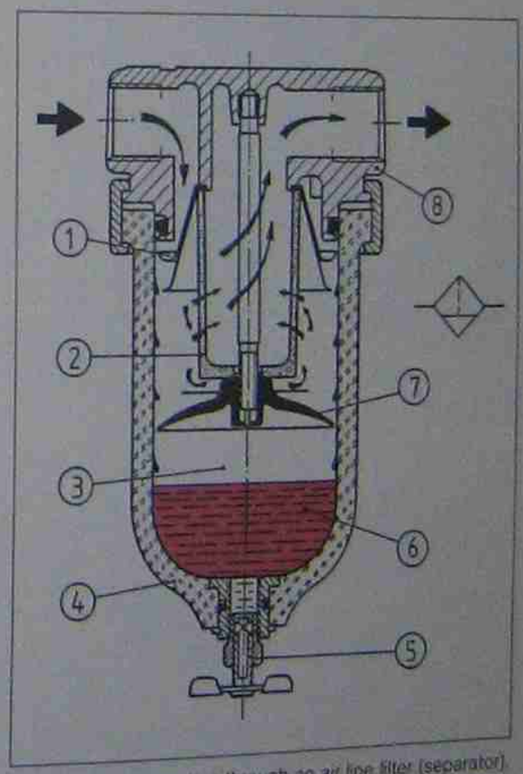


Fig. 12-2 Cross section through an air line filter (separator)

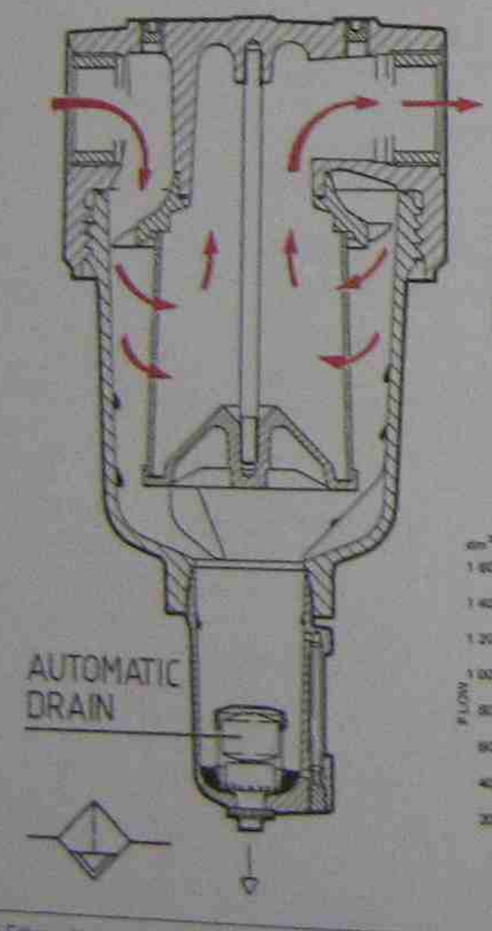
separates condensate from the passing air (fig. 12-2).

For most industrial applications, the air filter element is rated around 40 to 60 micrometres (microns). Some air control components and special tools require special filtration for maximum efficiency. Moving part logic components (see Chapter 8) and non-contact type air sensing equipment (see Chapter 6) are particularly sensitive to air contamination. It is therefore advisable to check with manufacturer's specifications to determine what filter rating is required.

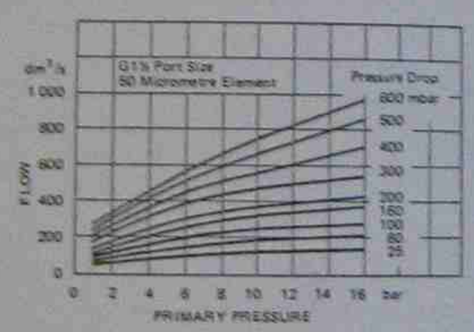
To avoid undue pressure drop, correct sizing of the filter is important. The air flow in cubic metres/min F.A.D. through the air service unit must be ascertained, and an appropriate filter selected. It is recommended that, wherever possible, a filter with an automatic drain should be chosen (fig. 12-3).

With manually drained filters, if at any time, the condensate in the bowl accidently rises above its maximum level, it could then find access into the filter element, which would mean that all the contaminants and the water accumulated in the bowl would be forced through the filter element and would stream into the pneumatic system. This would not only reduce the flow capacity of the filter, but would also block the filter and contaminate the pneumatic system.

The filter cartridge should not need servicing for periods of less than twelve months. The filter bowl, however, must be drained whenever the maximum water level is reached. Servicing normally requires dismantling and cleaning of the bowl. The filter element on some filters may be reverse-flushed with air and cleaned with kerosene. Some filter cartridges, however, are of the disposable type (impregnated paper), and can therefore not be washed and cleaned.



TYPICAL PERFORMANCE CHARACTERISTICS



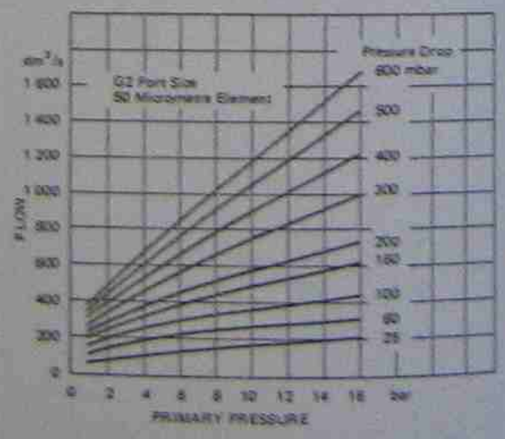


Fig. 12-3 Filter with automatic drain

Pressurised air enters the air inlet port and passes through directional vanes or louvres ①, which force the air into a swirling motion (whirlpool effect). The centrifugal force caused by this swirling motion throws the larger contaminant particles and condensate droplets outwards, where they collect on the side of the bowl ④ and fall past the baffle into the "quiet zone" ③ (see fig. 12-2). From there they can be drained off ⑤, either manually or automatically. The baffle ⑦ prevents condensate and contaminants in the quiet zone ③ from being stirred up again and carried into the outgoing airstream. This baffle may also serve as a maximum condensate level indicator.

As the pressurised air leaves the bowl it passes through a filter element ②, which removes smaller solid contaminants. From there the air streams through the exit of the filter. Filters are supplied with a transparent bowl made from polycarbonate plastic ④, but where required, they can be supplied with metal bowls or with protective metal guards. Such guards may be necessary, since the polycarbonate bowl can deteriorate and become dangerous, as it could explode under pressure.

If the bowl through ageing or cleaning loses its transparency, it is advisable to have it exchanged for one made from metal or a new plastic bowl with metal guard. This applies to all other pressurised items in the air service unit, which use transparent polycarbonate plastic parts. Volatile liquids, such as thinner and some solvents, are not compatible with the polycarbonate plastic parts in the air service units, and cannot therefore be used for cleaning. If cleaning is required, one may use soapy water, dish washing detergents, or kerosene. Even momentary exposure to volatile chemicals or chemical fumes will start chemical deterioration of the plastic parts. A list of materials that will attack polycarbonate plastic bowls is given below.

Some materials which will attack polycarbonate plastic bowls:

Acetaldehyde
Acetic acid (conc.)
Acetone
Acrylonitrile
Ammonia
Ammonium fluoride
Ammonium hydroxide
Ammonium sulfide
Antifreeze
Benzene
Benzoic acid
Benzyl alcohol
Brake fluids
Bromobenzene
Butyric acid
Carbolic acid
Carbon disulfide
Carbon tetrachloride
Caustic potash solution
Caustic soda solution
Chlorobenzene
Chloroform
Cresol
Cyclohexanol
Cyclohexanone
Cyclohexene
Dimethyl formamide
Dioxane
Ethane tetrachloride
Ethyl acetate
Ethyl ether
Ethylamine
Ethylene chlorohydrin
Ethylene dichloride
Ethylene glycol
Formic acid (conc.)
Freon (refrigerant & propellant)
Gasoline (high aromatic)
Hydrazine
Hydrochloric acid (conc.)
Lacquer thinner
Methyl alcohol
Methylene chloride
Methylene salicylate
Milk of lime (CaOH)
Nitric acid (conc.)
Nitrobenzene
Nitrocellulose lacquer
Phenol
Phosphorous hydroxy chloride
Phosphorous trichloride
Propionic acid
Pyridine
Sodium hydroxide
Sodium sulfide
Styrene
Sulfuric acid (conc.)
Sulphural chloride
Tetrahydronaphthalene
Thiophene
Toluene
Turpentine
Xylene
Perchlorethylene and others

Pressure reducing valve (pressure regulator)

Because the distribution system pressure must always be somewhat greater than the pressure required for any particular air operated device or system, some means of pressure reduction is required, preferably at each individual point of air consumption. The pressure reducing valve (regulator) is used for this purpose. Although the term "pressure reducing valve" more correctly describes the function of this device, the commonly used term is "pressure regulator". If air pressure driving an air operated device is greater than actually required, then some compressed air is wasted (and excessive air pressure means compression power unused). Since force output of an actuator or air tool depends on the system pressure, it can be said that the pressure reducing valve is a force regulator (force = pressure × area).

Pressure reducing valve without relief

Pressure reducing valves come in two versions, those with secondary system relief function (downstream relief) and those without. Providing the primary pressure is always somewhat higher than the adjusted secondary pressure, the pressure reducing valve will provide two important functions which may be summed up as follows:

- It maintains a nearly constant secondary pressure (adjusted pressure) independent of pressure fluctuations on the primary side (inlet side).

separates condensate from the passing air (fig. 12-2).

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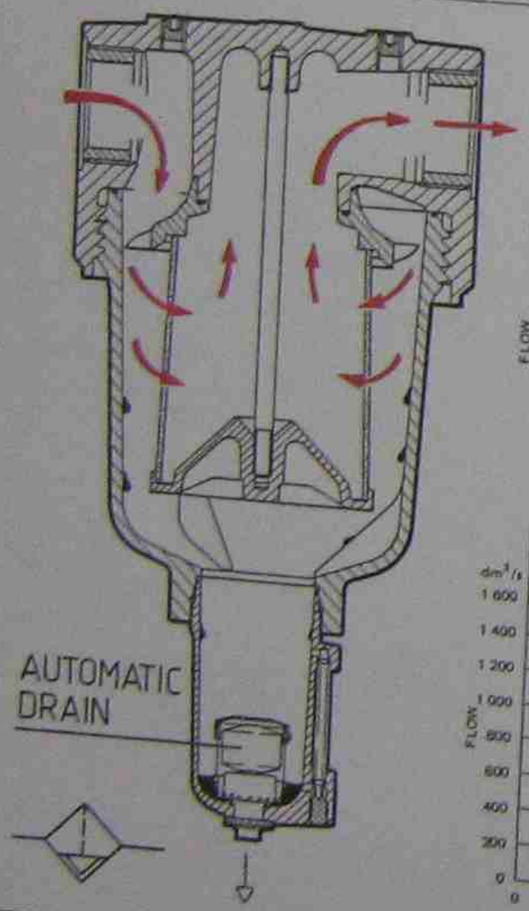
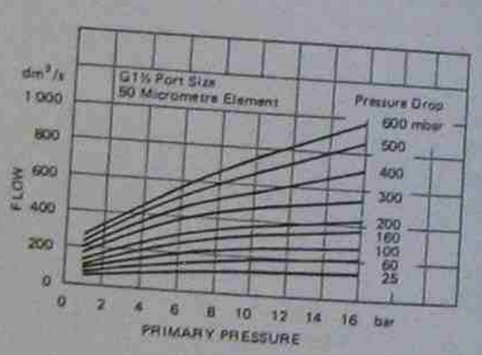


TYPICAL PERFORMANCE CHARACTERISTICS



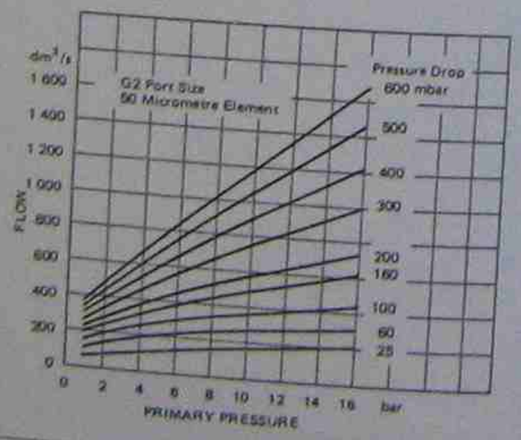


Fig. 12-3 Filter with automatic drain.

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Some materials which will attack polycarbonate plastic bowls:

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Acetic acid (conc.)
Acetone
Acrylonitrile
Ammonia
Ammonium fluoride
Ammonium hydroxide
Ammonium sulfide
Antifreeze
Benzene
Benzoic acid
Benzyl alcohol
Brake fluids
Bromobenzene
Butyric acid
Carbolic acid
Carbon disulfide
Carbon tetrachloride
Caustic potash solution
Caustic soda solution
Chlorobenzene
Chloroform
Cresol
Cyclohexanol
Cyclohexanone
Cyclohexene
Dimethyl formamide
Dioxane
Ethane tetrachloride
Ethyl acetate
Ethyl ether
Ethylamine
Ethylene chlorohydrin
Ethylene dichloride
Ethylene glycol
Formic acid (conc.)
Freon (refrigerant & propellant)
Gasoline (high aromatic)
Hydrazine
Hydrochloric acid (conc.)
Lacquer thinner
Methyl alcohol
Methylene chloride
Methylene salicylate
Milk of lime (CaOH)
Nitric acid (conc.)
Nitrobenzene
Nitrocellulose lacquer
Phenol
Phosphorous hydroxy chloride
Phosphorous trichloride
Propionic acid
Pyridine
Sodium hydroxide
Sodium sulfide
Styrene
Sulfuric acid (conc.)
Sulphural chloride
Tetrahydronaphthalene
Thiophene
Toluene
Turpentine
Xylene
Perchlorethylene and others

Pressure reducing valve (pressure regulator)

Because the distribution system pressure must always be somewhat greater than the pressure required for any particular air operated device or system, some means of pressure reduction is required, preferably at each individual point of air consumption. The pressure reducing valve (regulator) is used for this purpose. Although the term "pressure reducing valve" more correctly describes the function of this device, the commonly used term is "pressure regulator". If air pressure driving an air operated device is greater than actually required, then some compressed air is wasted (and excessive air pressure means compression power unused). Since force output of an actuator or air tool depends on the system pressure, it can be said that the pressure reducing valve is a force regulator (force = pressure × area).

Pressure reducing valve without relief

Pressure reducing valves come in two versions, those with secondary system relief function (downstream relief) and those without. Providing the primary pressure is always somewhat higher than the adjusted secondary pressure, the pressure reducing valve will provide two important functions which may be summed up as follows:

- It maintains a nearly constant secondary pressure (adjusted pressure) independent of pressure fluctuations on the primary side (inlet side).

- it maintains a nearly constant secondary pressure (adjusted pressure) independent of flow demand fluctuations on the secondary side (outlet side).

A simplified cross-sectional illustration of a pressure reducing valve without secondary system relief function is given in fig. 12-4. This illustration is used to explain the somewhat complex operation of this valve.

F_S = Spring force (adjust regulation force)
p2 = Secondary pressure (adjusted pressure)
p1 = Primary pressure (inlet pressure)
A = Diaphragm area
F_D = Force from p2 on diaphragm
Q = Flow rate through valve
Δp = Pressure drop p1 to p2

In a condition, where the primary pressure p1 does not fluctuate and the flow demand on the secondary side is stable, the valve will also remain stable and the forces F_S and F_D will be equal ($F_S = F_D$). During such a condition the valve disc assumes a position (regulated by the diaphragm to which it is attached) which causes a pressure drop (Δp) exactly to the amount required to reduce the pressure from p1 down to p2 (fig. 12-4).

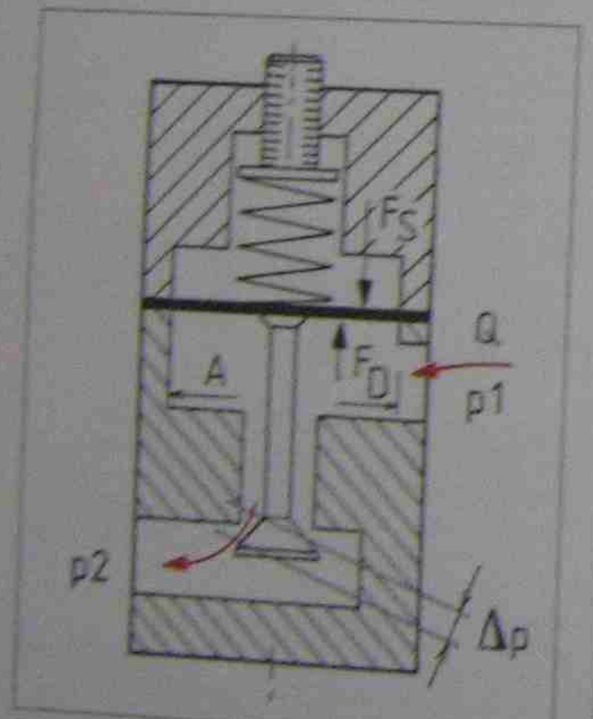


Fig. 12-4 Function principle of a pressure reducing valve.

Where the previously explained force balance is disturbed due to a reduction of p2 (caused by an increased flow demand [Q] in the system), the spring must force the diaphragm up, and the resulting disc increases the flow opening (orifice). By this the pressure drop (Δp) through the orifice decreases and p2 increases until the adjusted pressure and force balance is reached again ($F_S = F_D$).

Where p1 fluctuates, the pressure p2 in the secondary chamber will also tend to fluctuate, but the spring loaded diaphragm reacts to these fluctuations and constantly adjusts the valve disc. Using this it opens or closes the orifice to maintain a constant p2.

Where p2 is on the increase, so that the force balance ($F_S = F_D$) becomes disturbed, the diaphragm will move down. This reduces the valve orifice and increases the pressure drop across the orifice (Δp). By this the secondary pressure will decrease again to find its equilibrium with the

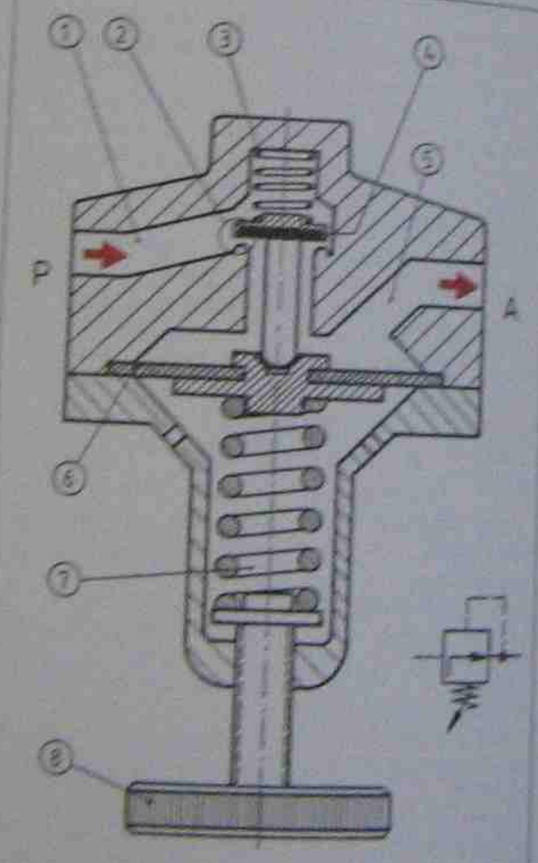


Fig. 12-5 Pressure reducing valve without secondary system relief feature.

spring force, and therefore, the force balance on the diaphragm is restored.

In a no-flow demand condition, the pressure in the secondary chamber (p2) will increase until it reaches the level of the primary pressure (p1). Pascal's Law may now be applied, for this is a static condition. The diaphragm is now forced down until the spring force $F_S = p1 \times A$. The valve disc now closes the orifice off completely until such time that flow from the system is demanded again (fig. 12-4 and 12-5).

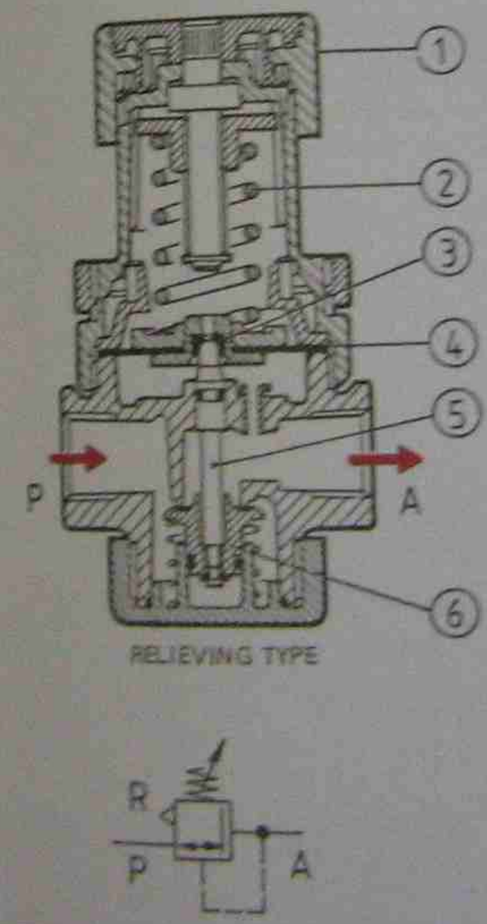
Pressure reducing valve with relief function

Most pressure reducing valves are equipped with an inbuilt secondary pressure relief function. Their construction has a relief orifice in the centre of the diaphragm hub (fig. 12-6). During non-relief operating conditions the relief orifice is closed by the valve stem. If an overpressure situation occurs in the downstream line, the diaphragm will move up and the valve disc closes the main orifice completely. This uncovers the relief orifice in the centre of the diaphragm hub and excess air from the secondary side (p2) can bleed off through the hub orifice into the spring housing and then via vent holes to atmosphere.

When the secondary system over-pressure is relieved, the diaphragm reseats onto the valve stem and closes the orifice completely off. Thus all the forces within the valve are again in balance ($F_S = F_D$). The pressure relieving feature is a great advantage in closed or "dead end" circuits (cylinder applications).

Applications of pressure reducing valves

The pressure reducing valve must have a flow capacity greater than the sum of all the compo-



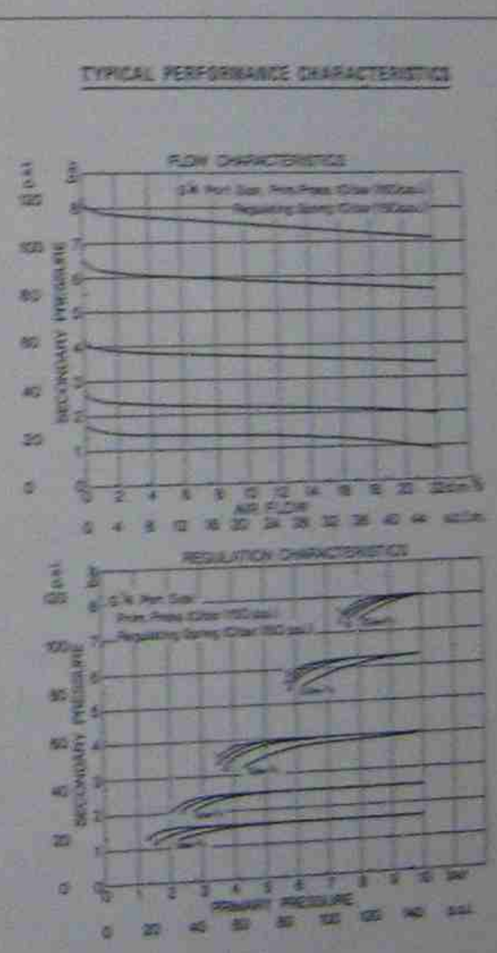


Fig. 12-6 Pressure reducing valve including secondary system relief feature.

LIBRARY

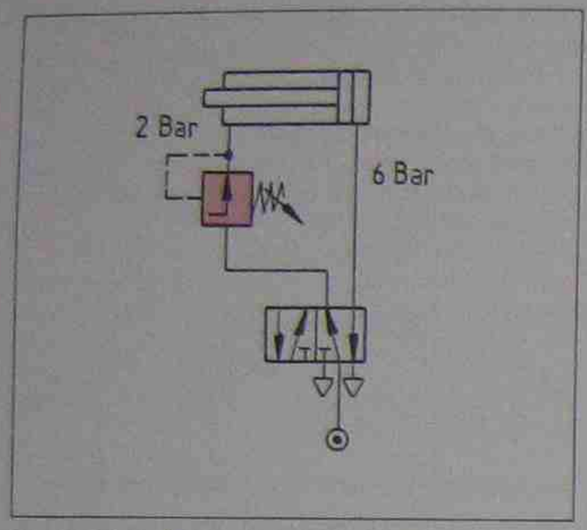


Fig. 12-7 Typical application circuit with reduced force for actuator retraction.

nents downstream of the valve. To provide individual control of actuator force in multi-actuator circuits, it is quite common to use a pressure reducing valve for each individual actuator, thus controlling the force and power consumption of each individual actuator.

Similarly, one may use maximum system pressure only on the extension stroke of a linear actuator, but greatly reduced pressure (force) for its retraction stroke (if that retraction stroke is not a power stroke). The savings achieved by such pressure reduction will soon pay for the pressure reducing valve (fig. 12-7).

Further compressor savings may be achieved if the power circuit (see fig. 12-8) is operated on the adjusted pressure of the pressure reducing valve in the air service unit (say at 700 kPa or 7 bar). An additional pressure reducing valve may now be used to supply compressed air of only 250 kPa (2.5 bar) to all limit valves. The pneumatic pilot signals emanating from these limit valves require a pressure of no more than 250 kPa (2.5 bar) to actuate the power valves or internal logic valves (cascade valves or step counter modules). Figure 12-8 shows a typical sequential circuit where reduced pilot pressure is applied.

Air lubrication

Air lubrication is still widely used today to reduce friction and corrosion in air valves, linear actuators and air motors. Physically speaking, lubricating oil is mixed into the air stream and this oil mist (fog) is in theory carried by the flow of compressed air into

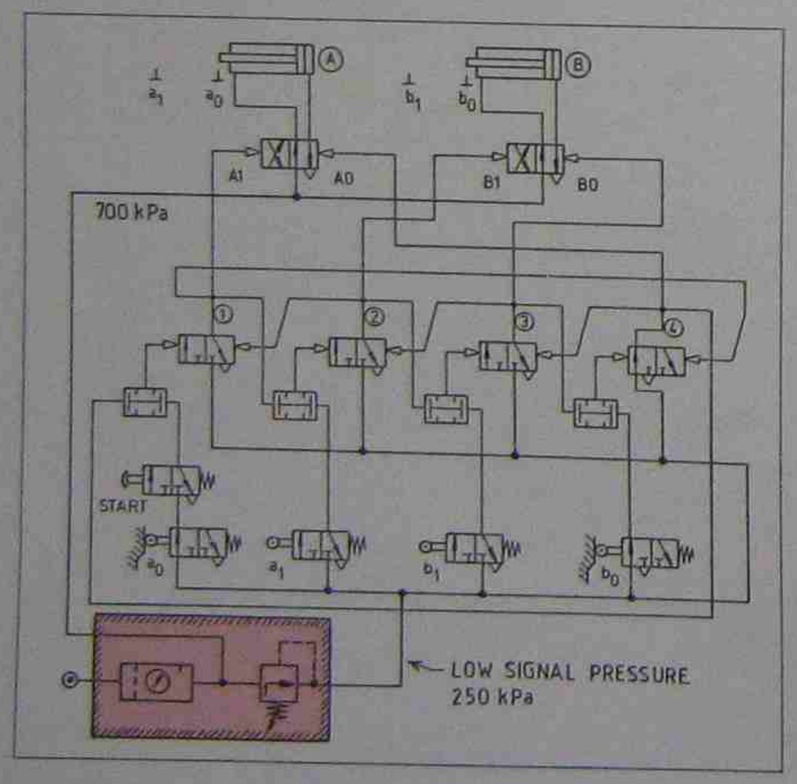


Fig. 12-8 Sequential circuit where reduced pilot pressure is applied.

every crevice, clearance gap and bearing, where sliding movements cause friction. When air exhausts through the exhaust ports of valves and air motors, the same quantity of lubricating oil which was previously injected into the air stream, must eventually emerge from these exhaust ports! In recent years, a number of reports have pointed out that pneumatic exhaust air, carrying oil mist has, in fact, found its way into the lungs of factory workers operating machines in close proximity to pneumatic circuitry or air tools.

For this reason, manufacturers have made extreme efforts to develop pneumatic valves and actuators, which no longer need any form of air lubrication. Numerous modern type logic control valves, better known as moving part logic control equipment, may even start to malfunction, if air lubrication were used for their supply. With these thoughts in mind, air line lubrication may for many applications be regarded as on its way out and air lubrication should, therefore, only be used where absolutely necessary!!

Air lubrication must be applied correctly, if the pneumatic components in need of such lubrication, are to receive the lubricant consistently and adequately, whilst they are in operation. For this reason, great care must be applied to the selection, installation and adjustment of a suitable lubricator especially when used on complex pneumatic control systems. Many such systems are composed of actuators demanding lubrication, but these actuators may be controlled and sequenced by components (valves), which must not receive any lubrication at all. For controls of this nature, special provisions must be made to keep the lubricated and the unlubricated systems separated. A typical circuit, showing limited air lubrication, is shown in fig. 12-9.

Venturi action to transfer lubricant into the air stream

Air lubricators utilise the pressure difference caused by the compressed air as it streams through a *venturi tube* (fig. 12-10). Transfer of lubricant is based on the Venturi principle, which states that different flow velocities produce different amounts of suction. The velocity increase that results from a restriction in a flow line (see point B in fig. 12-10) will have associated with it a decrease in static pressure. This decrease is directly used to draw the lubricant into the air

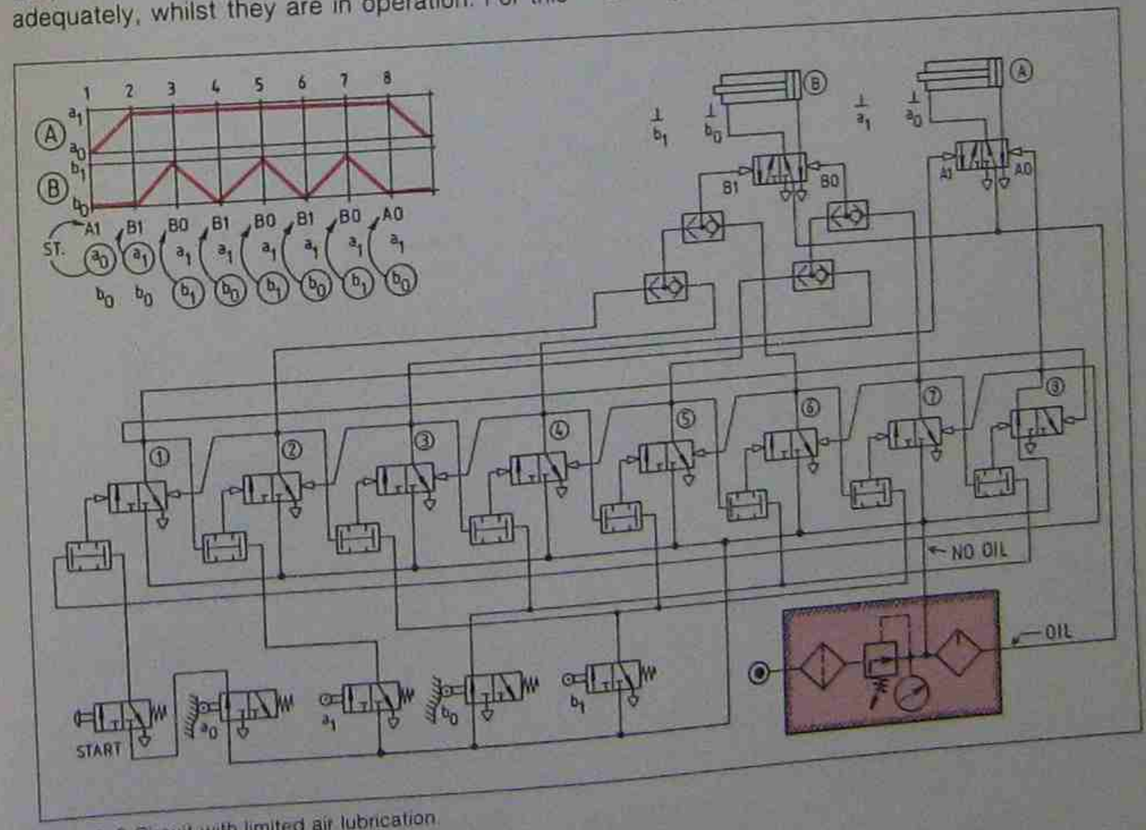


Fig. 12-9 Circuit with limited air lubrication.

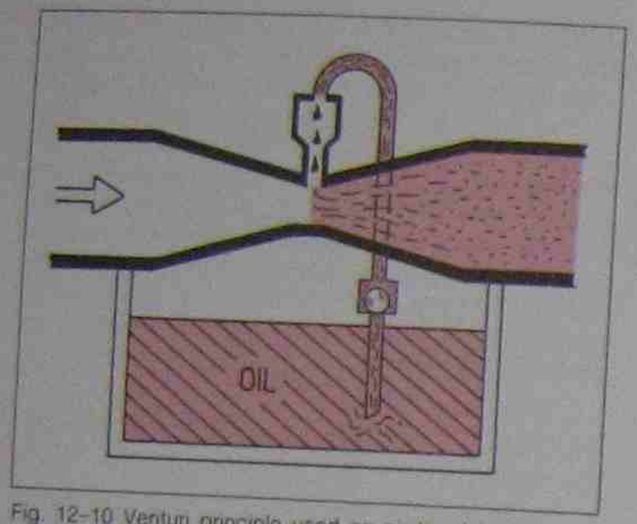


Fig. 12-10 Venturi principle used on air line lubricators to transfer lubricant into the air stream.

stream. The pressure measured at point A of the venturi acts onto the surface of the lubricant in the reservoir. When the compressed air leaves the venturi "throat" and enters section C at the end of the venturi tube, it has regained its original pressure, but its velocity has also returned to the lower velocity it had at point A. The velocity at point B, however, is much higher than at point A and point C.

Macro lubricator (oil fog lubricator)

Compressed air enters the lubricator at the inlet port ④ and streams through and around the venturi assembly ③ and past a flow sensor ⑨ to the outlet port ⑧. Inlet air pressure acts through hole ⑤ to pressurise the lubricant bowl (fig. 12-11). Differential pressure between the lubricant bowl and the sight feed dome ⑪ causes oil to flow up

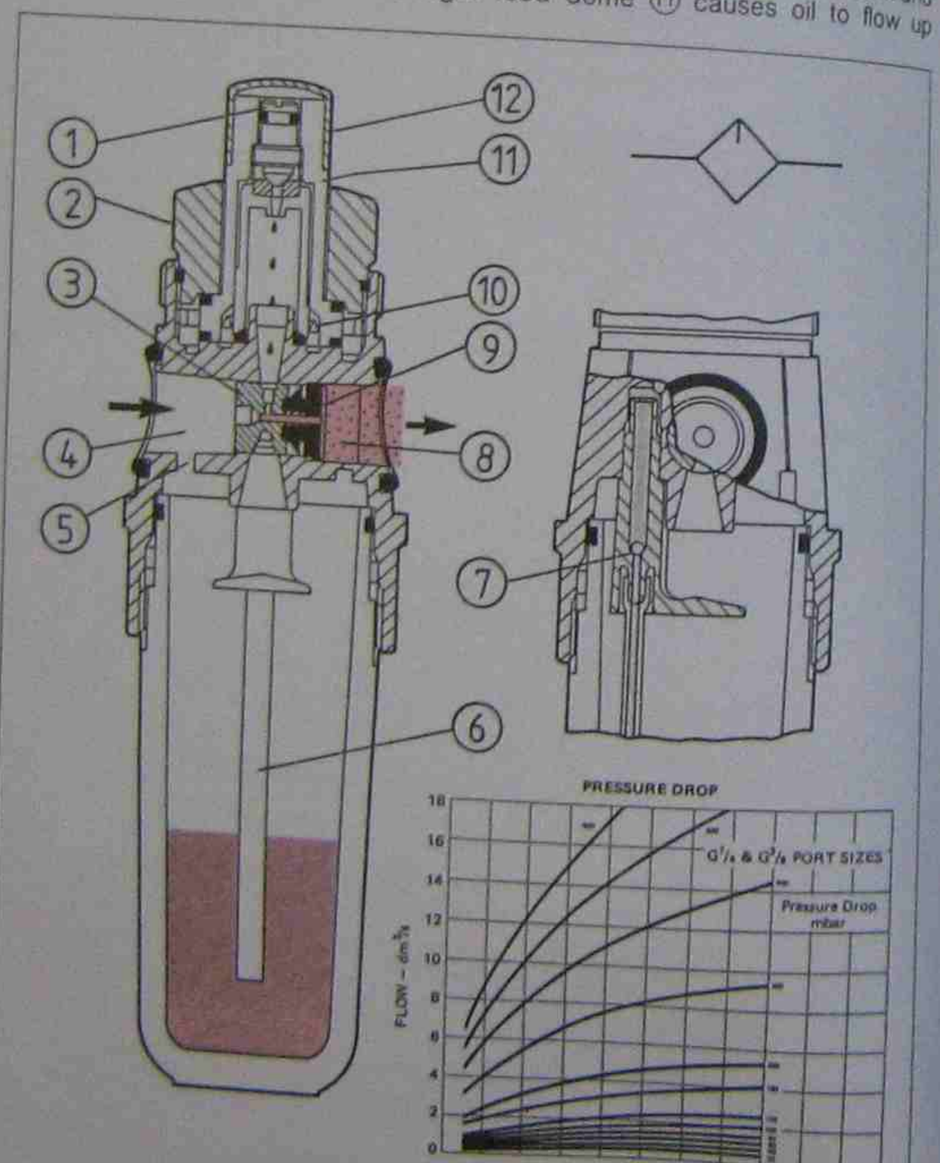


Fig. 12-11 Oil fog lubricator.

through the siphon tube ⑥ past a check valve ⑦. From there it flows through the filter screen ⑩ into passages of the sight feed dome. The oil drip rate is controlled by adjusting screw ① from where the oil drips into the venturi assembly, where it eventually is "atomised" by the passing air stream and becomes an airborne oil fog. This oil fog is then carried to the pneumatic devices or control circuit. The automatic flow sensor (elastomer plug) flexes as necessary to allow more or less air to flow past it, thus permitting changes in flow demand ⑨.

To refill the lubricant bowl, the air must be shut off (on some lubricators), and the system vented, before lubricant can be refilled through the filler cap ②. To adjust the drip rate for this particular lubricator the plastic cap ⑫ must be removed and a screw driver is used to rotate the adjusting screw ①.

With oil-fog lubricators all the oil dripping through the sight feed dome will enter the air stream and will be "atomised" into the air stream. This means that small or larger droplets are carried through the air stream, whereby the larger droplets tend to fall out of the air stream, which means they are no longer airborne. For this reason, oil fog lubricators should only be used for systems where the components to be lubricated are close to the lubricator.

Micro lubricator (oil mist lubricator)

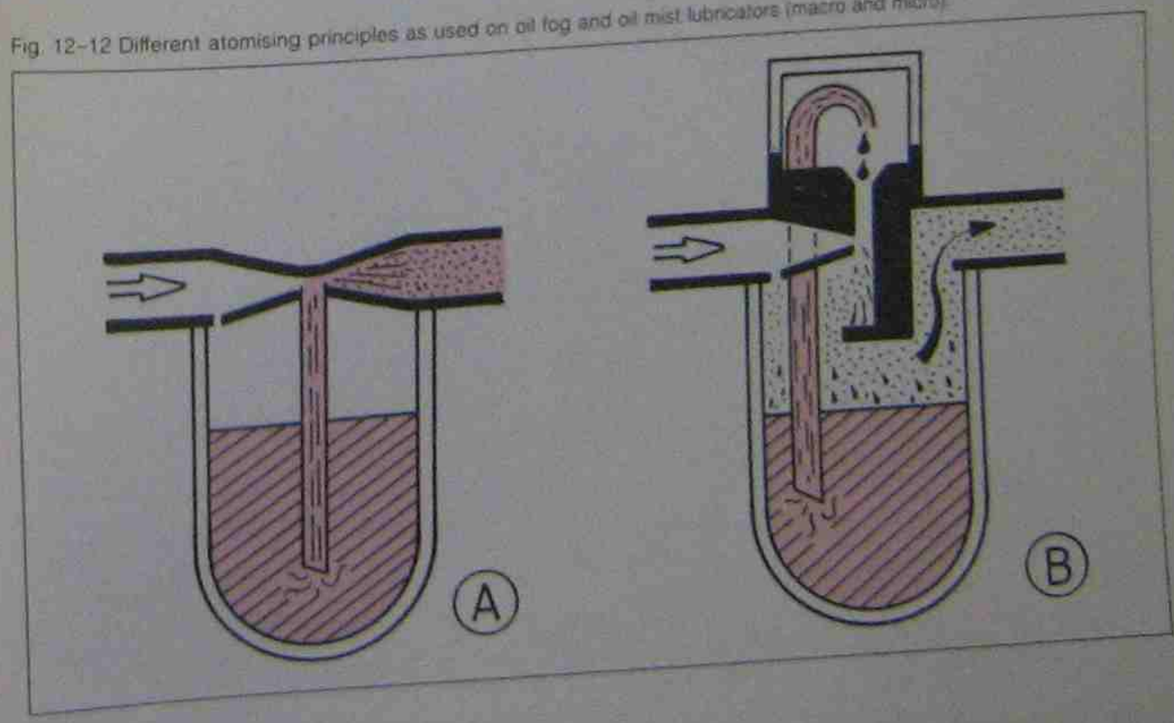
Oil mist lubricators use a totally different principle to "atomise" the lubricant (compare with oil fog lubricator fig. 12-12). Compressed air enters the lubricator at port p and flows through its main passage to the outlet port A (fig. 12-13). A small portion of the passing air is diverted to the venturi nozzle ⑥, which is located inside a "mist generator" (atomiser) ①. As the lubricant drips into the high velocity air stream it becomes "atomised". The air-oil mixture is then sprayed onto a baffle plate ③, which causes further oil fragmentation and most importantly redirects the air stream in vertical direction (90° turn). Leaving the baffle, the oil-laden air streams across the bowl to a large exit opening ⑤. Oil-laden air flowing through this opening then rejoins the air stream in the main passage, mixes thoroughly with it, and finally leaves the lubricator on its outlet port A.

Whilst the air-oil mixture is redirected on the baffle plate and travels to the exit opening, all large oil particles greater than 2 µm drop out of the air stream and fall back into the lubricator reservoir ④. Thus, only the smallest oil-mist particles find entry into the air stream and it is generally assumed that only about 5% of the injected oil quantity (of the oil drops counted in the drip dome), will find its way into the pneumatic system.

Most oil mist lubricators use a self-adjustable air diverter valve ② (usually a neoprene flap), to divert more or less flow to the mist generator, depending on the flow rate through the lubricator.

Since these oil particles from this type of lubricator are so small they stay airborne much longer, and tend not to coalesce into larger droplets. As

Fig. 12-12 Different atomising principles as used on oil fog and oil mist lubricators (macro and micro).



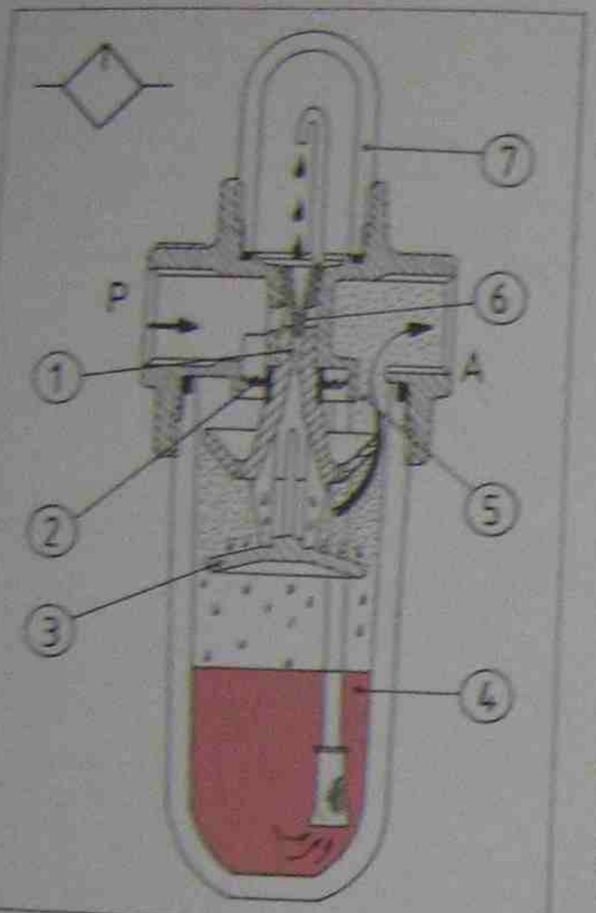


Fig. 12-13 Oil mist lubricator

This is not the case with oil fog lubrication! For this reason it is advisable to use predominantly oil mist lubrication for complex and diversified pneumatic systems.

Oil feed rate

Suggested oil feed rates are given in fig. 12-14, but as explained previously, these rates are to be strictly monitored and experimented with, to avoid overlubrication, which might cause hazardous situations to machine operators and factory personnel.

Suggested lubricants for air line lubrication

Manufacturers of lubricators and air equipment suggest that only light mineral oils should be used for air line lubrication. Oil viscosity should be approx. 9–11 mm^2/s (9–11 cSt) at 40°C. This corresponds to ISO-CLASS VG 10 as per ISO 3448.

Some suggested oil brands are: Avia Avilub RSL 10, BP Energol HLP 10, Esso Spinesso 10, Festo Special oil, Mobil DTE 21, Shell Tellus Oil C 10.

Installation of air service units

The air service unit is usually installed as close as possible to the pneumatic components supplied by its airflow. It should also be located in a position where it is easily accessible (for maintenance purposes) and where possible, the refill opening as

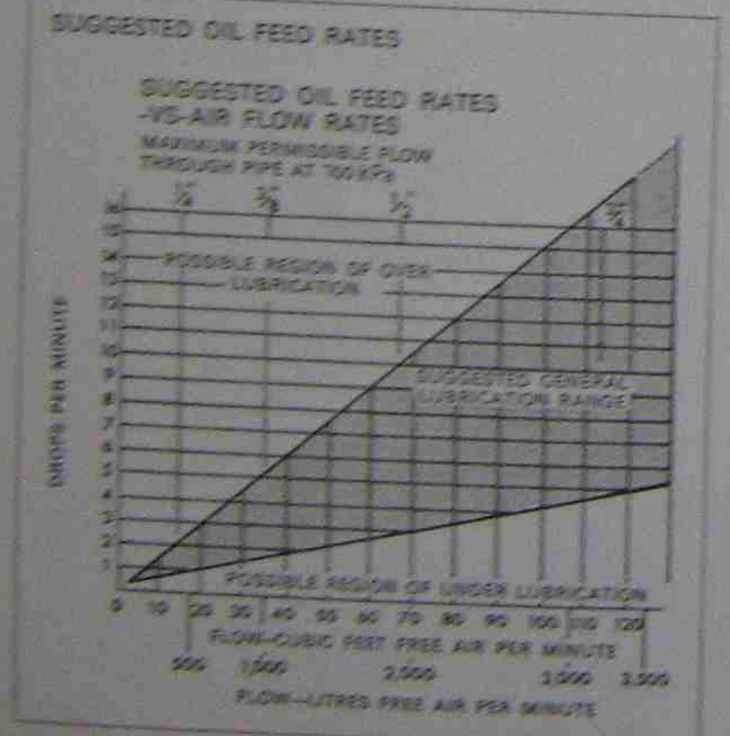


Fig. 12-14 Suggested oil feed rates

well as the drain opening should have ready access for servicing.

Most modern type air service units come in modular form, which makes them easy to install and service, since every item (filter, regulator and lubricator) can individually be removed, whilst the other items need not be removed from the assembly. It is advisable that each air service unit is equipped with a shut off valve on its upstream side. This permits isolation of the machine being serviced by the air service unit and also permits maintenance on the air service unit, whilst other machines and the compressor stay on stream.

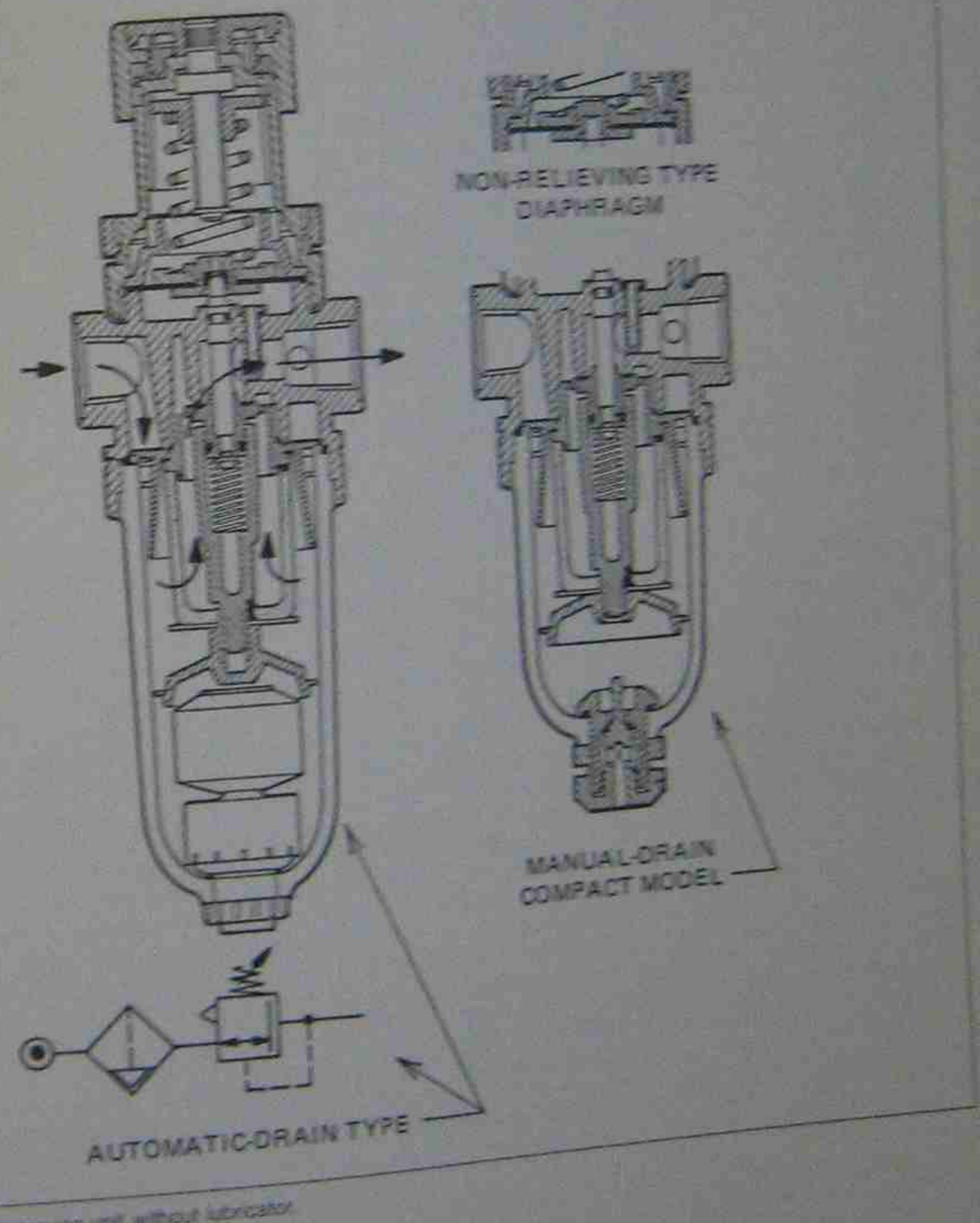


Fig. 12-15 Air service unit without lubricator

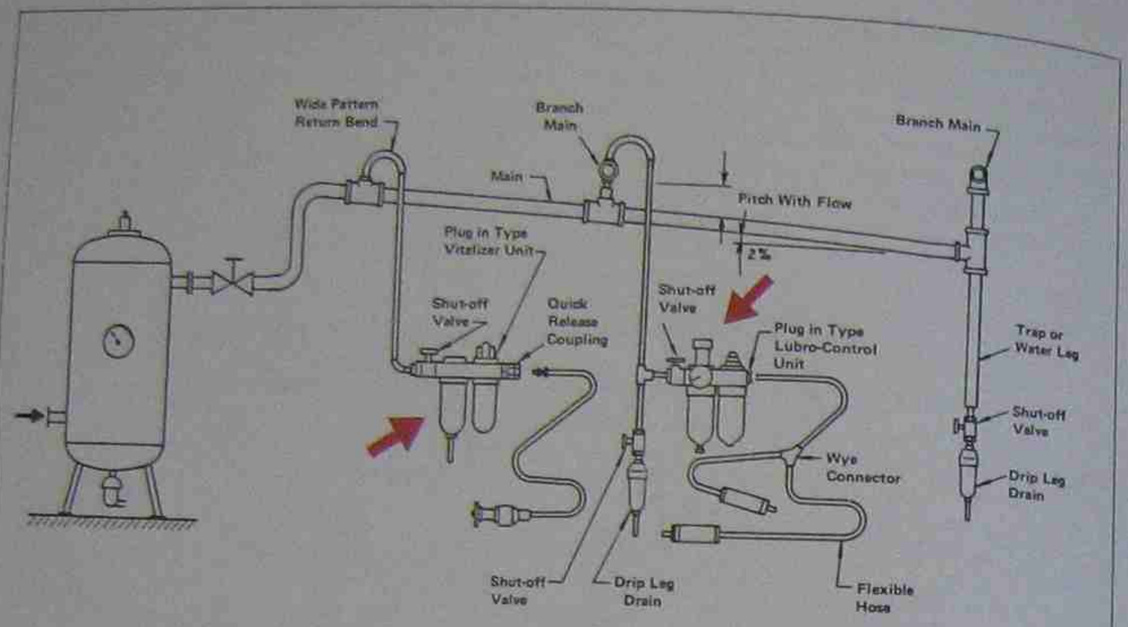


Fig. 12-16 Typical air service unit installations.

13 Air Compression

The preceding chapters explained how useful work and complex logic control may be obtained from compressed air by the design of pneumatic systems and control circuits for use in industry. But so far it has been assumed that the compressed air used to operate these actuators and systems is clean enough and at a sufficient pressure level and flow rate to enable the intended control and work functions to be performed efficiently for many thousands or indeed millions of cycles. How these already assumed requirements on the compressed air supply are accomplished and the methods and equipment used to bring this about, will be described in the following chapters.

Free Air

An understanding of the term "free air" and its significance in relation to compressed air is important, as it is the term used for measuring the flow rate of all devices producing, consuming, processing, distributing and storing compressed air.

Free air (or ambient air) is defined as air at atmospheric conditions at any specific location and time. It should be noted, however, that because the altitude, barometric air pressure and air humidity may vary at different geographical localities and times, the term "free air" does not mean air under identical or standard conditions. In view of such variations and in order that stated air flows relating to pneumatic equipment can be calibrated and compared, a standard is essential. There are unfortunately many standards depending on the industry or country where equipment is produced, but the two most common are the European Standard and the Imperial Standard. The European standard for free air is based on a pressure of 101.3 kPa absolute, at a temperature of 0°C, whereas the Imperial standard is based on 14.7 p.s.i. absolute at 15.6°C.

Hence, the term "free air" based on the previously mentioned standards is quite a simple and useful rating to size and compare delivery rates of air compressors. If the compressor, however, is installed in an environment which has a free air pressure and temperature other than either of the standards above, then its flow rate will alter from the manufacturer's standard specification.

Compressors, for example, are always rated for flow output based on the flow rate (ambient air) they take directly from the atmosphere through their air intake. To illustrate: If a compressor had a rated output of 4 m^3/min F.A.D. (free air delivery), for each minute the compressor was operating, eight cubic metres of "free air" would be drawn into the intake from the atmosphere. This would be comparable to a volume of air 2 metres long by 2 metres wide by 1 metre deep, being drawn in each minute (see fig. 13-1 (a) and (b)). The output rate from the compressor, however, would be far less, since the air would now be compressed to a much smaller volume, but to a much higher pressure than at the original ambient pressure prevailing at the compressor intake (see also Chapter 1, fig. 1-12).

Diagrams (a) and (b) of fig. 13-1 will assist in understanding this important concept of "free air". The gas laws explained in Chapter 1 can be used to calculate the relationship between the volumes and pressures given in these diagrams.

Altitude effects on air compression

In some locations, the effects of altitude on the output of air compressors and air consuming devices must be considered. At altitudes of for example 500 and 1000 metres, there is a corresponding reduction in atmospheric pressure of approx. 5 kPa and 10 kPa respectively.

For compressors, these reduced intake pressures cause a decrease in the compressor power requirement. However, the lower atmospheric intake pressure also means that the compression ratio of the compressor is higher. This results in an increased power requirement. The net result for a compressor operating at an altitude above sea level would mean a decrease in the power required to drive the compressor, and a decrease in the free air delivery.

Air consuming devices such as air tools and linear actuators, if operated at sea level, would consume more air than if operated above sea level.

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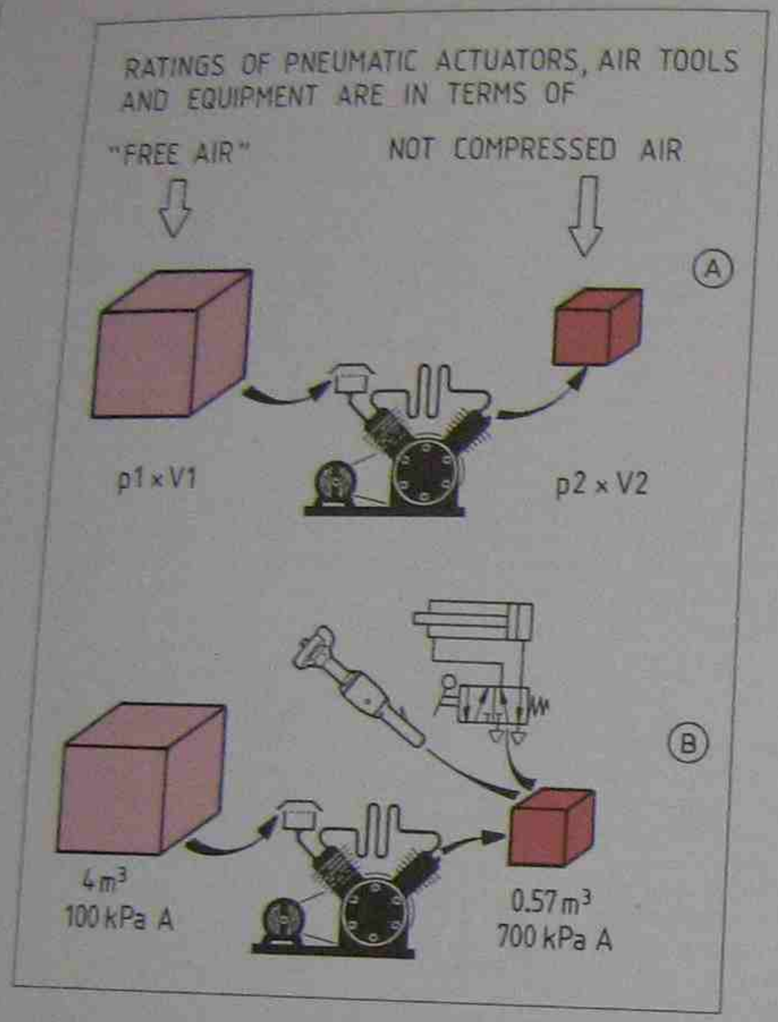


Fig. 13-1 (a) and (b) Diagram of the 'free air' concept.

Air flow rates

The S.I. standard unit for flow rate is cubic metres per second (m^3/s). This unit is not often used in air compressors and pneumatic component specifications, because the flow rate numbers involved are usually small decimal fractions and, therefore, would be difficult to comprehend. Hence, the units more commonly in use are: litres per minute (L/min), and cubic feet per minute. A conversion to these units can be made as follows:

To convert from:	Operation
$m^3/s \rightarrow m^3/min$	× 60
$L/min \rightarrow m^3/min$	÷ 1000
$c.f.m. \rightarrow m^3/min$	÷ 35.3
$m^3/min \rightarrow m^3/s$	÷ 60
$m^3/min \rightarrow L/min$	× 1000
$m^3/min \rightarrow c.f.m.$	× 35.3

Air flow rates used in the following chapters will be given in m^3/min, unless otherwise stated.

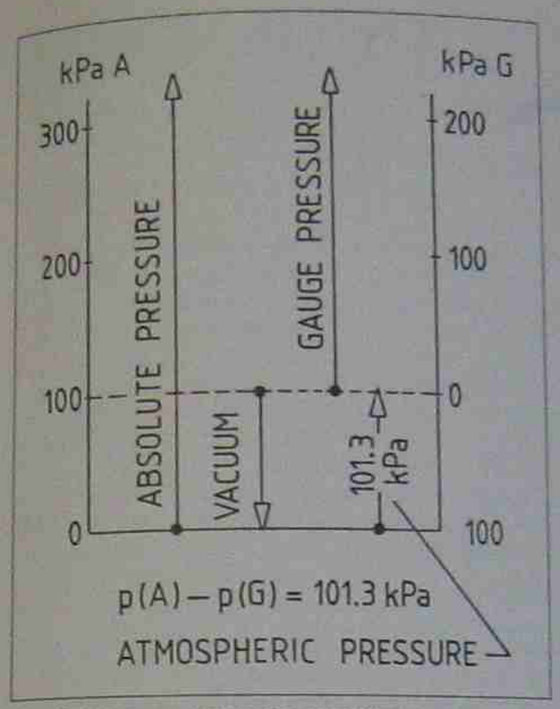


Fig. 13-2 Various methods of expressing pressure.

Air pressure

Pressures will be quoted in kilopascals gauge (kPa) and bar unless otherwise stated (see also Chapter 1).

An atmospheric pressure of 101 kPa absolute has been adopted for the conversion of gauge pressures to absolute pressures for use in calculations shown in the text. The relationship between gauge and absolute pressure is shown in fig. 13-2.

Most pressure gauges used on pneumatic equipment are calibrated in gauge pressure. Thus, if a pressure gauge is calibrated for kPa A it is capable of measuring pressures in the vacuum range ("A" stands for absolute pressure calibration). But if it is calibrated just for kPa then the pressure gauge shows pressures above atmospheric pressure only (see fig. 13-2).

Air compression process

Before studying the various types of compressors and their characteristics, it is necessary to look at some of the principles governing the compression process. Chapter 1 dealt with the gas laws, which define the relationship between volume, pressure and temperature of a gas. Comprehension of these laws is essential for understanding the design of compressors and their function.

Whenever air is compressed its temperature rises. This temperature rise may be experienced, for example, when a bicycle tyre is pumped up, and the pump and its connection become hot. The rise in temperature is due to an increase in the average velocity of the molecules bombarding the walls of the compression space: the volume of which is being rapidly reduced. This causes a transference of some of the kinetic energy of the molecules into heat energy. In an air compressor, if this temperature rise is not controlled by some cooling mechanism, it can lead to a very inefficient compression process, or worse still to excessive wear and final break down of the air compressor. Furthermore, the compressed air at the outlet of the compressor would be too hot for direct usage.

Air can theoretically be compressed by various processes, and these are described in the following definitions:

Adiabatic compression is that process in which the air under compression retains all the heat gained during the compression process. This purely theoretical process would require perfect insulation of the air under compression, and there would be a very large amount of power required for its compression. The increase in power required is a direct consequence of the expansion of the air, caused by the heat generated during compression. The compression element reduces the volume of air, but also has to compress an additional volume brought about by this rise in temperature. Hence, power is wasted (see Chapter 1, fig. 1-12).

Isothermal compression is also a purely theoretical process in which all the heat gained during the compression process is removed, and thus the air under compression is kept at a constant temperature. This process would require perfect cooling, in order to immediately carry away the heat generated during compression. The power required for isothermal compression is only about 36% of that required for the adiabatic process. It can therefore be understood, why compressor designers strive to design compressors which compress air as close to isothermal as possible (fig. 1-12).

Polytropic compression can be considered as that compression process which lies between adiabatic and isothermal. It is far more practical and is in fact the only commercially feasible process. Figure 13-3 shows theoretical performance

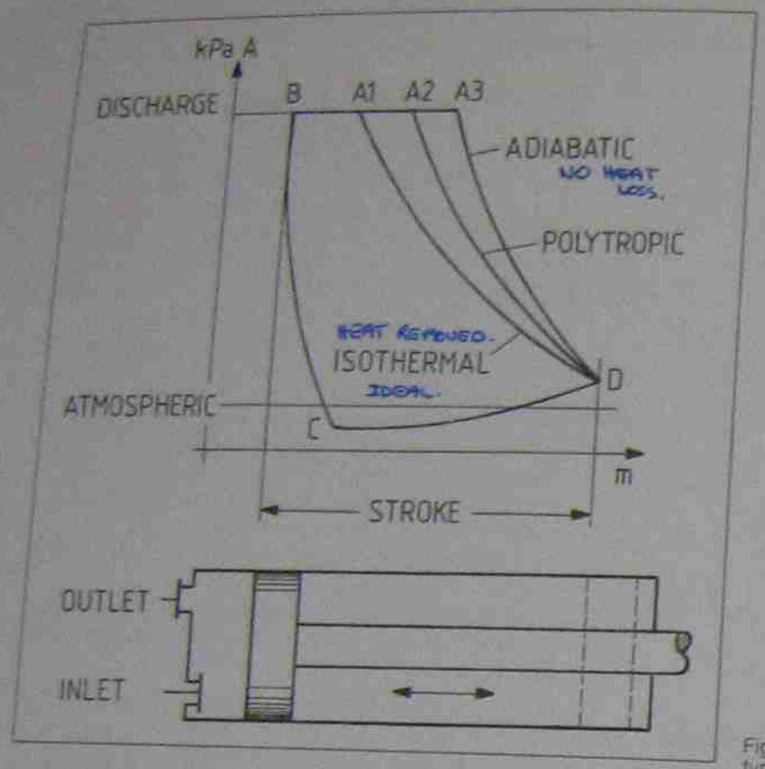
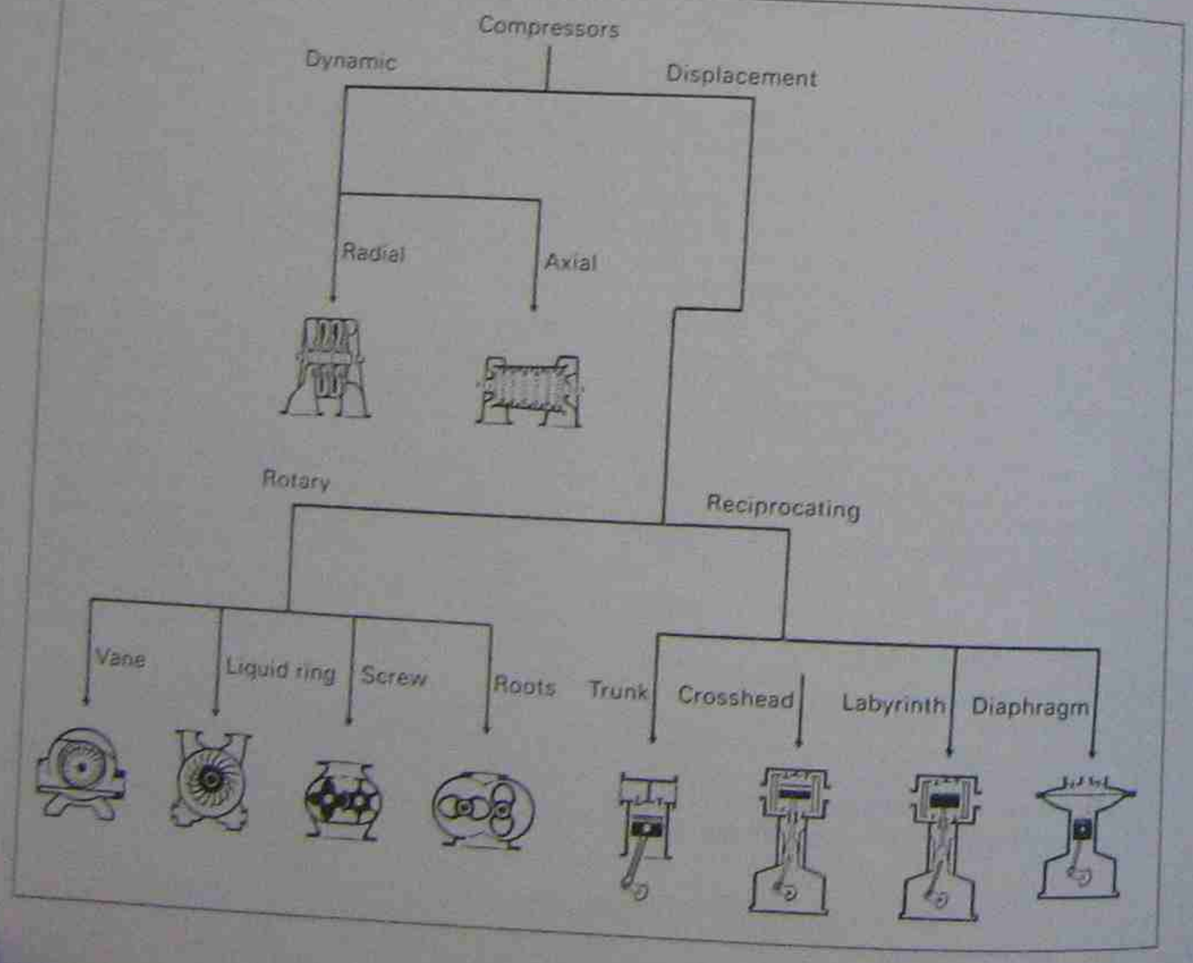


Fig. 13–3 *Left:* Theoretical compression curves for piston compressors. The areas under each curve represent the work required for each method.

A1 B C D — Isothermal
A2 B C D — Polytropic
A3 B D C — Adiabatic

Fig. 13–4 *Below:* Compressor design types.



curves for a reciprocating piston compressor for various compression methods. The areas under each curve, and plotted within the points A, B, C, D, represent the work requirements for each method.

Compressor design principles

There are many different types and designs of compressors operating in industry, from the simple type used in every garage for pumping up tyres and performing other garage jobs, to medium and mammoth compressors used in the manufacturing and mining industry. Compressed air is used in many different applications, and to suit these and still compress air efficiently requires compressors of different types and sizes.

There are basically two principles of compressor design; "positive displacement" and "dynamic". Emphasis will be placed on *positive displacement compressors* in this book, because these are most commonly used in industry. However, dynamic compressors will be discussed briefly.

Positive displacement compressors may be defined as those air compressors in which successive volumes of air are enclosed and then elevated to a higher pressure by reducing the volume of the enclosure holding the air.

Dynamic compressors are rotary continuous flow machines, in which a high speed rotating element accelerates the air, converting a velocity head into pressure. Figure 13–4 shows the various types of compressors in these two design methods.

Compressor Staging

Compressors of all types are made up of one or more individual compression spaces, called compression elements.

In order to obtain better efficiency and thus cut air compression power costs, larger compressors are designed to compress air in stages. By this method, two or more compression elements are used to raise the air pressure to the final delivery pressure. These compression elements are all driven from a single common source of power e.g. (electric motor).

Cooling of the air between each stage is essential, and is called intercooling (it cools the air whilst it passes from one stage to the next). The intercooler is an integral part of the staged compressor. Intercooling results in volume reduction of the compressed air which is directly responsible for the power reduction gained; thus intercooling combined with staging is a step towards the ideal isothermal compression process described previously.

Piston Compressors

The piston compressor (sometimes also called reciprocating compressor) is by far still the most common type of air compressor in use in industry today, and is available in a wide range of types and sizes. It is very versatile with respect to capacity and pressure level attained, since it is capable of compressing air up to 1200 kPa (12 bar) as a single stage compressor and up to 14000 kPa (140 bar) as a multi-stage compressor. It provides air flow deliveries from around 0.02 m^3/min F.A.D. to 600 m^3/min F.A.D.

The average motor service station would have a compressor of around 0.8 m^3/min F.A.D.

Reciprocating compressors tend to be noisy and cause vibration, and for this reason are anchored to their workplace. This makes them less desirable as a mobile unit (mounted on a trailer), especially for larger sizes. When compared with rotary type compressors, such as screw and vane compressors, these drawbacks are significant. Modern designs, however, have reduced the noise and vibration remarkably and depending on the application, such noise and vibration can sometimes be tolerated.

Because the air is compressed in pulses, pulsation damping is required to smooth out these pulses. Some compressors utilise a pulse tank especially matched to the compressor's pulsing characteristics and fitted directly after the outlet port. However, a receiver is generally used to smoothe pulsations. This makes the overall compressor package bulky. However, a receiver is required in any case, for compressed air storage and cooling.

The operation of a piston compressor is described below, in conjunction with fig. 13–5. On the intake stroke, a partial vacuum is created above the descending piston and air is therefore forced into the compression chamber through the inlet or suction valve. This valve opens automatically due to the pressure differential caused by the partial vacuum above the piston. When the piston reaches bottom dead centre (the lowest possible position) and starts to rise again, the trapped air due to a pressure imbalance above and below the inlet valve will close the inlet valve and thus compression of the trapped air begins to occur. Once the air pressure inside the compressor has risen to a level where it can force the inlet valve to open, the partially compressed air will then flow through the outlet valve into the compressed air system.

Both inlet and outlet valves are usually spring loaded, and are made to open and close automatically by a pressure differential across each valve. After the piston reaches top dead centre and begins to descend again, the outlet valve closes and the cycle of compression and air intake is repeated. Compressor cooling is of course essential to carry away the heat generated by the compression of the air, and either air or water cooling may be used.

Some piston compressors are double acting, meaning that compression takes place during both strokes. Figure 13-6 shows such a compressor, which requires the use of a crosshead to link the connecting rod to the piston rod. The crank end of the cylinder is closed and fitted with additional inlet and outlet valves to allow compression also to take place on the return stroke.

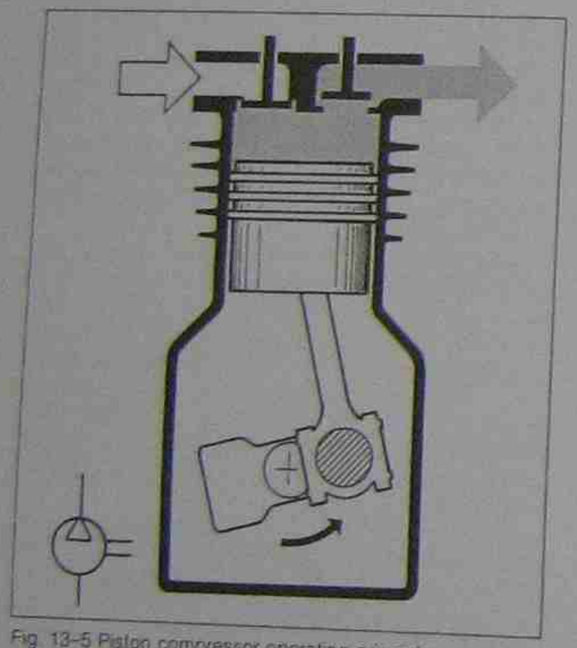


Fig. 13-5 Piston compressor operating principle.

Although making the compressor arrangement mechanically more complicated, double acting compression is beneficial for larger compressors, resulting in larger air delivery and greater efficiency whilst keeping the compressor size relatively small.

Staging of piston compressors

Most large piston compressors (single or double acting) above about 3 m^3/min F.A.D. employ two

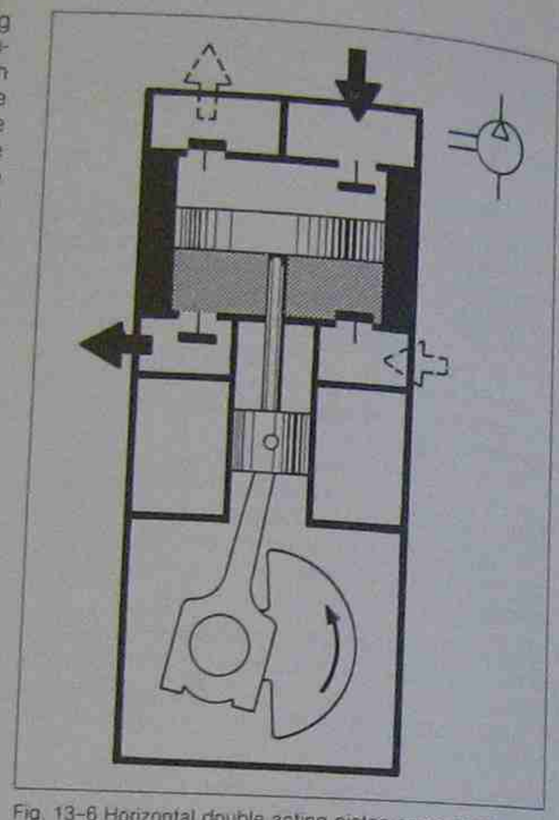


Fig. 13-6 Horizontal double acting piston compressor.

or more stages, but two stage types are the most common. Referring to fig. 13-7, there is a compression chamber (compression element) for each stage and both pistons are driven from the same power source.

The first stage, the low pressure stage, is comparatively large and takes in air directly from the atmosphere. It then raises the pressure to some portion of the total compressor output pressure. If 700 kPa is required, the first stage may raise the pressure to 500 kPa. The first stage cylinder discharges the partially compressed air into a heat exchanger (an intercooler), which may be air or water cooled. Whilst passing through the intercooler, the air is cooled and its volume is reduced, and whenever air can be cooled during compression, work savings can be made due to the reduction in volume and temperature (see fig. 13-8).

Whilst the partially compressed air passes through the intercooler, some condensate will drop out and can be removed. (Condensate is an important consideration in the compression of air, and is discussed more fully in Chapter 14.)

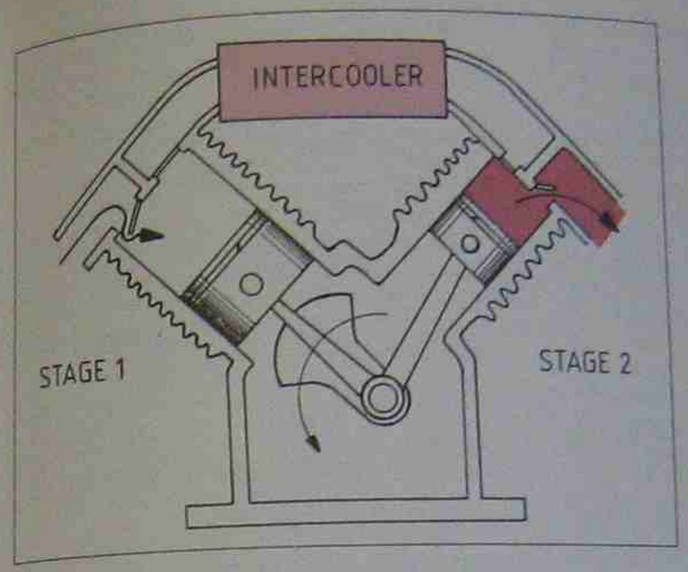


Fig. 13-7 Two stages, single acting piston compressor arrangement.

Leaving the intercooler, the air then passes into the second stage or high pressure cylinder, which is smaller in diameter than the first stage. The second stage cylinder compresses the air to the final output pressure. If extremely high pressures are required, more than two stages must be used. The following calculations, based on typical compression specifications, serve as an example to show how the gas laws can be used to solve a calculation problem relating to compressor staging.

Calculation example:

A two stage compressor with a capacity of 0.16 m^3/min F.A.D. takes in atmospheric air at a pressure of 101 kPa A (absolute) and a temperature of 20°C.

The first stage discharges compressed air at 124°C and 450 kPa gauge.

Whilst passing through the intercooler, this air is cooled to 40°C, and thus its pressure drops to 420 kPa gauge. With this reduced pressure and temperature the air then enters the second stage, where it is further compressed to 700 kPa.

Assuming 100% compressor efficiency, calculate the actual reduction in volume of the air across the intercooler per minute (m^3/min), and also the percentage reduction.

Conditions at the inlet and outlet ports of the first compression stage after one minute of operation.

At the inlet, these conditions are:

$p_1 = 101$ kPa A

$V_1 = 0.16\ m^3$

$T_1 = 20 + 273 = 293$ K (20°C) (1°C = 1K)

At the outlet these conditions are:

$p_2 = 450 + 101 = 551$ kPa A

$V_2 = ?\ m^3$

$T_2 = 124 + 273 = 397$ K (124°C)

Solving for V_2, the reduced volume after first stage compression is:

$$V_2 = \frac{p_1 \times V_1 \times T_2}{p_2 \times T_1}$$

$$V_2 = \frac{101 \times 0.16 \times 397}{551 \times 293} = 0.04\ m^3$$

Conditions at the inter-cooler inlet and outlet ports after one minute of operation.

At the inlet (i.e. as for first stage outlet):

$p_2 = 551$ kPa A

$V_2 = 0.04\ m^3$

$T_2 = 397$ K (124°C)

At the outlet these conditions are:

$p_3 = 420 + 101 = 521$ kPa A

$V_3 = ?\ m^3$

$T_3 = 40 + 273 = 313$ K (40°C)

Solving for V_2, the volume after intercooling:

$$V_2 = \frac{p_1 \times V_1 \times T_2}{p_2 \times T_1}$$

$$V_2 = \frac{551 \times 0.04 \times 313}{521 \times 397} = 0.033\ m^3$$

This is the reduced volume after intecooling.

The volume reduction per minute is:

$$= 0.04 - 0.033\ m^3/min$$

$$= 0.007\ m^3/min$$

Therefore the percentage reduction is:

$$\frac{0.007 \times 100}{0.04 \times 1} = 17.5\%$$

This sample calculation shows that the volume reduction is significant and amounts to 17.5%, but when all factors are taken into consideration, it can result in practical power savings of up to 15% for a two-stage compressor compared with a single-stage compressor (see fig. 13–18).

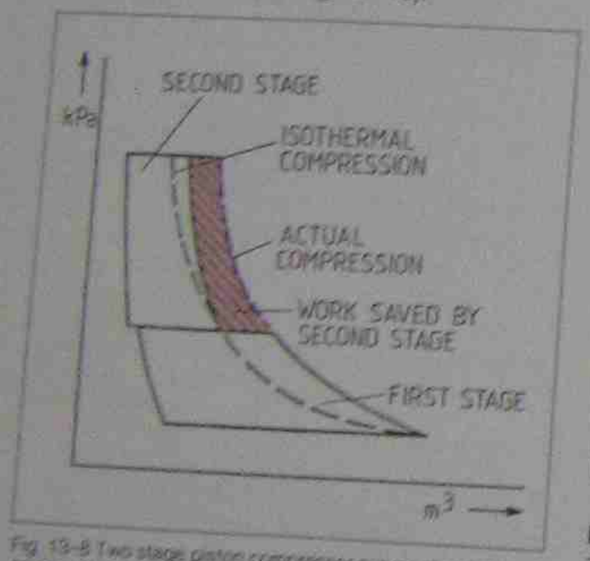


Fig. 13–8 Two stage piston compressor curves showing work savings due to staging

Theoretical compression curves for a two stage positive displacement compressor are shown in fig. 13–8, where the work saving is the result of intercooling. This graph plots the pressure rise as a direct result of the volume reduction of each compression stage, and therefore the shaded area represents work savings (pressure x volume). The shaded area, however, can also represent power savings if the cylinder volume is considered as volume per unit time or flow rate.

Oil free piston compressors

Oil inevitably gains entry into the air compressed in a standard compressor which has an oil filled crankcase and lubricating oil fed to valves, bearing and other points. Industries such as the food and chemical industries and hospitals cannot tolerate this oil contamination, and for these applications oil free piston compressors are made. These compressors have dry crankcases, and the piston rings, bearings and other sliding components are made of teflon, graphite or smilar substances. This overcomes the need for oil lubrication of the compressor which delivers air free of oil contamination.

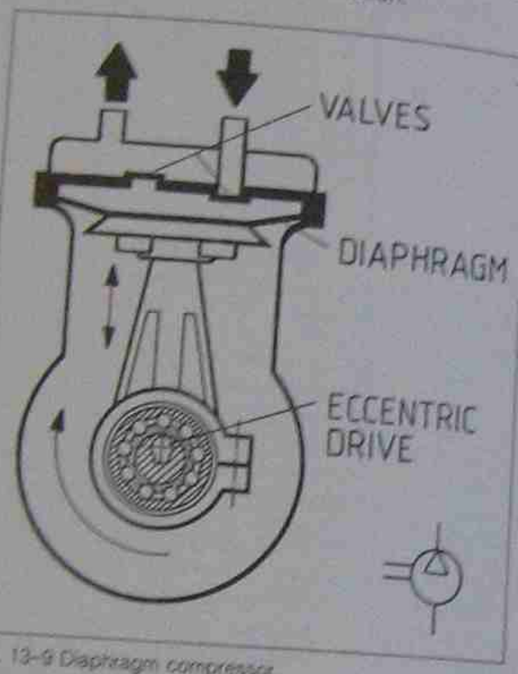


Fig. 13–9 Diaphragm compressor

Diaphragm Compressors

The diaphragm compressor (fig. 13–9) is a reciprocating compressor, but the piston is replaced by a disc and diaphragm assembly. The diaphragm is attached to the reciprocating disc and to the cylinder wall and acts like a piston in a piston compressor but positively isolates the compression chamber from the oil lubricated crank case, so that no oil comes in contact with the air being compressed. The air intake and outlet delivery is controlled by inlet and outlet valves. Diaphragm compressors are mechanically simple, and are available for a wide range of delivery volumes and pressures suitable for industrial shop air. They are easy to maintain and very reliable.

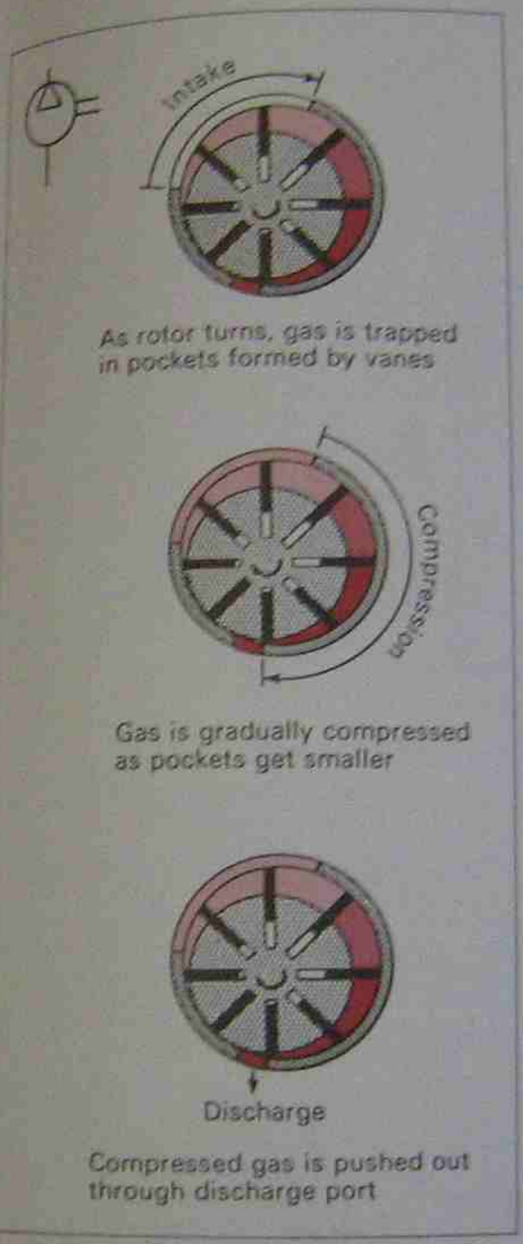


Fig. 13–10 Compression steps for a rotary vane compressor

Rotary Vane Compressors

In rotary vane compressors an eccentrically arranged slotted rotor with radially movable vanes inserted into the slots rotates within a circular stator or housing (fig. 13–10). During rotation, the centrifugal force drives the vanes outward against the circular housing where they make contact and follow the contour of the housing. These vanes, in conjunction with the rotor and the circular housing, form compression spaces. As the rotor turns these spaces are reduced in volume as they move towards the air outlet, and increased as they move towards the air inlet. Air is drawn into the inlet, and while it moves through the compressor, it is compressed by the reducing air spaces and then discharged into the pneumatic system. A non-return valve (check valve) is usually installed at the outlet port to prevent the compressor from motorising (being driven in reverse) when compression is stopped.

The rotary vane compressor is predominantly an oil flooded type in which oil is sprayed into the compression chamber where it performs three functions. It lubricates all the moving parts; it assists in sealing the clearance gaps between the vanes and the housing, and between the vanes and the rotor; and most importantly, acts as a heat exchange medium. The heat of compression is picked up by the oil and dissipated through an oil cooler (fig. 13–11).

Before the oil can be cooled, however, it must be separated from the compressed air by an oil separator. Two types are used: the felt pad type, and the replaceable cartridge type. When operating correctly, these separators remove virtually all the oil from the compressed air. This oil then passes through the oil cooler, before being returned to the compression chamber for reuse. Oil flooding provides relatively cool air (80–90°C) directly from the compressor which in many applications overcomes the need for further cooling.

Other benefical features of oil flooded rotary vane compressors are a non-pulsating air flow and low control pressure differential (see compressor control). These features make a receiver unnecessary which produces a compact compressor package, and this coupled with their low noise level and lack of vibration makes them the ideal choice for mobile "tow along" compressors and for general use in industry.

Rotary vane compressors are, however, most efficient when they are operated continuously at the top end of their air delivery ratings. These compressors are manufactured with more than one stage and their ratings are: 800 kPa for a single stage compressor, or 1900 kPa for a two stage compressor with capacities from 3 m³/min to 30 m³/min F.A.D.

Although oil free rotary vane compressors are manufactured, many of the benefits resulting from oil flooding are absent.

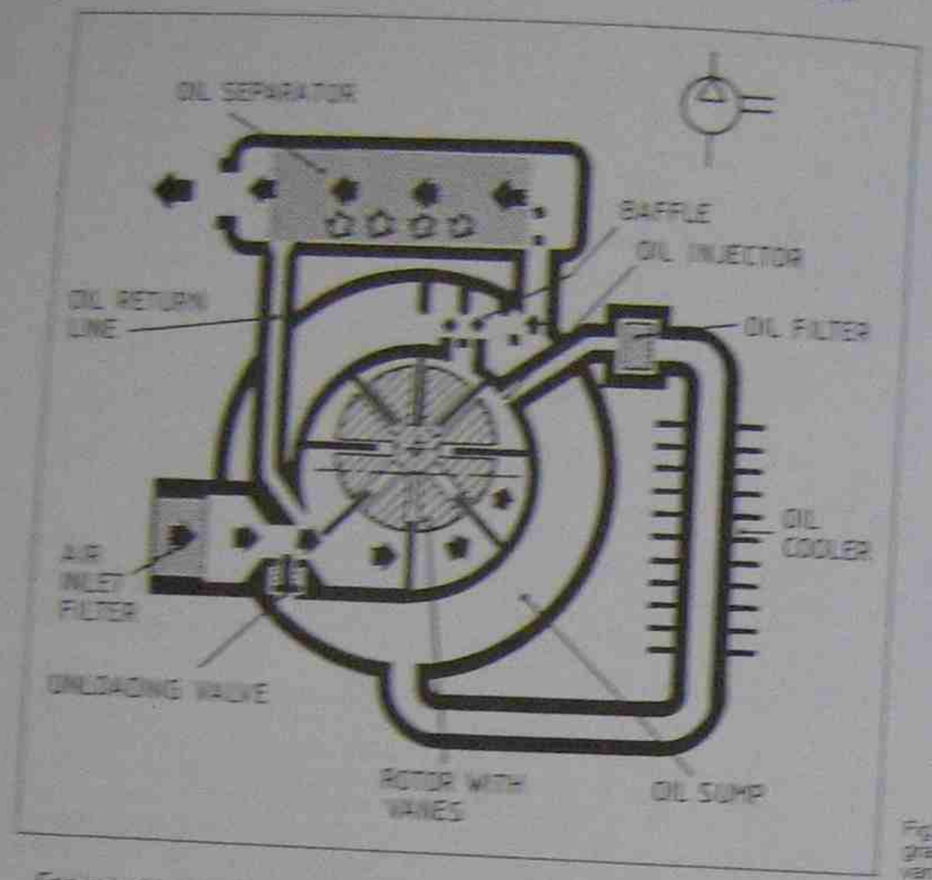


Fig. 13-11 Schematic diagram of an oil flooded rotary vane compressor.

For industrial applications, one important operating aspect of oil flooded compressors should be mentioned, particularly those types employing felt pad oil separators (fig. 13-11). Strict attention must be paid to correct periodical maintenance and supervision of the oil separator. If this is lacking, and the separator becomes ineffective, oil can be discharged from the compressor and enter the compressed air lines. This would cause malfunctioning of pneumatic control circuits due to clogging with oil.

Most recent designs of vane compressors have dispensed with the felt pad oil separator in favour of the replaceable cartridge type separator, thus making maintenance easier, and virtually overcoming the problem of "oil carry over".

Rotary screw compressors (helical lobe compressors)

Rotary screw compressors, which came into general use around 1950, have captured a large market for many applications. The rotary screw compressor consists essentially of a casing, which houses two screws or rotors, one male and one female (fig. 13-12). The male screw usually has one or two less lobes than the female has flutes into which the lobes mesh. The two screw shafts, in some designs (notably on oil free designs), are

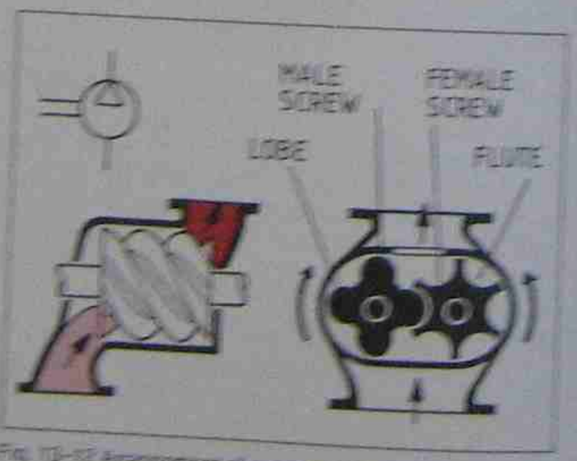


Fig. 13-12 Arrangement of a screw compressor showing the two screws and casing.

synchronized by gears and so kept from contact with each other. The screws also do not make contact with the casing which encloses them. The clearances between the screws and the housing, however, are very small.

As the screws revolve rapidly, air is drawn into the casing through the inlet port and into spaces between the screws, where the air is compressed between the lobes and flutes as the space becomes progressively smaller (see fig. 13-13). Compressed air then emerges from the outlet port into the casing. Both inlet and outlet ports are alternately covered and uncovered by the shaped end of the screws as they turn. The amount of compression (compression ratio) is predetermined by the shape of the lobes and flutes. A check valve is fitted at the outlet port of the compressor to prevent motorising when compression is stopped.

Rotary screw compressors can be supplied in either oil flooded or oil free versions. The oil flooded type has oil sprayed into the compression spaces in exactly the same manner as the rotary vane compressor and the same advantages are gained. Oil separation in rotary screw compressors, for virtually all designs, is of a replaceable cartridge type of oil separator.

The oil free screw compressor is used extensively in industry for those applications which require oil free air. Since oil is not injected, no internal air cooling occurs so the air has to be cooled by after cooling after it exits the compressor. Additional cooling is also required for the compressor itself.

Screw compressors have many of the same features and operating characteristics as vane compressors, such as steady and pulsation free air delivery, lack of vibration and low noise level. They are most efficient when operating to near full capacity.

Flow capacities start at 1.4 m³/min and extend to 60 m³/min F.A.D. Pressure ratings are up to 1000 kPa single stage and 2500 kPa staged.

Screw compressors are widely used in industry, and on civil and mining sites in the form of large mobile compressors. Many are also made as "packaged" units requiring only the connection to a source of electrical power to produce compressed air.

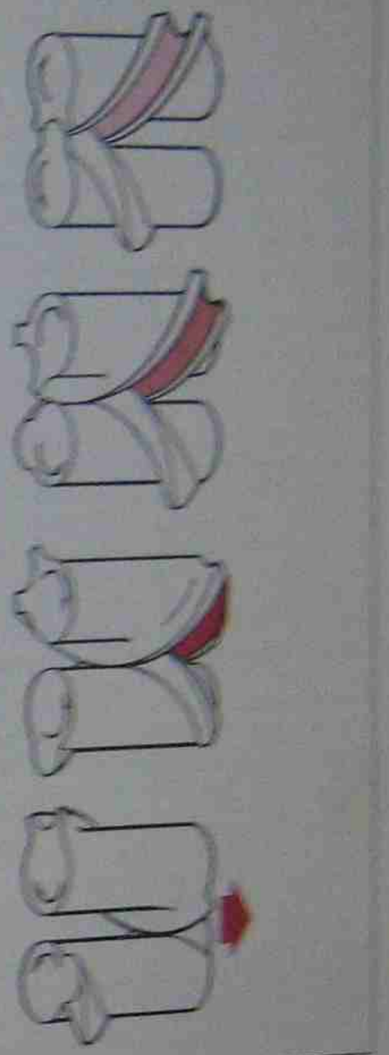


Fig. 13-13 Working principle of a screw compressor showing only one lobe and one flute.

Dynamic Compressors

Dynamic compressors fall into two main categories. These are centrifugal flow and axial flow. They are basically low pressure, high capacity machines, driven by electric motors, internal combustion engines or steam turbines. High pressure can however be obtained by multi-staging.

Advantages of dynamic compressors include oil free air delivery, high air delivery capacities relative to their physical size, pulsation free air delivery, and operation without vibration.

Some of the principal applications to which both the centrifugal and axial flow compressors are well suited are: air delivery to wind tunnels, blast furnace air delivery, tunnel ventilation, sewage agitation, and gas distribution.

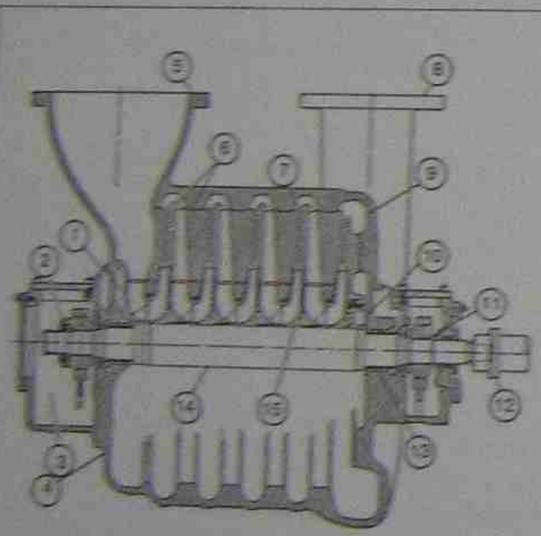
The axial flow compressor is generally not suitable for industrial shop air, but there is on the market a centrifugal compressor designed for shop air application, providing pressures up to 700 kPa. Its capacity is around 60 m³ /min, normally too large for general usage.

Centrifugal Compressors

In centrifugal compressors each stage consists of a casing, an impeller, a diffuser and a volute (fig. 13–14).

When the drive rotates the multi-bladed impeller at high speed, air is trapped between the impeller and the casing and thrown outwards, leaving the blade tips with pressure and high velocity. This outward thrown air then enters the stationary diffusor ring, where the air can expand and therefore reduce its velocity, but most importantly can increase substantially in pressure. From the diffusor, the air enters the stationary volute, where it expands further and increases in pressure, and is directed to the outlet or next stage.

In this type of compressor, unlike the axial flow type, air is thrown to the outside of the casing and so cooling and staging are relatively simple. By multi-staging, pressures as high as 25 000 kPa can be achieved, but generally the design pressures are below 700 kPa. However, large capacities of from 3000 m³/min to 20 000 are possible.



1. guide vane
2. thrust bearing
3. bearing housing
4. casing
5. inlet flange
6. diaphragm
7. diffuser
8. discharge flange
9. volute
10. thrust balancing drum
11. shaft bearing
12. coupling
13. seal
14. shaft
15. impeller

Fig. 13–14 Five stage centrifugal compressor

Axial Flow Compressors

In axial flow compressors the air is moved through a series of rows of alternating, rotating and fixed blades, with the direction of flow parallel to the axis of rotation. The rapidly rotating blades impart velocity to the air. As the rotor turns, the air velocity is converted to pressure as it passes through the adjacent stationary blades, which act as diffusors (fig. 13–15). The fixed and moving blades are curved opposite to each other, increasing the sectional area through which the air is flowing. Thus velocity is reduced, but pressure increased. Axial flow compressors are typically low pressure (up to 500 kPa) high flow machines with capacities from 280 m³/min to 3 300 m³/min F.A.D. Higher pressures of up to 30 000 kPa are possible with special designs.

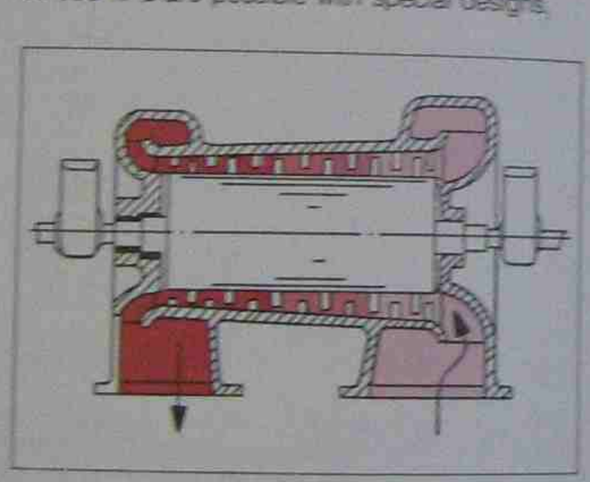


Fig. 13–15 Multi-stage axial flow compressor

Compressor capacity control

Because a compressor installation must be capable of supplying more compressed air flow than is required at peak demand, the output of a compressor must be controlled or regulated to match the system demand. This is usually accomplished by monitoring the system pressure at some point where the air pressure is relatively stable and free from pulsation, such as at the receiver. The rise and fall of pressure at this point is used to load and unload the compressor by a valve or other device. The pressure range between the high and low points is called the *pressure differential*.

An important operating factor in relation to any type of compressor control, is to determine which process or device in the system requires the highest pressure to operate satisfactorily. If, for example, a cylinder must operate at 600 kPa to provide a specified output force, or an air tool to do its work efficiently, then the monitored pressure must never be allowed to drop below about 700 kPa before the compressor again commences to feed compressed air into the system, otherwise the system pressure may drop below the required 600 kPa before the compressor has been able to recharge the system. Many pneumatic circuits and tools malfunction because this factor is ignored.

There are numerous methods of capacity control used in compressor systems, but the following three basic methods are used predominantly:

- start-stop control,
- constant speed control,
- variable speed control.

Start-stop control

The start-stop method uses the monitored pressure to operate an electrical pressure switch. This switch stops the electrical motor driving the compressor when enough pressure (that is, compressed air volume) has built up in the receiver or at the pressure sensing point. "Start-stop" control is best suited for use on electrically driven piston compressors up to about 1 m³/min F.A.D. (fig. 13–16).

A piston compressor using this form of unloading, requires a valve to automatically exhaust the compression cylinder after it has stopped, thus preventing restarting under load.

The start-stop method may also be used on compressors other than piston types as long as certain conditions are satisfied, especially with respect to the storage volume of the air receiver.

The cut-in/cut-out pressure differential for this method of control is around 140 kPa, and the system must be designed so that no more than about 10 starts per hour are required, otherwise the electric motor, due to the starting current, may overheat.

Rotary vane and screw compressors work most effectively and efficiently on constant load, and are not suited to "start-stop" capacity regulation. When vane compressors are stopped, the compression spaces must be exhausted to atmosphere. This may either be done manually or automatically, prior to restarting, otherwise scuffing between the vanes and cylinder walls will occur, which would lead to rapid wear.

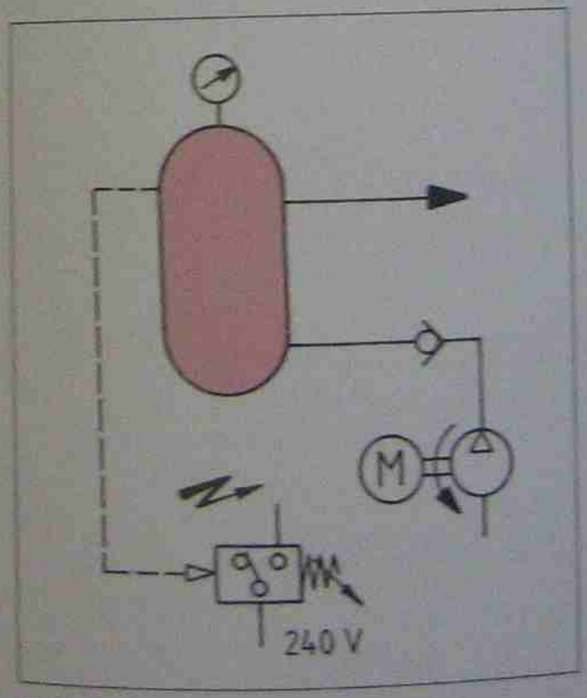


Fig. 13–16 Start-stop control circuit

Constant speed control

Constant speed control means that the compressor and its drive motor maintain for all practical purposes a constant speed. Capacity control (pressure unloading) is carried out by various means which still depend on the monitoring of the system pressure. The control once again is applied mainly to electrical drives, and is suitable for all types of compressors. Three design methods are used to achieve constant speed control.

Inlet valve unloading (constant speed control)

Inlet valve unloading is applied only to piston compressors and is sometimes also called "grip arm" control. The inlet valve is held open by an actuating device which grips the valve and prevents air from being compressed in the compression chamber. It is the most efficient method of constant speed control. Figure 13–17 shows a diagram of this arrangement and fig. 13–18 shows a cross-sectional drawing of an unloading actuator.

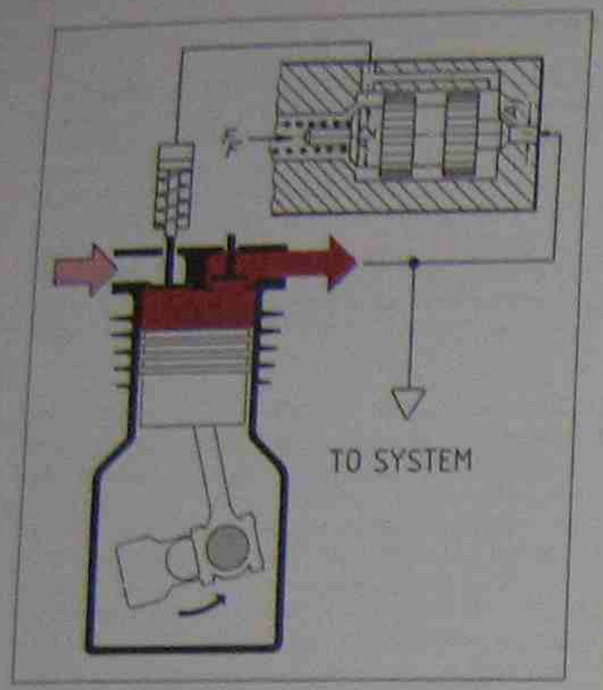
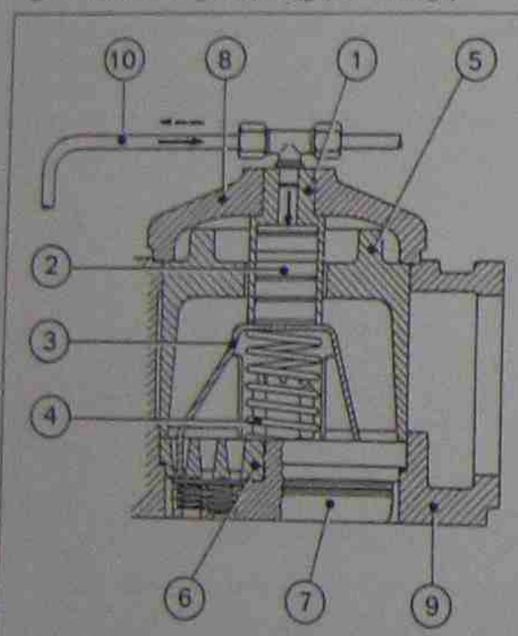


Fig. 13-17 Inlet valve unloading (grip arm constant speed control)

Fig. 13-18 Unloading actuator (grip arm design).



1 Unloading cylinder
2 Unloading piston
3 Unloading claw (depress the valve discs and keeps the suction valve open during the unloading period)
4 Unloading spring (returns unloading claw at start of loading)
5 Valve retainer
6 Seat of suction valve
7 Suction valve guard
8 Suction valve cover
9 Cylinder head
10 Compressed air to and from unloading device

The monitored pressure operates an unloading valve (sequence valve) which, when the system pressure has risen to a preset value, causes the unloading actuator with its claw to hold the inlet valve open. In some designs, this unloading actuator is simply an air cylinder built on to the inlet valve (fig. 13-17).

The only load that the drive motor has to overcome, when unloaded, is the friction of the free running compressor itself, and the movement of atmospheric air, in and out of the cylinder on each stroke. When the monitored pressure has dropped to the loading point, the unloading valve exhausts the actuator and the inlet valve is allowed to operate again, thus compression recommences.

The cut-in/cut-out differential for this method can be as low as 35 kPa, but is usually around 50 to 70 kPa.

Intake throttling (constant speed control)

Intake throttling is mainly used on rotary vanes, screws, and some dynamic compressors. The monitored pressure is used to throttle the intake valve either by a simple open-shut control (see fig. 13-19), or by varying the throttle opening to match system demand. A pressure operated servo valve as a pilot is used to control the opening and closing of the throttle valve. (See also fig. 13-11.)

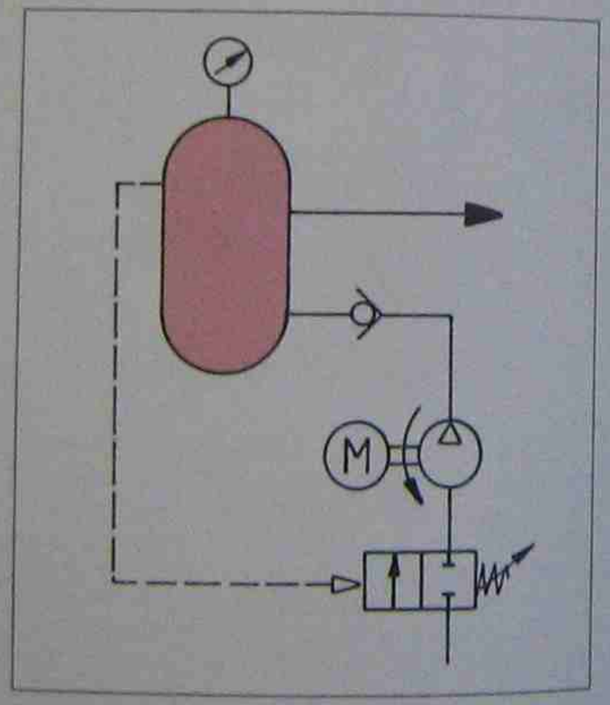


Fig. 13-19 Intake throttling control.

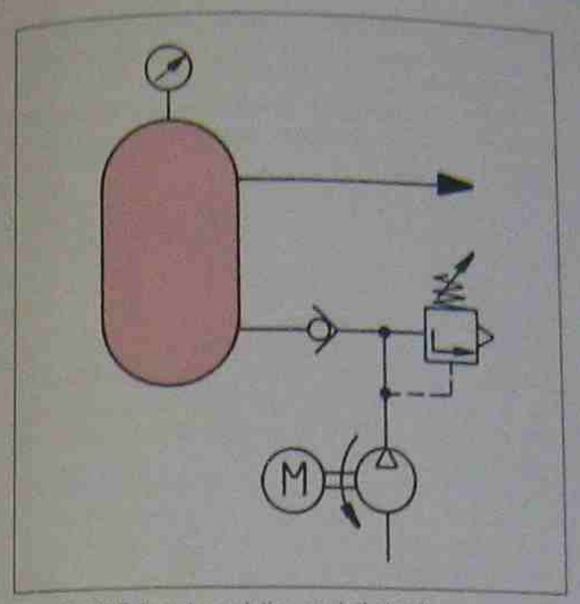


Fig. 13-20 Exhaust regulation control circuit

Intake throttling is not as efficient as "grip arm" unloading, as compression and expansion is still occurring within the compressor whilst the intake is throttled, and therefore power is being used unnecessarily. Overheating can also occur in the compressor if the throttle is fully closed for long periods. One advantage of intake throttling is its very narrow pressure differential, which may only be 7 kPa.

Exhaust regulation (constant speed control)

Exhaust regulation is used on very small reciprocating compressors. It blows the excess compressed air off to the atmosphere through a relief valve. This is extremely wasteful, as no reduction of power is achieved whilst the compressor is exhausting (fig. 13-20). A variation of this method, which also brings no power reduction, is external by-pass control, where the excess air is returned (by-passed) to the compressor inlet. This method is used on some vane and screw compressors.

Variable speed control

Variable speed control, as a means of capacity control, can be used on all types of compressors, but is most commonly used on internal combustion engine driven compressors. The speed of the engine and compressor is controlled, once again, by monitoring the system pressure. The controller then operates a pressure operated engine throttle governor. A minimum idle speed must, however, be maintained to prevent overheating of the compressor, and with vane type compressors, due to the lack of centrifugal force at low speed, the vanes may not fully extend.

Compressor site (location of installation)

The compressor installation site has a great influence on the quality of compressed air delivered into a distribution system and therefore deserves special consideration. The compressor should be sited in a location or building that is:

1. compressor
2. aftercooler
3. air receiver
4. drain valve
5. drain valve
6. inclination
7. branch pipe
8. service outlet

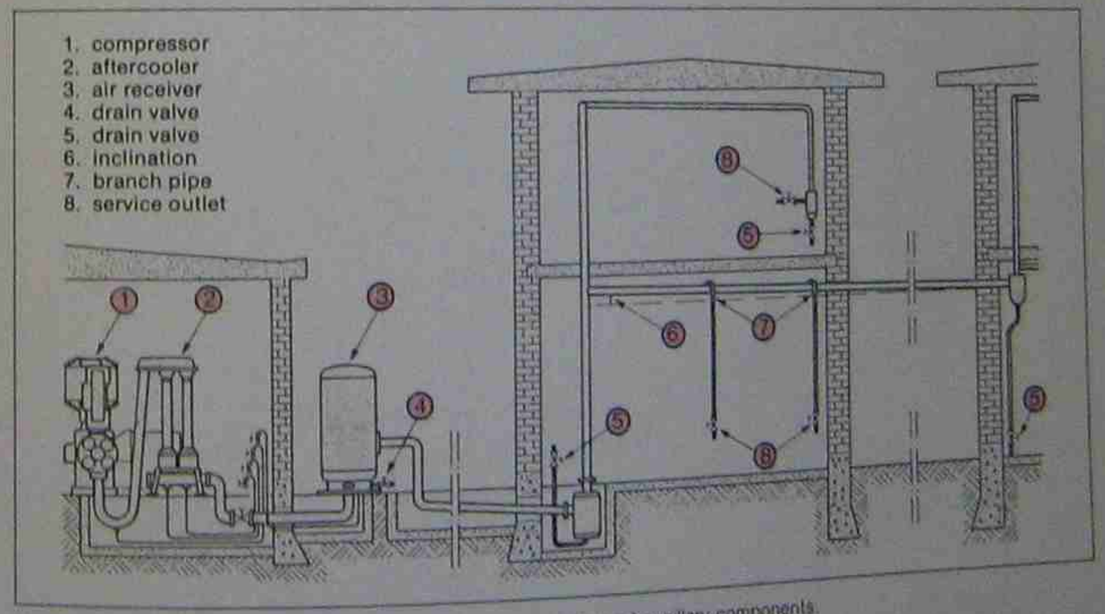


Fig. 13-21 Compressor installation showing some commonly used ancillary components.

- Cool and dry, to ensure that the minimum amount of water vapour is drawn into the compressor inlet (well away from steam boilers and other high humidity equipment).
- Dust free, to prevent blockage of the air cleaner, and the compressor cooling system.
- Adequately ventilated, to allow completely unrestricted entry of ambient air to the compressor inlet and ample air flow around the compressor to assist in its cooling.
- Adequately sized, to permit free and unrestricted access for servicing and maintenance of the compressor and its ancillary equipment.

Compressor ancillary equipment

A compressor performs the basic function of compressing air. However, to accomplish this function efficiently and effectively, it also requires accessory or ancillary equipment. A typical compressor installation is shown in fig. 13-21 and fig. 13-28, where such ancillary items are included. Some are essential to the compressor, and are ordered with it. One of these is the prime mover—an electric motor, or an internal combustion engine. Together with the compressor, it must be installed correctly to ensure efficient and reliable operation. Compressor installations, particularly for piston compressors, may require a solid foundation and it is therefore advisable to follow manufacturer's specifications.

The following ancillary items are not usually supplied with the compressor, but are optional:

- Intake silencer
- Air receiver (air storage tank)
- After cooler (compressed air cooler)
- Moisture separator

Intake filter/silencer

Each compressor needs an intake filter to remove particles of dirt before the air enters the intake port (fig. 13-23). These are either oil bath or paper type element filters which require periodic servicing or replacement.

An air silencer is sometimes required to silence the noise of the air rushing into the compressor. It can be fitted before or after the air filter, depending on the silencing effect required (figs. 13-23 and 13-24).

Air receiver

A compressor plant is normally equipped with an air receiver which must be large enough to suit the compressor flow rate, and must be matched to the selected compressor regulating system (com-

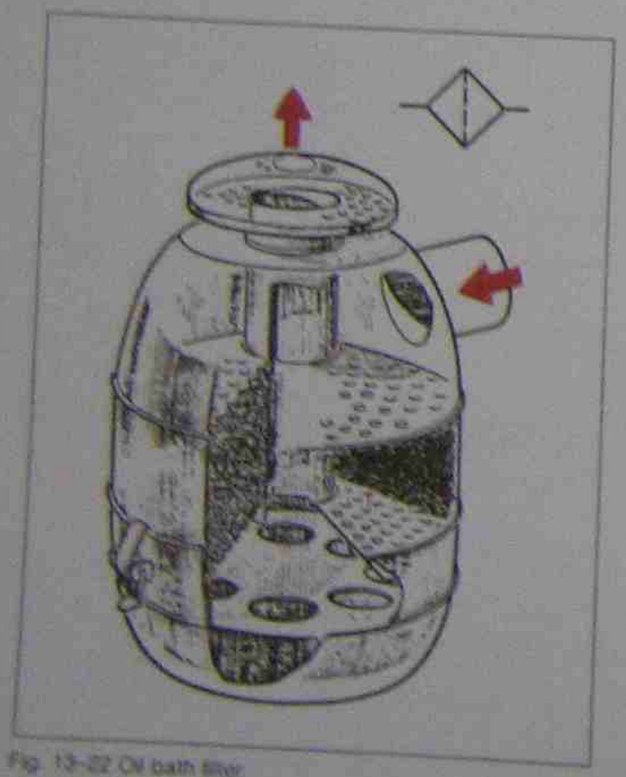


Fig. 13-22 Oil bath filter

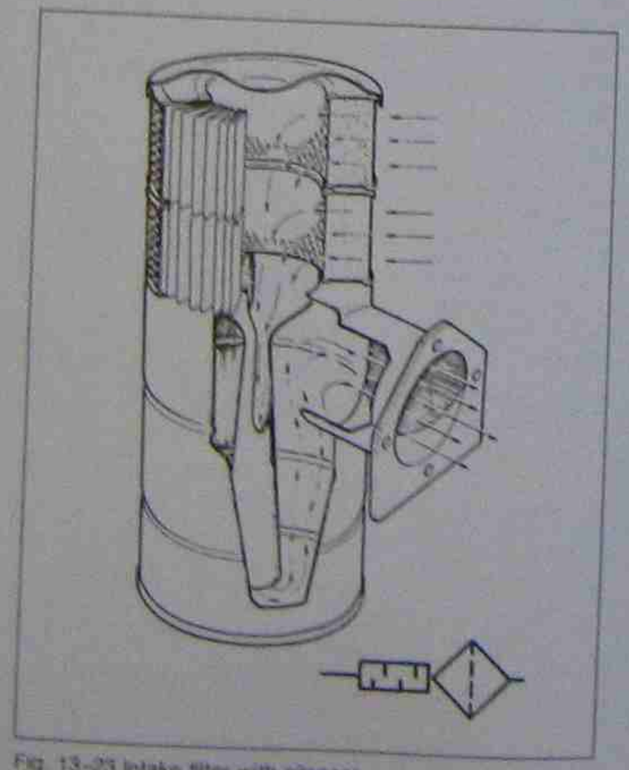


Fig. 13-23 Intake filter with silencer

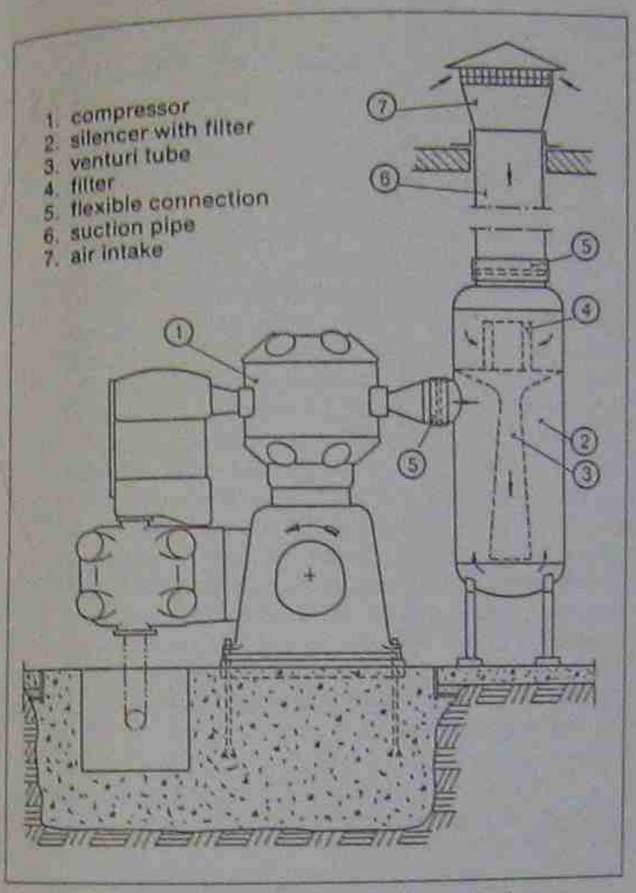


Fig. 13-24 Compressor with intake filter and silencer.

pressor capacity control). For some systems it may also be the only means of air cooling to reduce the moisture in the system (fig. 13-25). An air receiver serves four main functions:

- storage of compressed air; thus eliminating the need for the compressor to run continuously;
- pulsation damping to smooth the pulsing flow of air from the compressor;
- heat exchange to assist air cooling and thus produce condensate drop out before the air enters the distribution system;
- collection and drop out point for dirt and condensate accumulating in the air after compression.

Receivers are usually fitted with an automatic condensate drain, or if manually operated must be periodically drained. Air receivers must also be fitted with a safety air relief valve! Since air receivers are pressure vessels, they must be registered with the appropriate Government Authority, which controls and checks that the air receiver (pressure vessel) is properly constructed, installed, maintained and remains in a safe working condition. Figure 13-25 shows a receiver and its accessories.

A piston compressor must always work in conjunction with an air receiver and up to 2 m³/min F.A.D. compressors are usually supplied with a small air receiver which is part of the compressor package.

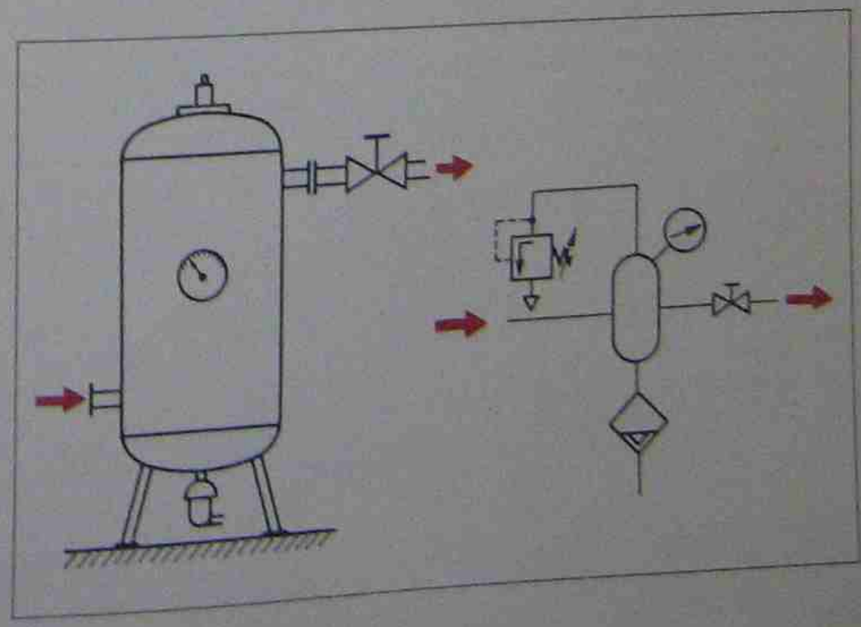


Fig. 13-25 Air receiver and its accessories

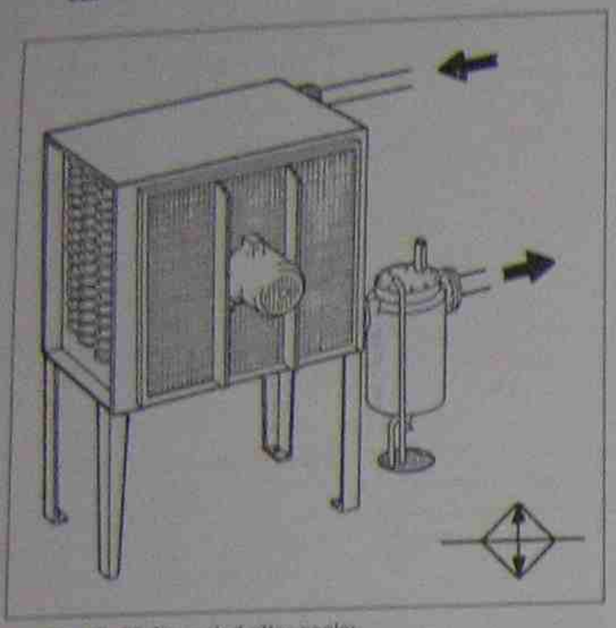


Fig. 13-26 Air cooled after cooler

Receiver volumes for compressors with start-stop regulation can be calculated by the following formula:

$$V_R = \frac{15 \times Q \times p_1}{\Delta p_2 \times c}$$

Where:

V_R = Receiver volume (m^3)
Q = Compressor delivery (m^3/min F.A.D.)
p_1 = Compressor intake pressure (kPa A)
p_2 = Pressure differential (cut-in/cut-out in kPa A)
c = Number of starts per hour

Air receivers may also be sized by a simple rule of thumb method which states:

Receiver volume (m^3) = capacity control factor × compressor F.A.D.

or: $V = K \times Q$

The factor K depends on the type of capacity control used on the air compressor and is given as follows:

for start-stop control:	K = 0.9-1.0
for constant speed control:	K = 0.5

After cooler

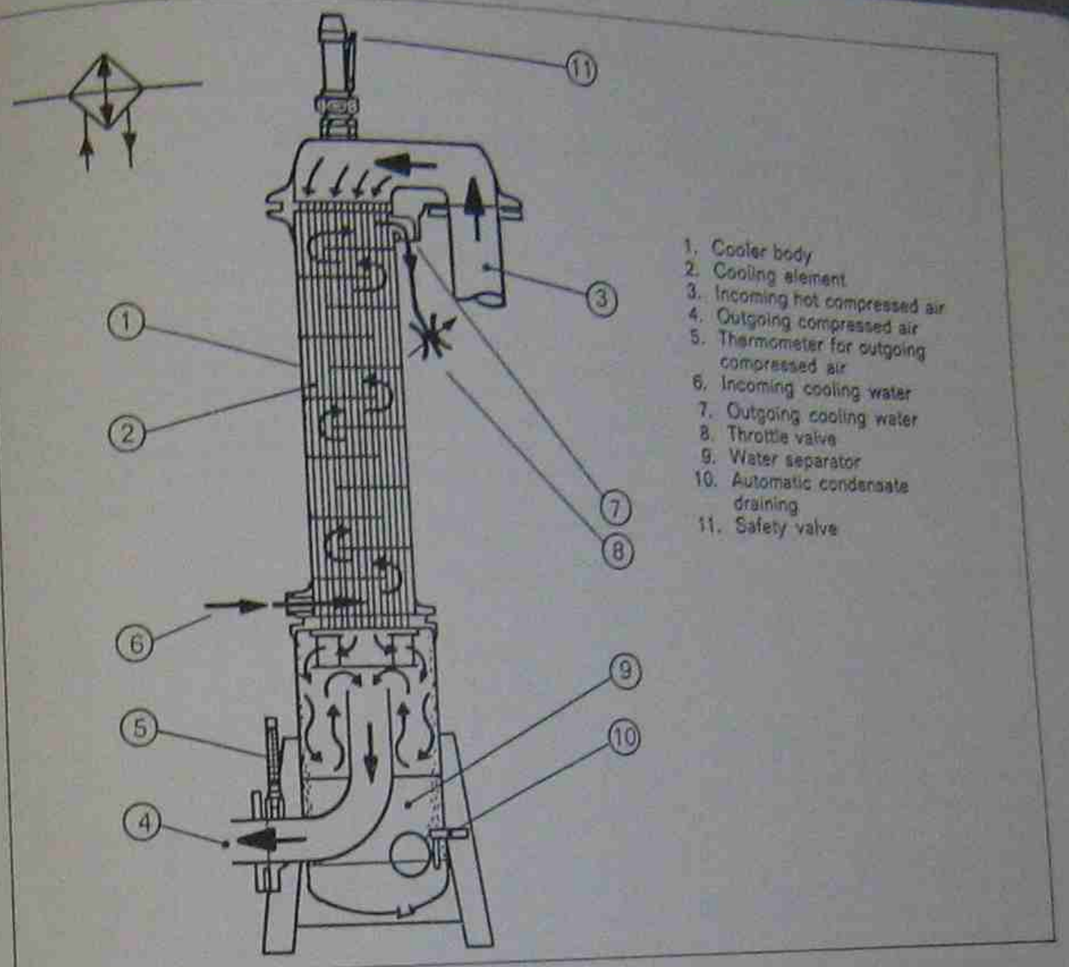
An after cooler is required to cool the air after it has left the compressor. The after cooler is a heat exchanger similar to the intercooler and can be either air or water cooled (figs. 13-26 and 13-27). Ideally, the compressed air temperature on leaving the compressor installation prior to use, should be cooled to no higher than 15°C above that measured at the compressor intake. The use of an after cooler is one method of achieving this. It is usually used in conjunction with larger capacity piston compressors and non-oil flooded rotary compressors. These compressors have no inbuilt oil cooling mechanism after the final compression element and, therefore, require after cooling. As the name implies, the after cooler cools the air, after it leaves the compressor and helps to remove much of the condensate. This removal of condensate is of prime importance, before the compressed air enters the distribution system. An after cooler is usually equipped with an automatic drain and requires frequent servicing much the same as an intercooler. There are many design types of after coolers and they are always installed directly after the compressor delivery outlet, prior to the receiver.

Moisture separator

A moisture separator is used to help rid the airline of condensate, oil and dirt. It is usually fitted before the receiver, but can be fitted virtually anywhere in the distribution system where condensate collects. Moisture separators are simple mechanical devices, designed to impose a sudden change of velocity and direction on the airstream, thus causing water and oil droplets to be flung out of the air stream, where they can be collected and drained off at the bottom of the separator. In some separator types, the air also passes through a filter element, which removes dirt particles.

Intercooler

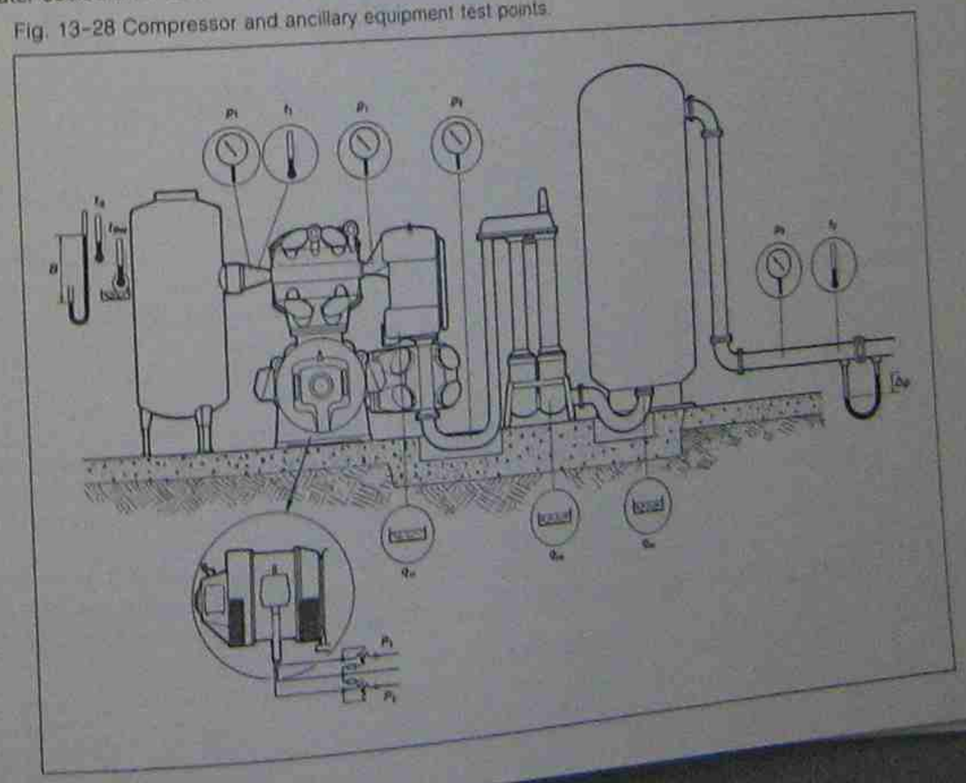
The intercooler is a heat exchanger, required between any two stages of a multi-stage compressor and is an integral part of a staged compressor (fig. 13-7). Whether it be air or water cooled, it requires periodic servicing to ensure the cooling mechanism is operating efficiently. Automatic condensate drainage must be fitted and its function and operation is described in the next chapter. This drain must never become blocked as otherwise one of the advantages of staging (the removal of condensate) would be negated.



1. Cooler body
2. Cooling element
3. Incoming hot compressed air
4. Outgoing compressed air
5. Thermometer for outgoing compressed air
6. Incoming cooling water
7. Outgoing cooling water
8. Throttle valve
9. Water separator
10. Automatic condensate draining
11. Safety valve

Fig. 13-27 Water cooled after cooler.

Fig. 13-28 Compressor and ancillary equipment test points.



14 Compressed Air Drying

Water condensate is the greatest single source of contamination of compressed air. If this water condensate is not removed, it can cause the malfunction of components and the spoiling of manufacturing processes, especially where the compressed air comes in direct contact with the manufactured product. It may also cause corrosion of the pneumatic components and discomfort for operators of air tools.

The quantity of water vapour in ambient air, and consequently the quantity of condensate (water) that can be released under pressure, can be considerable. A typical small 30 kW air compressor (6 m^3/min F.A.D.), taking in ambient air at 20°C with a relative humidity of 60%, will deposit 20 litres of water in the air line during each 8 hour shift. In other words, for every cubic metre/min F.A.D. of compressor capacity 0.4 litres of condensate is produced!

Through correct sizing, design, installation and maintenance of the compressed air system (this includes the air service unit), the problem of water condensate drop out can be reduced or made to occur before the compressed air enters the components to perform work.

However, many industrial automation and manufacturing processes cannot tolerate *any* moisture in the compressed air. To meet such stringent requirements a compressed air dryer must be used. Drying the compressed air is a complex procedure, and to understand it fully and make the correct decision when a suitable dryer must be selected one must understand the physical laws governing the transition of air moisture from water vapour to condensate.

Concepts and terminology

The atmosphere is composed of a mixture of various gases, such as oxygen 21%, nitrogen 78% and percentage fractions of carbon dioxide, hydrogen and helium. This mixture of gases called "air" also includes water vapour which is invisible, together with the other constituents.

The air can suspend specific amounts of water vapour, depending on air temperature. If the air temperature is lowered so that saturation occurs, the water vapour changes its state and becomes visible, in the form of fog or mist, which are forms of water condensate. Conversely, if the air temperature is raised sufficiently, the condensate will change its state once again and return to invisible water vapour. Air is said to be saturated when it has taken up all the water it can suspend (fig. 14-1) at that temperature.

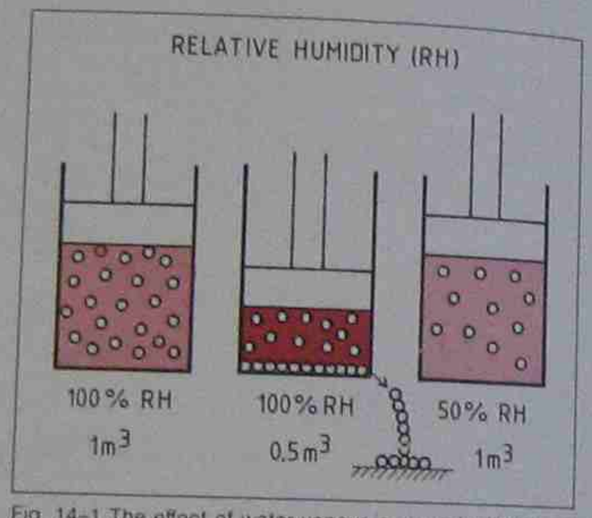


Fig. 14-1 The effect of water vapour in air under isothermal compression. RH = relative humidity.

The following terms and concepts are frequently used in compressed air drying:

- "*Saturation quantity*" is the maximum amount of water vapour by weight, which a sample of air can suspend at a particular temperature.
- "*Absolute humidity*" is that amount of water vapour by weight which a sample of air is suspending when not fully saturated. This humidity depends on geographical and atmospheric conditions. For example, on a rainy day the absolute humidity is much higher than on a dry sunny day. Absolute humitidy is expressed in grams of water vapour per cubic metre of air.
- "*Relative humidity*" is the ratio of the absolute humidity at a particular temperature, to the saturation quantity, at the same temperature. Relative humidity expresses the water vapour content of the air as a percentage (%) relative to the vapour concentration that would be required to reach saturation quantity. Relative humidity is measured with a "hygrometer". Relative humidity is an important factor for calculating the condensate drop out of a compressed air system (see calculation later in this chapter).
- "*Dew point*" is the *temperature* at which a given sample of moist air becomes saturated. This dew point definition is general and is usually applied to atmospheric or free air. It is that temperature at which a sample of atmospheric air in a closed vessel, when cooled sufficiently, will drop out condensate in one of its forms. Conversely, if the same sample is reheated, the dew point is that temperature at which all of the previously shed condensate reverts to vapour form. Dew point is sometimes referred to as "atmospheric dew point" or A.D.P. (see fig. 14-2).
- "*Pressure dew point*" is the term used to indicate the dryness of the compressed air when it leaves the air dryer. It is mainly used in connection with industrial compressed air dryer performance specifications. The pressure dew point (P.D.P.) is that temperature at which water vapour contained in compressed air of a specified pressure (other than atmospheric pressure) will condense to form liquid water. This P.D.P. is usually given for 700 kPa (7 bar) pres-

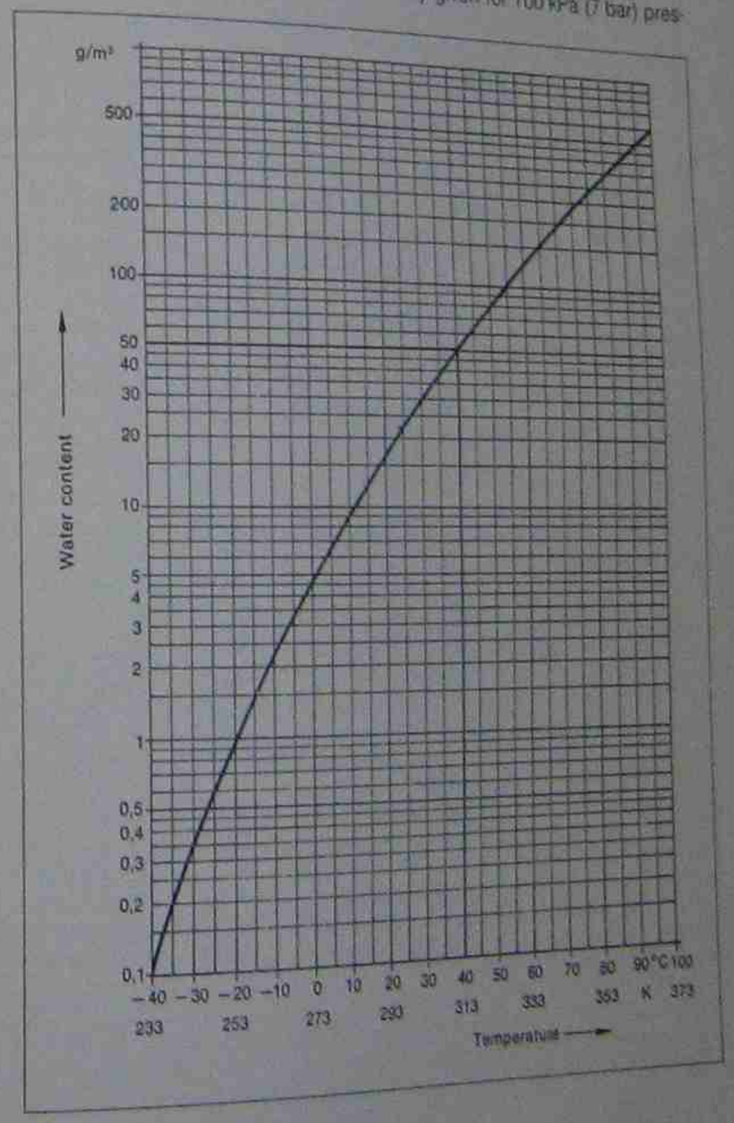


Fig. 14-2 Dew point chart for all pressures.

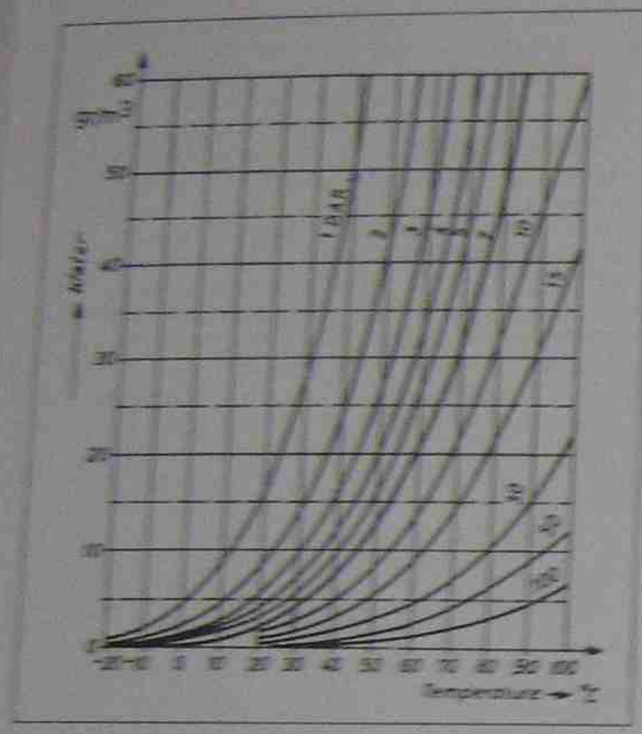


Fig. 14–3 Chart showing pressure dew points (P.D.P.) for various pressures and operating temperatures.

sure, the pressure predominantly used in industrial compressed air systems.

When comparing the performance of air dryers it is essential that the difference between atmospheric and dew points (A.D.P. and P.D.P.) is understood, as suppliers of dryers vary as to the form of dew point quoted.

The dew point capability of the dryer at the air pressure at which the compressed dryer is to be used must be known if a suitable dryer is to be chosen, because if the temperature of the compressed air at the point of use falls below the dew point, condensate drop out will occur.

To illustrate the difference between dew points of air at different pressures, refer to chart Fig. 14–3. This chart shows the effect that compressing a sample of air can have on the dew point. For example, consider a sample volume of air containing 10 gm/m³ of water at atmospheric pressure (1 BAR). The dew point (A.D.P.) will be 12°C. If this is compressed to 5 BAR its dew point (P.D.P.) will be 40° C and if compressed to 7 BAR its dew point will have risen further to 45°C. It can therefore be seen that the correct interpretation of dew point figures is essential in assessing an air dryer's performance.

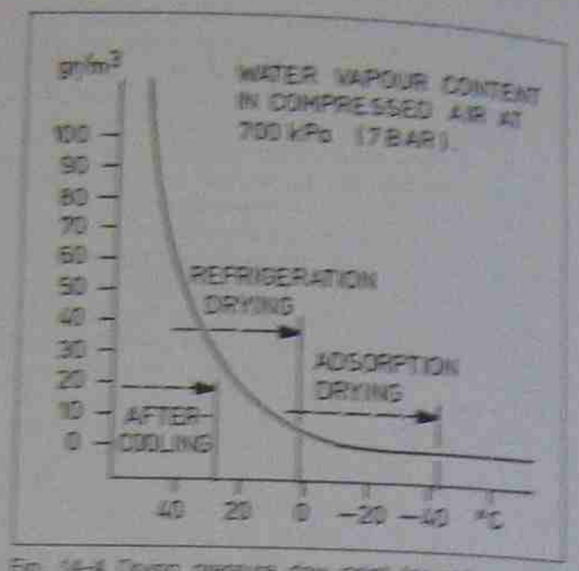


Fig. 14–4 Drying pressure dew point for various drying methods at a pressure of 700 kPa.

When a compressor operates, it takes in large volumes of atmospheric air, which always contains some moisture in the form of water vapour. The compression process reduces the volume of the air, but the volume of water cannot be reduced. For this reason it must be noted that the compressed air emerging from a compressor (at a temperature slightly higher than the ambient intake temperature) is always 100% saturated!

The following calculation, using the gas laws and the dew point graph (fig. 14–2), is a typical example of the amount of condensate generated during compression.

Example calculation:

A compressor is delivering 4 m³/min F.A.D. at 700 kPa gauge, and the air being drawn in at the compressor inlet has an ambient temperature of 25°C. The relative humidity of the drawn in air is 70% and its pressure is 101 kPa absolute. Calculate the amount of condensate per hour that would drop out at a point after the compressor, where the compressed air temperature has cooled down to 35°C.

Calculations over 1 hour:

4 m³/min F.A.D. = 240 m³/h F.A.D.

Conditions at the inlet port of compressor:

$p_1 = 101$ kPa A

$V_1 = 240$ m³

$T_1 = 25 + 273 = 298$ K

Conditions at the delivery port of compressor:

$p_2 = 700 + 101 = 801$ kPa A

V_2 = to be solved (m³)

$T_2 = 35 + 273 = 308$ K

Using the Gas Law

$$\frac{p_1 \times V_1}{T_1} = \frac{p_2 \times V_2}{T_2}$$

$$V_2 = \frac{p_1 \times V_1 \times T_2}{T_1 \times p_2}$$

The volume after compression is:

$$V_2 = \frac{101 \times 240 \times 308}{298 \times 801} = 31.25 \text{ m}^3$$

From the dew point graph (fig. 13-2) 1 m³ of air at 25°C can hold 22 g of moisture at 100% R.H.

At 70% R.H. 1 m³ holds $\frac{22 \times 70}{100} = 15.4$ g

Moisture taken in at the compressor inlet:

$= 15.4 \times 240 = 3696$ g

Referring again to the dew point graph 1 m³ of air at 35°C can hold 36 g of moisture at 100% R.H.

Moisture suspended by the air after compression is therefore:

$36 \times 31.25 = 1188.54$ g

Condensate drop out = moisture taken in minus the moisture the compressed air can suspend:

$3696 - 1188.54$ g $= 2507.36$ g

or 2.5 litres of condensate would be dropped out each hour.

(1 litre = 1000 grams water)

The calculation shows that 2.5 litres of condensate was dropped out for each hour the compressor was operating under these conditions. If by way of comparison the inlet temperature (ambient) was 30°C and then after compression the air temperature was dropped to 40°C (assuming relative humidity would remain the same), the previously calculated amount of 2.5 litres would increase to 3.7 litres per hour.

Figure 14–10, at the end of this chapter, further illustrates how temperature and pressure volume variations affect the moisture as it travels through a two stage compressor down the distribution line.

Aim of compressed air drying

The aim of compressed air drying is to dry the compressed air shortly after it leaves the compressor to a P.D.P. lower than that which is likely to occur in the distribution system or at the points of use. In doing so, all the moisture over and above that required will not cause trouble.

Most plant, which produces compressed air, will not avoid water. Therefore compressed air will condense when the air cools sufficiently to reach the critical point, where it is said, the dew point of the pressure dew point has been reached. To avoid this requires cooling of the air, as previously mentioned processes can also be used to achieve the same effect.

Dryer selection criteria

If pneumatically controlled and operated equipment or a manufacturing process demands dry air certain factors must be considered before an appropriate air dryer can be selected.

These factors are:

- total free air flow in m³/min F.A.D.
- maximum system pressure (kPa max. cut out),
- minimum system temperature (°C at point of use),
- air inlet temperature (°C at dryer inlet),
- pressure dew point (P.D.P.) at the dryer,
- drying energy costs (steam),
- pressure drop through the dryer (Δp).

The first four factors are pertinent to the system to be dried, whilst the last three are important dryer characteristics, usually obtained from manufacturers' specifications.

- Total free air flow is the flow rate in cubic metres/min F.A.D. (Q) which the dryer must be capable of passing and drying. Full compressed air from the compressor is to be used, then the flow capacity of the dryer (Q) in m³/min must be not less than the flow rate of the air compressor (Q) of air compressor in F.A.D. But to save energy and reduce capital costs, for some systems it may prove economical to dry only those branches of the system for which dry air is critical.
- Maximum system pressure is the pressure level of the compressor when it cuts out (capacity control). The dryer must have a pressure rating of no less than the maximum pressure.
- Minimum system temperature is the lowest ambient temperature ever likely to be encountered at any point in the distribution system or point of air usage. For a typical industrial manufacturing plant, this requires a study of the annual temperature conditions likely to be encountered over a full year. The temperature is particularly important to ascertain for installations in cold countries, or places with extreme fluctuating temperatures. When an air plant must operate over the building to another and cold weather conditions caused may affect the air temperature, this point must also be taken into consideration. For the most part, the ambient temperature of the

fig. 13-21). The pressure dew point (P.D.P.) achieved by the selected dryer must therefore always be lower than the lowest expected temperature in the system.

- *Air inlet temperature* is another factor to be considered when an air dryer is to be selected. A dryer treating compressed air at 45°C inlet temperature would have to extract 70% more water vapour than if the air entered at only 35°C.

The compressed air temperature at the inlet of absorption and adsorption dryers must never exceed 38°C, as this can damage and render ineffective the drying material (desiccant) used in these dryers. To satisfy such temperature requirements it is common to place the dryer downstream of the after cooler and the receiver (see fig. 14-5).

- *Pressure dew point* (P.D.P.) capability of a dryer is a major criterion. Even if the term P.D.P is understood, it can often be difficult to appreciate and judge the dryness between one P.D.P. and another. Figure 14-6 shows the variations in water content of compressed air starting with a P.D.P. of 20°C at a pressure of 700 kPa (7 bar), assuming 100% saturation. A refrigeration dryer with a P.D.P of 6°C would remove 57% of the moisture (water) contained in the air at 20°C. However, a refrigeration dryer with a P.D.P. of 2°C would remove up to 67% of the water. In other words, a small reduction of the P.D.P. (4°C reduction), achieves a sizeable reduction of the moisture content (10% less moisture).

To compare these figures, an adsorption dryer with a P.D.P. of −20°C would remove up to 95% of the water (moisture) contained in the compressed air at +20°C inlet temperature. Thus it can be seen that adsorption dryers are considerably more effective than refrigeration dryers and absorption dryers.

- *Drying energy costs* are a most important factor in the selection of air dryers. The following figures serve as a comparison for refrigeration and adsorption drying.

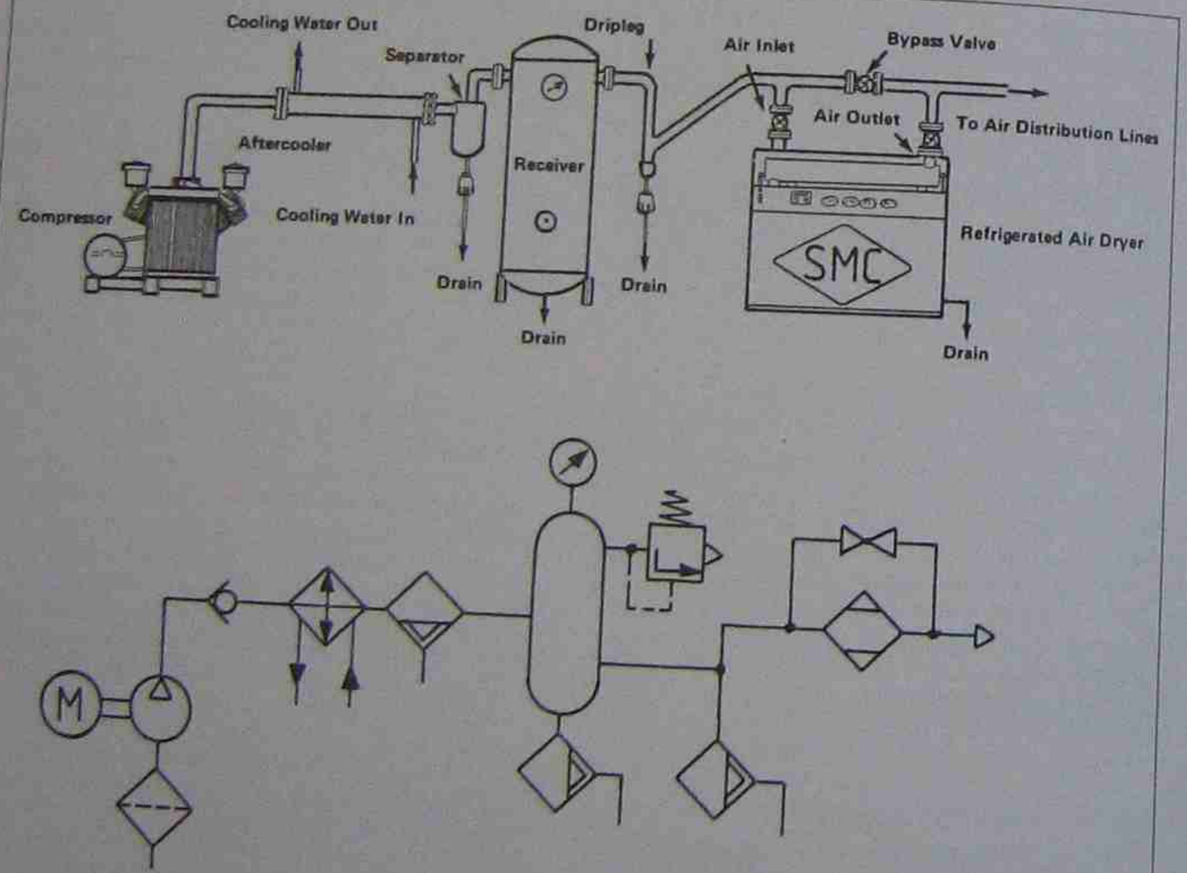


Fig. 14-5 Typical compressor air receiver and dryer arrangement.

REFRIGERATION:
+2°C P.D.P. 4 kWh/1000 m³ (F.A.)

ADSORPTION: (compressed air regeneration)
−20°C P.D.P. 18 kWh/1000 m³ (F.A.)

(electrical filament regeneration)
−20°C P.D.P. 8 kWh/1000 m³ (F.A.)

(heated fan-flow air regeneration)
−20°C P.D.P. 7 kWh/1000 m³ (F.A.)

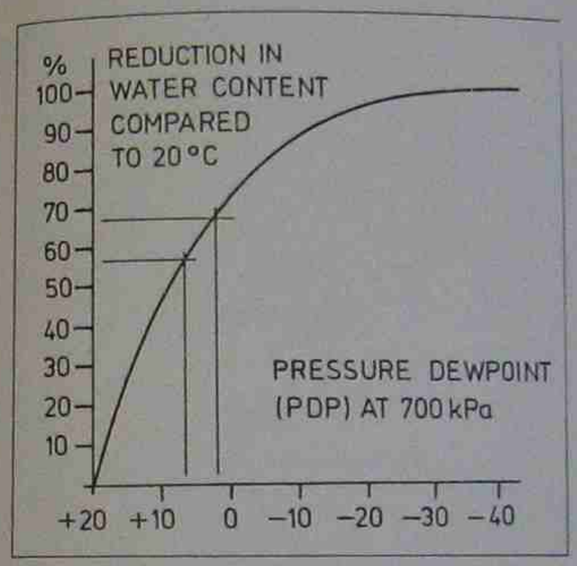


Fig. 14-6 Percentage reduction in moisture from compressed air at differing dew points, but relative to 700 kPa (7 bar) system pressure.

- *Pressure drop through dryers* must also be considered. Based on the energy required by the compressor to produce compressed air in the first place, it can be calculated that each 10 kPa (0.1 bar) pressure drop through the dryer requires a power input to the compressor of 0.8 kWh/1000 m³ (F.A.D.). This power figure in fact applies also to all other equipment producing pressure drops. The following figures serve as a comparison for refrigeration and adsorption dryers.

Refrigeration Dryers
Δp 30 kPa (0.3 bar) = 2.5 kWh/1000 m³ (F.A.)

Adsorption Dryers
Δp 70 kPa (0.7 bar) = 5.6 kWh/1000 m³ (F.A.)

There are basically three drying methods used for industrial systems:

- refrigeration drying (low temperature)
- adsorption drying
- absorption drying.

Refrigeration dryers

Only refrigeration dryers actually lower the temperature of the compressed air in order to lower the pressure dew point. They are sometimes referred to as "low temperature dryers". Refrigeration air drying is closely related to domestic refrigerators (fig. 14-7).

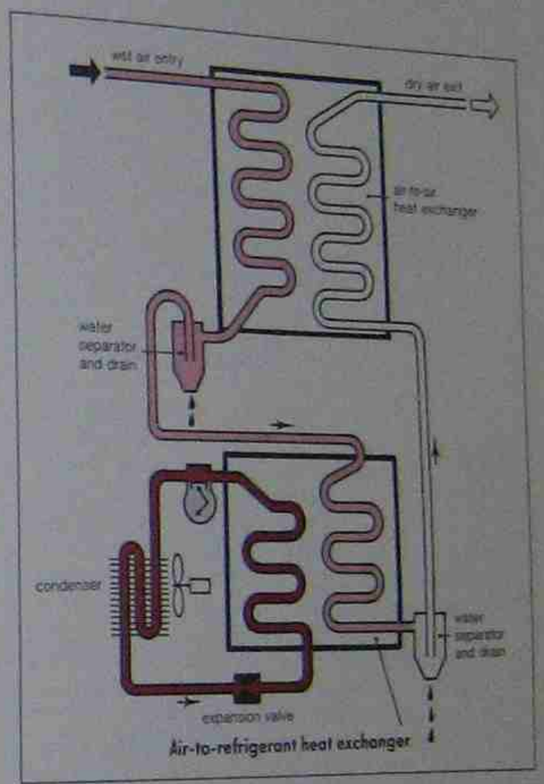


Fig. 14-7 Schematic diagram of a refrigeration dryer.

The compressed air to be dried enters at the inlet and flows through a "hot inlet air to a cold outlet air" heat exchanger. This "air to air" heat exchanger causes a temperature exchange between the two pipes passing through it, causing the incoming hot and saturated air to be cooled and thus releasing some of its moisture as condensate, whilst the outgoing cold and saturated air is warmed. In this way the relative humidity of the outlet air drops away from the saturation point, and therefore will stay dry during its flow through the distribution pipes.

After leaving the air to air heat exchanger, the air passes into the cooling unit (refrigeration unit), which further lowers the temperature of the air to about +2°C. This final cooling process removes

most of the moisture (see P.D.P. curve fig. 14–4). The extracted condensate is removed by automatic drains as it is generated. Air still in a saturated condition, but now at a much lower temperature, flows back into the air to air heat exchanger, where it is warmed again.

Refrigeration dryers, although only capable of drying compressed air to a pressure dew point of just above 0°C, are quite adequate for use in many general applications where moderate, minimum temperatures are experienced. Pressure drops of around 30 kPa are typical of such dryers, and their air inlet temperature (although not advisable) can be as high as 44°C. A certain quantity of oil in the air stream can be tolerated and removed with the moisture. To ensure that the specified dew point is maintained, and freezing does not occur, correct sizing of the dryer and correct adjustment of the refrigeration unit is important. Periodic maintenance is minimal and is virtually limited to checking the automatic drains.

Adsorption dryers

The adsorption dryer does not cool the air in order to lower the pressure dew point, but achieves this by a physical process called adsorption. Adsorption uses the properties of materials called desiccants. Such desiccants have the ability to attract and retain water vapour, whereby the moisture is deposited on the surface of the desiccant material. The moisture can be removed by various means, such as heating the desiccants or by purging it with dry air. This purging process is called regeneration (reactivation), and after completion the desiccant can be reused.

Adsorption dryers consist of two pressure vessels, which store the desiccant in pellet or granule form. Alternatively, one vessel is constantly in use, whilst the other is being "dried out" (regenerated).

Compressed air enters the drying vessel at the bottom and passes upwards through the desiccant material, where the process of adsorption occurs (fig. 14–8). The air then exits at the top of the vessel, having lost most of its moisture. In the meantime, the other vessel is being regenerated. The changeover from drying compressed air to regeneration is controlled automatically and reverses usually after a set period of time. The drying process, however, is continuous.

Adsorption dryers can achieve pressure dew points to −20°C and some may even reach a P.D.P. of −50°C, depending on desiccant material used. Pressure drop through such dryers may be as high as 70 kPa, but is generally about 20 kPa. Common desiccant materials are silica gel

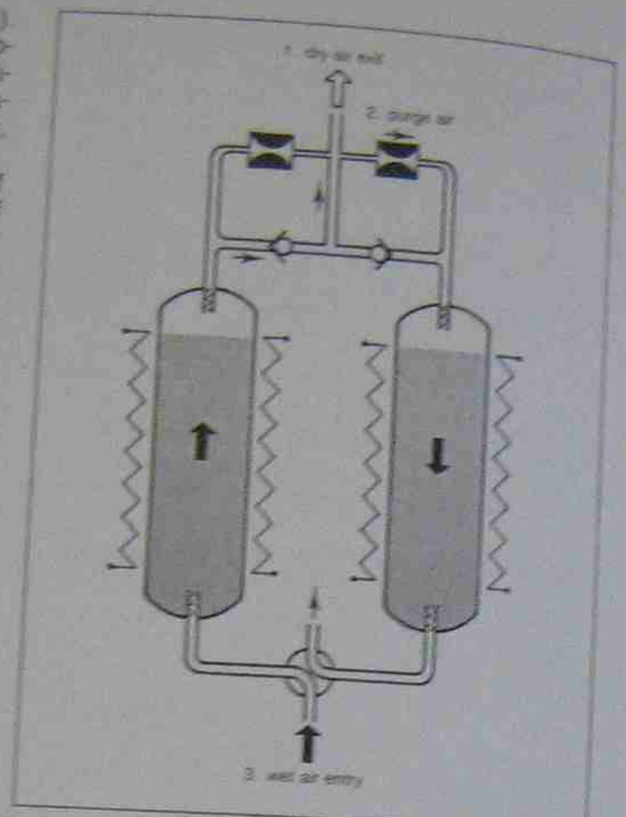


Fig. 14-8 Schematic diagram of a heat regenerated adsorption dryer

or activated alumina. In both adsorption and absorption dryers, the actual composition of the commmercial desiccant is a very closely guarded secret, as each company claims lower dew point depressions for its dryers and drying agents. For maximum efficiency, an inlet temperature of 38°C should not be exceeded. For adsorption dryers, oil must first be removed to avoid damage to the desiccant material.

Small single unit or cartridge adsorption dryers are also available for low air flow applications. Regeneration is carried out manually by removing the cartridge and applying heat or dry air.

Absorption dryers

The absorption dryer uses a special type of desiccant, called a deliquescent. This deliquescent, when it comes in contact with water vapour from the compressed air, reacts chemically and liquefies. By this process, water vapour is absorbed from the air.

The pressure vessel is constructed to hold a large amount of deliquescent material in pellet or granule form (fig. 14–9). Typical deliquescent materials in use are: urea, lithium, and calcium

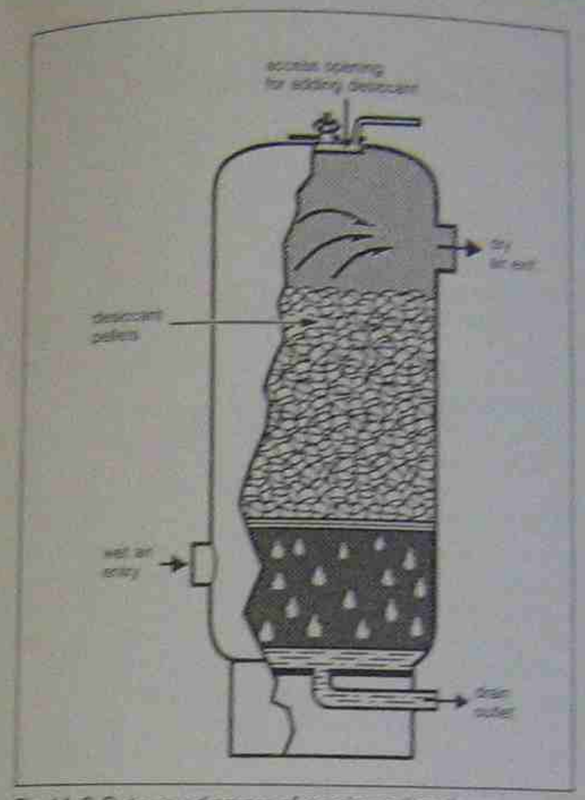


Fig 14-9 Cutaway diagram of an absorption dryer

chloride. In operation, the compressed air enters at the bottom of the vessel and passes upwards through the desiccant bed, where most of the moisture is absorbed, before it passes through the outlet port at the top end of the vessel. During absorption, the deliquescent desiccant slowly liquefies and seeps to the bottom of the vessel, where it is automatically drained off by a special automatic drain which can handle the fluid residue.

The pressure dew point or dew point "depression", as it is called in this type of dryer, is not a fixed temperature, but a function of the inlet temperature and can be as high as 15°C (Δ°C). If, for example, the temperature of the compressed air entering the dryer is 25°C, then the pressure dew point at the outlet will be 10°C. This low P.D.P. depression (Δ°C) is in many applications not a disadvantage, provided that the compressed air temperature at the dryer inlet has been lowered by aftercooling or an air receiver, to a temperature close to that at the point of usage.

Pressure drop through an absorption dryer is very low, typically less than 15 kPa. Any oil present in the air stream should, however, be removed before the air enters the dryer. Oil in the air can damage the desiccant material.

Absorption dryers are relatively economical, as they require no electrical power supply. The deliquescent desiccant, however, must be continually replaced as it is used (liquefied). With a correctly sized and operated dryer, refilling on a monthly basis should be sufficient. Some desiccant drying agents are strongly corrosive, and there is also the added risk that they might be carried along with the dried air, thus causing corrosion to pipe systems and pneumatic components. A further drawback is that the drying agents may soften and bake together, if the inlet temperature is not precisely controlled (exceeds 30°C). This may lead to increased pressure drop and added power costs.

The liquid residue (a hydrous solution) from most absorption dryers on the market may be directly discharged into storm water or sewage drains, as apparently there are no constituents in the liquid which do not meet the waste liquid discharge requirements of relevant statutory authorities. This should be positively ascertained, if pollution is to be avoided. If treatment of the liquid is required before discharge into drains can occur, this would then affect the operation and economy of absorption dryers.

Oil removal

Virtually all pneumatic processes which require dry air also require that this air is free of oil contamination.

Since no type of dryer can completely remove all oil particles present in the air stream, and desiccant material used in adsorption and absorption dryers can be damaged by oil contamination, oil must be removed from the air before it enters a dryer.

If the system does not warrant an oil free air compressor (see Chapter 13), oil removal filters are available with air flow capacities of up to 20 m³/min F.A.

There are two types of oil removal filter – coalescing (impingment) and adsorption. The coalescing filter uses a cartridge filled with a network of fibres. As air is passed through the filter any liquid oil particles present collide with the fibres (and each other), thus gradually forming larger droplets which gravitate to the bottom of the cartridge to be drained away.

The cartridge does not require changing until the air flow is restricted by dirt build-up, indicated by a pressure drop across the unit.

The adsorption oil filter uses a cartridge filled with particles which have a great affinity for oil, both in the liquid and vapour form, and adsorb this oil as air is passed through the filter.

When the particles can no longer adsorb any oil present in the air stream, a colour change occurs. The cartridge must then be discarded and replaced, as regeneration is not possible.

15 Compressed Air Distribution

Designing the system

After compression the air must be distributed to the points of usage, ideally with the least loss of pressure and flow. Pressure loss is caused by air turbulence in pipes and fittings, and flow loss is the result of external leakage. To achieve these goals proper sizing and designing of the air distribution system is thus of great importance and economical significance (fig. 15-1).

Sizing the system begins with calculation of the main pipe size required to carry the flow of compressed air from the compressor to the points of use (compressed air consumers). But first, a number of system operating factors or parameters must be determined:

- pressure drop through the system (Δp),
- calculated maximum system pressure (kPa max.),
- flow rate (Q) in free air,
- pipe length (m),
- pipe material (steel, copper, plastic),
- moisture drop out.

Pressure drop

In a compressed air system pressure drop is unavoidable. It is the result of turbulences and friction in the compressed air whilst it flows through pipes, fittings and valves. The sharper the bends in fittings and the rougher the inside surface of pipes, the greater the pressure drop will be.

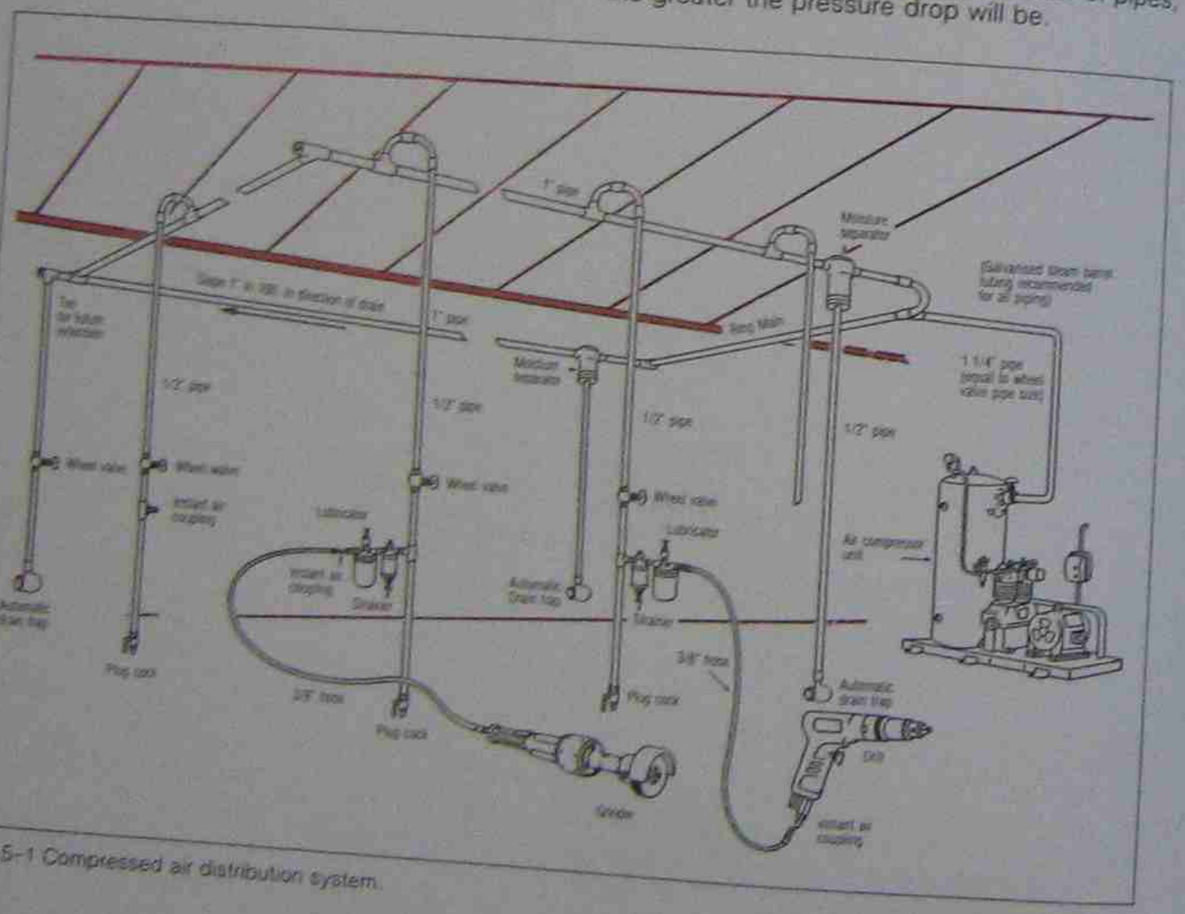


Fig. 15-1 Compressed air distribution system.

Tool	c.f.m.	m³/min
Adhesive guns (average)	10	0.28
Air hoists		
up to 1000 kg	1 cu.ft./ft. lift	0.09 m³/m lift
1000 kg to 5000 kg	5 cu.ft./ft. lift	0.45 m³/m lift
5000 kg and larger	15 cu.ft./ft. lift	1.38 m³/m lift
Air winches (1000 kg)	123	3.5
Blow guns (average)	18	0.5
Chipping hammers		
1 kg to 2 kg weight	12	0.34
2 kg to 7 kg weight	28	0.8
Concrete vibrators	30	0.85
Drills		
6 mm chuck capacity (1/4")	6	0.17
10 mm chuck capacity (3/8")	20	0.57
12.5 mm chuck capacity (1/2")	35	1.0
38 mm chuck capacity (1 1/2")	95	2.7
Air feed drill and tappers		
6 mm capacity (1/4")	21	0.6
12.5 mm capacity (1/2")	33	0.93
Grinders		
die 6 mm collet (1/4") (average)	10	0.28
disc 100 mm wheel (4")	20	0.57
175 mm wheel (7")	40	1.13
Jack hammers, pavement breakers etc.	180	5.1
Paint sprays (average)	7	0.2
varies from	2 to 20	0.06 to 0.57
Polishers		
175 mm diameter buff (7")	20	0.57
Sand-blasting units		
small	67	1.9
medium	113	3.2
large	300	8.5
Sanders		
disc 125 mm disc (5")	14	0.4
175 mm disc (7")	20	0.57
orbital average	10	0.28
Screw drivers (clutch type)		
bit size 4 mm (3/16")	5	0.14
bit size 6 mm (1/4")	10	0.28
bit size 10 mm (3/8")	21	0.6
Sheet metal shears and nibblers	10	0.29
Sump pumps (at 30 m head)		
2 l/s Diaphragm actuation	60	1.7
7 l/s Air motor actuation	109	3.1
13 l/s Air motor actuation	205	5.8
Wrenches		
ratchet 1/4" drive	7	0.2
3/8" drive	10	0.28
1/2" drive	12	0.34
impact 3/8" drive	9	0.25
1/2" drive	17	0.48
3/4" drive	25	0.71
1" drive	28	0.79

Fig. 15-2 Free air consumptions of tools

Air speed through the pipe system is also important. Fast air flows will invariably lead to large pressure drops, particularly if these speeds exceed 10 m/s. A pressure drop of more than 50 kPa (for large systems) is uneconomical (see fig. 15–5).

Flow rate

The flow rate (Q) calculation of compressed air for a system with many actuators and processes consuming compressed air may seem to be straightforward if one simply adds together the free air consumptions of all compressed air actuators, tools and processes. This flow would however be uneconomically high, unless all the air consuming devices were operating together and continuously all day long. Therefore, in determining the real total flow required for such multi-use systems, one must assess their duty cycles. This assessment invariably brings a substantial reduction of the total flow requirement, with a consequent reduction of the distribution pipe diameter, and compressor size.

A typical chart of various tools and their relevant air consumptions is given in fig. 15–2.

System pressure

The *total system pressure* is made up from the *minimum operating pressure* plus the *system pressure drop* plus the *cut-in/cut-out* pressure differential plus a *safety margin pressure*.

The minimum operating pressure is that pressure which is required to efficiently operate all the actuators in a pneumatic system (air motors, air tools, linear actuators and air consuming processes—see Chapter 3, fig. 3–21). That pressure is usually about 600 to 700 kPa (6 to 7 bar), and must be based on that actuator in the system which requires the highest pressure to operate to its designed force or torque output.

The system pressure drop is an assumed pressure drop caused by turbulence and friction, whilst the compressed air flows through the distribution pipes. It includes pressure drops caused by ancillary equipment such as after coolers and dryers. For economy, this pressure drop should not exceed 50 kPa (0.5 bar).

The cut-in/cut-out pressure differential is governed by the compressor capacity controller and its purpose was explained in the previous chapter. The cut-in/cut-out differential is in the range of 50–100 kPa (0.5–1 bar).

The safety margin pressure or contingency allowance is an assumed pressure of approx. 10% based on the minimum system pressure.

Example calculation:

Minimum operating pressure	650 kPa
System pressure drop	30 kPa
Cut-in/cut-out pressure differential	100 kPa
Safety margin pressure	65 kPa
Total system pressure	845 kPa

From this calculation the total system pressure required for the calculation of the pipe size would be approx. 850 kPa.

Air leakage

Ideally the leakage factor should always be zero, but practically about 10% must be allowed for system leakage and must be added to the total flow rate required. The importance of such air leakage prevention cannot be underestimated. Figure 15–3 shows a chart for leakage air flow rates through various size holes, together with the associated power loss.

Compressed air leakage is power wastage, therefore measures should be taken for its prevention. One method of assessing and rectifying compressed air leakage is to periodically run leakage tests. Such leakage tests are carried out when the distribution system is not in use.

To carry out this test, the compressor is started and after the system pressure has been reached and the compressor has unloaded (cut-out) the system pressure will then begin to fall. The period of time (T) for the compressor to come on load (cut-in) is recorded and also the period of time (t) when unloading again occurs (cut-out). For greater accuracy the average time of a number of such cycles must be taken.

The leakage rate (Q_L) of the system can then be calculated as follows:

Q_L = System leakage rate (m^3/min F.A.)
Q_C = Compressor free air delivery (m^3/min)
T = Time taken between cut-out and cut-in (leakage time in minutes)
t = Time taken between cut-in and cut-out (charging time in minutes)

Formula

$$Q_L = \frac{Q_C \times t}{(T + t)} \text{ m}^3/\text{min}$$

Steps can then be taken to locate and rectify the leakage.

Hole diameter		Air leakage at 6 bar	Power required for compression	
True size	mm	m³/min	hp	kW
	1	0.06	0.4	0.3
	3	0.6	4.2	3.1
	5	1.6	11.2	8.3
	10	6.3	44	33

Fig. 15–3 Table showing actual hole size, equivalent leakage and power loss.

Air leakages, therefore, represent money wasted. A calculation carried out on a compressed air installation producing 15 m^3/min F.A.D. for a large electrical appliance manufacturer in 1977, when the cost of electrical power at that time was 5 cents/kW hour, showed that the air leakage was in fact 25% of the total flow rate. The cost to that company at that time was $5,695 per year! The system was to all outside appearances well maintained and leak free. This unfortunately would be a typical leakage figure for many compressed air installations.

Air leakages are often unseen and in many cases also unheard, and therefore require periodical checks and stringent system maintenance, if they are to be avoided.

Pipe Length

The calculated pipe length can be ascertained by calculations or nomograms, and is made up of the actual pipe length and the equivalent pipe length.

The actual pipe length is that distance of the main pipe which is actually measured from the compressor to the closed off end of the pipe for a single line system, and for a ring main system the total pipe loop length is measured and then divided by two (fig. 15–4). The equivalent pipe length is an imaginary length of pipe which would have the same resistance to flow, and therefore cause the same pressure drop, as all the pipe fittings or valves used in the main pipe system (fig. 15–6).

Sizing can be carried out by mathematical formulae and calculation, but the most commonly used and easier method is by the application of nomograms and tables (figs. 15–5 and 15–6).

The calculation procedure for an air distribution system using both the nomogram (fig. 15–5) and

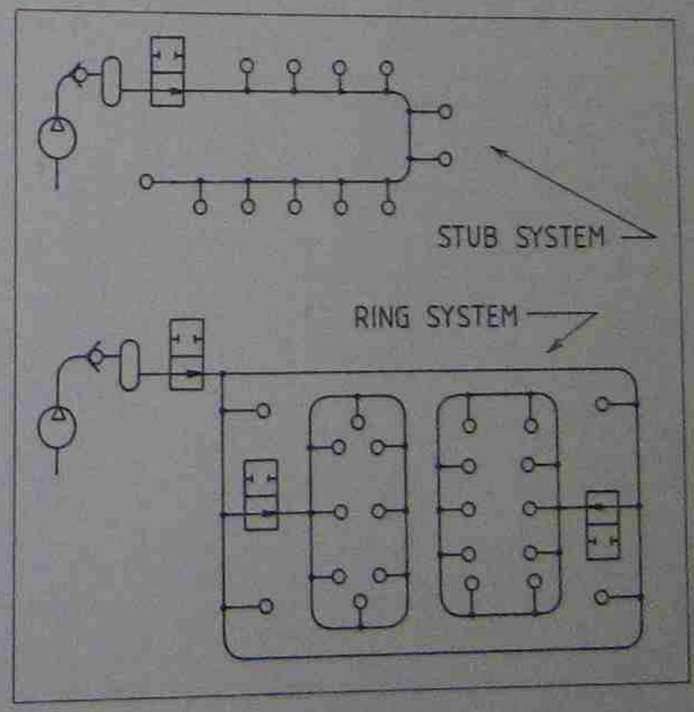


Fig. 15–4 Typical air distribution systems.

the pressure drop table (fig. 15–6), is presented below.

Example calculation:
Determine the diameter of a main distribution pipe to carry air at a flow rate of 10 m³/min F.A. The maximum system pressure is 700 kPa and the total actual length of the main pipe line is 200 metres. A maximum pressure drop of 10 kPa is permitted. The distribution main must include the following fittings:

6 bends with a radius of twice the pipe diameter,
2 elbow fittings,
4 tee connection fittings with 90° turn and 2 gate valves.

Step 1
Disregarding for the time being the equivalent pipe length, the previously given values must now be plotted into the nomogram shown in fig. 15–5 (200 m actual pipe length, 10 kPa permitted pressure drop, 10 m³/min F.A. flow rate and 700 kPa

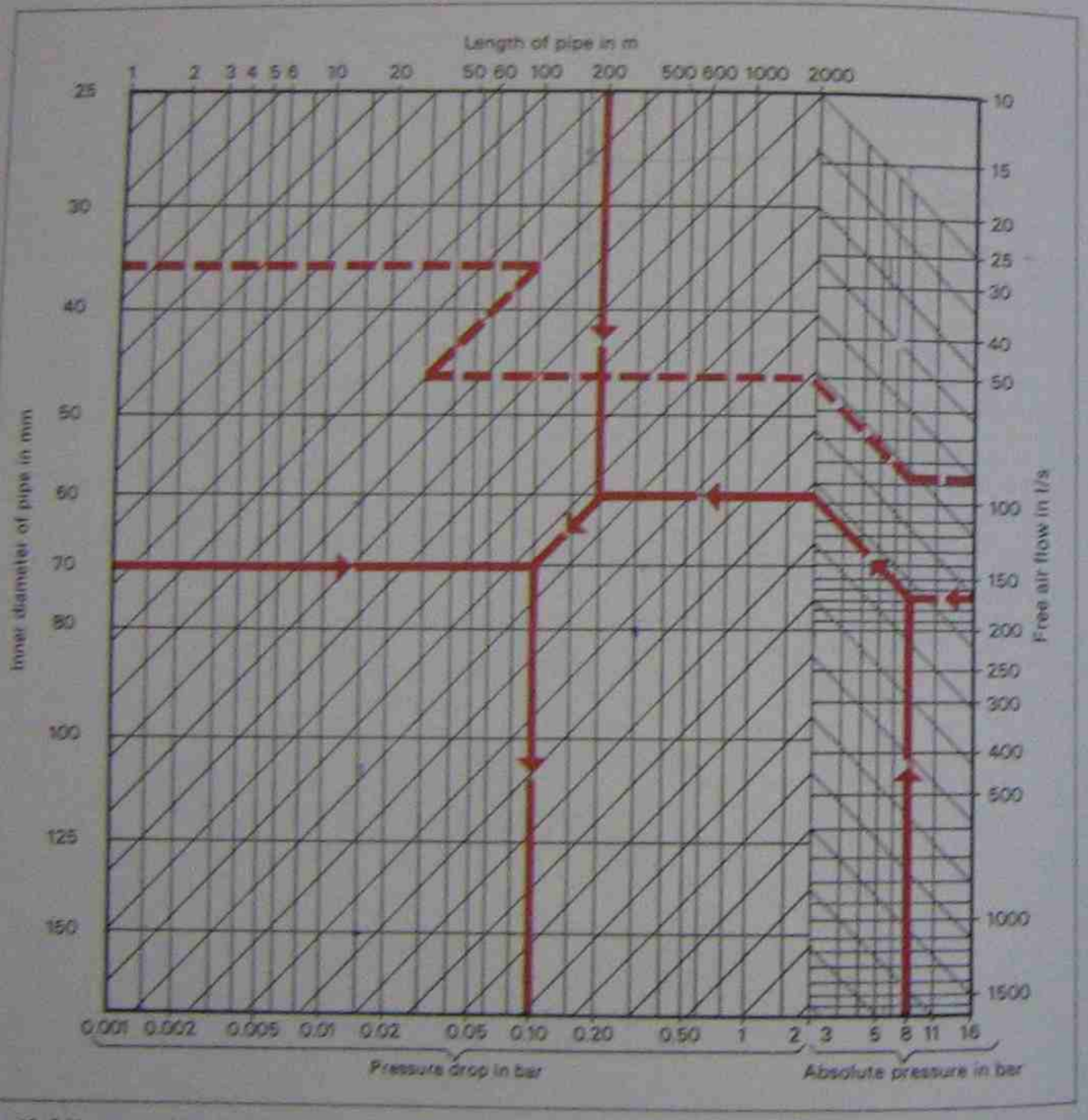


Fig. 15–5 Nomogram for calculation of pipe line dimensions.

Valves, etc.		Equivalent pipe length in m						
		Inner pipe diameter in mm						
		25	40	50	80	100	125	150
Seat valve		2–4	3–10	7–15	15–25	15–30	20–40	25–45
Diaphragm valve		1.2	2.5	3.5	4.5	5	8	10
Gate valve		0.2	0.5	0.7	1.5	1.5	2.5	2.5
Elbow		1.5	2.5	3.5	5	7	10	15
Bend R = d		0.3	0.5	0.5	1.5	1.5	2.5	2.5
Bend R = 2d		0.15	0.25	0.3	0.5	0.5	1.5	1.5
Hose connection T-piece		2	3	4	7	10	15	20
Reducer		0.5	0.7	1.0	2.5	2.5	3.5	4.0

Fig. 15–6 Table of equivalent pipe lengths for valves and fittings as used on air distribution systems.

maximum system pressure). From this nomogram, a pipe internal diameter of approx. 70 mm can be derived. This, however, is not the final pipe diameter since no consideration has been given to the pressure drop caused by fittings and valves. Therefore, this internal pipe diameter must be regarded as an interim result.

Step 2
The closest (next largest) commercially available pipe diameter to the 70 mm interim diameter derived in step 1 is 75 mm. This is the size now used in conjunction with values shown in table fig. 15–6 to calculate the total equivalent pipe length for all the fittings.

6 Bends (R = 2d)	6 × 0.5 m = 3 m
2 Elbow fittings	2 × 5 m = 10 m
4 T-connections (90° turn)	4 × 7 m = 28 m
2 Gate valves	2 × 1 m = 2 m
Total equivalent pipe length	= 43 m

Step 3
Total equivalent pipe length is now added to the actual pipe length of 200 m, to give 243 m the calculated pipe length. The nomogram is now again worked through exactly as before, but this time 243 m is used and a final pipe diameter of approx. 73 mm can be found. Since a 75 mm diameter pipe has already been selected, the additional pipe internal diameter required to account for the pressure drop caused by the fittings has been amply covered. The second plotting is not shown, for reasons of clarity.

Step 4
If at a later stage the system network had to be expanded, requiring the insertion of more fittings, and thus increasing the calculated pipe length to 550 metres, then an internal pipe diameter of 85 mm would be derived from the nomogram. This, however, is not a standard size and a pipe diameter of 100 mm would have to be bought (see fig. 15–5).

There are significant advantages in increasing the diameter wherever possible, as an increase for example of 1/3 (75 to 100 mm) increases the flow capabilities by the square of the diameter, or nearly twice in this case. This does not substantially increase the price of pipe and installation space required. A larger pipe diameter adds volume to the air distribution system, which can be regarded as additional air receiver volume. This volume brings advantages such as a less pressure drop, better cooling of the compressed air, and additional storage volume—which all help to increase the system economy and air quality.

Choice of pipe material

The usual choice for tubing for distribution systems is galvanised steel pipe screwed together with galvanised fittings. This choice is very popular, as the system can be built up relatively easily from pipe and fittings "off the shelf". It can be used in both large and small installations. Its main disadvantage is the connections, and since the pipe sections are screwed together, they require some form of thread sealing, which usually takes the form of hemp and sealing compound or thread sealing tapes (Teflon). If such sealing materials are not applied correctly, they can enter the pipe and cause air contamination and component failure further down the line. All such connections are also sources of turbulence, which lead to excessive pressure drop and often also become potential air leaks.

Galvanised pipe also tends to corrode at the joints due to the moisture condensation in the pipe system, and therefore becomes a contamination source (rust particles and scale), which is carried to the point of usage. When internal surfaces of the galvanised pipe become rusty, they tend to

increase the pressure drop (turbulence) and for this reason alone long term system economy may be enhanced by the use of copper piping.

Galvanised steel pipe properly installed and fitted can, however, be an economical method of distributing compressed air for small to medium sized systems. For large systems galvanised steel pipe is not ideal and can prove extremely expensive, if long term economy is calculated.

Copper pipe is gaining popularity on compressed air distribution systems. Contrary to expectation, copper piping can be much more economical than a galvanised steel pipe system, has excellent pressure drop characteristics, and is almost corrosion-free.

Copper pipe systems are usually constructed by welding or brazing together all the joints and fittings, thus the problems associated with the connection and installation of galvanised tubing are automatically eliminated.

Wherever a medium to large distribution system is being designed (more than 10 m^3/min F.A.D.), careful comparison of total costs including materials, labour and system economy should be made. The long term benefits of copper tubing should be carefully considered.

Moisture condensation and system design

The design of the distribution system should be such that the continually generated condensate can be drained away together with contaminants before the air reaches the pneumatically controlled machinery or air consuming processes.

Where take-off pipes leading to individual machines or compressed air tools are connected to the main air distribution line, they must be taken off with a half loop and connected into the top of the main air distribution line (see fig. 12–16). With such a connection, water condensate cannot flow into the take-off line. Arrows indicate that the piping of the ring system (main system line) falls or is graded down in the direction of flow. This grading is usually about 1–2 degrees.

Such grading permits the condensate to drain (flow) towards the drain valves, which are installed at the end of the air distribution lines at drop legs (fig. 12–16).

At the drain points (drop legs), it is advisable to fit automatic condensate drains. Such automatic condensate drains are also fitted to the intercooler, after cooler and air receiver. It is advantageous to automatically drain away the condensate as soon as it forms.

An automatic drain is a very important and valuable device used in compressed air distribution systems, since it eliminates the need for manual draining of the condensate at its collection points (fig. 15–7).

An automatic drain consists essentially of a small reservoir with a float. The float responds to the level of collected condensate in the reservoir and when the condensate reaches a set level, the float lifts and the condensate drain valve opens, thus discharging the condensate together with some compressed air. When the condensate level drops in the reservoir to the minimum level, the valve closes again.

Automatic drains can become "air locked". When this happens, a cushion of air builds up and prevents the condensate from flowing into the reservoir. Some automatic drains overcome this problem by fitting an anti-locking vent to the reservoir, which is connected to the drop leg by a small vent pipe (shown by the dotted line in figure 15–8).

An isolating valve should always be fitted ahead of an automatic drain to allow maintenance of the drain while the pipe system is under pressure.

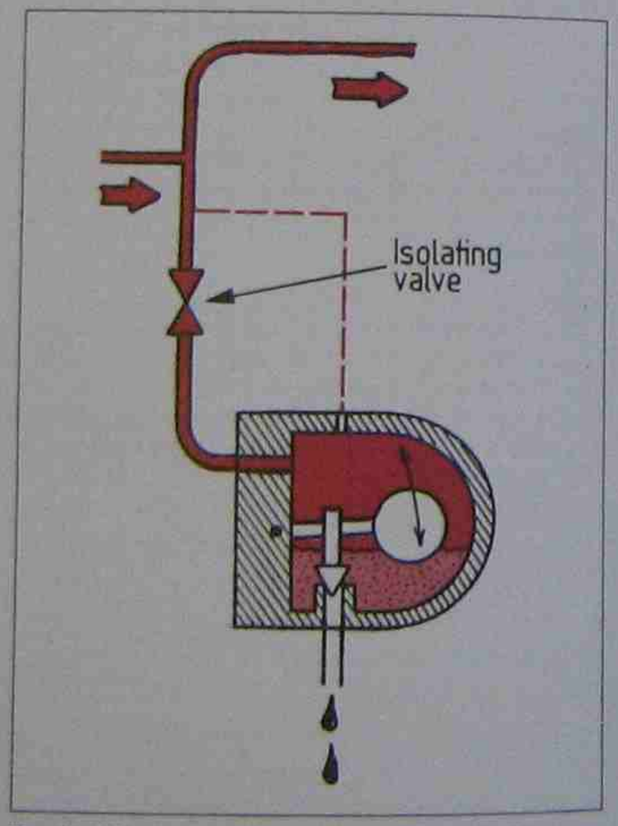


Fig. 15–7 Distribution pipe arrangement for controlling condensate drop out.

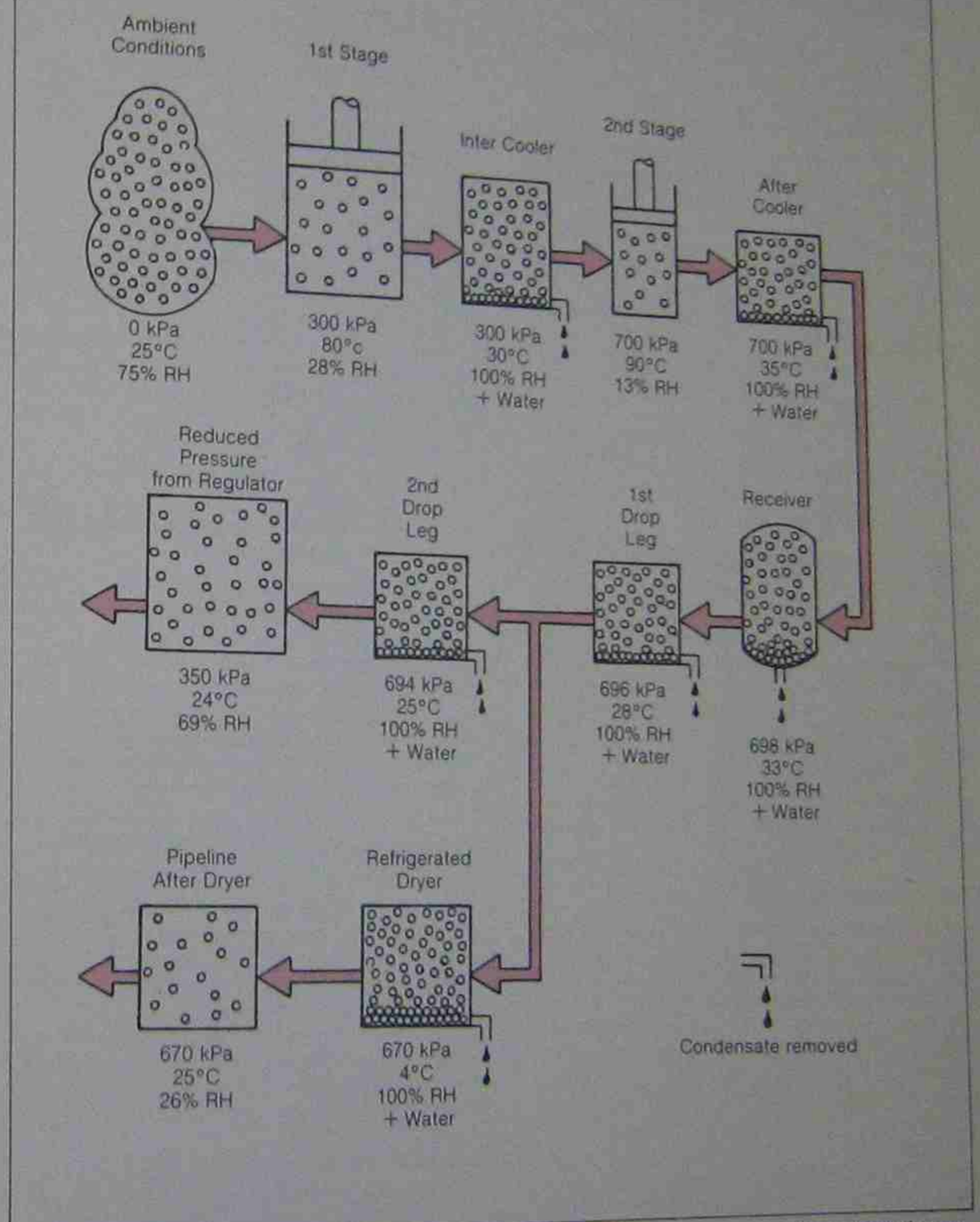


Figure 15–8 The effects of moisture in a compressed air distribution system from the compressor intake to points of usage. (Diagram by Gordon Smith.)

16 Circuit Documentation and Circuit Construction

The machine and its fluid power control functions should be fully documented. Documentation helps to translate the designed circuit into actual componentry such as cylinders, valves, fittings and tubing, and serves as an important reference for the operation and maintenance of the machine to help ensure trouble free operation over a long period of time. Such documentation must therefore include:

- complete and neatly drawn circuit drawing showing all fluid power components,
- traverse-time diagram,
- parts list of all fluid power components,
- servicing, maintenance and fault finding instructions,
- other relevant data.

Circuit drawing and documentation

The circuit drawing must conform to the internationally agreed symbols (see Appendices) and must show all components involved in the fluid power circuit. The power circuit, the logic control circuit (step-counter circuit, cascade circuit, limit valves) and the fringe condition modules should be clearly separated (see figs. 8-31, 8-47 and 9-22).

Time and pressure control valves must show their relevant time and pressure setting values (see fig. 2-52) and *all* signal lines must be labelled (START, b_1, A0 etc.).

Traverse-time diagram

The traverse-time diagram describes the sequence of the circuit step by step. This step by step description will assist a serviceman, for example in understanding the operation of the circuit for fault finding or other maintenance purposes. It should also include the emergency sequence if the circuit is equipped with an emergency start-stop provision (see fig. 8-36).

Parts List

Should the parts list not be included on the circuit drawing, then it must be added as a separate item in the documentation. Parts lists should carry the following suggested headings, but these can be varied, as required. Although the headings are self-explanatory, a few words of clarification are given (see fig. 16-2).

- The *item number* is referenced to the circuit diagram (fig. 16-1). Each component on the circuit diagram should carry an item number (preferably circled) which matches with a corresponding number in the parts list (fig. 16-2).
- The *part description* of the component (together with the port size) should be such that by referring to this description it can be easily identified on the machine without reference to a brand name, or a part number.

  For example: 4/2 Double pilot operated, flat slide valve.
  3/2 Roller operated poppet valve, normally open.

- *Port size* and thread type of the component. This may also include the type of tube fitting used on this component (push-in, push-on, etc.).
- The *brand* and *part number* which positively identify the valve or pneumatic component.
- *Comments* should state any noteworthy feature of the component such as pressure or time setting, or any deviation or modification from the original standard component.

Servicing, maintenance and fault-finding instructions

A detailed listing of the periodic servicing frequency which the machine requires, the type of oils used, and any other pertinent servicing information should be provided. This entails air service unit refill, draining and adjustment.

The servicing instruction must also include the compressor and other ancillary equipment such as a dryer if the operation of the machine is dependent on such items.

Other relevant data

Such data must include a general but brief *description* of the purpose of the machine and its method of operation.

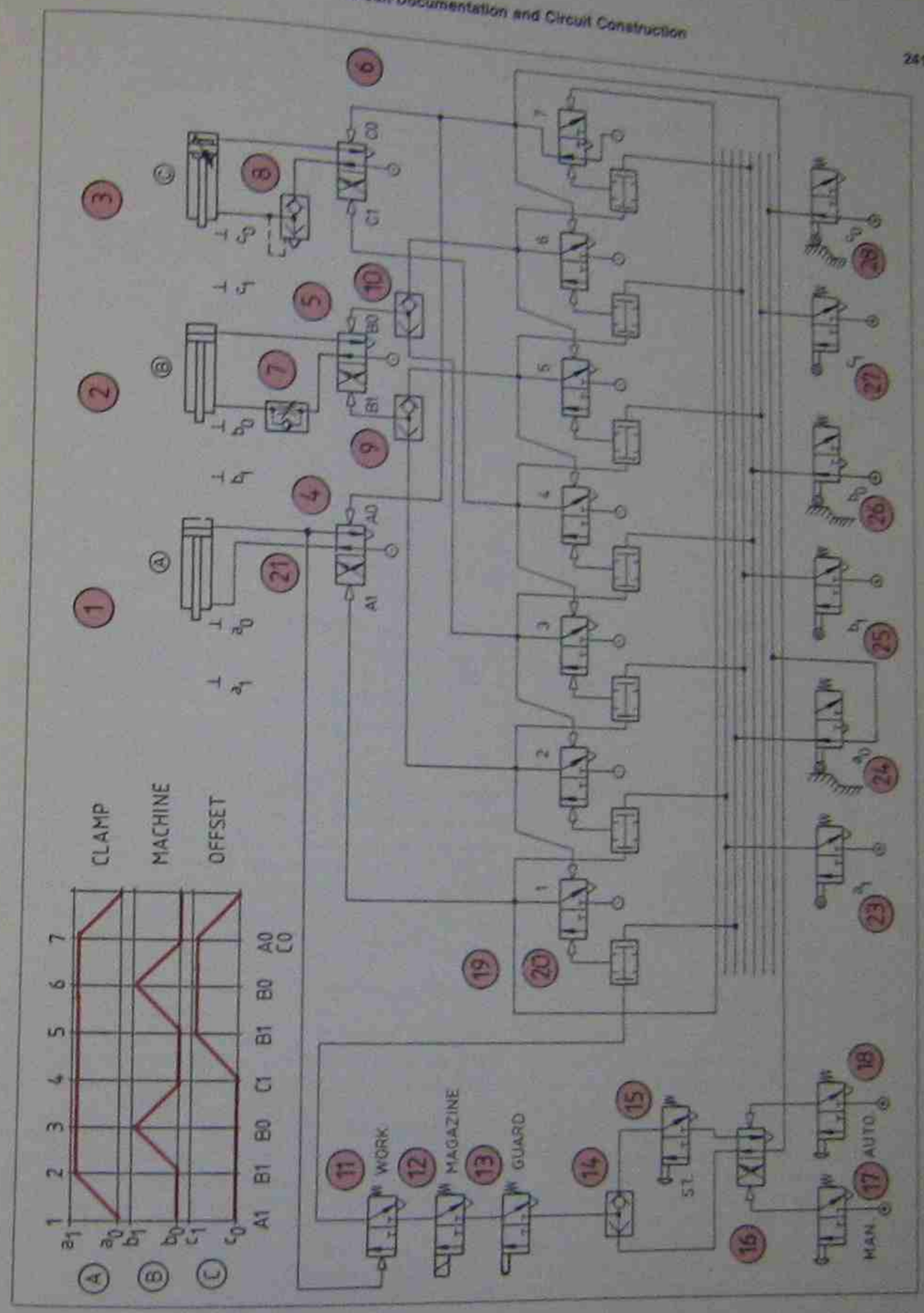


Fig. 16-1 Typical Circuit Diagram

PARTS LIST

Item No	Part Description	Port Size	Brand	Part Number
1	25 mm bore x 25 mm stroke double acting cylinder	⅛" B.S.P.	Festo	DGS-25-25
2	50 mm bore x 70 mm stroke double acting cylinder	¼" B.S.P.	Festo	HC-50-70
3	50 mm bore x 50 mm stroke double acting cushioned cylinder	¼" B.S.P.	Festo	HC-50-50-100771
4 & 16	4/2 Flat slide valve	⅛" B.S.P.	Festo	JP-4⅛
5 & 6	4/2 Flat slide valves	¼" B.S.P.	Festo	JP-4¼
7	Throttle relief valve	¼" B.S.P.	Festo	GR-¼
8	Quick exhaust valve	¼" B.S.P.	Festo	SE-¼
9, 10 & 14	"OR" element	⅛" B.S.P.	Festo	OS-⅛
11	3/2 pilot operated valve	⅛" B.S.P.	Bosch	0820212001
12	3/2 solenoid operated valve	⅛" B.S.P.	Bosch	0820005104
13	3/2 plunger operated valve	⅛" B.S.P.	Bosch	0820402001
15, 17 & 18	3/2 palm operated valve	⅛" B.S.P.	S.M.C.	VM430-01-30
20	7 off step counter modules complete with AND elements bases and end blocks	4 mm push in	Crouzet	81-550-401 81-522-501 81-551-101 81-552-001
23 to 28	3/2 Roller operated valves	⅛" B.S.P.	Bosch	0820402002
19	Air service unit module consisting of filter regulator & lubricator	½" B.S.P.	Norgren	M4A-406 -A3EB -18-013-0111

Fig. 16-2 Typical Parts List

The *method of operation* should describe the loading and operation of the machine, particularly from the operator's point of view. It should describe all connections which have to be made (power, air, water, etc.) to enable the machine to be installed, commissioned and operated.

Initial settings. These settings are very important for start up and machine commissioning.

Settings listed should be: regulator pressures, pressure sequence valve settings, time delays, valve settings, lubricator drip rates etc. Furthermore, these listings should be updated whenever any of these inital settings are altered.

Circuit Construction

The components for the sequence control of the actuators should be laid out and attached to a circuit board or preferably mounted into a control cabinet. Electrical control boxes make ideal control cabinets for pneumatic control components. They are reasonably priced, are available in various sizes and are fitted with a detachable door for ease of access. The door may also have a compartment for the storage of the circuit diagram and its control documentation.

Control cabinets provide considerable advantages, which increase in importance with the size and complexity of a control system. These include:

- clear layout of all control elements
- short line connections for fast signal processing
- rapid access to all control elements
- simpler fault finding
- no unauthorised access to control
- less, or no, soiling of control elements
- no tangle of lines on the machine
- only signal lines from limit valves and signal lines leading to positioning or operating elements emerge from the control cabinet; they can be combined by means of multi-connectors and protective hoses (flexible conduit)
- manual signal input devices can be grouped together in a small but accessible area
- modular design allows the use of standard size mounting frames for rapid component mounting

Installation of Components

Pneumatically actuated machinery inherently vibrates, due to the action of the reciprocating cylinders, and although in many instances this vibration may be minimal, all components should therefore be secured by means of shakeproof fasteners (such as spring washers).

When correctly installed and efficiently maintained, pneumatic controls provide many hours of trouble-free operation. However, to achieve optimum performance, a few points should be noted to assist all users of pneumatic equipment.

- Mount pneumatic cylinders securely, ensuring that the piston rod moves freely through its full stroke.
- Check that no undue side stress is placed on the piston rod.
- Where piston rod or other machine components actuate signaling devices, ensure that this actuation is correct and that no excessive load is applied onto such signalling devices.
- Mounting brackets for cylinders and limit valves should have sufficient support and should not flex during system operation.
- For easier identification, label all components as per the circuit diagram (fig. 16-1).
- Make certain that components waiting to be assembled are covered and/or capped to eliminate the ingress of foreign particles.
- Tubing and fittings require leakproof joints. If thread or gasket sealants are used, apply to male thread only. This minimises the possibility of the sealant being forced into cylinder valve ports or tube.
- Install air-line filters as close as practical to the actual point of use. If quick-disconnect couplings fall into dirt, chips etc., these contaminants could inadvertently be introduced into the circuit when the couplings are reconnected (see fig. 16-3). Filtration close to point of use removes such contaminants.
- When mounting pneumatic equipment on hot surfaces, check the manufacturer's specifications on temperature range for the equipment.
- Mount valves so they are protected and cannot be damaged by heavy falling parts, fork-lift trucks, etc.
- Make sure that the air supply is not restricted by undersized hose, kinked tubing and restrictive fittings.
- Assume that dirt, dust and water will settle on all components. Protect therefore exhaust ports facing up with silencers to prevent dirt from entering the component, but preferably mount all valves with exhaust ports facing down.
- Rapidly exhausting air is likely to be noisy. It may therefore be necessary to muffle the exhaust noise. Quick exhaust valves are usually noisiest! Plan to use silencers on all valves.
- Plan to mount all control components inside a cabinet, and where possible collect all exhaust air from the components into a common manifold to exit through a side of the cabinet.

Tubing

The layout of the interconnecting tubing between valves, cylinders, and other components is important if the circuit is to be pleasing in appearance and efficient in distributing the air signals to the components with minimal loss of pressure. Tubing size is usually set by the port sizes of the components, and if unrestricted flow (fast cylinder movement) is required, these sizes should be adhered to since they are designed to give optimal performance.

Where possible for ease of identification, colour coding of the tubing should be adopted, such as black for air supplies, white for cylinder port connections (working lines) and blue for valve pilot signal lines (these are only suggestions).

The material used for tubing is generally plastic. Plastic tubing is easy to cut, bend and fit and is inexpensive. However, in areas where excessive

heat or physical damage may occur, copper is usually the preferred choice. It must be remembered that even though copper is stronger than plastic, physical damage may flatten copper tube, and cause a permanent flow restriction.

There is also a range of flexible tubing available which has an outer metal mesh covering (metal braiding), and this can be used to advantage for applications where abrasion damage could occur.



Fig. 16–3 Quick connect coupling.

For plastic tubing one may use one of the many brands of "push-in" fittings now available on the market. Such fittings are made for metric and imperial thread and tube sizes. Most brands of moving part logic components provide porting plates with permanently embedded push-in connections (see fig. 16–4(A)).

Push-in connectors are re-usable, inter-changeable, and easy to connect and disconnect. To make the connection, the tube is simply pushed into the fitting. To disconnect, either a screwdriver, fingernail, or special tool applied to a release ring on the fitting allows the tube to be removed. "Push on" fittings on which the tubing is pushed over a bulge on the fitting and secured with a sleeve nut are also widely used. They are also easy to connect and disconnect, however not as rapidly as the "push in" fitting. See fig. 16–4(B).

Plastic tubing used together with push-in fittings has made the piping up of the pneumatic system much easier than with the nut and olive compression fitting shown in fig. 16–5. The nut and olive fitting is, however, still used on copper or plastic tubing.

Air line Fittings

Pneumatic fittings are made from materials such as brass, aluminium and plastic, and have various ways of making the connection to the tubing and to the valves or actuators.

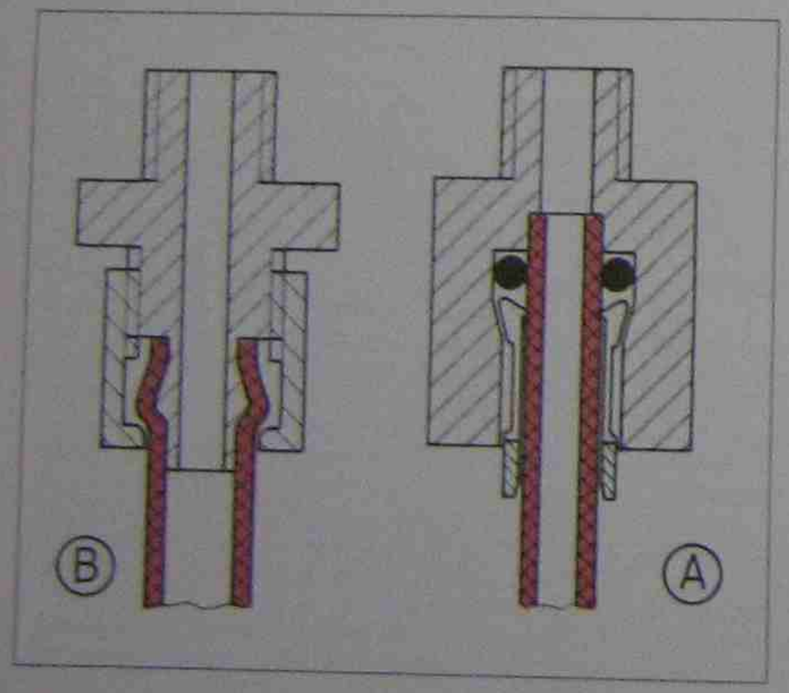


Fig. 16–4(A) Push in tube fitting (B) Push on tube fitting.

Silencers

Compressed air devices have an inherent tendency to be noisy because pressurised air is allowed to exhaust to atmosphere on completion of its work. The pressure ratio between the exhaust and the surrounding static air is normally high. As a result the velocity of the exhaust jet is supersonic, and thus generates shock waves and a considerable amount of turbulence as it mixes with the static atmosphere.

Much of this energy change is in the form of audible shock waves, capable of producing severe discomfort and damage to the human ear. Noise reduction is now required by health regulations and can be achieved by:

- eliminating shock wave formation, and
- reducing the exit air velocity to minimise turbulence.

The only effective way to reduce exhaust air noise is to allow the air to escape into an expansion chamber (silencer). Often, piping back the exhaust pipe through a long, larger pipe to a reservoir or atmosphere can effect considerable dampening.

The silencer acts as a filter to oil as well as other contaminants, and can gradually become saturated. A saturated silencer is indicative of an incorrectly adjusted or maintained air lubricator, and corrections must be applied. However there is a limit, and some fine oil mist will prevail, requiring consideration of the operator and the system's application/function positioning during design and installation.

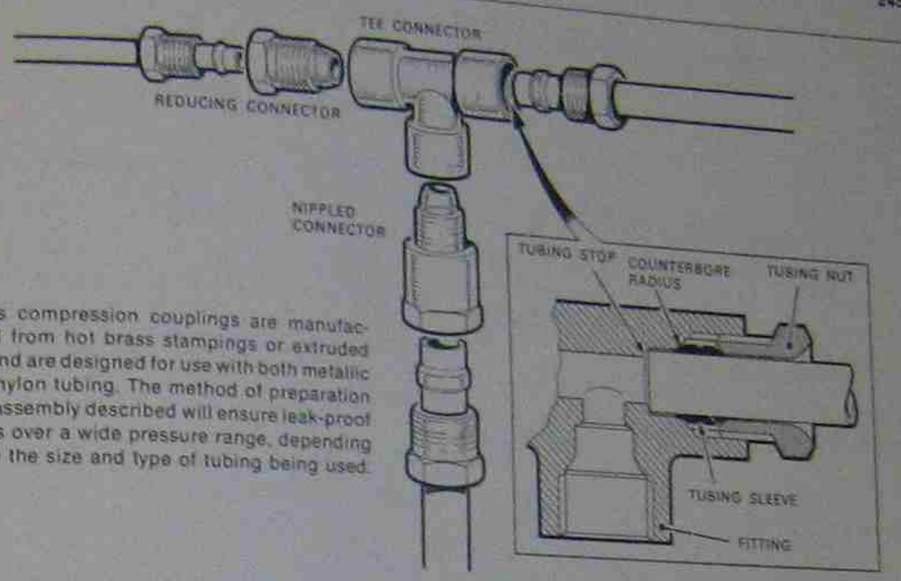


Fig. 16–5 Compression fittings.

Sintered bronze silencers

These silencers are made from sintered bronze, and some incorporate all the key requisites of the ideal silencer:

- high strength; withstands up to 100 MPa (1000 bar)
- does not deform and withstands high mechanical shock; unlike plastic or fabric types, can be attached to moving devices
- can quickly and easily be cleaned with common industrial solvents such as trichlorethylene, perchlorethylene, benzol, etc. and does not require replacement spares
- does not swell or deform in water or oil, as do some plastics and fabrics, thus preventing change of characteristics
- readily obtained in different grain sizes
- double chamber principle uses coarse size grains virtually unaffected by dirt, yet provides excellent damping ensuring high, predictable efficiency
- competitively priced
- provides deflector cap with 360° adjustment
- does not retain fluid contaminant or readily become saturated
- highly predictable pressure drop characteristic, and a wide range of use.

Appendices

1 Industrial fluid power symbols

These symbols are based upon the international I.S.O. 1219 fluid power symbols. Only the most common symbols have been included.

Composite symbols can be devised for any fluid power components by combining the relevant basic symbols.

Pumps, motors, and drives

	Fixed	Variable
Single direction pump		
Double direction pump		
Single direction motor		
Double direction motor		
Single direction pump/motor with reversal of flow direction		
Single direction pump/motor with single flow direction		
Double direction pump/motor with two directions of flow		
Hydrostatic drive, split system type		
Hydrostatic drive, compact, reversible output		
Semi rotary actuator		
Air compressor		
Vacuum pump		

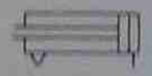
Air motor, single direction 

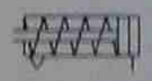
Air motor, double direction 

Semi rotary actuator 

Linear actuators

Single acting ram (load returns the ram) 

Single acting actuator (load returns the piston) 

Single acting actuator (spring returns the piston) 

Double acting actuator 

Differential actuator with oversize rod 

Double acting actuator with double ended rod 

Piston with adjustable end cushioning 

Piston with fixed end cushioning 

Telescopic, single acting actuator 

Telescopic, double acting actuator 

Pressure intensifier 

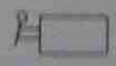
Rodless acting, Double acting with cushioning 

Double acting with impact stroke 

Rodless with magnetic coupling 

Valve control mechanisms

Undefined control 

Hand lever (rotary or linear) 

Push button 

Foot lever 

Cam roller

Plunger (piston or ball)

Spring

Detent mechanism

Pressure relief

Pressure applied

Pneumatic pilot

Hydraulic pilot

Solenoid

Solenoid/hydraulic pilot

Pneumatic/hydraulic pilot

Two stage amplifier

One way trip lever

Wire sensor (whisker)

Key operator

Air spring (internal)

Spring centred

Directional control valves

Directional control valve with two discrete positions

Directional control valve with three discrete positions

Directional control valve with significant cross over positions

Valve with two discrete and an infinite number of intermediate throttling positions

Valve with three discrete and an infinite number of intermediate throttling positions

Two position, two port valve

Two position, three port valve

Two position, four port valve

Two position, five port valve

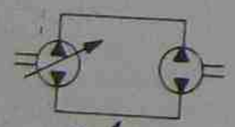
Appendices

1 Industrial fluid power symbols

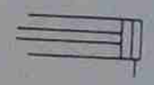
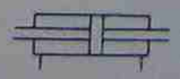
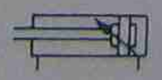
These symbols are based upon the international I.S.O. 1219 fluid power symbols. Only the most common symbols have been included.

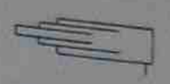
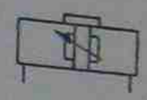
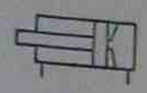
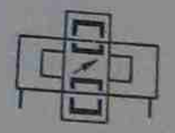
Composite symbols can be devised for any fluid power components by combining the relevant basic symbols.

Pumps, motors, and drives

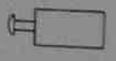
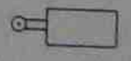
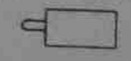
	Fixed	Variable
Single direction pump		
Double direction pump		
Single direction motor		
Double direction motor		
Single direction pump/motor with reversal of flow direction		
Single direction pump/motor with single flow direction		
Double direction pump/motor with two directions of flow		
Hydrostatic drive, split system type		
Hydrostatic drive, compact, reversible output		
Semi rotary actuator		
Air compressor		
Vacuum pump		

Linear actuators

Single acting ram (load returns the ram)	
Single acting actuator (load returns the piston)	
Single acting actuator (spring returns the piston)	
Double acting actuator	
Differential actuator with oversize rod	
Double acting actuator with double ended rod	
Piston with adjustable end cushioning	

Piston with fixed end cushioning	
Telescopic, single acting actuator	
Telescopic, double acting actuator	
Pressure intensifier	
Rodless acting, Double acting with cushioning	
Double acting with impact stroke	
Rodless with magnetic coupling	

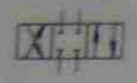
Valve control mechanisms

Undefined control	
Hand lever (rotary or linear)	
Push button	
Foot lever	
Cam roller	
Plunger (piston or ball)	
Spring	
Detent mechanism	
Pressure relief	
Pressure applied	
Pneumatic pilot	

Directional control valves

Directional control valve with two discrete positions	
Directional control valve with three discrete positions	
Directional control valve with significant cross-over positions	
Valve with two discrete and an infinite number of intermediate throttling positions	
Valve with three discrete and an infinite number of intermediate throttling positions	
Two position, two port valve	
Two position, three port valve	
Two position, four port valve	
Two position, five port valve	

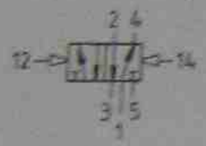
Three position, four port valve with fully closed centre configuration



Port labelling
Working lines A B
Pilot lines X Y
Pressure line P
Tank line T



Port labelling with numbers



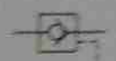
Check valve



Spring loaded check valve



Pilot operated check valve



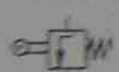
OR function valve



AND function valve



Deceleration valve



Deceleration valve



Pressure controls

Throttling orifice normally closed or normally open (*optional)



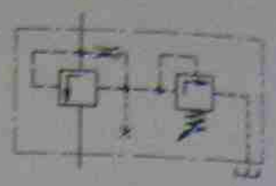
Pressure relief valve (fixed)



Pressure relief valve (adjustable)



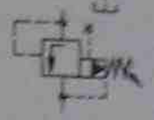
Detailed symbol of pilot operated pressure relief valve (compound relief valve)



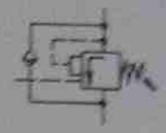
Simplified symbol of compound relief valve
(Pilot flow externally drained)



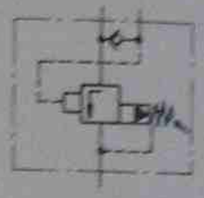
(Pilot flow internally drained)



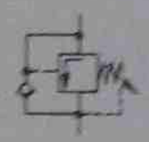
Brake valve



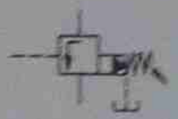
Unloading valve (accumulator charging valve)



Counter balance valve (back pressure valve)



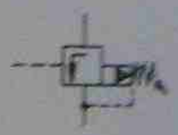
Sequence valve with remote control (external pilot)



Sequence valve with direct control (internal pilot)



Offloading valve



Pressure reducing valve (fixed)



Pressure reducing valve (adjustable)



Pilot operated pressure reducing valve



Pressure reducing valve with secondary system relief



Pneumatic pressure sequence valve



Pneumatic pressure reducing valve with secondary relief

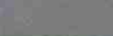


Flow controls

Throttle valve not affected by viscosity



Throttle valve (fixed)



Throttle valve (adjustable)



Flow control valve, pressure and temperature compensated



Flow control valve with reverse free flow check



By-pass flow control valve



Flow divider



Pneumatic flow control valve with reverse free flow check



Quick exhaust valve



Pneumatic cam operated deceleration valve



Fluid plumbing and storage

Pressure source



Working line, return line, feed line



Pilot control line

Drain line

Enclosure line

Flexible line

Electric line

Pipeline connections

Cross pipeline (not connected)

Air vent

Reservoir with inlet below fluid level

Reservoir with inlet above fluid level

Miscellaneous symbols

Electric motor

Heat engine

Electric motor with pump and drive coupling

Plugged line

Plugged line with take-off line

Quick connect coupling

Rotary connection

Accumulator

Filter strainer

Cooler with coolant lines

Heater

Pressure gauge, pressure indicator

Flow meter

Thermometer

Pressure switch (electrical)

Shut-off valve

Airline lubricator

Water separator with automatic drain

Complete air service unit

Air dryer

Visual indicator

Pneumatic counter with set/reset

Exhaust silencer

Logic symbols for step-counter

Classical and commercial version

Step-counter with end plates

Electrical symbols

Electrical contact (n/o)

Electrical contact (n/c)

Contactor relay

Set/reset relay (latching relay)

Set/reset flip-flop, single output

Set/reset flip-flop for complementary output

Electrical switch

Solenoid coil

Solenoid coil

2 Fluid power for formulae

	Calculation parameter	Formulae with standard symbol	Formulae with customary units, see text
Physical principles	Combined gas laws	$\frac{p_1 \times V_1}{T_1} = \frac{p_2 \times V_2}{T_2}$	$\frac{psi \times in^3}{R_1} = \frac{Psig \times in^3}{R_2}$
	Kinetic energy	$E = \frac{m \times v^2}{2}$	$J = \frac{N \times m/s}{2}$
	Lifting force	$F_L = m \times g \times \sin \alpha$	$F_L = kg \times 9.81 \times \sin \alpha$
	Frictional force (horizontal load)	$f = m \times g \times \mu$	$lb = kg \times 9.81 \times \mu$
	Frictional force (inclined load)	$F = m \times g \times \mu \times \cos \alpha$	$lb = kg \times 9.81 \times \mu \times \cos \alpha$
	Inertia force	$F_a = m \times a$	$F_a = kg \times m/s^2$
	Acceleration	$\frac{v^2}{2 \times s}$	$m/s^2 = \frac{m/s}{2 \times s}$
Linear	Total piston force	$F_T = F_L + F_f + F_a$	$N_{tot} = N_L + N_f + N_a$
Actuators	Force output including friction	$F = \frac{D \times P \times \eta}{100}$	$N = \frac{Ps \times in^2 \times \eta}{100}$
	Extension force	$F_{ext} = \frac{D \times d^2 \times 0.7854 \times \eta}{100}$	$N_{ext} = \frac{Ps \times in^2 \times 0.7854 \times \eta}{100}$
	Retraction force	$F_{ret} = \frac{D \times (D^2 - d^2) \times 0.7854 \times \eta}{100}$	$F_{ret} = \frac{Ps \times (in^2 - in^2) \times 0.785}{100}$
	Compression ratio	$\varepsilon = \frac{p\,abs + p\,gauge}{p\,abs}$	$\varepsilon = \frac{Ps\,A + Ps\,G}{Ps\,A}$
	Cylinder consumption	$Q = \pi \times d^2 \times 0.7854 \times L \times n$	$in^3/min = \pi \times in^2 \times 0.785$
	Rotary power output	$P = 2 \times \pi \times n \times T$	$W = \frac{2 \times \pi \times RPM \times Nm}{60}$
Air motors	Torque	$T = F \times L$	$N_m = N \times m$
Air receivers	Receiver volume	$V_R = \frac{15 \times Q \times P_a}{\Delta P_R \times C}$	$in^3 = \frac{15 \times in^3/min \times atm\,abs}{atm \times no.of\,starts}$
Compressed air distribution	System leakage rate	$Q_L = \frac{Q_K \times T}{T \times t}$	$in^3/min = \frac{in^3/min \times min}{min \times min}$

3 Units of measurement and their symbols

Mechanical oscillations are commonly expressed in cycles per unit of time, and rotational frequency in revolutions per unit of time. Since 'cycle' and 'revolution' are not units, they do not have internationally recognised symbols. However they are often expressed as abbreviations and in English the common expressions for them are c.p.m. (revolutions per minute) and c.p.m. (cycles per minute).

The bar and Pascal are given equal status as pressure units. The American and Australian fluid power industries still do not agree on one preferred unit. However, the Pascal is the SI unit for pressure. Thus, common current usage in industry opts for the multiples kiloPascal (kPa) and megaPascal (MPa) and for the bar which is equivalent to 100 kPa. The European fluid power industry predominantly uses the bar as the preferred unit, and both equipment and product information from European countries has its pressure ratings specified in bars.

Symbols used in this book (base units)

Quantity	Symbol	SI unit	Other recognised units
Area	A	m^2	mm^2, km^2, cm^2
Acceleration	a	m/s^2	
Displacement	V	m^3	mL, cm^3
Flow rate	Q	m^3/s	L/min
Force	F	N	kN, MN
Frequency	f	Hz	1/s
Circle constant	π	3.1416	
Length	l	m	mm, cm, km
Mass	m	kg	
Moment	M	Nm	kNm, MNm
Power	P	W	kW, MW
Pressure	p	Pa	kPa, MPa, BAR
Radius	r	m	mm, cm
Revolutions	n	1/s	1/min
Temperature	T	K	°C
Torque	M	Nm	kNm, MNm
Velocity	v	m/s	m/min, km/h
Time	t	s	ms, min, h, d
Viscosity (Dyn)	η	Pa s	$\frac{N\,s}{m^2}$
Viscosity (Kin)	ν	m^2/s	mm^2/s = 1cSt
Volume	V	m^3	mL, cm^3
Work	W	J	kJ, mJ

Commonly used area and volume conversions

$1m^2 = 10000\ cm^2 = 1000000\ mm^2$

$1m^3 = 1000\ dm^3 = 1000\ L = 1000000\ cm^3 = 1000000000\ mm^3$

Commonly used pressure conversions

1 bar = 100000 Pa 1 bar = 100 kPa 1 bar = 0.1 MPa	1 MPa = 10 bar 1 MPa = 1000 kPa 1 MPa = 1000000 Pa
1 kPa = 1000 Pa 1 kPa = 0.01 bar 1 kPa = 0.001 MPa	1 bar = 14.5 psi 100 kPa = 14.5 psi 1 MPa = 145 psi

Prefixes for fractions and multiples of base units

Fraction	Prefix	Symbol	
10^{-18}	atto	a	
10^{-15}	femto	f	
10^{-12}	pico	p	
10^{-9}	nano	n	
10^{-6}	micro	µ	0.000001
10^{-3}	milli	m	0.001
10^{-2}	centi	c	0.01
10^{-1}	deci	d	0.1
Multiple	**Prefix**	**Symbol**	
10^{1}	deca	da	10
10^{2}	hecto	h	100
10^{3}	kilo	k	1000
10^{6}	mega	M	1000000
10^{9}	giga	G	1000000000
10^{12}	tera	T	

Examples for using fractions and multiples of base units
***units used in Europe**

Fract./Mult.	Symbol	Pa	m	L	N	W
10^{-3}	m		mm	mL		mW
10^{-2}	c		cm			
10^{-1}	d		dm^3	dL*		
10^{1}	da				daN*	
10^{2}	h			hL		
10^{3}	k	kPa	km			kW
10^{6}	M	MPa			MN	MW

4 Conversion table

Dots indicate SI units.

TO CONVERT →	TO →	MULTIPLY BY
FORCE		
10^5 dyne	newton (N)	10^{-5}
0.10197 kilogram-force (kgf)	• newton (N)	9.806650
7.233 poundal (pdl)	newton (N)	0.1383
0.2248 pound-force (lbf)	newton (N)	4.448
2.2046 pound-force (lbf)	kilogram-force (kgf)	0.4536
0.1004 ton-force (UK)	kilonewton (kN)	9.964
32.174 poundal (pdl)	pound-force (lbf)	0.0311
1.000 kilopond (kp)	kilogram-force (kgf)	1.000
TORQUE		
0.7376 pound-force foot (lbf ft)	• newton metre (Nm)	1.356
0.1020 kilogram-force metre (kgf m)	newton metre (Nm)	9.807
8.851 pound inch (lb in)	newton metre (Nm)	0.1130
1.39×10^{-2} ounce inch (oz in)	gram-force centimetre (gf cm)	72.01
PRESSURE and STRESS		
9.869×10^{-3} atmosphere (atm)	kilopascal (kPa)	101.30
0.1450 pound-force/in² (psi)	kilopascal (kPa)	6.89476
0.01020 kilogram force/cm² (kgf/cm²)	kilopascal (kPa)	98.0665
0.06804 atmosphere (atm)	pound-force/in² (psi)	14.70
20.89 pound-force/ft² (lbf/ft²)	kilopascal (kPa)	0.04788
0.01 bar	• kilopascal (kPa)	100
10.000 millibar (mbar)	kilopascal (kPa)	0.1000
33.86 millibar (mbar)	inches mercury (inHg)	0.02953
68.95 millibar (mbar)	pound-force/in² (psi)	0.01450
7.501 torr or mm mercury (mmHg)	kilopascal (kPa)	0.1333
0.2953 inches mercury (inHg)	kilopascal (kPa)	3.386
760.0 torr or mm mercury (mmHg)	atmosphere (atm)	1.316×10^{-3}
4.015 inches water (inH_2O)	kilopascal (kPa)	0.2491
13.60 inches water (inH_2O)	inches mercury (inHg)	0.07355
1.000 newton/metre² (N/m²)	• pascal (Pa)	1.000
0.0648 ton-force (UK)/inch²	megapascal (mPa)	15.44
6.895×10^{-3} megapascal (mPa)	pound-force/inch² (psi)	145.0
DENSITY		
0.062428 pound/foot (lb/ft³)	kilogram/metre³ (kg/m³)	16.0185
0.010022 pound/gal (UK)	kilogram/metre³ (kg/m³)	99.776
10^{-3} gram/centimetre³ (g/cm³)	• kilogram/metre³ (kg/m³)	1000
7.5248×10^{-4} ton/yard³	kilogram/metre³ (kg/m³)	1328.94
0.160544 pound/gal (UK)	pound/foot³ (lb/ft³)	6.22884
ENERGY, WORK, and HEAT		
10^7 erg	joule (J)	10^{-7}
0.7376 foot pound-force (ft lbf)	• joule (J)	1.3558
0.2388 calorie (cal)	joule (J)	4.1868
0.1020 kilogram-force metre (kgf m)	joule (J)	9.8066

MULTIPLY BY ← TO ← TO CONVERT

TO CONVERT →	TO →	MULTIPLY BY
9.478×10^{-4} British thermal unit (Btu)	joule (J)	1055.1
0.3725 horsepower hour (hph)	megajoule (MJ)	2.6845
1.3410 horsepower hour (hph)	kilowatt hour (kWh)	0.7457
0.2778 kilowatt hour (kWh)	• megajoule (MJ)	3.600
3412.1 British thermal unit (Btu)	kilowatt hour (kWh)	2.931×10^{-4}
9.478×10^{-3} therm	megajoule (MJ)	105.51
MASS		
0.035274 ounce (oz)	gram (g)	28.3495
2.20462 pound (lb)	• kilogram (kg)	0.453592
1.10231 ton US (short ton)	tonne (t)	0.907185
0.984207 ton UK (long ton)	tonne (t)	1.01605
19.6841 hundred weight (cwt)	tonne (t)	0.05080
1.429×10^{-4} pound (lb)	grain	7000
0.03108 slug	pound (lb)	32.174
0.01 quintal	kilogram (kg)	100
0.001 kip	pound (lb)	1000
5.0 carat	gram (g)	0.200
LENGTH		
0.0393701 inch (in)	millimetre (mm)	25.40
3.28084 feet (ft)	metre (m)	0.3048
1.09361 yard (yd)	• metre (m)	0.914400
0.621371 mile	kilometre (km)	1.60934
0.0497 chain	metre (m)	20.1168
4.97 link	metre (m)	0.21168
0.5468 fathom	metre (m)	1.8288
39.370 thou or mil	millimetre (mm)	0.02540
0.001 millimetre (mm)	micron (μm)	1000
10^{10} angstrom (A)	metre (m)	10^{-10}
1.644×10^{-4} mile UK nautical	feet (ft)	6080
5.396×10^{-4} mile UK nautical	metre (m)	1853.2
5.399×10^{-4} mile International nautical (n mile)	metre (m)	1852.00
1.894×10^{-4} mile	feet (ft)	5280
AREA		
2.471 acre	hectare (ha)	0.4047
2.066×10^{-4} acre	sq. yard (yd²)	4840
2.471×10^{-4} acre	sq. metre (m²)	4047
1.973×10^{3} circular mil	sq. millimetre (mm²)	5.067×10^{-4}
1.2732 circular mil	square mil	0.7854
0.1550 sq. inch (in²)	sq. centimetre (cm²)	6.4516
10.764 sq. feet (ft²)	• sq. metre (m²)	0.09290
1.562×10^{-3} sq. mile	acre	640
3.861×10^{-3} sq. mile	hectare (ha)	259.0
VOLUME		
0.2200 gal (UK)	• litre (l)	4.546
0.2642 gal (US)	litre (l)	3.785
0.0238 barrel (US)	gal (US)	42
0.03532 cu. feet (ft³)	litre (l)	28.32
0.1605 cu. feet (ft³)	gal (UK)	6.229

MULTIPLY BY ← TO ← TO CONVERT

TO CONVERT	⟶	TO	⟶	MULTIPLY BY
35.31		cu. feet (ft^3)		0.02832
1.308		cu. yard (yd^3)		0.76456
0.061026		cu. inch (in^3)		16.39
0.0352		fluid ounce (fl oz)		28.41
1.76×10^{-3}		pint (UK) (pt)		568.2
1×10^{-3}		litre (l)		1000
1×10^{-3}		cu. metre (m^3)		1000

VELOCITY

0.0393701	inch/sec (in/s)	centimetre/sec (cm/s)	2.540
3.28084	feet/sec (ft/s)	• metre/sec (m/s)	0.304800
1.9685	feet/min (ft/min)	centimetre/sec (cm/s)	0.5080
0.621371	miles/hr (mph)	kilometre/hr (km/h)	1.609344
2.23694	miles/hr (mph)	metre/sec (m/s)	0.44704
0.5397	knot (UK)	kilometre/hr (km/h)	1.853
0.5400	knot International (kn)	kilometre/hr (km/h)	1.852

ACCELERATION

3.28084	feet/sec^2 (ft/s^2)	metre/sec^2 (m/s^2)	0.304800
0.10197	gravitational acceleration (g)	• metre/sec^2 (m/s^2)	9.806650

POWER and HEAT FLOW RATE

3.4121	British thermal unit/hr (Btu/h)	watt (W)	0.2931
0.8598	kilocalorie/hour (kcal/h)	• watt (W)	1.163
0.7376	foot pound-force/sec (ft lbf/s)	watt (W)	1.3558
0.1020	kilogram-force metre/sec (kgf m/s)	watt (W)	9.807
1.360	metric HP	kilowatt (kW)	0.7355
1.3410	horsepower (hp)	kilowatt (kW)	0.7457
7.457×10^{-4}	megawatts (MW)	horsepower (hp)	1341
0.2843	ton of refrigeration	kilowatt (kW)	3.517
8.333×10^{-5}	ton of refrigeration	British thermal unit/hr (Btu/h)	12000
1.000	joule/sec (J/s)	watt (W)	1.000
1.818×10^{-3}	horsepower (hp)	foot pound-force/sec (ft lbf/s)	550

ILLUMINATION

0.0929	foot candles	lux (lx)	10.764
0.0929	lumen/$foot^2$ (lm/ft^2)	lux (lx)	10.764
0.0929	candela/sq. foot (cd/ft^2)	• candela/sq. metre (cd/m^2)	10.764

ANGULAR MEASURE

57.296	degree (...°)	radian (rad)	0.017453
9.5493	revs per min (rpm)	radian/sec (rad/s)	0.10472

ELECTROMAGNETIC

2.778×10^{-4}	ampere hour (Ah)	coulomb (C)	3600
10^4	gauss	weber/sq metre (Wb/m^2)	10^{-4}
2.5407	microhms/cm^3	microhms/in^3	0.3937
10^5	gamma	gauss	10^{-5}

MULTIPLY BY ⟵ TO ⟵ TO CONVERT

TO CONVERT	⟶	TO	⟶	MULTIPLY BY
KINEMATIC VISCOSITY				
10^6		centiStoke		
10.764		square feet/sec		square metre/sec (m^2/s) 10^{-4}
10^6		square millimetre/sec		square metre/sec 0.09290
10^4		Stoke (St) (cm^2/s)		square metre/sec (m^2/s) 10^{-6}
				square metre/sec 10^{-4}
DYNAMIC VISCOSITY				
10^3		centipoise (cP)		
2.419		pound/ft hr (lb/ft h)		pascal second (Pa s) 10^{-3}
0.02089		pound-force sec/$foot^2$ ($lbf\ s/ft^2$)		centipoise (cP) 0.4134
1.000		gram/metre sec (g/m s)		pascal second (Pa s) 47.88
				centipoise (cP) 1.000
HEAT TRANSFER				
0.1761		Btu/ft^2 h°F		
6.933		Btu in/ft^2 h°F		watts/metre² K (W/m^2 K) 5.678
2.388×10^{-4}		Btu/lb°F		watts/metre K (W/m K) 0.1442
4.299×10^{-4}		Btu/lb		joule/kilogram K (J/kg K) 4186.8
2.388×10^{-4}		kilocalories/kg		joule/kilogram (J/kg) 2326
				joule/kilogram (J/kg) 4187
SOUND LEVEL				
0.1151		neper		decibel (Db) 8.686

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PHYSICAL CONSTANTS

3.141593	π
2.718282	e
2.302585	$\log_e 10$

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Automation of manufacturing processes in industry today is extremely important, not only for its economic benefits but also for its role in producing a consistent quality product. It has created numerous job opportunities for properly trained and qualified people in all areas of fluid power. For many years pneumatics has played an important role in automated manufacturing and handling processes, ranging from the so-called "low-cost automation" applications to the sophisticated and complex powering and control of entire transfer machines and robots. Pneumatics must therefore be seen and respected for its dual role: that of power transmission and that of logic control.

The purpose of this book is to facilitate a thorough understanding of the fundamental principles of industrial pneumatic control and power transmission, as well as production and distribution of clean, compressed air. It is also intended to provide a practical working knowledge of the commonly encountered components for designing, installing and maintaining industrial pneumatic systems.

Peter Rohner (Dip. Mech. Eng.) has studied mechanical engineering, design and drafting, and has worked in the packaging, can manufacturing, and material handling industries for more than twelve years. During that time he gained wide experience in the design of Industrial Automation and Fluid Power Control.

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ISBN 0-471-33463-4

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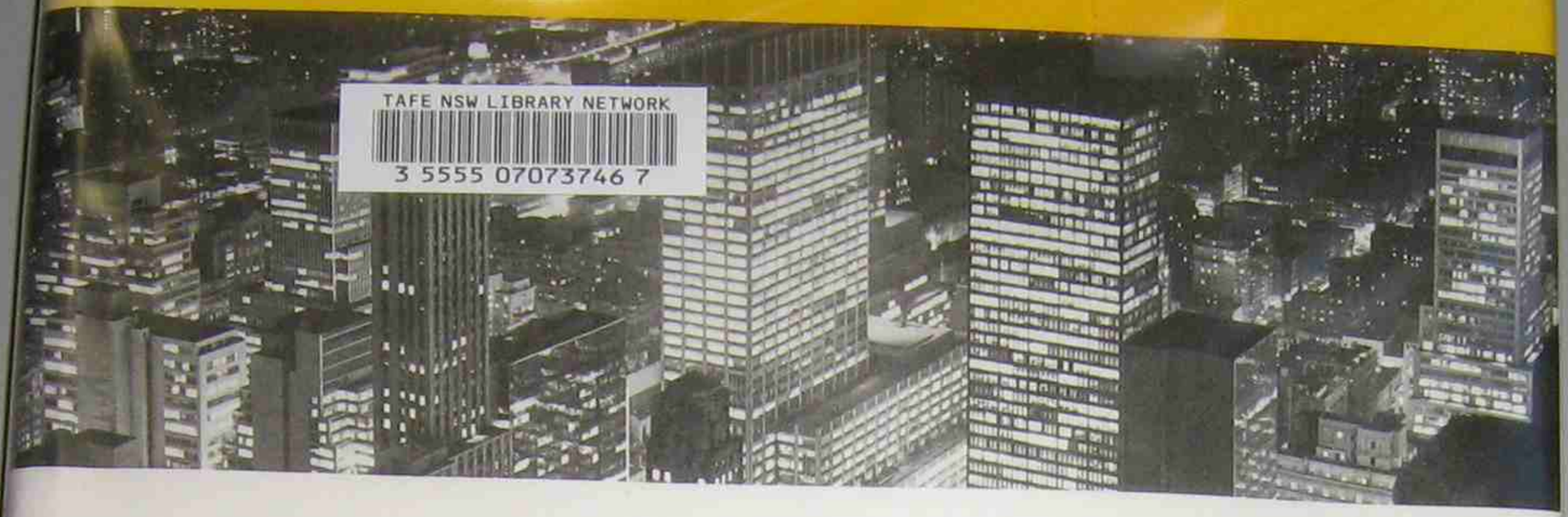

Electrical Design for Building Construction

JOHN E. TRAISTER

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Electrical Design For Building Construction

by John E. Traister

John E. Traister Associates

Long needed in the field, this practical book provides step-by-step guidelines for designing, laying out, and drafting—from start to finish—electrical systems in any type of building. Electrical designers, engineers, contractors, and draftspersons will find this an indispensable working tool for solving a wide variety of electrical problems encountered in commercial, industrial, and residential buildings.

Containing sketches drawn from actual projects, the volume provides realistic methods for . . .

- lighting with incandescent lamps
- lighting with fluorescent lamps
- lighting with HID lamps
- lighting with combinations of lamps
- power wiring for convenience outlets
- power wiring for special outlets
- power wiring for heating, ventilating, and air conditioning
- designing service equipment
- designing panelboards and feeders
- designing special electrical systems

Methods of lighting design for both incandescent and fluorescent lamps are covered, including practical applications of the use of the Zonal Cavity Method of lighting calculations. Characteristics and practical applications of HID lighting are provided, together with methods of calculating and designing outdoor lighting. In addition to methods for facilitating design, many of the National Electrical Code articles pertaining to power wiring are reviewed in a section on power wiring for convenience outlets.

Procedures for designing circuits for various electrical apparatus such as motors, appliances, exhaust fans, and other special applications are outlined. And methods for calculating and designing circuits for heating, ventilating, and air conditioning are presented in a section that includes actual problems and suggested solutions. The volume also covers the generally recognized sections of an electrical system, voltages available, and the most accepted methods of service installations, together with a step-by-step

(continued on back flap)

Electrical Design for Building Construction

Library of Congress Cataloging in Publication Data

Traister, John E
Electrical design for building construction.

Includes index.
1. Electric lighting – Drawings. 2. Electric wiring – Diagrams.
3. Buildings – Electric equipment – Drawings. I. Title.
TK4169.T7 621.319'24 76-14971
ISBN 0-07-065127-2

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The editors for this book were Tyler G. Hicks and Ruth L. Weine, the designer was Richard A. Roth, and the production supervisor was Frank P. Bellantoni. It was set in VIP Memphis Medium by Progressive Typographers.

Printed and bound by Halliday Lithograph Corporation

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Preface

The analysis of existing drawings prepared by professional engineers has long been a major part of the "serious" engineering student's method of study. Unfortunately, the young electrical engineering student who hopes to become an engineer/designer in a consulting engineering firm has no wealth of material to aid him. Printed working drawings of electrical systems in buildings are rare. The basic purpose of this book is to remedy this situation by giving the budding professional a means of seeing and analyzing actual working drawings of electrical systems used in residential, commercial, institutional, and industrial structures.

We will not concern ourselves with too much theory as hundreds of previous books have taken ample care of this for us. Our main concern is the application of practical electrical designs for light and power that must be dealt with by the professional engineers in consulting firms.

Practically all of the examples given are in working-drawing form with written explanations to clearly illustrate at a glance exactly what is taking place and also for what purpose. No further data are necessary to understand the examples except the written specifications found in Appendix A of this book.

Our examples are taken from these projects:

Residence
J. C. Bowman, ARA, Architect
Harrisonburg, Va.

Tenant Residence
Baughan & Baukhages, AIA, Architects
Luray, Va.

The First National Bank—Branch
Baughan & Baukhages, AIA, Architects
Luray, Va.

Laundry Building
G. Lewis Craig, Architect
Waynesboro, Va.

The First National Bank – Main Office
Baughan & Baukhages, AIA, Architects
Luray, Va.

Church
Dwight E. Miller, AIA, Architect
Harrisonburg, Va.

Department Store
Baughan & Baukhages, AIA, Architects
Luray, Va.

Nursing Home
Baughan & Baukhages, AIA, Architects
Luray, Va.

A deep and grateful bow must be made in the direction of the draftspersons, designers, and engineers who prepared these drawings. I am especially indebted to Boyd G. Headley, III, who prepared many of the illustrations for this book, and to Ruby R. Updike, whose encouragement and many hours of typing helped make this project much easier than it otherwise would have been.

No matter how many books a person has read on the subject and no matter how many sets of working drawings he has seen and analyzed, his progress can only be measured by what he actually designs and what designs have been constructed.

If this book can take a few of the stumbling blocks out of the student's path and light the way somewhat, my purpose will have been fulfilled.

John E. Traister

Chapter 1 The Essentials

OBJECTIVES

The fundamental objective of this chapter is to give the reader an overall picture of the electrical construction industry and the electrical designer's relationship to it. Familiarity with these relationships is considered necessary to give designers a proper background for approaching their work more intelligently.

This chapter will also introduce fundamental design procedure, electrical symbols, and other basic essentials necessary to the electrical design profession.

THE HISTORICAL RELATION OF THE ELECTRICAL DESIGNER TO THE BUILDING CONSTRUCTION INDUSTRY

The earliest recorded use of commercial electricity was the installation of an arc lamp in the Dungeness lighthouse in England in 1862. This early type of light, while not entirely steady or

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free from smoke, was able to produce great amounts of very bright light—for the time—by drawing electric arcs or flames between two carbon electrodes. However, it was not until seventeen years later, in 1879, that the first successful carbon-filament incandescent lamp was invented by Thomas A. Edison. He also developed the first efficient electric generator to supply current for his lamps in the same year. The experiments were continued, and in 1882 Edison developed the first central-station electric generating plant in New York City.

Prior to Edison's generating plant, naturally there was no inclusion of electrical systems in building construction. However, this new generating plant brought on a public demand for the use of electric lighting and power in existing buildings, as well as for new construction.

These first electrical wiring installations were usually laid out by workers employed and trained by the power companies, and the majority of these installations were "designed" by the mechanics on the job—often as the work progressed. Building contractors then began hiring mechanics of their own to install the electrical wiring systems, but because of the special skills and knowledge required, these same builders soon began leaving the wiring installations to mechanics who began to specialize in this work as electrical contractors. In fact, most of the building contractors were more than happy to subcontract this work since the electrical installations of that time pertained to only a small percentage of the overall contract.

Owing to the potential hazards caused by the improper handling and installation of electrical systems, certain rules in the selection of materials, quality of workmanship, and precautions for safety had to be followed in order to minimize these hazards. The National Electrical Code (NEC) was prepared in 1897 to standardize and simplify these rules and also to provide some reliable guide for electrical construction. It is recommended that the reader obtain the latest edition of the NEC for reference in all design projects.

As the electrical construction continued to become a more important part of the general building construction, the architects began to prepare layouts of the desired electrical systems on the architectural drawings. This layout usually indicated the lighting outlets, base "plugs," and light switches by means of certain symbols. A line was sometimes drawn from a lighting outlet to a wall switch to indicate how the various lamps were to be controlled, but this was usually the extent of the electrical design. The details of wiring, number of circuits, etc., were still left to the mechanics installing the system. As the electrical systems became more extensive and complex, the electrical contractors began hiring draftsmen to prepare working drawings to supplement the sketchy outlet layout on the architectural drawings, to provide a basis for preparing estimates, and to give instructions to electricians in the field who were installing the systems. These early electrical draftsmen were probably experienced architectural or mechanical draftsmen who were trained in the field of electricity by the electrical contractors.

From that point on, electrical construction continued to become a more important part of general building construction, and soon the architects began to prepare more extensive layouts of the electrical systems until finally separate drawings were included along with the architectural drawings. As the volume of such layout work increased and the electrical systems became still more extensive and complex, a greater engineering knowledge of power and illumination requirements became necessary. Persons with the proper knowledge and training began to devote their time exclusively to designing and laying out electrical installations as consulting engineers, selling their services to the architects. These consulting engineers conveyed their designs by means of working drawings which used symbols, lines, notations, etc. Thus, the electrical designer has become a very important cog in the wheel of electrical construction.

THE CONSTRUCTION OF A BUILDING

In nearly all instances, when an owner decides to have a building constructed, an architect is hired to prepare the complete working drawings and specifications for the building. The drawings usually include (1) a plot plan indicating the location of the building on the property; (2) elevations of all exterior faces of the building; (3) floor plans showing the walls and partitions for each floor or level; (4) sufficient vertical cross sections to indicate clearly the various floor levels and details of the foundation, walls, floors, ceilings, and roof construction; and (5) large-scale renderings showing such details of construction as may be required.

For jobs of any consequence, the architect usually includes drawings and specifications covering the design of plumbing, heating, ventilating, air conditioning, and electrical work. A brief description of such drawings follows.

Mechanical Drawings

The mechanical drawings cover the complete design and layout of the plumbing, piping, heating, ventilating, air conditioning, and related mechanical construction. They also include floor-plan layouts, cross sections of the building, and necessary detailed drawings. The control wiring for mechanical equipment is usually indicated on the mechanical drawings, not on the electrical drawings as one might imagine.

Electrical Drawings

The electrical drawings generally cover the complete electrical design of the electrical wiring for lighting, power, signals and communications, special electrical systems, and related electrical equipment. These drawings should also include a plot plan or site plan showing the location of the building on the property and the interconnecting electrical systems; floor plans showing the location of power outlets, lighting fixtures, panelboards, etc.; power-riser diagrams; a symbol list; schematic diagrams; and larger-scale details where necessary.

The architect will often represent the owner in soliciting quo-

tations from general contractors and advise the owner as to the proper award to make. The architect will also usually represent the owner during construction of the building, inspecting the work to ascertain that it is being performed in accordance with the requirements of the drawings and specifications.

The relations of the consulting engineer parallel those of the architect, inasmuch as the consulting engineer often represents the architect and owner in soliciting from the contractors quotations which pertain to the engineer's line of work. The engineer also inspects his or her portion of the work to assure the architect that this portion is carried out according to the working drawings and specifications. The engineer approves shop drawings (material submittals), checks and approves progress payments, and performs similar duties—all pertaining only to the engineer's phase of the construction.

Architects sometimes require the engineer to prepare an approximate estimate of the electrical work to aid them in determining the probable cost of the building prior to the actual request of formal quotations. This is especially true on government projects. The book *Rapid Electrical Estimating & Pricing*, written by C. Kenneth Kolstad and published by McGraw-Hill Book Company, is a handy reference for this type of electrical estimating.

Quality of Designs

The consulting engineering firms should strive to produce designs and working drawings which are no less than excellent in quality. They should not only be correct as far as wiring methods, feeder sizes, etc., are concerned, but they should also be presented in such a manner as to be easily interpreted by the electrical contractor, the electrical estimators, and the electricians on the job. The electrical drawings combined with the written specifications should leave no doubt as to exactly what is required of the electrical contractor for the proper installation of the electrical system on the project.

ELECTRICAL WIRING SYMBOLS

The purpose of an electrical drawing is to show the complete design and layout of the electrical systems for lighting, power, signal and communication systems, special raceways, and related electrical equipment. In preparing such drawings, the electrical layout is shown through the use of lines, symbols, and notation which should indicate, beyond any question or any doubt, exactly what is required.

Many engineers, designers, and draftsmen use symbols adapted by the United States of America Standards Institute (USASI). However, no definite standard schedule of symbols is always used in its entirety. Consulting engineering firms quite frequently modify these standard symbols to meet their own needs. Therefore, in order to identify the symbols properly, the engineer provides, on one of the drawings or in the written specifications, a list of symbols with a descriptive note for each—clearly indicating the part of the wiring system which it represents.

Figure 1-1 shows a list of electrical symbols which are currently recommended by USASI, while Fig. 1-2 shows another list of symbols which was prepared by the Consulting Engineers Council/U.S. and the Construction Specifications Institute, Inc.

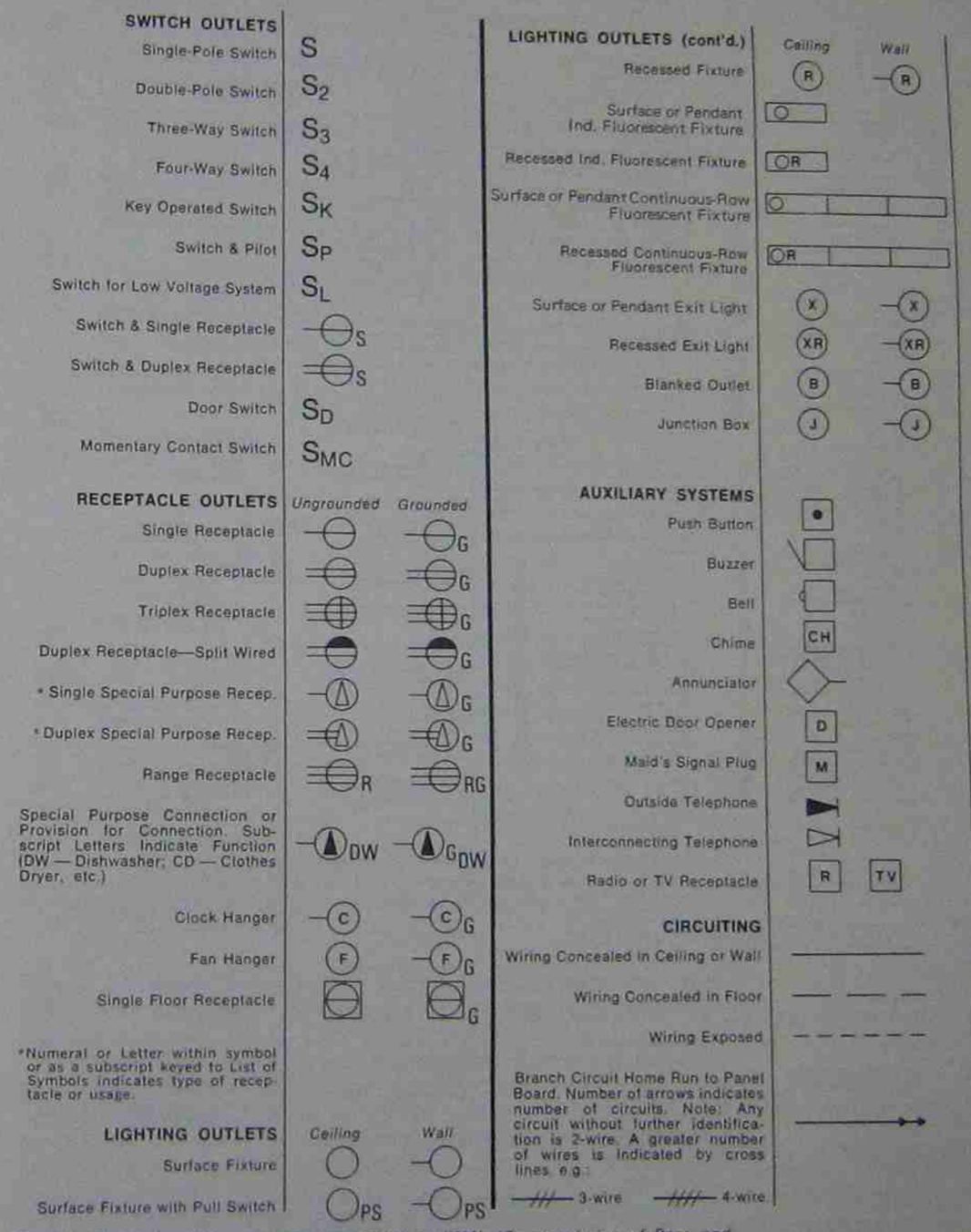


Fig. 1-1 Electrical symbols currently recommended by USASI. (*By permission of Pass and Seymour, Inc.*)

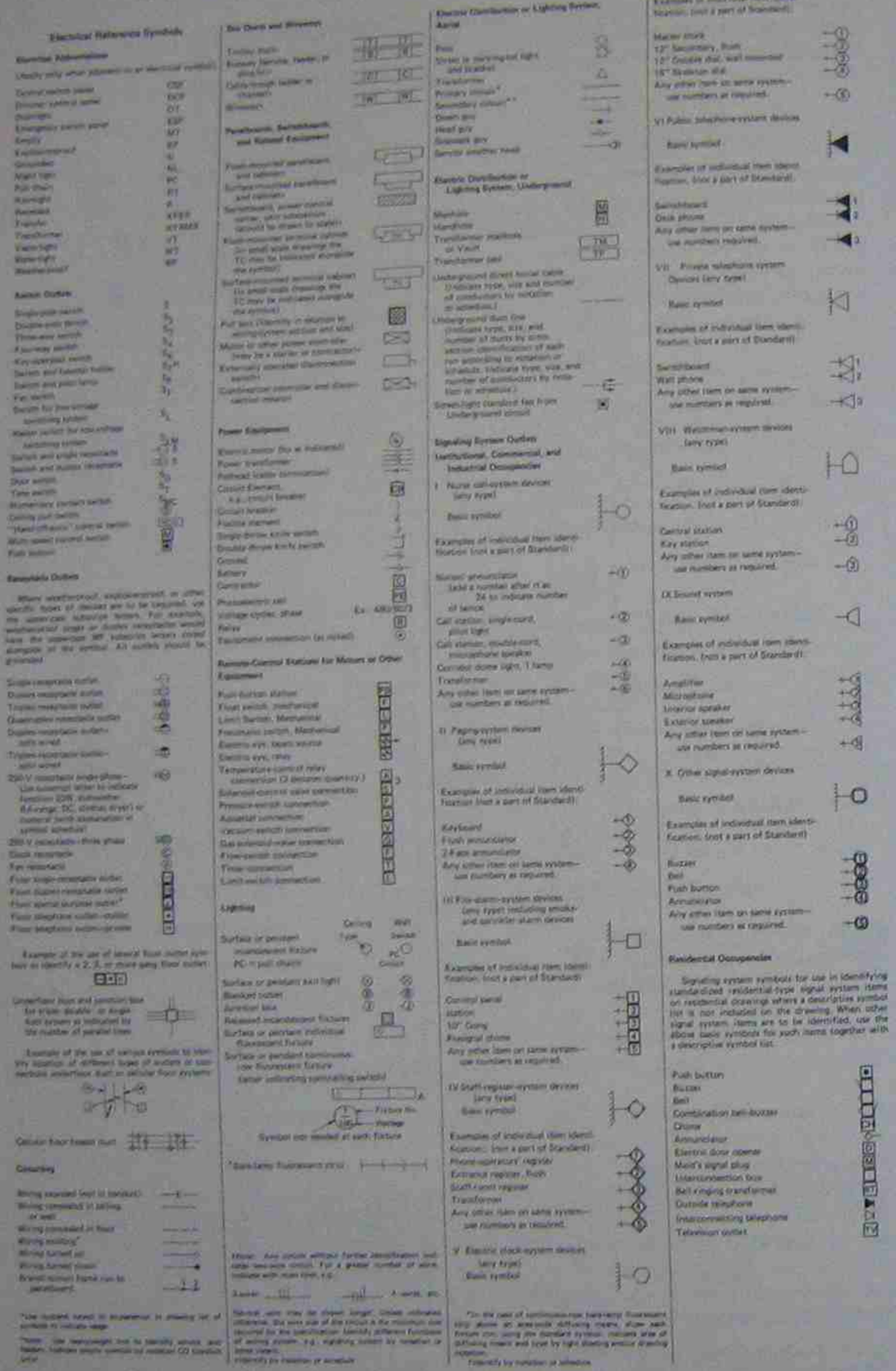


Fig. 1-2 (Facing page) A list of electrical symbols recommended by the Consulting Engineers Council/U.S. and the Construction Specifications Institute, Inc.

- Fluorescent strip
- Fluorescent fixture
- Incandescent fixture, recessed
- Incandescent fixture, surface or pendant
- Incandescent fixture, wall-mounted
- Letter "E" inside fixtures indicates connection to emergency lighting circuit

  Note: on fixture symbol, letter outside denotes switch control.
- Exit light, surface or pendant
- Exit light, wall-mounted
- Indicates fixture type
- Receptacle, duplex-grounded
- Receptacle, weatherproof
- Combination switch and receptacle
- Receptacle, floor type
- Receptacle, polarized (poles and amperes indicated)
- Switch, single-pole
- Switch, three-way, four-way
- Switch and pilot light
- Switch, toggle w/ thermal overload protection
- Push button
- Buzzer
- Light or power panel
- Telephone cabinet
- Junction box
- Disconnect switch-FSS: fused safety switch; NFSS: Non-fused safety switch
- Starter
- Above finished floor
- Conduit, concealed in ceiling or wall
- Conduit, concealed in floor or wall
- Conduit exposed
- Flexible metallic armored cable
- Home run to panel - number of arrowheads indicates number of circuits. Note: any circuit without further designation indicates a two-wire circuit. For a greater number of wires, read as follows: 3 wires, 4 wires, etc.
- Telephone conduit
- Television-antenna conduit
- Sound-system conduit-number of crossmarks indicates number of pairs of conductors.
- Fan coil unit connection
- Motor connection
- Mounting height
- Fire-alarm striking station
- Fire-alarm gong
- Fire detector
- Smoke Detector
- Program bell
- Yard gong
- Clock
- Microphone, wall-mounted
- Microphone, floor-mounted
- Speaker, wall-mounted
- Speaker, recessed
- Volume control
- Telephone outlet, wall
- Telephone outlet, floor
- Television outlet

Fig. 1-3 A modified list of electrical symbols used by a consulting engineering firm. These are standard symbols and may not all appear on any one project drawing; however, wherever the symbol appears on a project drawing, the item shall be provided and installed.

Figure 1-3 shows still another list of electrical reference symbols which have been modified for use by one consulting engineering firm.

It is evident from the preceding symbols that many have the same basic form, but, because of some slight difference, their meaning changes. For example, the outlet symbols in Fig. 1-4 each have the same basic form—a circle—but the addition of a line or an abbreviation gives each an individual meaning. A good procedure to follow in learning symbols is to first learn the basic form and then apply the variations for obtaining different meanings.

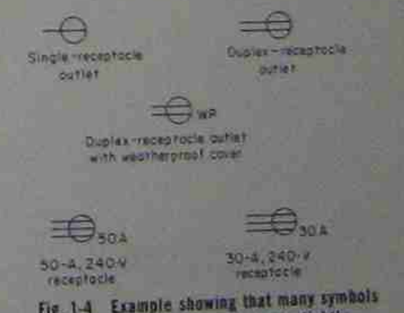


Fig. 1-4 Example showing that many symbols have the same basic form but are slightly changed to give each an individual meaning.

The electrical symbols described in the following paragraphs represent a system of electrical notation whose compactness and clarity may be of assistance to electrical engineers, designers, and draftsmen.

The system should be used in place of standard symbols only if there seems to be a decided advantage in doing so.

Some of the symbols are abbreviated idioms, like "WP" for weatherproof and "AFF" for above finished floor. Other symbols are simplified pictographs, like  for a double floodlight fixture or  for an infrared electric heater with two lamps.

In some cases that are combinations of idioms and pictographs, as in  for fusible safety switch,  for nonfusible safety switch, and  for double-throw safety switch, where the pictograph of a switch enclosure is combined with the abbreviated idioms of F (fusible), N (nonfusible), and DT (double-throw), respectively. The numerals indicate the bus bar capacity in amperes.

This list came about as a result of much discussion with consulting engineers, electrical designers, electrical draftsmen, electrical estimators, electricians, and others who are required to interpret electrical drawings. It is felt that this list represents a good set of symbols in that they are:

1. Easy to draw
2. Easily interpreted by workers
3. Sufficient for most applications

Lighting Outlets

Ceiling outlet with surface-mounted incandescent lighting fixture

Wall outlet with surface-mounted incandescent lighting fixture

Practical use of these symbols is shown in Fig. 1-5.

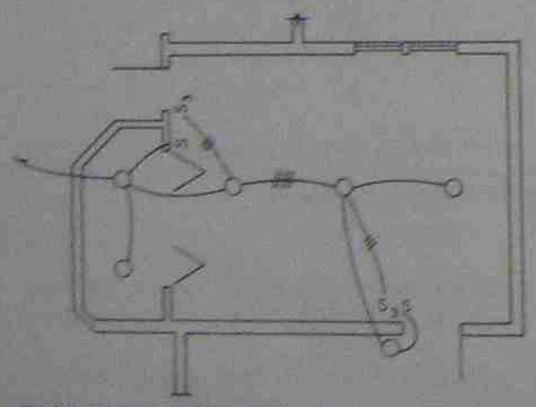


Fig. 1-5 Practical application of surface-mounted incandescent fixtures.

Wall outlet with recessed incandescent lighting fixture

Ceiling outlet with recessed incandescent lighting fixture

Practical use of the symbols at the left is shown in Fig. 1-6. Sometimes these symbols are modified in order to indicate the physical shape of a particular incandescent fixture. The

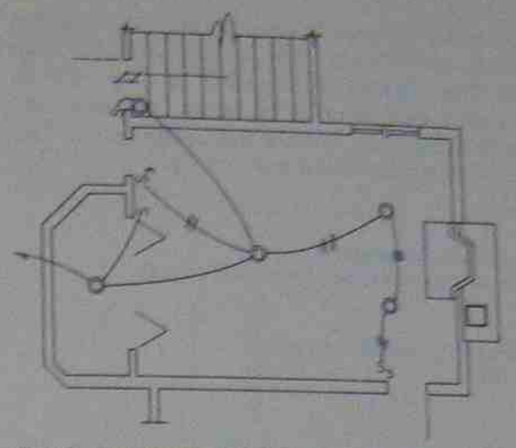


Fig. 1-6 Practical application of recessed incandescent lighting fixtures.

lighting fixture in Fig. 1-7 consists of four 6-in. cubes. This type of lighting fixture may be indicated on the electrical floor plan as shown in Fig. 1-8.

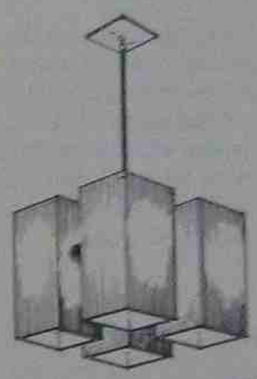


Fig. 1-7 Pictorial drawing of a lighting fixture consisting of four 6-in. cubes, one-cube lighting fixture on the drawings.

A lighting fixture consisting of one cube may be indicated as shown in Fig. 1-9. All should be drawn as close to scale as possible.

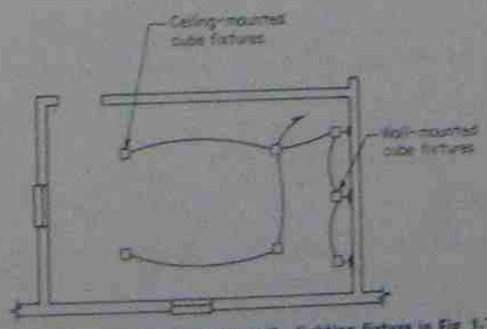


Fig. 1-8 Example showing how the lighting fixture in Fig. 1-7 may be indicated on working drawings.

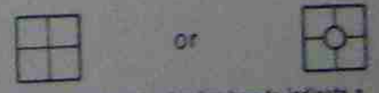


Fig. 1-9 Example showing how to indicate a one-cube lighting fixture on the drawings.

The type of mounting of all fixtures is usually indicated in the lighting fixture schedule shown on the drawings or in the written specifications. The fixture illustrated in Fig. 1-7 is obviously pendant-mounted and should be so indicated in an appropriate column in the lighting fixture schedule, since the floor-plan view in Fig. 1-8 does not indicate this fact.

Ceiling or wall outlet with incandescent lighting connected to emergency circuit (Emergency white light)

Exit light on emergency circuit, surface- or pendant-mounted

Exit light on emergency circuit, wall-mounted

Surface- or wall-mounted exit light with directional arrowheads

The mounting height of wall-mounted lighting fixtures is sometimes indicated in the symbol lists, especially where most are to be mounted at one height. For example, it might read ". . . wall outlet with incandescent fixture mounted 6 ft 6 in. above finished floor to center of outlet box unless otherwise indicated." If a few wall-mounted fixtures were to be mounted at 8 ft 0 in. above finished floor, they could be indicated as shown in Fig. 1-10, the letters AFF meaning "above finished floor."

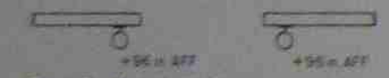


Fig. 1-10 Method of indicating mounting height of a few wall-mounted fixtures.

Ground-mounted incandescent uplight

Post-mounted incandescent fixture

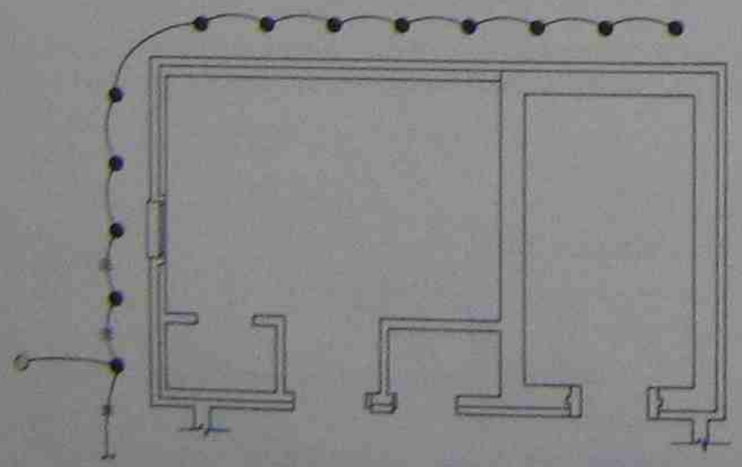


Fig. 1-11 Practical application of ground- and post-mounted incandescent fixtures.

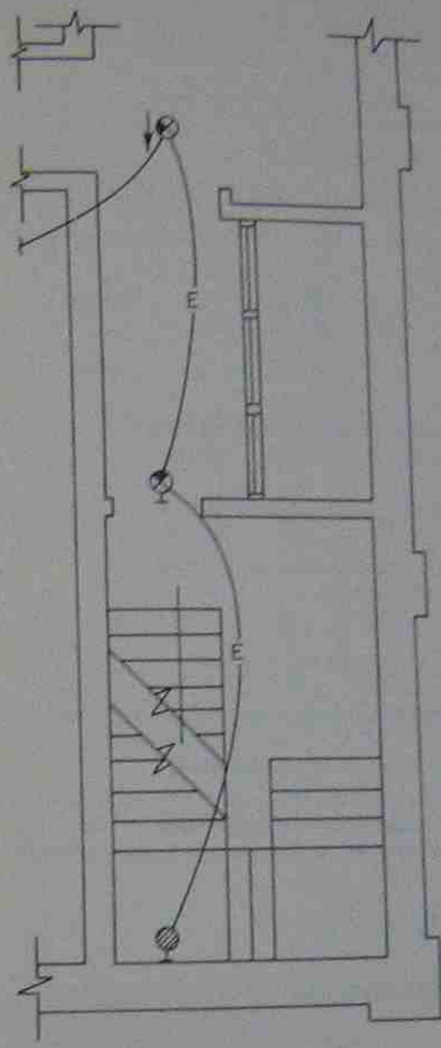


Fig. 1-12 Practical application of exit lights and emergency white incandescent fixtures.

Ceiling- and wall-mounted floodlight fixture

If only one lamp (or more than two lamps) is required on the floodlight outlet, it can be shown as in Fig. 1-13 or Fig. 1-14.



Fig. 1-13 Practical application showing floodlights on the drawings, either one lamp or more than two lamps.

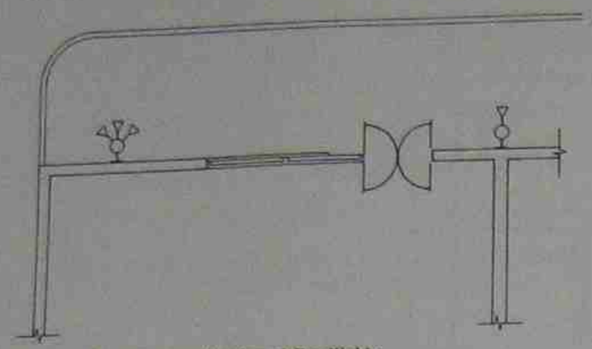


Fig. 1-14 Practical application of floodlights.

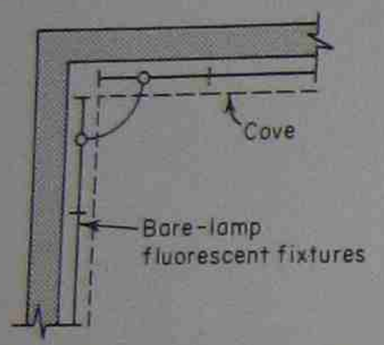
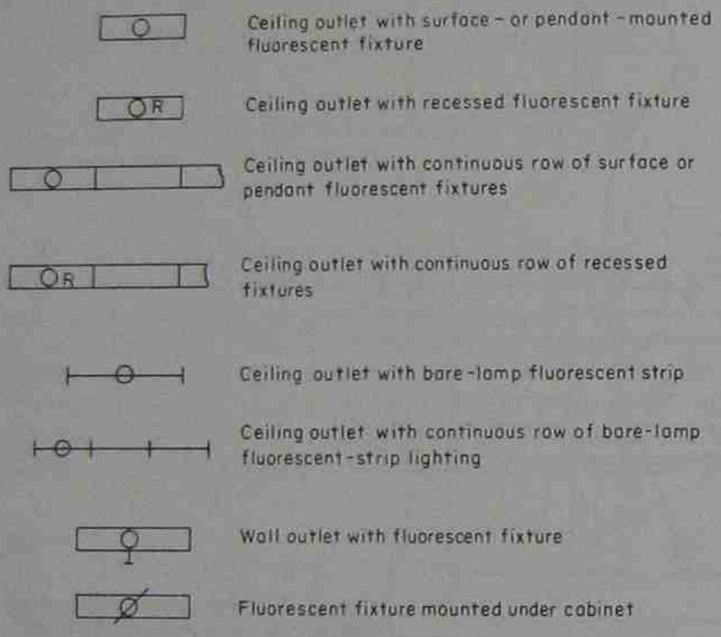


Fig. 1-15 Example showing how to indicate bare-tube fluorescent fixtures on the drawings.



Modification of the symbols for fluorescent lighting is common. For example, cove lighting with bare-lamp fluorescent strips may be indicated on the drawings as shown in Fig. 1-15.

The lighting layout illustrated in Fig. 1-16 shows practical applications of all fluorescent symbols covered in this writing.

Many electrical drawings do not differentiate between recessed, surface, or pendant-mounted fixtures on the floor plans. Rather, the mounting is indicated either in the lighting fixture schedule or in the written specifications. However, since a major variation in the type of outlet box, outlet supporting means, wiring system arrangement, and outlet connection, plus need of special items such as plaster rings or roughing-in cans, depends upon the way in which a fixture is mounted, the electrician should be able to know the type of mounting in a glance at the drawings. Therefore, the mounting of a lighting fixture should be indicated on the floor plans as well as in the lighting fixture schedule.

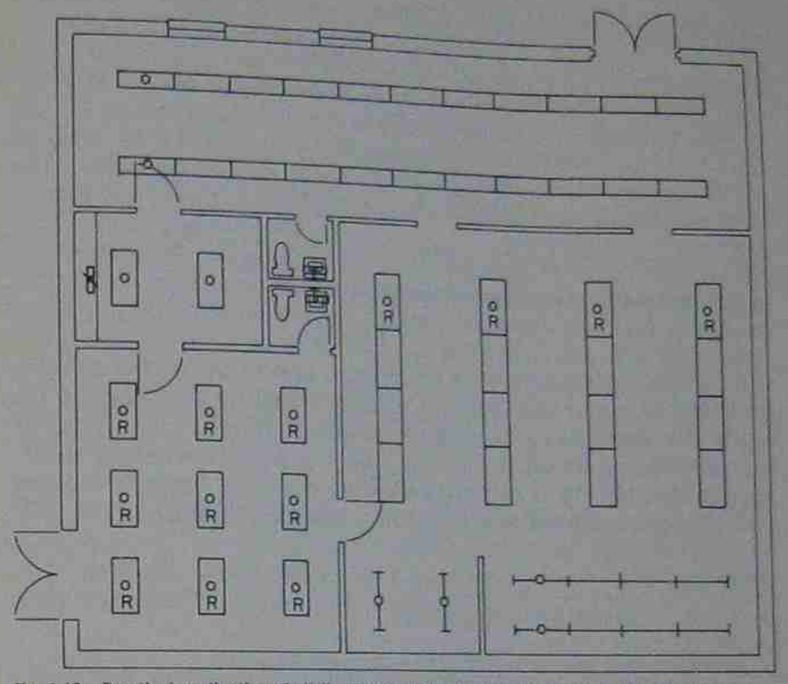


Fig. 1-16 Practical application of all fluorescent lighting symbols covered in this chapter.

Lighting fixtures are identified as to type of fixture by a numeral placed inside a triangle near each lighting fixture, as shown to the right and in Fig. 1-17.

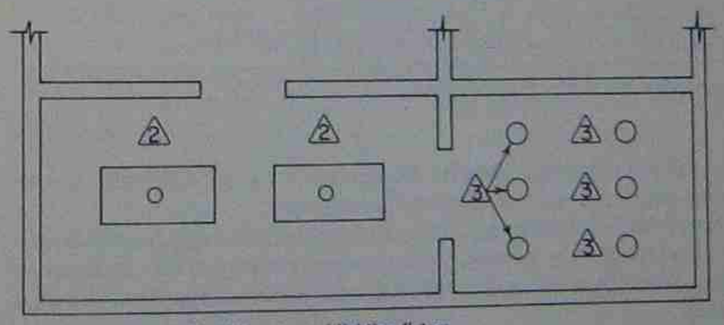


Fig. 1-17 Method of identifying type of lighting fixture.

The indicated fixture is shown in the symbol lists as follows:

△5 Indicates type of lighting fixture — see schedule

If one type of fixture is used exclusively in one room or area, as shown in Fig. 1-18, the indicator need only appear once with the word "All" lettered at the bottom.

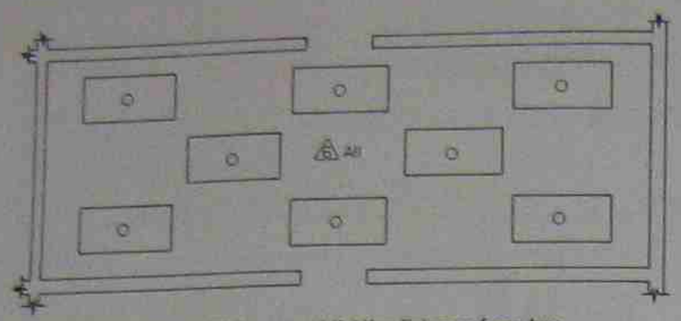


Fig. 1-18 Method of identifying several lighting fixtures of one type.

A complete description of the fixture identified by the symbol must be given in the lighting fixture schedule and should include the manufacturer, catalog number, number and type of lamps, voltage, finish, mounting, and any other necessary information needed for a proper installation of the fixtures. Figure 1-19 shows an example of a lighting fixture schedule.

LIGHTING FIXTURE SCHEDULE

FIXT. Type	Manufacturer's Description	LAMPS No.	LAMPS Type	Volts	Mounting	Remarks

Fig. 1-19 Example of a lighting fixture schedule.

Fluorescent fixtures should be drawn to approximate scale, showing physical size whenever practical.

Mercury vapor and other electric-discharge lighting fixtures are indicated on the drawings in the same way as incandescent fixtures. The type of lamp is indicated in the lighting fixture schedule.

Receptacles and Switches

Every day those who work in the electrical construction industry hear the word "standard." Yes, it would be the ideal situation if all electrical engineers could use one set of standard electrical symbols for all their projects. However, with the present symbols known as "standard" this is not practical.

For example, one consulting engineering firm in Washington, D.C., did a large amount of electrical designs for hospitals all over the eastern United States. On one of their jobs, there were over 100 duplex receptacles mounted horizontally in the backsplash of lavatory countertops, while there were over 300 conventional duplex receptacles.

If a draftsman had to letter a note at each of the receptacles located in the backsplash, it is easily seen that much time would be spent on the drawings. On the other hand, a simple symbol with a written explanation in the legend would tell exactly what work was to be done, and the draftsman could indicate the location of these outlets on the drawings in little, if any, extra time.

Our firm recently designed the electrical systems for a group of quick-service restaurants where several of the duplex receptacles were located in the ceiling. If we had used standard symbols, each location would have looked like the following:

Flush mounted 120V duplex receptacles mounted in the ceiling

We saved much time by composing a new symbol for the ceiling-mounted receptacles and eliminated the descriptive note at each of the dozen or so receptacles. A note appeared only once in the symbol list as follows:

Flush-mounted 120 V, duplex "twist-lock" receptacle mounted in ceiling with stainless steel plate

The cases are endless, and until a sufficient number of different symbols is available in the standard symbol list, it is highly impractical to use the standard throughout.

If a special outlet is shown on a drawing in only a few locations, then perhaps a descriptive note at each location is best; but if the "special outlet" appears in several locations, then an individual symbol can save much drawing time.

The following are switch and receptacle symbols used in our office on working drawings.

- **S** Single-pole toggle switch mounted 50 in. AFF to center of box unless otherwise indicated.
- **S_2** Two-pole toggle switch mounted 50 in. AFF to center of box unless otherwise indicated.
- **S_3** Three-way switch mounted 50 in. AFF to center of box unless otherwise indicated.
- **S_4** Four-way switch mounted 50 in. AFF to center of box unless otherwise indicated.
- **S_L** Low-voltage switch to relay mounted 50 in. AFF unless otherwise indicated.
- **S_D** Flush-mounted door switch to control closet light.
- **S_P** Switch with pilot light.

Figure 1-20 illustrates some practical applications of switch symbols used on working drawings. Notice that the single-pole switches are used to control lighting from one point, while the three- and four-way switches, used in combination, control a light or series of lights from two or more points.

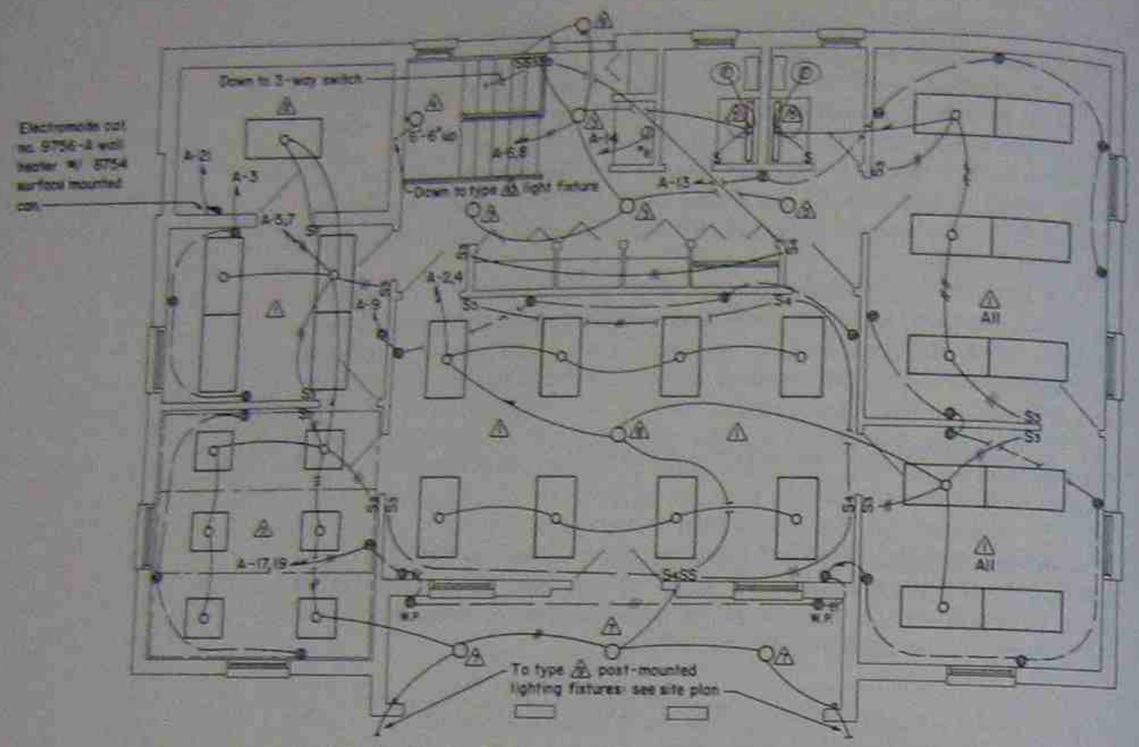


Fig. 1-20 Practical applications of switch symbols used on working drawings.

The two-pole switch is used to control a series of lights on two separate circuits with only one motion. The switch–pilot light combination is used where it is practical to notice if the item controlled by the switch is energized, such as a light in an attic or closet.

Door switches to control closet lights are quite common in residential construction. When the closet door is opened, the switch button is released and in turn energizes the circuit to the closet light. When the door is closed, the light is de-energized.

Receptacle symbols used in consulting engineering firms are numerous. Some firms have used over 50 different symbols for receptacles and power outlets. However, our firm has been able to work with only six different symbols to cover most of our needs. They are as follows:

Duplex grounded receptacle mounted 18 inches AFF to center of box unless otherwise indicated

Duplex grounded receptacle mounted 6 in. above countertop to center of box

Split-wired duplex grounded receptacle with top half switched. Mount 18 in. AFF unless otherwise specified

30a 3-pole, 3-wire, 240-V receptacle, amperage as indicated

a Special outlet or connection, letter indicates type; see legend at end of symbol list

Floor outlets are indicated on our drawings by a square with the appropriate symbol drawn inside:

Floor-mounted single receptacle, grounded

Floor-mounted duplex receptacle, grounded

Floor-mounted junction box

Figure 1-21 shows some practical applications of receptacle symbols as used on working drawings.

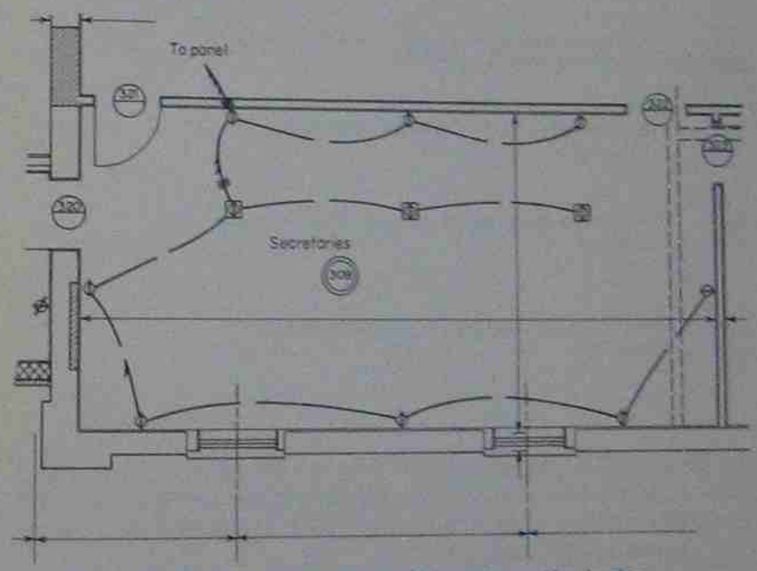


Fig. 1-21 Practical applications of receptacle symbols used on working drawings.

If other symbols are required to indicate various outlets on working drawings, they may be composed and added to the symbol list or legend with a description of their use. Examples are as follows:

Duplex grounded receptacle with "Twist-Lock" connection

Whatever the need may be

Whatever the need may be

When outlets are located in areas requiring special boxes, covers, etc., they are usually indicated by abbreviations. Example:

W.P.	Indicates weatherproof cover
E.P.	Indicates explosionproof device, fittings, etc.
E or EMERG.	Indicates outlet on emergency circuit

Service Equipment, Feeders, and Circuits

Panelboards, distribution centers, transformers, safety switches, and similar components of the electrical installation are indicated by electrical symbols on floor plans and by a combination of symbols and semipictorial drawings in riser diagrams. Some of these symbols are as follows:

Power panel or main distribution panel

(A) Surface-mounted lighting panel; numeral indicates type; see panelboard schedule

(A) Flush-mounted lighting panel; numeral indicates type; see panelboard schedule

F 60A Fusible safety switch; numerals indicate ampere capacity.

N 30A Nonfusible safety switch; numerals indicate ampere capacity

DT 30A Double-throw switch; numerals indicate ampere capacity

The description of panels and service equipment is usually covered in panelboard schedules such as those in Figs. 1-22 and 1-23; at other times a description of the panelboard is covered in the written specifications.

PANELBOARD SCHEDULE

Panel No.	Type Cabinet	Panel Mains Amperes	Volts	Phase	Branches 1P	2P	3P	Prot	Frame	Item Fed or Remarks

Fig. 1-22 Example of a panelboard schedule.

Panel _____ 1Ø 3 Wire _____ Mounted _____ Amperes Main _____
Location _____ Amperes Bus _____

Ckt. No.	Volt - Amperes ◊ A	◊ B	Description	Outlets	Outlet	Phase A	B	Outlet	Outlets	Description	Volt - Amperes ◊ A	◊ B	Ckt. No.
1													2
3													4
5													6
7													8
9													10
11													12
13													14
15													16
17													18
33													34
35													36
37													38
39													40
			Subtotals										
			Total VA / ◊										
			Total volt-amperes										
			Line amperes										

Fig. 1-23 Another example of a panelboard schedule.

Figure 1-24 (*a* and *b*) shows how service equipment is shown on working drawings.

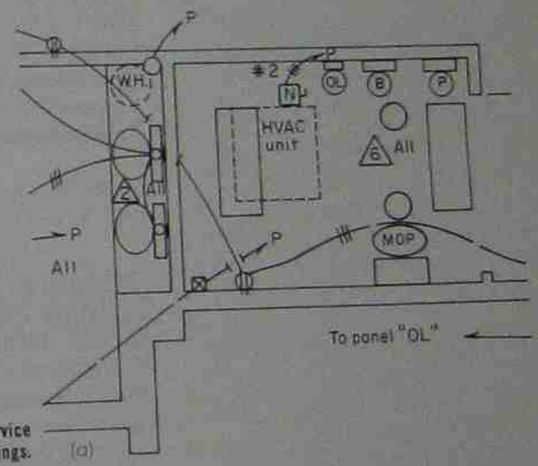
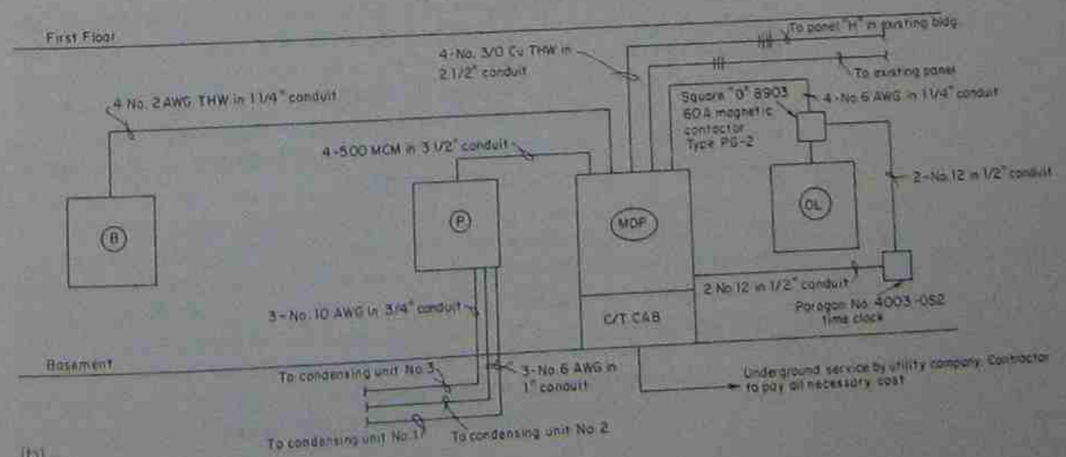


Fig. 1-24 Method of showing service equipment on working drawings. (a)



(b)

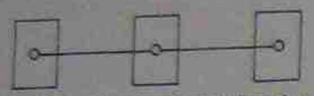


Fig. 1-25 Example of circuit lines drawn with a straightedge.

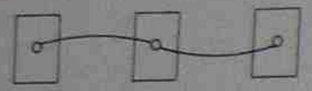


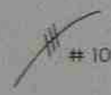
Fig. 1-26 Example showing circuit lines drawn with a French curve.

Circuit and feeder symbols have been nearly standardized in that most consulting firms use a solid line ——— to indicate circuits concealed in ceiling or wall and a broken line — — — for conduit or raceways concealed in floor or ceiling below. Exposed conduit or raceway is also shown with a broken line, but the dashes are shorter than those used for concealed circuits: - - - -.

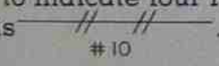
The variation between designers comes with the method of drawing these lines. Some designers prefer to draw all circuit lines with a straightedge, as shown in Fig. 1-25. Others prefer to use a French curve to draw the circuit line; this is illustrated in Fig. 1-26. Our firm prefers curved lines for all concealed circuits, for such lines are seldom, if ever, mistaken for building or equipment lines. However, on straight conduit wiring where conduit is run parallel with building lines, we do use straight lines to indicate such conduit, and the lines are drawn to show as closely as possible the actual route of installation.

We have seen some drawings using the symbol — X —— X —— X —— to indicate BX or flexible metallic armored cable in electrical systems where both rigid conduit and flexible cable were to be used.

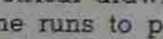
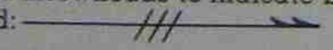
The number of conductors in a conduit or raceway system may be indicated in the panelboard schedule under the appropriate column, but we prefer to show this information on the floor plans along with the circuits because workers have found this method to be the easiest to follow. For example, our symbol list contains the following symbol:



Branch circuit concealed in ceiling or walls; slash marks indicate number of conductors in run—two conductors not noted; numerals indicate wire size—no. 12 AWG not noted

We are saying that a solid-line circuit with no slash marks or numerals indicates a circuit containing two No. 12 AWG conductors. Three slash marks with no numeral indicates three No. 12 AWG conductors, etc. If we want to indicate four No. 10 AWG conductors in a circuit, the symbol is 

.

Most electrical drawings use the symbol  to indicate home runs to panelboard, with the number of arrowheads indicating the number of circuits in the run and the slash marks indicating the number of conductors in the run. However, since we use full arrowheads for call-outs as shown in Fig. 1-27, we use half-arrowheads to indicate branch-circuit home runs to panelboard: 

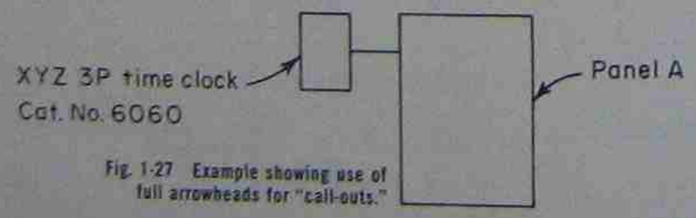


Fig. 1-27 Example showing use of full arrowheads for "call-outs."

Other circuits are indicated as follows:

——T—— Telephone conduit with pull wire
——TV—— Television-antenna conduit
——E—— Emergency circuit
— - - — Low-voltage cable
——EC—— Empty conduit with pull wire

Communication and Alarm Symbols

Symbols for communication and signal systems, as well as symbols for light and power, should be drawn to an appropriate scale and accurately located with respect to the building in order to minimize the necessity to refer to architectural drawings. Where an extremely accurate final location of outlets and equipment is necessary, exact dimensions should be noted on the drawings.

If the communication and/or signal systems are highly complex, it is best to show these systems on drawings separate from the lighting and power systems. In any case, all circuits for communication, control, and signal systems should be laid out in complete detail on the electrical drawings, including identification of the number, size, and type of all conductors.

A complete communication and signal-system layout should include at least the following on one or more drawings:

1. Floor-plan layout, to scale, of all outlet and equipment locations, including routes of all circuits and wiring.
2. A complete schedule of all symbols used, with a clear description of each.
3. Where necessary for clarity, a single-line diagram showing the electrical relationship of the component items and sections of the wiring system.
4. Sections of the building or elevation of the structure may be required to clearly show outlet and equipment heights, relation to the established grade, general type of building construction, etc.

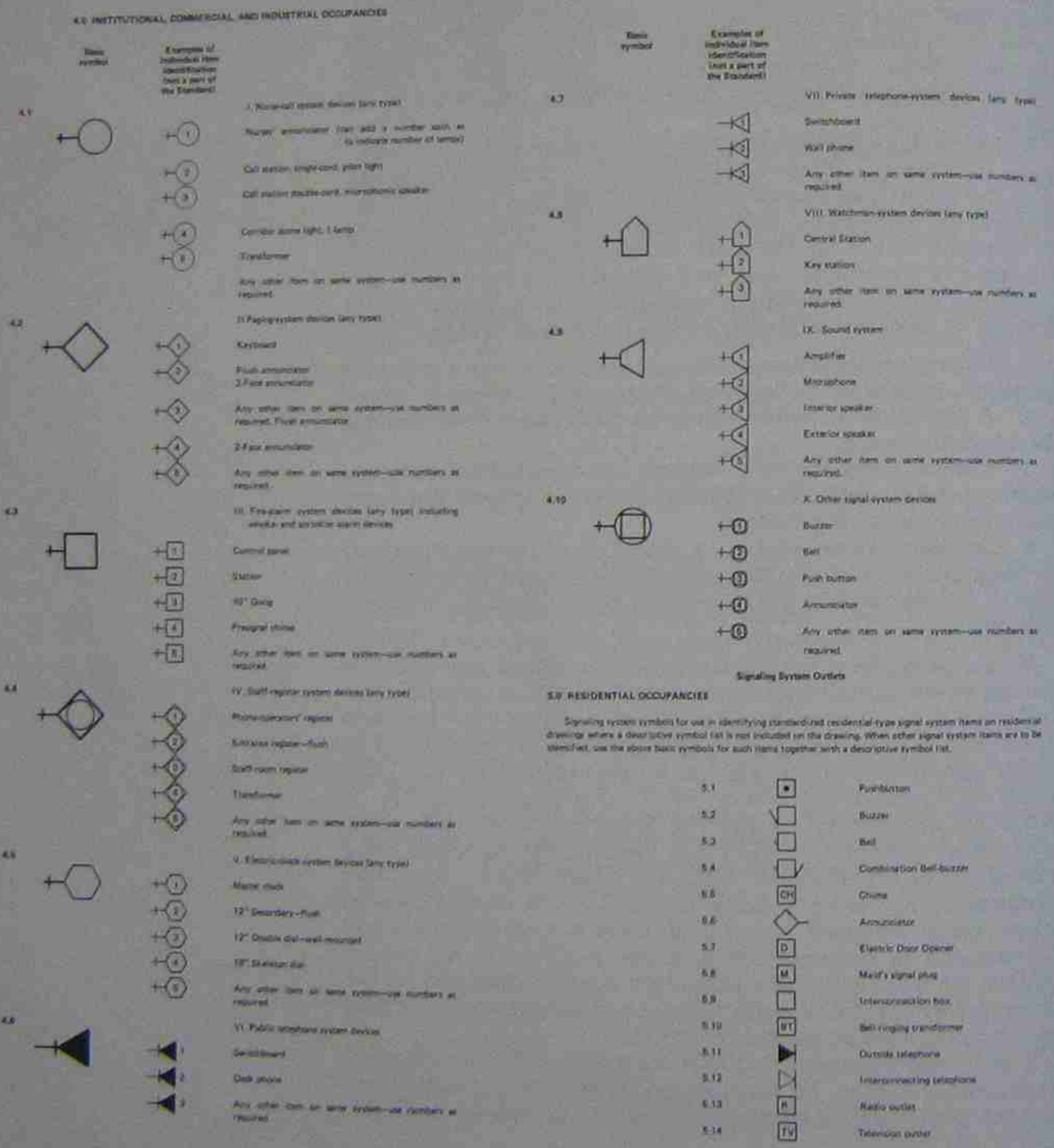
When the general wiring method and material requirements for the entire signal system are described in the specifications or by note on the drawings, no special notation need be made in relation to symbols on the drawing layout. For example, if an entire signal-system installation is required by the specifications and general references on the drawings to be "No. 14 AWG TW conductors; number as indicated in the wiring diagram; and installed in electrical metallic tubing (EMT) sized according to the National Electrical Code (NEC)," the outlet symbols do not need to have special identification. However, when certain different wiring methods or special materials will be required in different areas of the building or for certain outlets, such requirements should be clearly identified on the drawings by special identification or outlet symbols rather than only by reference in the specifications.

It has been recommended that each different basic category of signaling system be represented by a distinguishing basic symbol. Every item of equipment or outlet comprising that cate-

gory of system is to be identified by that basic symbol. Then, different types of individual items of equipment or outlets indicated by a basic system symbol are further identified by a numeral or other identifying mark placed within the open-system basic symbol. All such individual symbols used on the drawings are included in the symbol list or legend.

The following (Fig. 1-28) is a list of signaling system outlets recommended by the American Institute of Electrical Engineers

Fig. 1-28 Signaling system outlets.



and published in 1962. While only basic signal-system outlet symbols are included in this list, the designer can readily improvise to fit any particular need which may arise.

Symbols used by our firm include the following with their respective descriptions.

- Pushbutton switch for door chimes
- CH Chimes
- TV TV outlet mounted 18 in. up to centerline of box
- Telephone outlet
- F Fire-alarm gong
- G Fire detector
- SD Smoke detector
- P Program bell
- Y Yard gong
- M Microphone, wall-mounted
- M Microphone, floor-mounted
- S Speaker, wall-mounted
- S Speaker, recessed

Each year, electrical systems for new construction are augmented; new equipment and devices are introduced monthly which in turn require new electrical symbols for working drawings. Electric heat is being used more and more in new construction, and while forced-air systems are normally handled on the mechanical drawings, individual electric heating units are often specified to be supplied by the electrical contractor. We use the following symbols for electric heating equipment.

- Electric baseboard heater
- Flush-mounted electric floor
- Ceiling-mounted electric panel
- Two-lamp infrared electric heater
- One-lamp infrared electric heater
- Wall-mounted fan-forced electric heater
- J 12 kW — Electric duct heater, numerals indicate kilowatts

All the preceding symbols are drawn to approximate scale on the working drawings. An indicating mark identifies each unit.

and a description of each appears in an electric heat schedule as shown in Fig. 1-29.

ELECTRIC HEAT SCHEDULE

No. type	Manufacturer's description	Dimensions	Volts	Mounting	Remarks
1	Electromode CAT No. 9955-H	104" in length	240	Baseboard	1,500 Watts
2	Electromode CAT No. 9955-G	72" in length	240	Baseboard	1,000 Watts
3	Electromode CAT No. 5990-W	16 1/4"h X 14 1/4"w	240	Recessed in wall	4,000 Watts
4	Electromode CAT No. 8181-A	6" X 30" X 8"d	240	Recessed in floor	600 Watts
5	Electromode CAT No. 9260/9261	22"l X 11"w X 3 1/2"	240	Recessed in kickspace	2,000 Watts

Fig. 1-29 Example of an electric heat schedule.

Ceiling or in-slab heat cables are indicated by the pictorial symbol:



All thermostats are shown by a circle with the letter T inside:

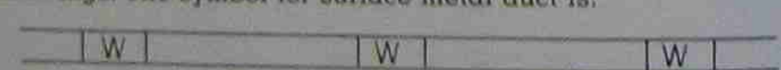


Electric heating contactors, when used, are indicated by a rectangle of the approximate scale size of the contactor cabinet; a descriptive note is then inserted to give an exact model number, etc., or it is indicated in the electric heat schedule and is given an indicating mark:



All circuits and feeders for electric heating equipment are shown in the conventional manner.

Surface metal raceway is also used a great deal on electrical drawings. The symbol for surface metal duct is:



If this metal duct contains outlets commonly known as Plugmold, it is indicated by the symbol  with the shaded squares indicating the outlets. These outlets are also drawn to approximate scale to indicate the center-to-center distance.

Other such symbols include:

 Trolley duct

 Busway (service, feeder or plug-in)

 Cable trough

We use one common symbol for all motors regardless of their use. It consists of a circle with the motor horsepower inside:  . If the motor is enclosed inside a housing such as an air-handling unit, the approximate physical size and shape of the equipment are indicated by broken lines, and the motor is placed at the appropriate location inside the equipment, as shown in Fig. 1-30.



Fig. 1-30 Practical application showing motors on working drawings.

The Construction Specifications Institute, Inc., located at 1150 Seventeenth St., N.W., Washington, D.C. 20036, has just released Document no. 16015, "Electrical Reference Symbols." This document is a special publication of suggested abbreviations and symbols for use on engineering drawings and was prepared jointly with the Consulting Engineers Council/U.S. It is recommended that the reader obtain a copy of this document for reference.

Some electrical abbreviations include:

CSP	Central Switch Panel
DCP	Dimmer Control Panel
DT	Dusttight
ESP	Emergency Switch Panel
MT	Empty
EP	Explosionproof
G	Grounded
NL	Night Light
PC	Pull Chain
RT	Raintight
R	Recessed
XFER	Transfer
SFRMR	Transformer
VT	Vaportight
WT	Watertight
WP	Weatherproof

Chapter 2
Lighting with Incandescent Lamps

In the early days of electricity it became apparent that if a metal wire was heated by an electric current, it would glow and emit light. But such glowing metals—even platinum—rapidly deteriorated in air through oxidation. The problem was to find the proper combination of a filament and its environment.

As early as 1870, Thomas A. Edison used carbonized strips of paper in poorly evacuated glass envelopes to produce light with some degree of success. However, it was not until nine years later that he gave a practical demonstration of his lamps. Operating an electric generator in his laboratory, Edison provided light in the streets outside the laboratory as well as in a few of the adjacent houses.

Many great improvements in filament lamps were made in the years to follow, so that today such lamps have a much higher efficiency and longer life than anyone thought possible 50 years ago.

Incandescent lamps are now made in thousands of different types and colors from a fraction of a watt to over 10 kW each, and for practically any conceivable lighting application.

Regardless of the type or size, all incandescent filament lamps consist of a sealed glass envelope containing a filament. Light is produced when the filament is heated to incandescence (white light) by its resistance to a flow of electric current. Figure 2-1 illustrates the basic components of an incandescent lamp.

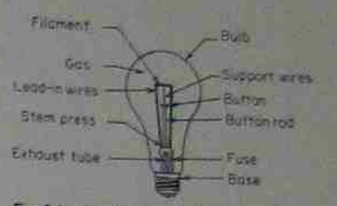


Fig. 2-1 Illustration showing the basic components of an incandescent lamp.

The quartz-iodine tungsten-filament lamp is basically an incandescent lamp, since light is produced from the incandescence of its coiled tungsten filament. However, the quartz lamp envelope is filled with an iodine vapor, which prevents the evaporation of the tungsten filament. This evaporation is what normally occurs in conventional incandescent lamps; then the bulb begins to blacken, light output deteriorates, and eventually the filament burns out. While the quartz-iodine lamp has approximately the same efficiency as an equivalent conventional incandescent lamp, it has the advantages of double the normal life, low lumen depreciation, and a smaller bulb for a given wattage. Figure 2-2 illustrates the basic components of a quartz-iodine lamp.

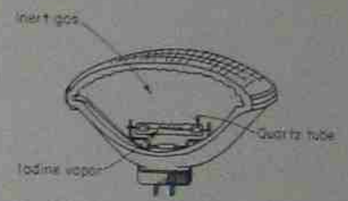


Fig. 2-2 Illustration showing the basic components of a quartz-iodine lamp.

While fluorescent lighting has all but replaced incandescent lighting for general use in commercial buildings, incandescent fixtures are still the chief source of illumination for residences and for decorative lighting throughout the building construction industry. Incandescent fixtures are also very popular for localized or accent lighting in stores and other commercial interiors where special attention is demanded. The reason for their popularity is that incandescent lamps usually are more easily controlled than fluorescent or other electric-discharge lamps.

Projector and reflector incandescent lamps have proved useful for many special applications in the lighting of commercial buildings—especially for restaurants, motels, banks, various stores, and similar establishments. All such lamps, when carefully aimed to avoid creating annoying glare or reflections from mirrorlike surfaces, add greatly to the sales appeal, decor, and visual environment of the areas.

Colored reflector lamps are a convenient and effective source of colored light, especially when control of such light is needed. There are at least six colors available, all designed for maximum effectiveness when used either singly or in combination. For example, pink and blue-white lamps can be used to give an entire display a warm or cool tone with very little color distortion. Pink lamps compliment complexion tones; blue-white lamps are excellent for lighting displays of silverware, jewelry, or home appliances.

As mentioned previously, fluorescent lighting fixtures are the main source of light where a cool atmosphere or greatest economy is desired. A predominantly incandescent lighting system is used where a warmer atmosphere is desired or where color is of a critical nature, although deluxe warm-white fluorescent lamps give almost the same effect.

Most sales areas display high-profit or impulse items at the end of a counter or near the checkout area. These locations

should have from two to five times as much illumination as the rest of the counter, and incandescent spotlights with their accompanying highlights and shadows are very effective for this purpose.

Some of the advantages of incandescent lamps are as follows:

- Relatively low initial installation cost
- Not greatly affected by ambient temperatures
- Easily controlled as to direction
- Easily controlled as to brightness
- High color quality

Some of the disadvantages include:

- Less efficient than most electric-discharge lamps
- Higher operating cost per lumen
- More heat produced per lumen than electric-discharge lighting, causing the need for a larger air-conditioning system which in turn increases operating cost

RESIDENTIAL LIGHTING

With the exception of very large residences and tract development houses, the size of the average residential electrical system has not been large enough to allow for the expense of preparing complete electrical working drawings and specifications. Usually such electrical systems were laid out by either the architect—in the form of a sketchy outlet layout—or the electrician on the job, often only as the work progressed. However, many technical developments in residential electrical use—such as electric heat, greater use of electrical appliances, various electronic alarm systems, new lighting techniques, and electrical remote-control systems—have greatly expanded the demand and extended the complexity of today's residential electrical systems.

Architects are finding they need a greater engineering knowledge for the modern all-electric residence and now are seeking the services of consulting engineers. Since incandescent lamps are the chief sources of lighting in the home, residential lighting techniques will be discussed in this chapter. Other design techniques for residential electrical systems will be covered later.

The basic requirements for residential lighting are that it provide adequate light of the right quality and give proper attention to the appearance and artistic features of the lighting fixtures and the effect they produce.

Properly designed lighting is one of the greatest comforts and conveniences that any home owner can enjoy, and lighting should be considered as important as furniture placement, choice of draperies, color schemes, etc., because it is one of the most important features of decorating the home.

Residential lighting does not require elaborate calculations, but until designers have acquired the necessary experience, they should use some guide for the initial planning. The following method has been recommended by General Electric. In order to understand this procedure, the reader should be familiar with the following definitions:

Lumen: a unit of light quantity (luminous flux) produced by a light source.
Footcandle: the amount of direct illumination on a surface 1 ft from the flame of a standard candle.
One lumen per square foot equals one **footcandle.**

It is important to remember, when calculating the total lumen requirements by this method, that lighter colors reflect light while darker colors absorb it. Therefore, to achieve the same lighting level, a room with dark surfaces will require a greater number of lumens than a room with lighter surfaces.

The following table lists the required lumens per square foot for various areas in the home. These are recommended lumens when portable lamps, surface-mounted fixtures, and structural-lighting techniques are used. When a high percentage of the light for the area comes from recessed lighting fixtures, the figures in the table should be approximately doubled.

LUMENS REQUIRED PER SQUARE FOOT

Living room	80	Bedroom	70
Dining room	45	Hallway	45
Kitchen	80	Laundry	70
Bathroom	65	Work bench area	70

SAMPLE PROBLEM

Determine the total lumens required to achieve 80 lm per sq ft in a living room that is 15 ft wide and 20 ft long.

SOLUTION

a Multiply room width by room length to find square footage

15 ft × 20 ft = 300 sq ft

b Multiply square footage by desired lumens per square foot to get total lumens

300 sq ft × 80 lm per sq ft = 24,000 lm

c Select the proper bulbs and/or tubes from the Lamp Lumen Output Table on page 31 to total 24,000 lm and decide where and how they will be used.

A typical room lighting plan based on a 24,000-lm total is as follows:

1. Four 40-W WWX (warm-white deluxe) fluorescents, at 2,080 lm each, installed in a drapery cornice.
2. One 200-W inside-frosted bulb, at 3,940 lm, used in a study lamp.
3. Two 75-W recessed R-30 spotlights, at 860 lm each, over the piano.
4. Two three-way (100–200–300-W) soft-white bulbs, at 4,730 lm each, in two table lamps.
5. One (50–100–150-W) soft-white three-way bulb, at 2,190 lm, in a chairside table lamp.

The total of all lamps used yields 25,630 lm, or 85 lm per sq ft. While this is slightly over the "desired" illumination level, it should be pointed out that this lumen method should be used only as a guide and not as an absolute rule. A slight differential between "desired" and "actual" lumens is thus permitted.

This lumen method of calculating residential lighting can be an important aid in planning the lighting for a single room or for an entire home. With this guide, it is possible to determine the "total light output" of all light sources in a given area. This makes it possible for a lighting designer to determine quickly the number of lumens required in a specific lighting design to achieve the desired illumination level.

PRACTICAL APPLICATION

The floor plan of a small residence is illustrated in Fig. 2-3 and serves to demonstrate how the lighting system of a residence is laid out.

Vestibule

The vestibule or entrance hall is the area which gives visitors their first impression of the house. Here the owners greet their guests and help to remove their coats. Carefully planned

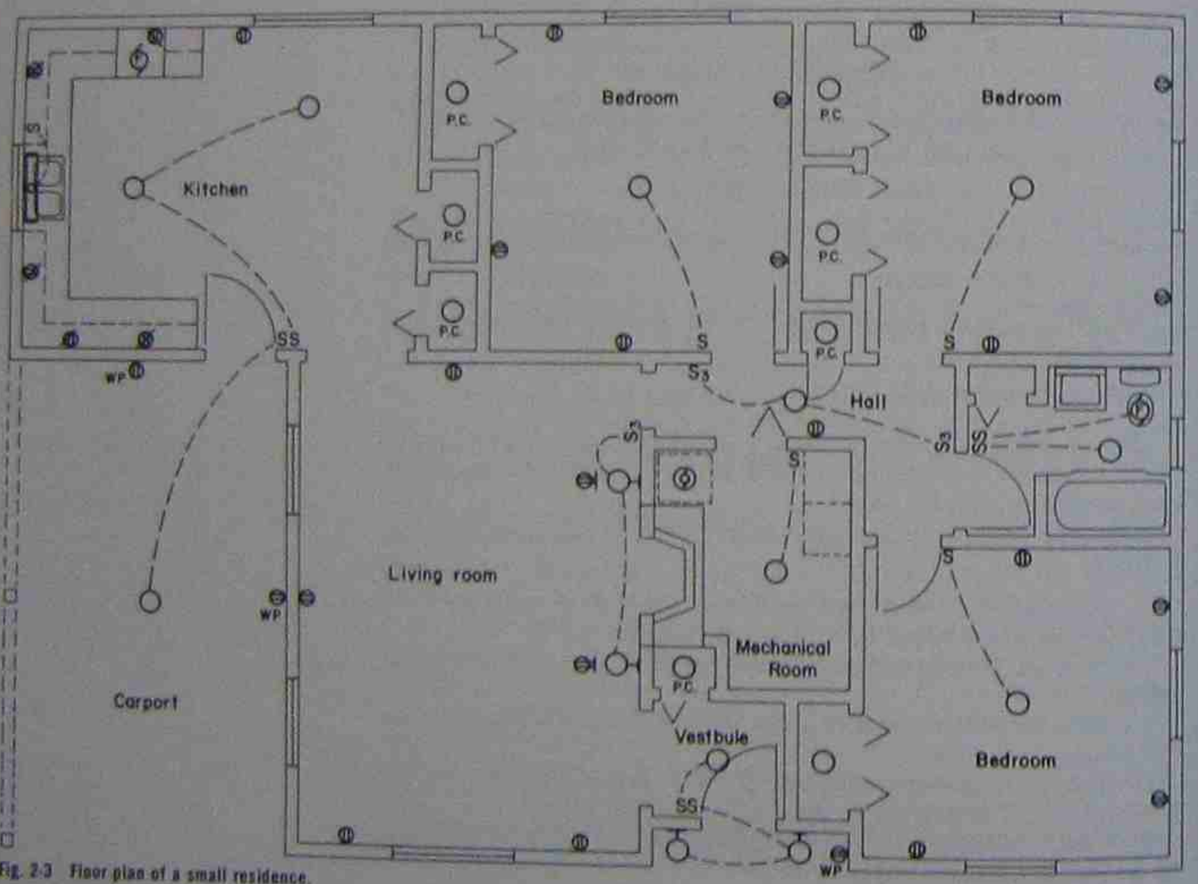


Fig. 2-3 Floor plan of a small residence.

LAMP LUMEN OUTPUT TABLE

Incandescent

Watts	Bulb	Designation and finish	Approx. initial lumens
25	A-19	Inside Frosted	232
		Soft-White	222
40	A-19	Inside Frosted	450
		Soft-White	435
		Dawn Pink	340
50	A-19	Inside Frosted	680
60	A-19	Inside Frosted	855
		Soft-White	840
		Dawn Pink	650
75	A-19	Inside Frosted	1170
		Soft-White	1140
		Dawn Pink	870
		Sky Blue	450
100	A-19	Inside Frosted	1750
		Soft-White	1710
100	A-21	Dawn Pink	1200
		Sky Blue	610
150	A-21	Inside Frosted	2830
		Soft-White	2710
150	R-40	Soft-White	2300
200	A-23	Inside Frosted	3940
		Soft-White	3840
3-Way bulbs			
30/70/100	A-21	Soft-White	275/1010/1285
50/100/150	A-23	Soft-White	560/1630/2190
		Dawn Pink (med. base)	435/1253/1688
50/100/150	R-40	Soft-White Indirect	560/1630/2190
50/200/250	PS-25	Soft-White	550/3560/4110
100/200/300	PS-25	Soft-White	1290/3440/4730
		Dawn Pink (mogul base)	968/2580/3548

Clear spots and floodlights			
Watts	Finish and bulge type	Bulb designation	Approx. initial lumens
30	Spot	R-20	200
50	Spot	R-20	430
75	Spot or Flood	PAR-38	745
75	Spot or Flood	R-30	860
150	Spot or Flood	PAR-38	1730
150	Spot or Flood	R-40	1950

Colored spots and floodlights

Percent initial lumen output – colored sources as relates to corresponding clear floodlights.

Watts and bulb designation	Amber	Blue	Sun white	Green	Pink	Red	Yellow
50wR20	–	–	55	–	74	–	–
75wR30/ 150wR40	35	10	30	15	60	15	95
100wPAR38	57	5	39	17	52	7	77
150wPAR38 DICHRO SP/FL	52	6	–	18	–	27	78

NOTE: Flair Chandelight as well as colored light sources are generally for decorative lighting and would not be included in a total lumen count.

Fluorescent

Deluxe warm- or cool-white fluorescent			
Watts	Identification	Tube designation, thickness and length	Approx. initial lumens
14	WWX or CWX	T-12 (1½" × 15")	460
15	WWX or CWX	T-8 (1" × 18")	600
15	WWX or CWX	T-12 (1½" × 18")	505
20	WWX or CWX	T-12 (1½" × 24")	820
30	WWX or CWX	T-8 (1" × 36")	1520
30	WWX or CWX	T-12 (1½" × 36")	1480
40	WWX or CWX	T-12 (1½" × 48")	2080

Deluxe warm- or cool-white circline fluorescent			
Watts	Identification	Tube designation, thickness and diameter	Approx. initial lumens
22	WWX or CWX	T-9 (1⅛" × 8½")	745
32	WWX or CWX	T-10 (1¼" × 12")	1240
40	WWX or CWX	T-10 (1¼" × 16")	1760

NOTE: Deluxe white fluorescents render colors as they really are rather than distorting. Deluxe warm white nearly duplicates the color of incandescent light while deluxe cool white closely resembles daylight.

SOURCE: The General Electric Company.

lighting will show it to best advantage and will help the owners impart graciousness and hospitality.

By scaling the vestibule in Fig. 2-3, it is found that the dimen-

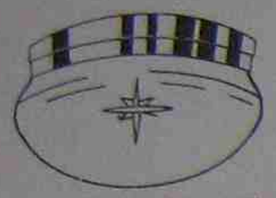


Fig. 2-4 Illustration of a close-to-ceiling lighting fixture.

sions are 4 ft 10 in. × 4 ft 4 in., or approximately 21 sq ft. According to the table on page 29, the recommendation for a hallway is 45 lm per sq ft. Thus, 21 sq ft × 45 lm per sq ft = 945 lm of lighting required in this area.

The table indicates that a 75-W inside-frosted A-19 lamp produces 1,170 lm (this is close enough for our purposes). The designer then selects a close-to-ceiling lighting fixture with diffusing glass, as shown in Fig. 2-4. This unit is lamped with the 75-W inside-frosted bulb.

Living Room

The living room is, of course, one of the most important rooms to have well lighted, since in the average home, which is the one under consideration, this room is the one in which members of the family spend much of their time, and also one that the owners wish to have most attractive when guests are present.

Referring again to the lumen method and to the drawing in Fig. 2-3, we find that the living room scales to 14 ft 0 in. × 16 ft 0 in., or 224 sq ft. The square footage is then multiplied by 80, the number of lumens per square foot recommended in the table.

224 sq ft × 80 lm per sq ft = 17,920 lm required

The owners expressed their desire to have mostly table lamps in the living areas which would provide local or functional lighting for visual tasks. Enough duplex receptables were placed around the perimeter to furnish electricity for these table lamps, which were to include: two (100–200–300-W) soft-white three-way bulbs, at 4,730 lm each, in two large table lamps at each end of the sofa; and one (50–100–150-W) soft-white three-way bulb, at 2,190 lm, in another table lamp placed next to a reclining chair. The three table lamps produced a total of 11,650 lm.

In order to achieve the desired 17,920 lm, the designer then chose two wall-mounted fixtures to be placed on each side of the fireplace. Each of these fixtures contained two 100-W A-19 inside-frosted lamps, at 1,750 lm each, or a total of 7,000 lm. Together with the table lamps, a total of 18,650 lm was available for lighting in the living area. A rheostat dimmer controlled the two wall fixtures for added versatility.

Bedroom Lighting

Bedrooms should be lighted with soft light that is not tiring to the eyes of a person lying in bed. Ceiling fixtures of the type shown in Fig. 2-5 are very good.

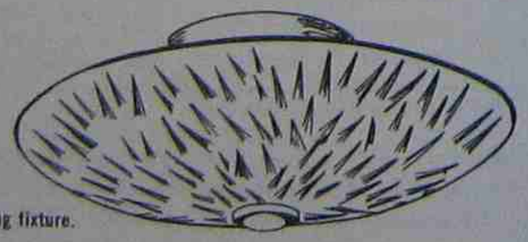


Fig. 2-5 One type of bedroom ceiling fixture.

It is also very important to have sufficient light at dressing tables and on mirrors; either wall-mounted lamps or vanity-table lamps should be provided on each side of the mirror.

Portable lamps on small tables by the beds or clamp lights to mount on the headboards are ideal for reading. A lamp at one side of the bed should direct its light so as to provide adequate reading light for the person on that side of the bed, yet not greatly disturb the person on the other side.

A switch controlling one of the lights in the room should be located near enough to a bed to be within easy reach of a person either in the bed or right at its edge. A table lamp with a built-in switch will, of course, accomplish this.

All the bedrooms in the floor plan in Fig. 2-3 are approximately the same size, that is, 158 sq ft. Referring to the chart, we find that bedrooms require 70 lm per sq ft. Therefore,

70 lm per sq ft × 158 sq ft = 11,060 lm required

The surface-mounted ceiling fixtures installed in the center of each room contain three 75-W inside-frosted lamps, at 1,170 lm each, for a total of 3,510 lm. The remaining lumens (7,550) desired were obtained by using table lamps at each side of the bed, each containing one (50–100–150-W) soft-white three-way bulb at 2,190 lm, and two more table lamps on the dresser with a 100-W inside-frosted lamp in each (1,750 lm apiece). This gave a total of 11,390 lm of illumination in the bedroom.

Hall

Since the hallway in the residence under consideration has a total of 36 sq ft, the total of lumens required is 36 × 45 = 1,620. A lighting fixture similar to the one in the vestibule is used, except that this time one 100-W A-19 inside-frosted lamp is used, and this produces 1,750 lm.

Mechanical Room

The mechanical room in this residence contains the furnace and water heater, also a washer and dryer. Therefore, this room is treated as a laundry area requiring 70 lm per sq ft.

60 sq ft × 70 lm per sq ft = 4,200 lm

A lighting fixture was chosen that contained four 75-W inside-frosted lamps at 1,170 lm each. This fixture is shown in Fig. 2-6, and the diffusing shade gives a relatively soft and comfortable light for such a high intensity of illumination. The fixture produced 4,680 lm of light.

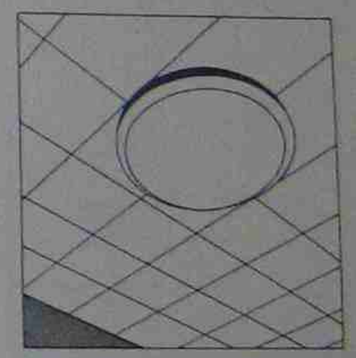


Fig. 2-6 One type of lighting fixture recommended for mechanical or utility rooms.

Kitchen

The kitchen should always receive careful attention, because it is an area where the homemaker spends a great deal of time.

Good kitchen lighting begins with a light source located in the center of the room and close to the ceiling. Since this is the fixture to furnish general illumination, it should be a glarefree source which will direct light to every corner in the kitchen. The homemaker will find work a lot easier if certain "task" areas are specially lighted—for example, counter lights beneath cabi-

nets, or, as shown in our house plan, a recessed fixture over the sink to provide good supplementary lighting and eliminate shadows.

The kitchen-dinette shown in the floor plan has a pulldown fixture directly over the table for functional, yet decorative illumination. A combination hood/fan/light is also installed over the kitchen range, producing supplementary lighting for cooking. The two rooms are treated as one area needing 80 lm per sq ft.

80 lm per sq ft × 219 sq ft = 17,520 lm

Recessed fixture over sink		875 lm
Surface-mounted fixtures in center of kitchen area		4,680 lm
Range light		2,340 lm
Dinette light		4,730 lm
	Total	12,625 lm

The owners did not want to add any additional lights at this point for reasons of economy. However, three 30-W undercabinet lighting fixtures would have brought the total lumens to the desired 17,520.

Bathroom

Bathrooms should have either two wall-mounted fixtures, one on each side of the mirror, or one fixture mounted above the mirror for general light inside the room as well as for grooming. The light should be sufficient to illuminate one's face and the underside of the chin for shaving.

In the example of the house plan, one 20-W fluorescent fixture was used over the mirror to produce 820 lm. Since this was somewhat short of the 2,275-lm requirement determined previously, another lighting fixture was installed in the ceiling; this fixture contained one 100-W inside-frosted lamp at 1,750 lm. A similar fixture, containing one 60-W inside-frosted lamp, was placed in the area containing the linen closet.

OUTDOOR LIGHTING

Outdoor lighting is a partner in modern living. It welcomes guests and lights their paths, creating a hospitable look. As a safety factor, it protects the home from prowlers and reduces the incidence of outdoor accidents.

A pair of outdoor wall brackets, such as those shown at the front entrance on the floor plan in Fig. 2-3, is basic. If a long walk is necessary, a decorative yet practical post light should be included.

The carport is a separate lighting area, and, as shown in the floor plan, an all-purpose lighting fixture centered in the ceiling is adequate to light the owner's way to the back door.

RESIDENTIAL LIGHTING SUMMARY

The examples just given are basic for lighting a house. Obviously, no elaborate lighting effects were incorporated into the residence in Fig. 2-3 owing to the size and simplicity of the

design. A larger or more elaborate house, such as that shown in Figs. 2-7 and 2-8, warrants added lighting effects, which may include:

1. Wall-wash fixtures except lights to dramatize fireplaces and bring out the texture of the bricks
2. Supplementary accent lighting over planters as well as for paintings or other pieces of art
3. Additional supplementary lighting around windows or in valances, or cove effects with hidden fluorescent lighting
4. Pendant-hung fixtures over bar areas
5. Luminous ceilings in kitchen and bathrooms
6. "Dressing-room" lighting around bath and vanity mirrors
7. Decorative yet functional lights in game and hobby areas
8. Swimming-pool lighting
9. Outdoor lighting which turns the patio and yard into an extra living or recreation room at night
10. For decorative and safety reasons, recessed or "bullet" lights installed in soffits at house corners

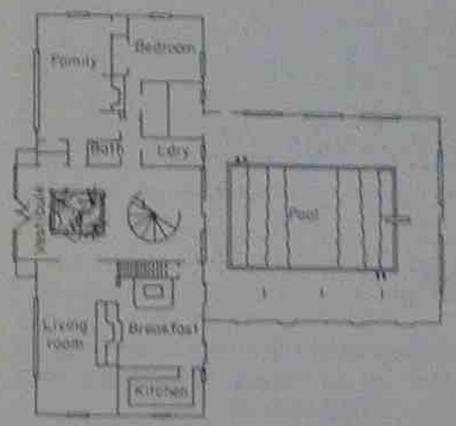


Fig. 2-7 First-floor plan of a more elaborate house.

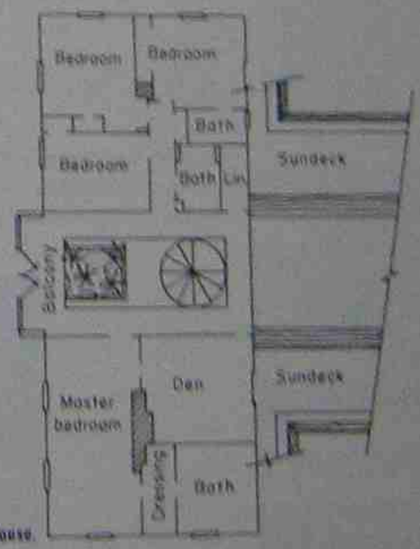


Fig. 2-8 Second-floor plan of a more elaborate house.

The varieties are endless, and lighting designers should use their experience and judgment to give the very best lighting system to fit the home owner's needs and budget.

COMMERCIAL LIGHTING

The floor plan of a branch bank in Fig. 2-9 illustrates a few applications of incandescent lighting fixtures in commercial buildings. While the general lighting is provided by recessed fluorescent fixtures, various effects could not have been accomplished without the use of incandescent lamps.

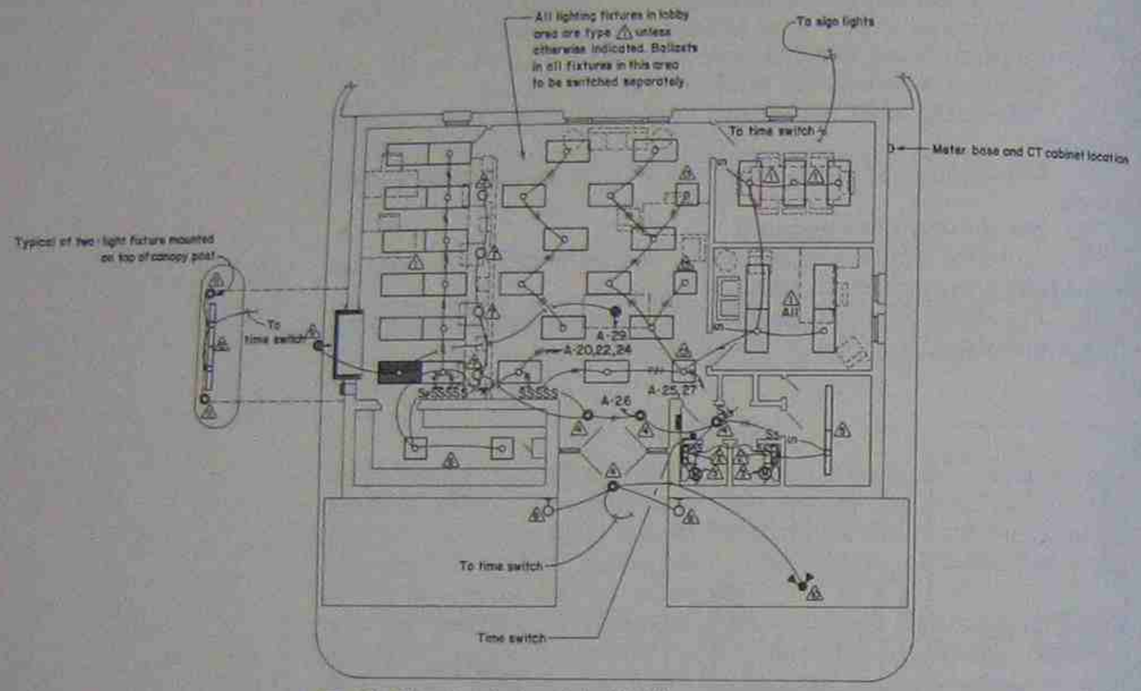


Fig. 2-9 Floor plan of a branch-bank building.

For example, the chandelier shown in Fig. 2-10 (without lamps) provides a decorative fixture during office hours and serves as a night light during closing periods.

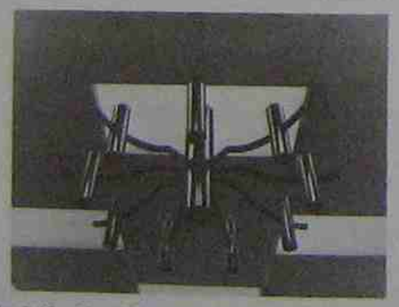


Fig. 2-10 Chandelier used in lobby of branch bank.



Fig. 2-11 Pendant cylinders used over each teller area in the branch bank.

The pendant cylinders over each teller area are used as decorative fixtures as well as supplementary lighting for teller functions. See Fig. 2-11 at the left.

Recessed downlights are used in the vestibule to provide adequate lighting where the ambient temperature might be too low during cold weather to allow fluorescent fixtures to start properly. See Fig. 2-12.

The outside wall brackets shown in Fig. 2-13 contain 100-W incandescent lamps inside a frosted chimney to provide a Colonial feeling and blend with the Williamsburg style of the building.



Fig. 2-12 Recessed downlights used in the vestibule of the branch bank.

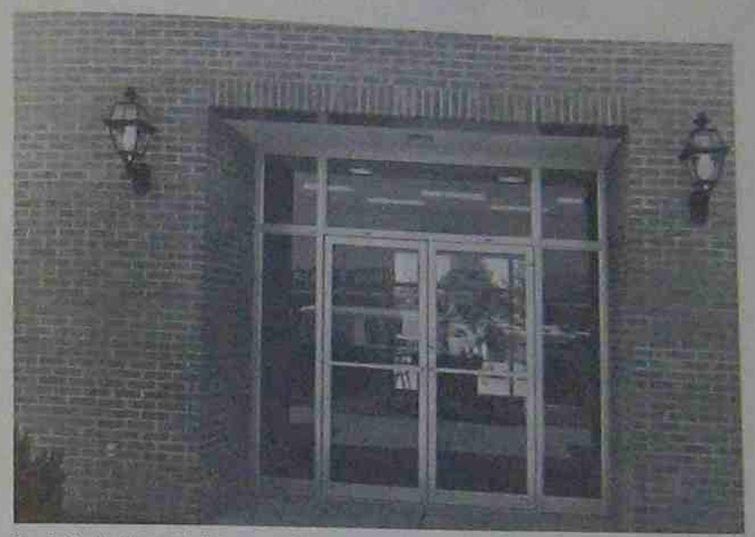


Fig. 2-13 Wall-bracket fixtures used on the outside of the branch bank.

The inexpensive ground-mounted floor lights shown in Fig. 2-14 are used to illuminate the sign mounted on a vertical building wall.

Other examples of the use of commercial incandescent lamps are described in Chap. 5.



Fig. 2-14 An inexpensive ground-mounted floodlight used to illuminate a sign mounted on a vertical building wall.

Chapter 3
Lighting with Fluorescent Lamps

Since fluorescent lighting was introduced to the general public during the Chicago Centennial Exposition of 1933, it has become the major light source for the general interior lighting of commercial and institutional buildings, and during recent years, it has challenged other sources of light for use in residential, exterior, and other lighting applications.

One of the reasons for the popularity of fluorescent lighting is its high efficiency as compared to incandescent lamps. The average 40-W inside-frosted (IF) incandescent lamp delivers approximately 470 initial lm, while a cool-white fluorescent lamp of the same wattage delivers over 3,100 lm. This power efficiency not only saves on the cost of power consumed, but also lessens the heat produced by lamps which in turn reduces air-conditioning loads (another saving in power) and makes it more comfortable for those working under bright lights during warm weather.

Fluorescent lamps are available in straight, U-shaped, and circular configurations of various diameters. The insides of

these glass-tube configurations are coated with a highly sensitive fluorescent powder (phosphor) which is activated by ultraviolet radiation and, in turn, converts the invisible energy to visible light. Each phosphor produces a characteristic visible light. Variation in the mixtures of various phosphors offers lamps in a wide range of visible-light colors. The most commonly used are as follows.

Cool White

This lamp is often selected for offices, factories, and commercial areas where a psychologically cool working atmosphere is desirable. This is the most popular of all fluorescent lamp colors since it gives a natural outdoor-lighting effect and is one of the most efficient fluorescent lamps manufactured today.

Deluxe Cool White

This lamp is used for the same general applications as the standard cool white, but contains more red, which emphasizes pink skin tones and is therefore more flattering to the appearance of people. Deluxe cool white also gives a good appearance to lean meat, keeps fats white, and emphasizes the fresh, crisp appearance of green vegetables. This type of lamp is generally chosen wherever very uniform color rendition is desired. However, it is less efficient than cool white.

Standard Warm White

Whenever a warm social atmosphere is desirable in areas that are not color-critical, this color is used. It approaches incandescent lamps in color and is appropriate whenever a mixture of fluorescent and incandescent lamps is used. While it gives an acceptable appearance to people, it has some tendency to emphasize sallowness. Yellow, orange, and tan interior finishes are emphasized by the standard warm-white lamp, and its beige tint gives a bright, warm appearance to reds, brings out the yellow in green, and adds a warm tone to blue. It imparts a yellowish white or yellowish gray appearance to neutral surfaces.

Deluxe Warm White

Deluxe warm-white lamps are more flattering to complexions than the standard and are very similar to incandescent lamps in that they impart a ruddy or tanned hue to the skin. They are generally recommended for applications in homes or social environments and for commercial use where flattering effects on people and merchandise are considered important. This type of lamp enhances the appearance of poultry, cheese, and baked goods. Deluxe warm-white lamps are approximately 25 percent less efficient than standard warm-white lamps.

White

White lamps are used for general lighting applications in offices, schools, stores, and homes where a cool, working atmosphere or warm, social atmosphere is not critical. They emphasize yellow, yellow-green, and orange interior finishes.

Daylight

In industry and work areas where the blue color associated with the "north light" of actual daylight is preferred, this lamp is often used. While it makes blues and greens bright and clear, it tends to tone down reds, oranges, and yellows.

In general, the designations "warm" and "cool" represent the differences between artificial light and natural daylight in the feeling they impart to an area. Their deluxe counterparts have a greater amount of red light, supplied by a second phosphor within the tube. The red light shows colors more naturally, but at a sacrifice of efficiency.

Other colors of fluorescent lamps are available in sizes that make them interchangeable with white lamps. These colored lamps are best used for flooding large areas with colored light; where a colored light of small area must be projected at a distant object, incandescent lamps using colored filters are best.

PRACTICAL APPLICATION: THE FIRST NATIONAL BANK, BRANCH BANK

From preliminary conferences with the architect and owners of the building the electrical designer has determined that the lighting system for this building should provide adequate lighting levels for the various areas, must complement the architectural design, and must fit within a predetermined budget. With these data in hand the electrical designer begins her or his design.

First, lighting calculations are begun by using the form shown in Fig. 3-1. The project identification is entered in the appropriate space at the top of the form; the designer's initials and the date are also entered—at the bottom of the form. Since the office (see Fig. 3-3) will be the first area under consideration, this area designation is entered in the same space as the project identification.

A check through the IES *Lighting Handbook*, under "Recommended Levels of Illumination," reveals that an office of this type requires between 100 and 150 fc. This fact is then entered in the appropriate space on the form.

The architectural drawings indicate an inverted T-bar ceiling system with 2- by 4-ft lay-in accoustical-tile panels. From this the designer decides upon a 2 by 4 ft recessed-troffer lighting fixture for the light source in this area. The catalog data are then entered in the correct space, again as shown in Fig. 3-1. Note that this fixture is designed to handle four 40-W fluorescent lamps, and the designer decides upon cool-white lamps for reasons described earlier in the chapter. A manufacturer's lamp catalog gives the initial lumens of this type of lamp to be 3,150. Since the fixture contains four such lamps, simple multiplication (4 × 3,150) gives the total lumens for each fixture as 12,600. All these data are again entered on the form.

The maintenance for this building is assumed to be good and the factor (MF) will therefore be 0.75, as given in the lamp manufacturer's data in Fig. 3-2 on page 42.

Selection of coefficient of utilization requires five basic steps (Fig. 3-1) and begins by filling in the sketch on the form.

ILLUMINATION CALCULATION SHEET

For Use with the IES Zonal Cavity Method

General Information

Project Identification: First National Bank - Office

Average Maintained Illumination for Design: 150 footcandles

Luminaire Data:

Manufacturer: Bustlite Corp

Lamps (type & color): 40 WF (cool white) Catalog Number: [illegible]

Total Lumens per Luminaire: 12,600 Number per Luminaire: 4

Maintenance Factor: .75

Selection of Coefficient of Utilization

Step 1: Fill in sketch at right

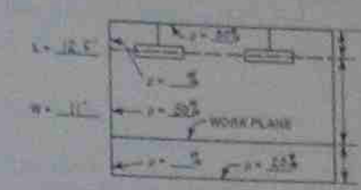
Step 2: Determine cavity ratios by the formula:

$$\frac{5 \times h \begin{bmatrix} CC \\ RC \\ FC \end{bmatrix} \times (L+W)}{L \times W}$$

Room cavity ratio, RCR = 4.7 or 5

Ceiling cavity ratio, CCR = 0

Floor cavity ratio, FCR = 2.13



Step 3: Obtain effective ceiling cavity reflectance (pCC) pCC = 80%

Step 4: Obtain effective floor cavity reflectance (pFC) pFC = 20%

Step 5: Obtain coefficient of utilization (CU) from manufacturer's data. CU = 49%

4.42 or 4

Calculations

Step 6:

Average Maintained Illumination Level

$$\text{Footcandles} = \frac{(\text{Total lamp lumens per Luminaire}) \times (\text{CU}) \times \text{maintenance factor}}{\text{area per Luminaire}}$$

$$= \frac{12{,}600 \times .49 \times .75}{344}$$

$$= 134.6 \text{ footcandles on work area}$$

Area per Luminaire: (This area divided by the Luminaire length gives the approximate spacing between continuous rows, or it may be divided into the total room area to determine the number of Luminaires required.)

$$\text{Area per Luminaire} = \frac{(\text{total lamp lumens per Luminaire}) \times (\text{CU}) \times \text{maintenance factor}}{\text{footcandles}}$$

$$= \frac{12{,}600 \times .49 \times .75}{134.6}$$

$$= 344 \text{ square feet}$$

CALCULATED BY: [illegible] DATE: [illegible]

Fig. 3-1 Lighting calculation form.

Step 1. (*a*) Room length (*L*) is found to be 12 ft 6 in. by scaling the architectural floor plan. Room width (*W*) is 11 ft 0 in. and is found by the same method.

(*b*) The ceiling, wall, and floor finishes are also found on the architectural drawings; then by checking the IES *Lighting Handbook*, the reflectances are as follows:

1. Ceiling, 80 percent
2. Walls, 50 percent
3. Floors 20 percent

Average luminance in footlamberts			Distribution and efficiency	Spacing ratios and reflectance	Effective ceiling cavity reflectance, R_{CC}									
					80%			50%			10%			
					% Wall reflectance, R_{CW}									
Angle from nadir	End-wise	Cross-wise	CIE % Luminaire		Room cavity ratio	50%	30%	10%	50%	30%	10%	50%	30%	10%
						Coefficients of utilization for 20% floor cavity reflectance, R_{FC}								
45	1286	1526	0	Spacing not to exceed 1.4 x mounting height	1	75	73	71	71	69	67	66	64	63
55	1011	1086			2	67	63	60	64	61	58	60	57	56
65	648	700			3	61	56	52	58	54	51	54	51	49
75	357	685			4	55	49	45	52	48	44	49	47	43
85	357	623			5	49	43	39	47	42	39	44	41	38
				Maintenance factors	6	44	38	34	42	37	34	40	36	33
					7	40	34	30	38	33	30	36	32	29
			100	Good 75	8	36	30	26	34	29	26	32	29	26
				Med 70	9	32	27	23	31	26	23	29	25	22
				Poor 65	10	29	24	20	28	23	20	27	23	20

Fig. 3-2 Example of a lamp manufacturer's data sheet.

(c) The ceiling cavity ratio (CCR) is zero because the fixtures are recessed.
(d) The work plane is determined to be 30 in. (height of desk), or 2.5 ft above the floor.
(e) Since the total ceiling height has been determined from the architectural drawings to be 8 ft 0 in., the room cavity height is 5.5 ft (8 ft − 2.5 ft).

All these data are entered in the appropriate space (see Fig. 3-1).

Step 2. Determine Cavity Ratios (a) The room cavity ratio (RCR) is determined by substituting values in the formula given in Fig. 3-1. Thus.

$$\frac{5 \times 5.5\ (12.5 + 11)}{12.5 \times 11} = 4.7$$

(b) The ceiling cavity is zero and requires no calculations.
(c) The floor cavity ratio is determined by substituting values in the formula used for (a). Thus.

$$\frac{5 \times 2.5\ (12.5 + 11)}{12.5 \times 11} = 2.13$$

These values are also entered in the appropriate spaces on the form.

Step 3. Obtain Effective Ceiling Cavity Reflectance Since the CCR is zero, because of recessed fixtures the ceiling cavity reflectance is full value, or 80 percent in this case.

Step 4. Obtain Effective Floor Cavity Reflectance The floor cavity ratio has been calculated to be 2.13; therefore an adjustment may be necessary for the initial 20 percent floor reflectance. However, since there are many books available which explain the method of adjustment, we will not go into the method in detail at this point. Rather we will assume the floor reflectance to be the initial 20 percent.

Step 5. Obtain Coefficient of Utilization This is obtained from the manufacturer's data shown in Fig. 3-2. That is, in the column for 80 percent ceiling reflectance, 50 percent wall reflectance, 20 percent floor reflectance, and a RCR of 5 (4.7 rounded off), the coefficient of utilization is (CU) 49 percent.

Again all data are entered in the appropriate spaces on the form. With the data now complete, the number of lighting fixtures can be determined as well as the average illumination in footcandles.

Although the form in Fig. 3-1 does not have a space provided for calculating the number of fixtures required to produce the desired level of illumination, this will be the next step. The formula is as follows:

$$\text{No. of fixtures} = \frac{\text{floor area} \times \text{desired footcandles}}{\text{total lumens per fixture} \times \text{CU} \times \text{MF}}$$

Substituting known values in the formula, we have:

$$\text{No. of fixtures} = \frac{137.5 \times 150}{12{,}600 \times .49 \times .75} = 4.42$$

This figure (4.42), rounded off, indicates to the designer that four lighting fixtures should be used for this area. They are spaced as shown on the drawing in Fig. 3-3. It is now desirable to know the exact illumination of this area since the number of fixtures did not come out even. Proceed to step 6.

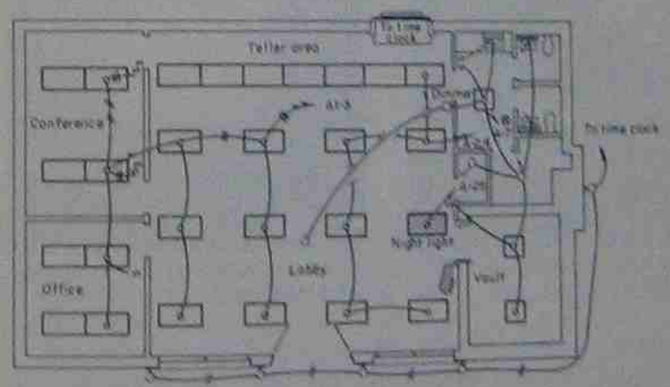


Fig. 3-3 Lighting diagram for bank office.

Step 6. Substitute known values in the formula.

$$\text{FC} = \frac{12{,}600 \times .49 \times .75}{(137.5 \div 4) = 34.4} = 134.6 \text{ fc}$$

This satisfies the requirements of between 100 and 150 fc as recommended by the IES *Lighting Handbook*.

The remaining areas of this branch bank are designed in a similar manner in that the conference room was designed for approximately 125 fc, the lobby for 75 fc (using two-lamp fixtures), the teller area for 150+ fc, and the vault area about 50 fc.

Notice the fluorescent lighting fixture mounted on the outside of the building and over the drive-in window (Fig. 3-4). This fixture was provided to produce a level of illumination immediately outside the window that is approximately equal to the illumination level inside the bank. The reason is that during darkness, many drive-in-window tellers have found it difficult to see clearly out of the window because of interior reflections. This lighting fixture eliminates this problem.

After all the lighting fixtures have been laid out on the drawing, circuiting is the next step. In this building, all lighting branch circuits consist of No. 12 AWG TW conductors in ¾-in. conduit, protected with one-pole, 20-A circuit breakers installed in panel A. Therefore, the designer connects a lighting load of between 1.2 and 1.6 kW to each circuit. The electrical symbols given in Chap. 1 will clarify the meaning of each circuit.

The uses of the incandescent lighting fixtures were described in Chap. 2, and the power wiring, alarm system, etc., will be described later in this book.

The photographs (Figs. 3-4 to 3-7) are illustrations of the installed electrical system of the branch bank just described.



Fig. 3-4 Lighting fixture at a drive-in bank window.



Fig. 3-5 Office lighting fixtures installed in lay-in ceiling.



Fig. 3-6 Lighting in bank lobby and teller areas.



Fig. 3-7 Surface-mounted 2- by 2-ft lighting fixture in vault area.

On actual working drawings, a lighting fixture schedule and other details are usually provided on the drawing as shown in Fig. 3-3. However, due to limited space on the pages of this book, such details are not shown. A lighting fixture schedule such as that shown in Fig. 3-8 should be provided on all working drawings. This schedule should give all the information necessary to tell the contractors or their electricians exactly what fixture is to be installed, the type of mounting, number of lamps, etc.

LIGHTING FIXTURE SCHEDULE

FIXT. Type	Manufacturer's Description	LAMPS No.	LAMPS Type	Volts	Mounting	Remarks

Fig. 3-8 Lighting fixture schedule used for bank project.

PRACTICAL APPLICATION: LAUNDRY BUILDING

Figure 3-9 is the floor plan of a laundry building constructed to handle the in-house laundry for a district home for the aged. Since the building is of a utility class and a limited budget was provided for its construction, a very simple, low-cost lighting layout was designed.

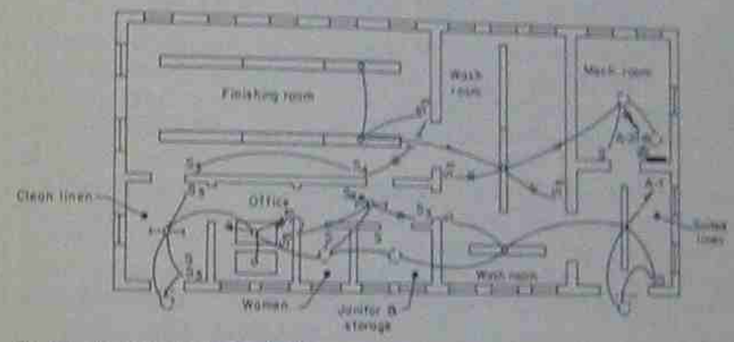


Fig. 3-9 Floor plan for laundry building.

Bare-lamp, 4-ft, surface-mounted lighting fixtures are used in the clean linen area and in the corridor. Each fixture contains two 40-W cool-white fluorescent lamps, and approximately 25 fc is provided in each area.

The office has two 18-in. by 4-ft fluorescent fixtures with acrylic prismatic diffusers which give the area over 150 fc of illumination.

Due to the fact that moisture is ever present in the remaining areas of the laundry, enclosed and gasketed 8-ft fluorescent fixtures are used. Each of these fixtures contains one 8-ft, 150-W fluorescent lamp and an 800-mA ballast. The acrylic clear prismatic lens on these fixtures provides for excellent light control; the prisms assure good brightness and hide lamp image. The continuous one-piece vinyl gasketing has no seams and is therefore dirt-, dust-, bug-, and watertight.

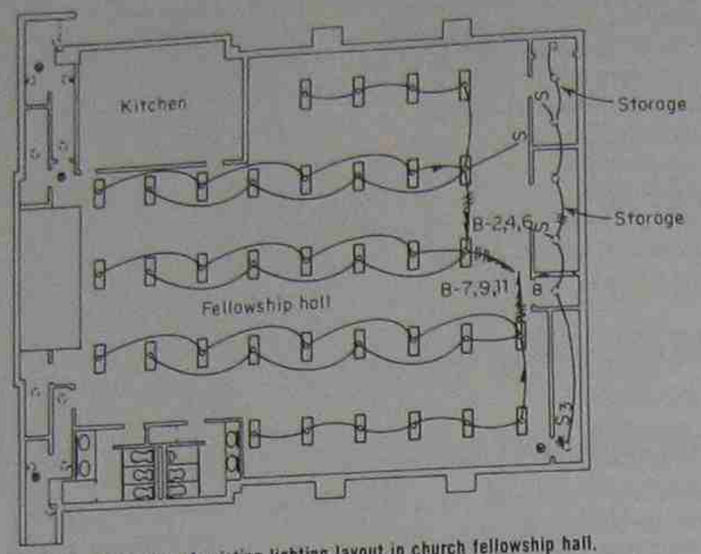


Fig. 3-10 Floor plan of existing lighting layout in church fellowship hall.

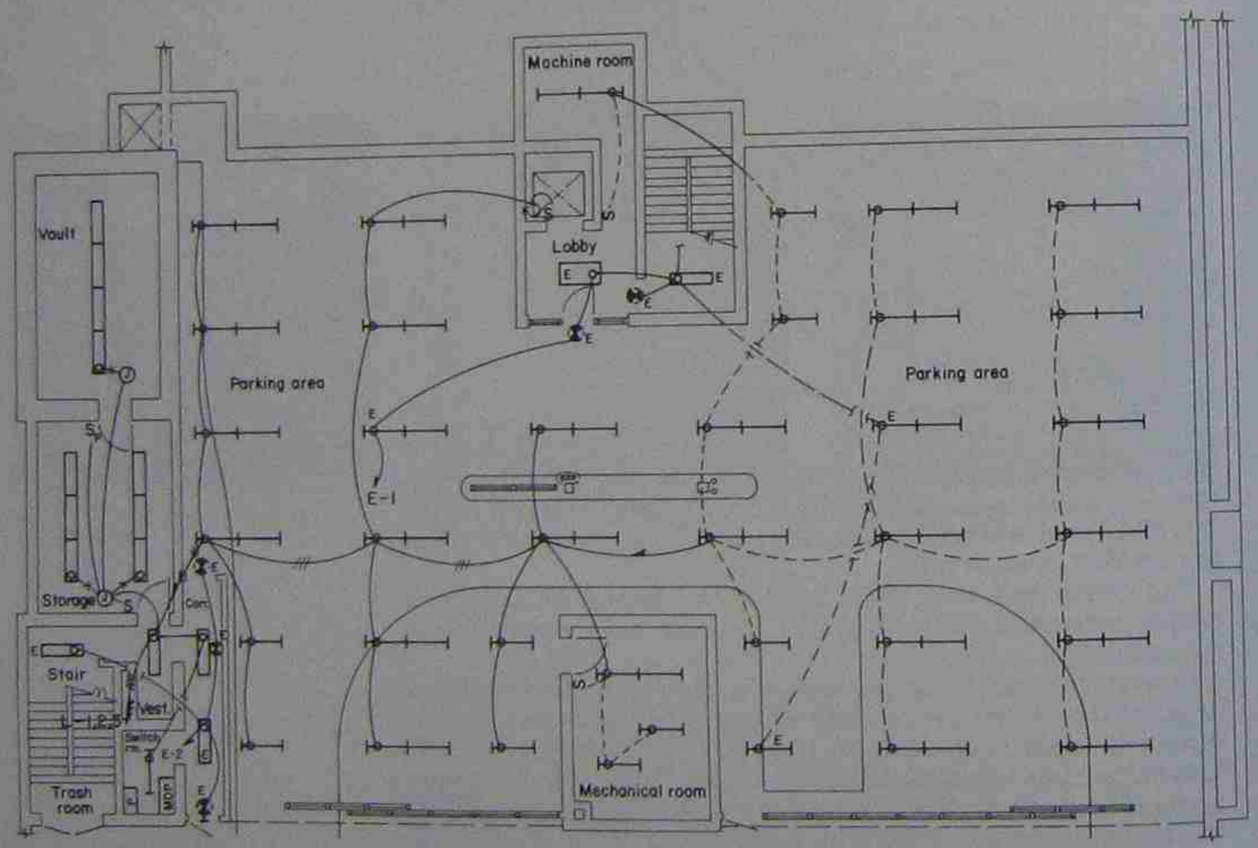


Fig. 3-11 Floor plan of lower floor of new bank building.

PRACTICAL APPLICATION: CHURCH BUILDING

Incandescent lighting fixtures were the principal light source for lighting the main worship area of the church building described in Chap. 1. The fellowship hall (located in the basement) of this same church is lighted with fluorescent fixtures as shown in Fig. 3-10. The general lighting source for this area consists of thirty-five 18- by 48-in. lighting fixtures containing four rapid-start 40-W fluorescent lamps. Acrylic prismatic diffusers are used throughout.

Notice that the fixtures are circuited so that several combinations of illumination are possible. For example, with all lamps energized, the illumination level is approximately 70 fc. Half of the fixtures may be lighted with the remaining half "out"; this gives approximately 40 fc. Although this is not shown on the floor plan in Fig. 3-10, the lamps in each fixture are controlled in pairs, giving further flexibility of lighting control.

The toilets are lighted with surface-mounted fluorescent strips with diffusers—two single-tube rapid-start 40-W fluorescent lamps in each area on the ceiling, and wall-mounted fluorescent fixtures over each mirror at the sinks.

Other sources of light for this area as well as the power wiring are described later in this book.

PRACTICAL APPLICATION: THE FIRST NATIONAL BANK, MAIN OFFICE

Figure 3-11 shows the floor plan of the lower floor area of a new bank building. It is obvious that this area is mainly used for parking and a route to the vacuum-tube drive-in units. Other areas include storage room, vault, stairwells, and the mechanical and machine rooms.

The entire parking area is illuminated with surface-mounted bare-tube fluorescent strips—each 4 ft in length and containing one 40-W rapid-start fluorescent lamp. This lighting arrangement gives a minimum of 5 fc of illumination. Each fixture is also provided with wire lamp guards to protect them from automobile radio antennas.

Most of the other areas are lighted with surface-mounted fluorescent lighting fixtures containing two 40-W rapid-start lamps each. Diffusers are also provided for better appearance of the fixture itself and for greater visual comfort.

Most of the parking area lighting is controlled by circuit breakers within the lighting panel. However, five of these fixtures as well as two other fixtures are connected to the emergency panel for 24-hr lighting.

Figure 3-12 shows the plan of the main level of this same bank. The third level of this bank building (office level) is shown on the floor plan in Fig. 3-13. The book vault, women's lounge, and the toilets are lighted with surface-mounted, two-lamp, fluorescent fixtures with diffusing lenses. The corridor and stairwells are illuminated with single-tube fluorescent fixtures with diffused lenses. The remaining area on this floor is illuminated with 2- by 4-ft recessed troffers, each containing four 40-W fluorescent lamps.

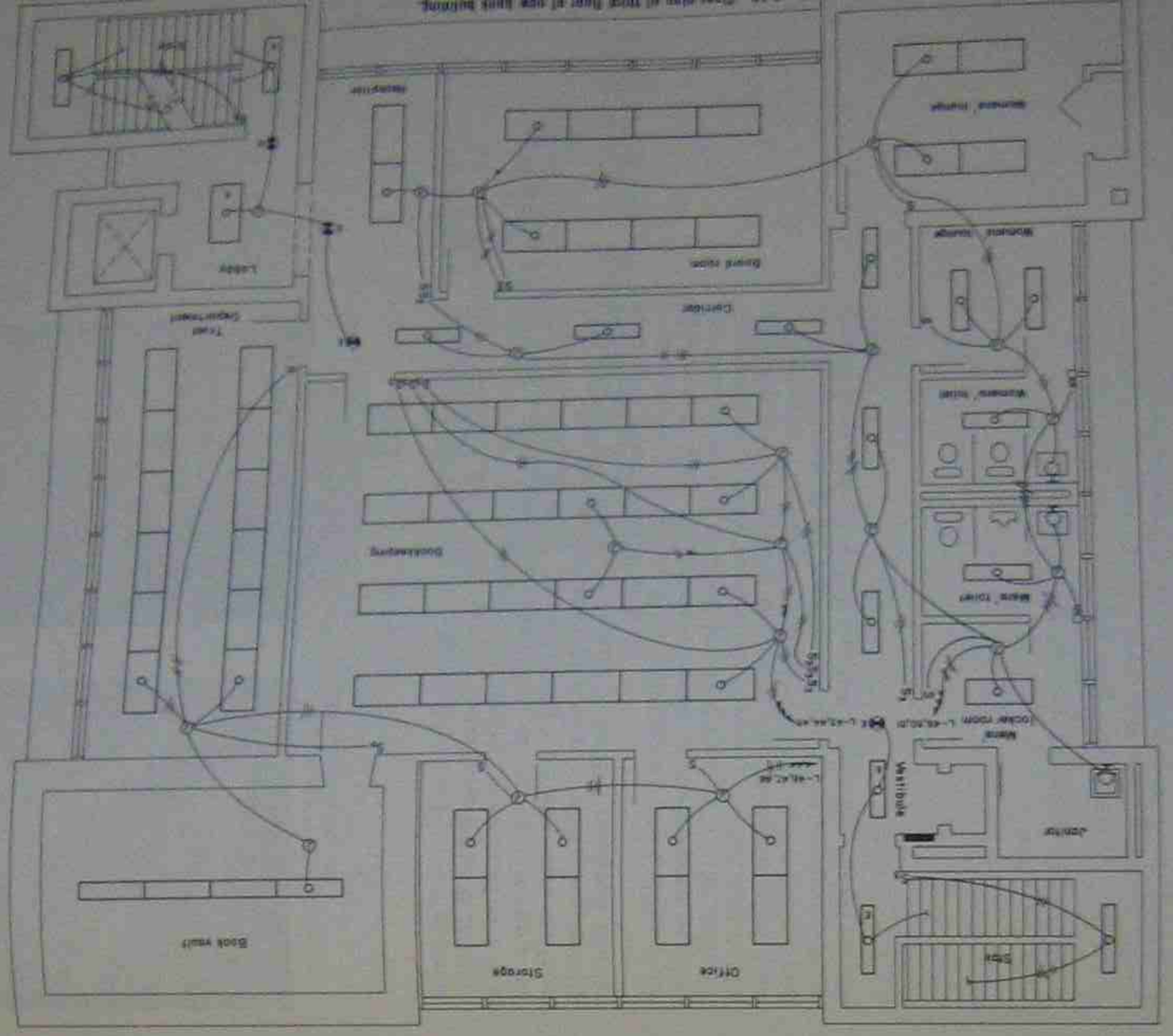


Fig. 3-11 Plan of main level of new bank building.

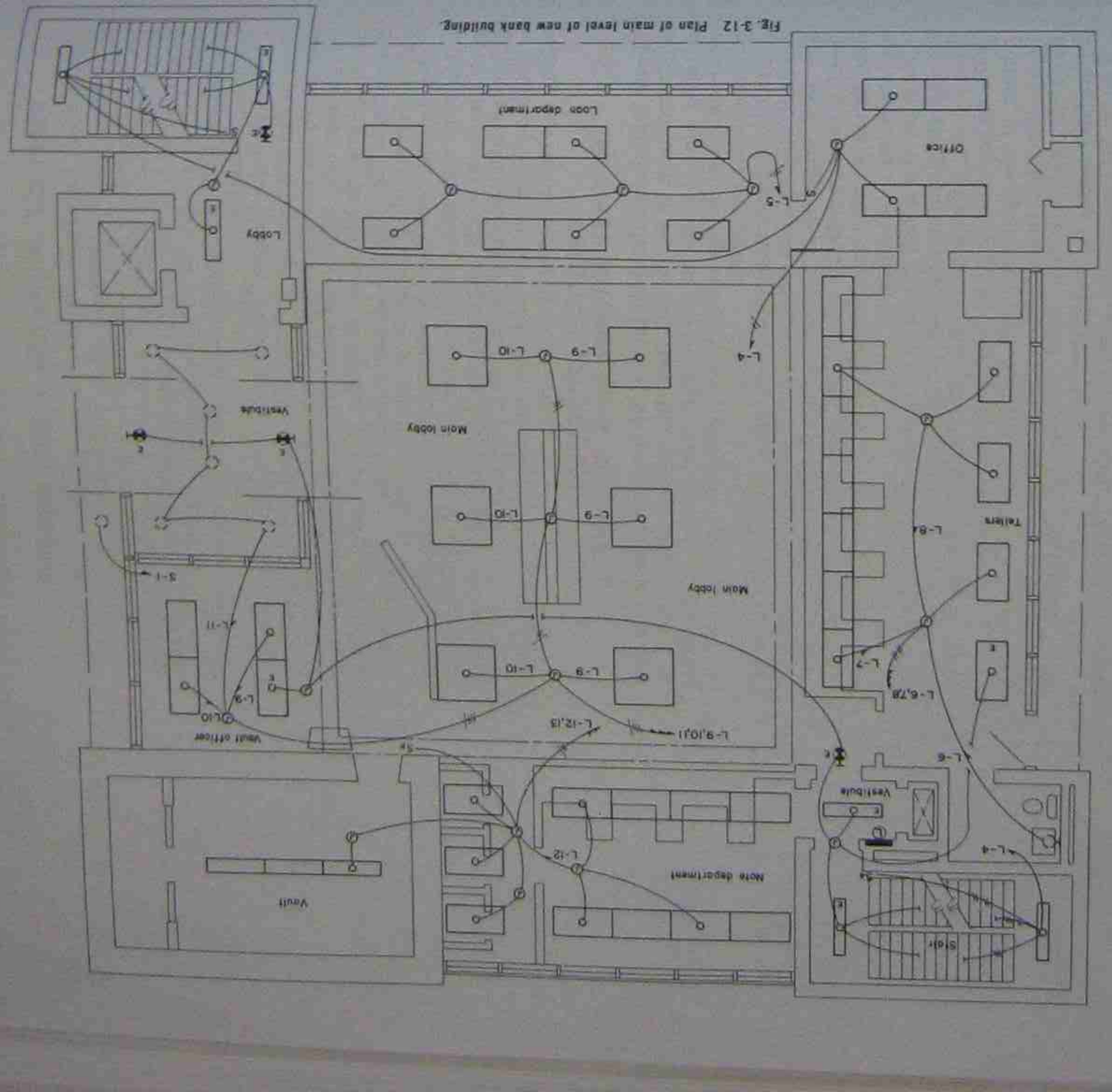


Fig. 3-12 Plan of main level of new bank building.



Fig. 3-14 Four-foot-square fluorescent fixtures in bank lobby.



Fig. 3-15 Two-foot by four-foot recessed lighting fixtures in teller area.

The lobby (Fig. 3-14) is illuminated with six 4- by 4-ft surface-mounted fluorescent fixtures, each containing eight 40-W fluorescent lamps. This arrangement provides between 50 and 70 fc of illumination—the recommendation of the Illuminating Engineering Society (IES). The vault and corridors have surface-mounting fluorescent fixtures with diffusers, while the remaining lighting fixtures are four-tube, 2- by 4-ft recessed troffers with dual-prism lenses (Fig. 3-15).

Incandescent lamps used for highlighting the building are explained in Chap. 2. The power wiring, alarm systems, service, and feeders for this building are described in a later chapter. The explanation of electrical symbols was given in Chap. 1. The circuiting of these lighting circuits should be self-explanatory.

Other uses of fluorescent fixtures will be given in the chapter on outside lighting and also in the chapter on using combinations of incandescent and fluorescent lamps for varied effects (Chap. 5).

Chapter 4
Lighting with High-Intensity Discharge Lamps

ADVANTAGES AND DISADVANTAGES

The basic mercury vapor (MV) lamp produces light with a predominance of yellow and green rays combined with a small percentage of violet and blue. In light of this color small objects, such as screws, pins, nuts, bolts, etc., stand out very sharply; this effect can result in increased industrial production speed and fewer errors—with less eyestrain for employees. For the reasons just mentioned, the mercury lamp became highly popular for certain industrial applications—especially in automobile manufacturing plants and machine shops.

While a modern mercury lamp, when lighted, appears to emit a white light (red, blue, and green), red is absent; therefore red

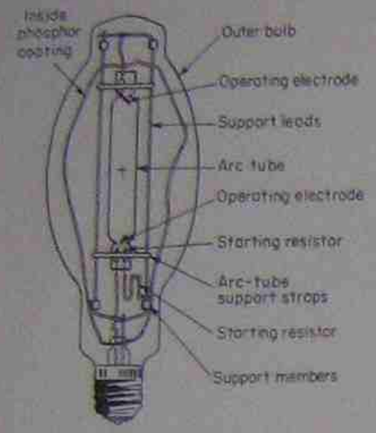


Fig. 4-1 Components of a typical mercury-vapor lamp.

objects appear black or dark brown under mercury vapor lamps. This color distortion has, in the past, prevented its use in many applications; however, it has now been overcome to a certain extent by the use of red light–generating chemicals within the bulb. Consequently, this lamp is now finding its way indoors for more and more commercial lighting applications.

Figure 4-1 shows typical mercury lamp components which include the following: an arc tube made of quartz to withstand the high temperatures resulting when the lamp builds up to normal wattage; two main operating electrodes located at opposite ends of the tube; a starting electrode connected in series with a starting resistor which is connected to the lead wire of the operating electrode; tube leads and supports; and an outer phosphor-coated bulb that helps to stabilize lamp operation and prevent oxidation of metal parts.

Mercury lamps for general-lighting purposes are available in wattages from 40 to 2000 W, in clear and various types of color-improved lamps. All types of mercury lamps require their own specially designed transformers, or ballasts, for proper starting and operating performance. While these ballasts are usually located outside the lamps, self-ballasted lamps with built-in filament-type ballasts are available.

One disadvantage of mercury lamps is that they are extinguished in the event of current interruption or excessively low voltages. They will not restart until they have cooled down and the internal vapor pressure has been reduced to the point of restarting the arc with the available voltage. The restarting-time interval is between four and seven minutes.

Besides being used to produce visible light, mercury lamps have been used to produce ultraviolet radiation as a source of "black light." This type of light requires that all visible light be screened out by filters while the ultraviolet energy passes through. Black-light lamps are used for decorative and theatrical effects, industrial inspection, medical and chemical analysis, criminal investigations, mineralogy, and varied military applications.

Metal halide lamps closely resemble regular clear mercury lamps, except that the inner arc tube in a metal halide lamp contains additional halide compounds to increase the light output and improve the lamp color. This improved color has made the metal halide lamp suitable for many indoor applications, including food displays in supermarkets. It has found more use, however, in outdoor floodlighting, sports lighting, and certain general street-lighting applications.

The high-pressure sodium lamp is another type of high-intensity discharge (HID) lamp in that it utilizes an arc tube to enclose gases through which an electric current passes. However, its unique light-transmitting ceramic tube enables sodium to be used at higher temperatures and pressures than were previously attainable. The result is a warm yellow light at nearly maximum theoretical efficiency, that is, 100 to 115 lm per watt.

Since some amount of every color is present in the high-pressure sodium lamp, it is used for practically all general lighting under most conditions.

Advantages of HID (Mercury) Lamps

- Long life.
- High lumen output.
- Compactness of incandescent lamps.
- Not affected by ambient temperatures as are regular fluorescent lamps.
- Better degree of light control than with fluorescent.

Disadvantages of HID (Mercury) Lamps

- Color acceptability low with clear mercury lamps.
- Sensitive to voltage variation.
- Long restarting time required.
- Light is extinguished if momentary current interruption occurs.
- Delay of between four and seven minutes from starting time to full brightness.

Obviously, the lighting demands of one area will be different than those of another, and since the available light sources have different performance characteristics, the demands of the application will dictate selection of the proper light source.

The following table illustrates the performance characteristics of the prevalent HID light sources.

Light source	Predominant color-spectrum properties	Normal life rating, hr	Initial luminous flux, lm/W	Beam control
MV (clear)	Blue	24,000	54	Good
MV (color improved)	Blue-green	24,000	54	Fair
MV (deluxe white)	Green-yellow	24,000	54	Fair
Metal halide additive	Green-yellow-red	7,500	80	Excellent
High-pressure sodium	Yellow	10,000	115	Excellent

DESIGN PROCEDURE

When lighting outdoor horizontal surfaces such as parking lots, storage lots, etc., the location, mounting height, and spacing of lighting fixtures are extremely important factors in attaining a uniform illumination on the surface. One rule of thumb is never to have a distance between pole locations of more than four times the mounting height of the fixtures, or not more than twice the mounting height from a central pole to the nearest perimeter.

This rule provides for the widest spacing permissible to obtain up to 10 fc of illumination on the surface. In areas which must receive higher levels of illumination, closer spacing between pole locations is necessary to accommodate the greater number of fixtures required. However, the reverse is not necessarily true. That is, if a lower level of illumination is desired, it would be better to use lamps of lower intensity than to increase the spacing of the lighting fixtures.

SAMPLE PROBLEM

A large parking lot (150 × 400 ft) is to be lighted to an average illumination level of 1 fc.

SOLUTION

Refer to the chart in Fig. 4-2 at 1.0 fc. Read horizontally to the right until this line intersects diagonal line *A*. Now read down vertically and notice that this line intersects at approximately 3.3—the initial lumens per square foot of area required to attain an average of 1 fc using a lighting fixture with a white translucent globe.

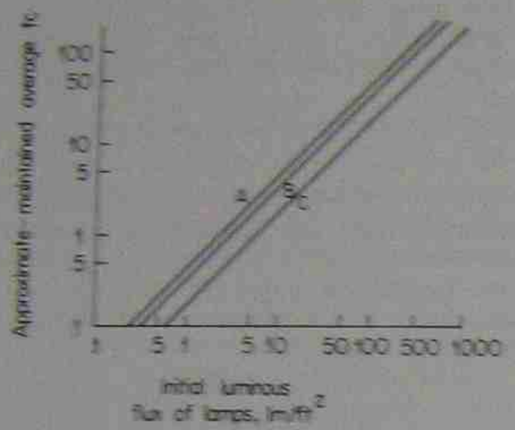


Fig. 4-2 Lighting calculation chart: *A*: clear globular lens; *B*: translucent globe; *C*: white ball globe.

Therefore

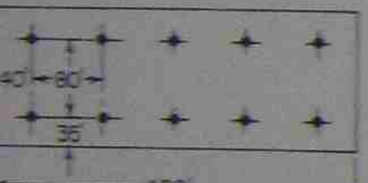
3.3 lm per sq ft × area = total lm required
3.3 lm per sq ft × 150 ft × 400 ft = 198,000 lm

A lamp catalog states that a 400-W mercury lamp provides 20,500 lm.

Therefore

$$\frac{198{,}000 \text{ lm required}}{20{,}500 \text{ lm per lamp}} = 9.65 \text{ or } 10 \text{ lamps}$$

Ten lighting fixtures and standards (poles) would be required to light this area, and they may be laid out as illustrated in Fig. 4-3.



4-3 Layout of parking-lot lighting fixtures.

Illumination uniformity is even more important when one is lighting such vertical surfaces as signs and billboards and in architectural lighting for vertical surfaces of buildings. After establishing footcandle levels required from the IES *Lighting Handbook*, the type and wattage of lamp necessary to produce these levels should be determined; the number of fixtures can then be calculated. Selection of lighting-fixture beam-spread and mounting distance to best achieve uniformity would be the next step.

The example in Fig. 4-4 demonstrates how medium-beam lighting fixtures, narrow-beam fixtures, and a combination of both types can be arranged to produce the most uniform beam distribution.

Lighting fixtures with various beam-spreads may be selected

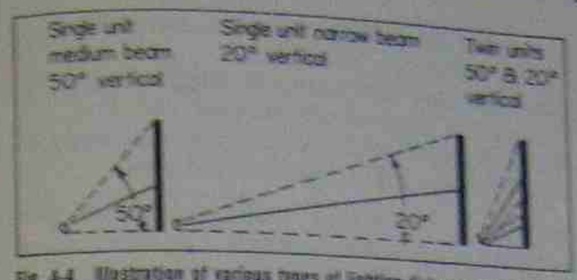


Fig. 4-4 Illustration of various types of lighting fixtures arranged to produce the most uniform beam distribution.

from manufacturers' catalogs. The best practice in selecting from available beam-spreads is to choose a lighting fixture which projects most of its effective beam-spread within the area to be illuminated with a minimum of "wasted" light (Fig. 4-5).

As the lamp lumens are distributed in a wider beam-spread, the candlepower decreases proportionately. Thus, the farther the light must be projected, the narrower the beam-spread should be. Narrow beam-spreads can also be used to advantage at closer ranges to provide concentrated high-intensity illumination levels.

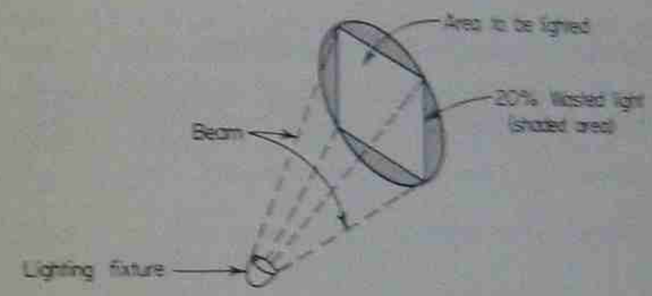


Fig. 4-5

Another point to remember is that projection-type lighting fixtures should never be mounted at an angle less than 30 degrees below horizontal. If this standard is maintained, the resultant glare will be minimized. In actual practice, if recommendations for pole spacing and lighting-fixture mounting height are followed, the aiming angle will automatically be greater than the minimum 30 degrees below horizontal. See Fig. 4-6.



Fig. 4-6 Illustration showing aiming angle of projection-type lighting fixture.

PRACTICAL APPLICATION

The "watts per square foot" method is the easiest and most rapid procedure for calculating the number of lighting fixtures needed in most applications requiring general illumination levels of 10 fc or less. The formula is

$$\frac{\text{Area (sq ft)} \times \text{desired footcandles} \times \text{WSF}}{\text{Luminaire lamp watts}} = \text{number of lighting fixtures}$$

where Area = square feet of surface to be illuminated

Footcandles = recommended illumination level for type of area to be illuminated
Luminaire lamp watts = total watts of lamp selected for given application
WSF = a utilization factor which combines lamp lumens, beam efficiency, and maintenance factor

It was determined that a single WSF factor would not give accurate results for areas of all sizes; however, the four factors in the following table will suffice for most areas as given.

WSF FACTOR	
Small area (1,000 to 5,000 sq ft)	0.16
Medium area (5,000 to 20,000 sq ft)	0.11
Large area (20,000 to 80,000 sq ft)	0.08
Extra-large area (over 80,000 sq ft)	0.06

For example, in the table above, the WSF factor for an extra-large area lighted with mercury vapor lamps is 0.06. This indicates that such an area requires 0.06 W of "lamp power" to place 1 fc of illumination within 1 sq ft of the area to be illuminated.

EXAMPLE: SHOPPING CENTER PARKING LOT

The site plan of a relatively small shopping center is shown in Fig. 4-7. The lighting designer was required to design a lighting layout for the parking lot which had good appearance by day, gave efficient performance at night, and blended tastefully with the architectural design of the shopping center buildings. Illumination levels were to meet IES criteria.

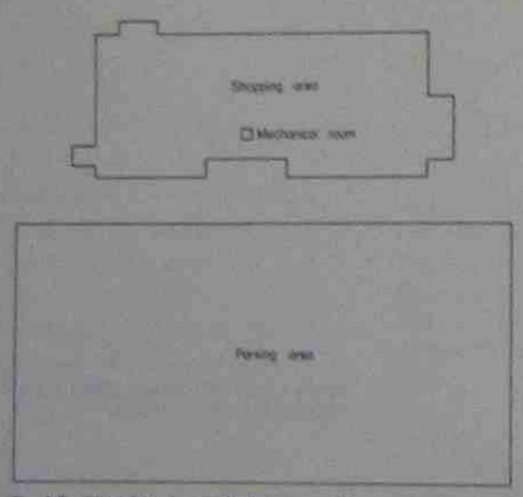


Fig. 4-7 Site plan of a small shopping center.

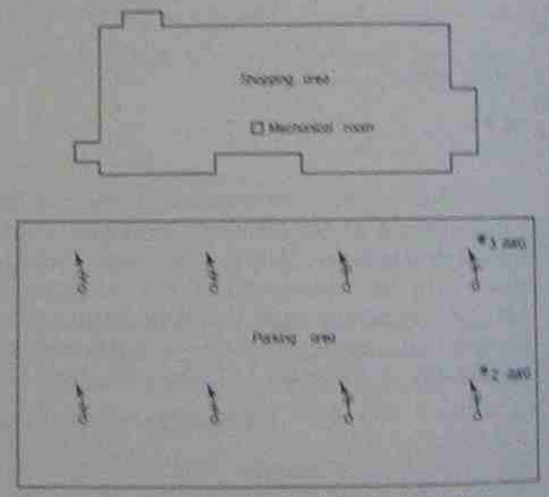


Fig. 4-8 Site plan, as shown in Fig. 4-7, with electrical components and circuits completed.

SOLUTION

Step 1. Using the watts per square foot method as a basis, the designer first found the area of the parking lot by scaling the site plan drawings: 240 × 480 = 115,200 sq ft. Since the total area is over 80,000 sq ft, 0.06, the WSF factor for an extra-large area, must be used.

Step 2. The designer than referred to the table of recommended illumination levels in the IES *Lighting Handbook* and found the recommended level to be 2 to 5 fc for automobile parking areas in shopping centers. The designer chose 3 fc as a basis for design.

Step 3. Then 400-W lamps were chosen as the first trial lamps for use in the design. A large lamp catalog indicated that this type of lamp provided 20,500 initial lumens.

Step 4. Substituting known values in the WSF formula, we have

$$\frac{115{,}200 \times 3 \times 0.06}{400} = 51.84 \text{ or } 52 \text{ lamps}$$

Step 5. A judgment is now required of the designer. Fifty-two 400-W lamps would require 13 four-lamp fixtures and posts, a design found to be economically unwise. The designer then selects a lighting fixture which contains four lamps – two 400-W mercury lamps and two 1-kW mercury lamps. This of course requires two different sizes of ballast for each fixture.

Step 6. The new lamp wattages are entered in the WSF formula and recalculated.

$$\frac{115{,}200 \times 3 \times 0.06}{2(400 + 1{,}000)} = 7.41 \text{ or } 8$$

This makes an even number of fixtures.

Step 7. The designer then uses 8 four-lamp fixtures (2,800 W total per fixture) mounted on 30-ft aluminum standards and spaced 120 ft on centers. The location of the fixtures, as well as electrical circuits for each, is sketched and then given to an electrical draftsman for completion. The completed site plan drawing appears in Fig. 4-8. Meanwhile, the voltage drop must be considered before circuits can be sized. Control of these lighting fixtures must also be determined before the drawing will be complete.

Step 8. The owners' service-equipment room is located in one of the shopping-center buildings. The largest lighting-fixture circuit is approximately 370 ft distant from this room. Therefore, 370 ft will be used to calculate the voltage drop and, in turn, the required conductor size. It is desired to keep the voltage drop below 2 percent, i.e., 0.02 × 120 or 2.4 V.

Step 9. The total amperes per fixture is 2,800W/120 V = 23.3 A; the total length is 370 ft; the maximum voltage drop allowed is 2.4 V. The formula for determining wire size is, then,

$$\text{Circular mils} = \frac{370 \times 23.3 \times 19}{2.3} = 71{,}216$$

Reference to a circular mil wire-size chart shows that the closest wire size available to the 71,216 circular mils is No. 1 AWG copper. However, experience tells us that a No. 2 AWG conductor with an area of 66,370 circular mils will be sufficient, since the lighting fixtures will only operate an average of one or two hours per day.

The next fixture is 250 ft from the service equipment. Therefore, the conductor size for this fixture will be

$$\frac{250 \times 23.3 \times 19}{2.3} = 48{,}120 \text{ circular mils}$$

or No. 3 AWG conductor.

Each circuit is calculated in the same manner, and the appropriate wire size is indicated on the drawings. Since the total calculated load for each fixture is 23.3 A, all circuits for these parking-lot lighting fixtures are protected with a 30-A overcurrent device.

Step 10. Each lighting fixture is controlled by its own built-in photoelectric cell.

SUPERMARKET LIGHTING

It was mentioned earlier in this chapter that new HID lamp designs show a remarkable color improvement over earlier mercury lamps, and that they are now suitable for many indoor applications. One such application is the lighting system for the supermarket shown in Fig. 4-9.

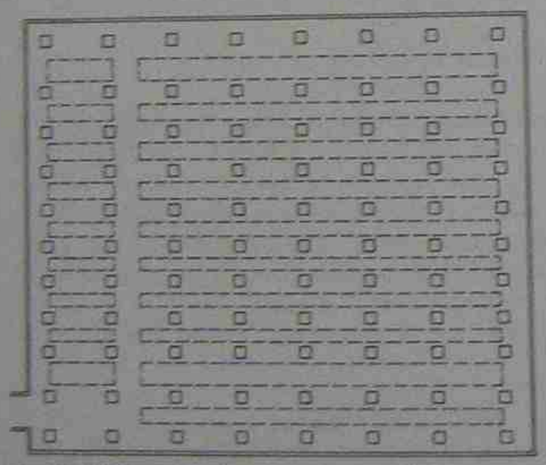


Fig. 4-9 Lighting system for a supermarket.

The required number of fixtures to produce the desired illumination level was calculated by using the zonal cavity method. Recessed HID lighting fixtures were used and were spaced 6 ft

on center. The result of this design gave the ceiling a more spacious, clean, and nondistracting look. Hot spots and glare were kept to a minimum, while the acrylic refractors provided even illumination throughout the store area. Since the HID lamps provided more lumens per watt than incandescent or fluorescent fixtures, much energy was saved in both illumination and air-conditioning use.

INDUSTRIAL APPLICATIONS

Most industrial lighting applications are not color-critical, and all the HID light sources are usually satisfactory. The following suggestions for choosing the proper industrial light sources were furnished by General Electric.

1. Use Lucalox (high-pressure sodium) lamps where minimum cost of light is desired.
2. Use Multi-Vapor (tandem fixtures) where low cost of light and a cooler-appearing environment are desired.
3. Use semireflector deluxe white lamps in practically all mercury lamp applications. Some incandescent or fluorescent lighting fixtures should be added for standby lighting in case of a power interruption. Some HID lighting fixtures can be purchased with optional built-in quartz lamps connected to the same circuit which can be used for standby lighting.
4. Use silver-reflector mercury lamps in combination with silver-reflector filament lamps in areas with severe dirt conditions.

The lighting system illustrated in Fig. 4-10 consists of 400-W mercury fixtures mounted 10 × 10 ft on centers and produces approximately 100 fc of illumination.

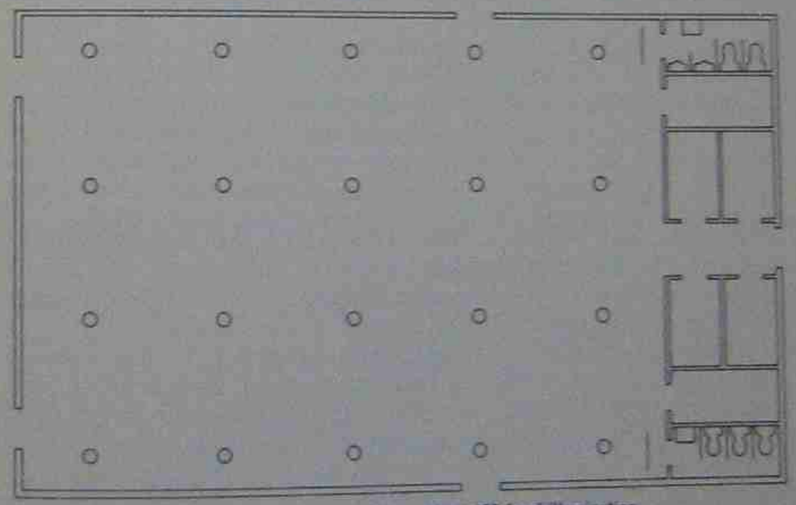


Fig. 4-10 Industrial lighting system designed to produce 100 fc of illumination.

Chapter 5
Lighting with Combinations

While you were reading Chaps. 1 through 4, it probably became apparent to you that modern lighting techniques, combined with new ideas of interior architectural design, have greatly influenced the appearance of interior environments.

When we consider interior lighting practice in the various fields of application, we are inclined to think, first of all, of the general overall lighting of a room and of the various types of lamps and lighting fixtures employed. In many interior lighting applications, however, other specialized lighting facilities may be just as important, if not more so. For such facilities, the use of a combination of different types of lamps with their related lighting fixtures offers an endless number of moods and effects.

For critical color matching, no one light source is completely satisfactory, since colors which match under one light source may not match under another. Consequently, for the most accu-

rate work, two sources having different light-color characteristics are used. For example, a fluorescent lighting fixture using "daylight-color" lamps in combination with an incandescent lamp and fixture offers widely different colors and should be satisfactory for critical color matching for most items. However, both light sources should be well diffused.

Light-source combinations, such as a combination of fluorescent and incandescent lamps, are also widely used in most stores, to achieve a particular objective. One example would be the use of incandescent downlights alternated between sections of fluorescent fixtures, or an arrangement of eyeball spotlights at each end of an 8-ft fluorescent fixture.

A combination of different light sources adds greatly to the appearance of merchandise. A deep-pile rug, for example, has a textured finish. Evenly diffused fluorescent light may illuminate each fiber of such a rug so uniformly that it would be difficult to appraise the pattern and depth of the pile. However, if directional incandescent light is used in combination with diffused fluorescent light, the soft texture and deep nap of the rug will be greatly emphasized.

Shadows of various objects are sometimes excessively sharp if only a single light source is used; two or three different light sources with overlapping beams may give better results. In fact, most kinds of merchandise will show up better under a dual system of fluorescent and incandescent lighting than under an all-fluorescent or all-incandescent system.

Show-window lighting is another application where combinations of light sources are desirable. If fluorescent lamps, for example, are used alone, the window display will lack the highlights, shadows, and dramatic contrasts that can be had by using a combination of both incandescent and fluorescent lamps.

The lighting flexibility necessary in stage lighting can only be accomplished by the use of several different light sources. For example, fluorescent lamps may be used to supply a certain level of illumination, but several controllable—in both directional and light intensity—spots and floods are required to achieve the best color combination for dramatizing a setting. Various colors of lamps such as red, blue, green, etc., are also necessary for various effects.

Another important use of light-source combinations is where mercury vapor (MV) lamps are used. As discussed in Chap. 4, even a momentary power interruption will cause the lamps to go out, and it may be 10 to 15 minutes before they will restart and come up to full light output again. Therefore, for safety reasons, any MV lighting installation for building interiors should be supplemented with either incandescent or fluorescent light sources.

In the following pages there is a discussion of several lighting projects where combinations of two or more different light sources were used simultaneously. While these examples barely touch upon the various combinations possible, they will give one an idea of what is possible so that one may approach any such design with greater assurance.

OTTERBEIN METHODIST CHURCH

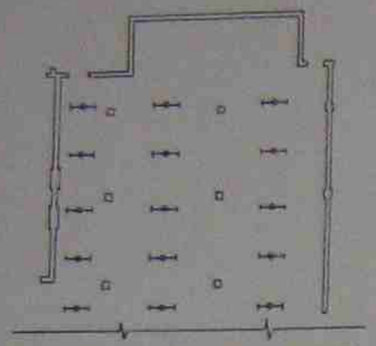


Fig. 5-1 Church basement prior to renovation.

When the members of the Otterbein Methodist Church of Harrisonburg, Virginia, agreed to renovate their multipurpose basement area, a local architect and his lighting consultant were hired to study the various problems.

There were three clearly defined lighting problems. A general-lighting system was necessary to provide adequate, quality lighting during the men's Sunday School class and similar meetings; a different type or mood of lighting was required when the area was used for church dinners; and finally, indirect lighting was sought to enhance the architectural and decorative features of the area.

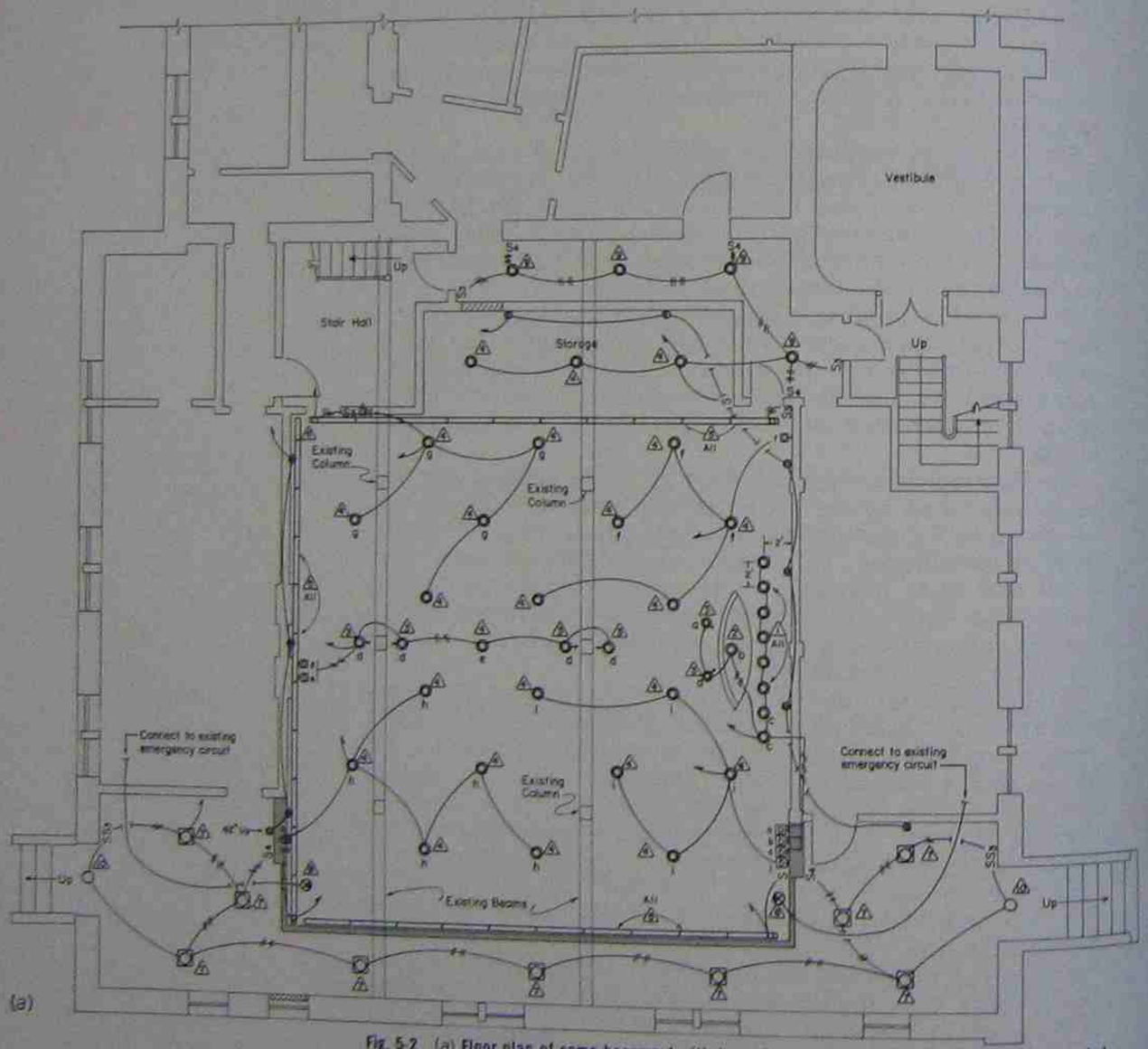
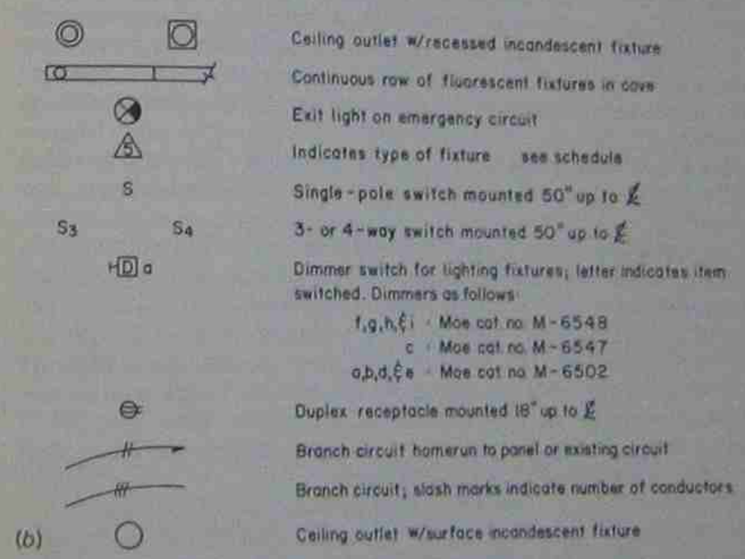


Fig. 5-2 (a) Floor plan of same basement with incandescent recessed fixtures laid out; (b) symbol list; (c) lighting fixture schedule (see page 63).

To these were added stringent qualifications by the church's minister and the building committee. The lighting design not only was to serve the functional needs of the area, but must also be particularly successful in its fusion of the architectural and the spiritual needs.

Figure 5-1 illustrates the problems of the area prior to renovation. The existing surface-mounted two-tube fluorescent lighting fixtures not only gave little or no versatility in lighting control and inadequate illumination, but were also very obtrusive to standing speakers because the ceiling was extremely low for an area of this size. This low ceiling also was a problem to the new lighting design as there was no practical way to raise the ceiling or to lower the existing floor.

An examination of the existing ceiling structure showed that the rough 2- by 10-in. joist was placed approximately 16 in. on center. With this information, the electrical designer laid out a uniform pattern of 300-W incandescent recessed fixtures, as shown on the floor plan in Fig. 5-2a and b. Twenty of these fixtures were controlled (in groups of five) by 2-kW rheostat dimmers. The twenty-first fixture, mounted between the two columns, was controlled separately by a 500-W rheostat dimmer. These 21 incandescent fixtures, having fresnel lenses, and con-



Lighting Fixture Schedule

Fixture Type	Manufacturers description	Lamps No.	Lamps Type	Volts	Mounting	Remarks
1	Hole cat. no. [illegible]	1	[illegible]	120	Recessed	
2	Hole cat. no. [illegible]	1	[illegible]		Recessed	
3	Hole cat. no. [illegible]	1	[illegible]		Recessed	
4	Hole cat. no. [illegible]	1	[illegible]		Recessed	
5	Lithonia cat. no. [illegible]	1	[illegible]		Cove	Reflector lamps
6	Lithonia cat. no. [illegible]	1	[illegible]		Cove	Reflector lamps
7	Hole cat. no. [illegible]	1	[illegible]		Recessed	
8	Hole cat. no. [illegible]	2	[illegible]		Surface	No exposed screws
9	Hole cat. no. [illegible]	1	[illegible]		Recessed	
10	Moe cat. no. M-979-1	2	[illegible]	[illegible]	Surface	

NOTE: It is imperative that the electrical contractor visit the ect site and consult with the architect before the bid date i are any questions.



Fig. 5-3 Lighting fixtures used to highlight paneled wall.



Fig. 5-4 Recessed lighting fixtures used to highlight speaker.



Fig. 5-5 Illustration of lighting-dimmer control.



Fig. 5-6 Recessed lights used to highlight column.

trolled by rheostat dimmers, gave an average calculated footcandle range of 0 to over 50 fc. This varied range of illumination was adequate, and also provided a good atmosphere for any function that would be held in this area. Since the fresnel lenses were flush with the ceiling, the appearance was not objectionable to either the speakers or the audience. The fixtures blended very well with the accoustical tile ceiling and also maintained a spiritual mood, as can be seen from the accompanying photographs.

The 300-W IF (inside-frosted) incandescent lamps in the 21 recessed lighting fixtures also improved the general appearance of furnishings, people, and especially food. It has been the designer's experience that cool-white fluorescent lamps have always given all food, and especially meats, a very poor appearance.

The various highlights throughout the area were relatively simple to provide. The nine direct wall-wash lighting fixtures (Fig. 5-3) located behind the speaker to highlight the paneled wall behind the speaker come from recessed fixtures; each has a half-ellipsoid reflector, a block Coilex baffle, and a rimless scoop trim. Then, 150-W reflector-type lamps were used to produce a very nice wall-wash effect without glare.

The speaker was further highlighted by two ceiling-recessed fixtures (Fig. 5-4). Each houses a 100-W adjustable narrow-beam reflector lamp. The speaker's podium was lighted by one direct ceiling-recessed fixture with a 2-in. pinhole lens. This lighting fixture provides adequate illumination on the speaker's reading material.

All of the wall-wash and speaker highlight fixtures are also controlled by rheostat dimmers (Fig. 5-5) for added effects and versatility.

The designer had some reservations concerning the highlighting of the speaker with incandescent lamps at such close range. However, while some heat is felt from the lamps, it has been reported that this heat is not too objectionable for a period of 30 to 45 minutes. The dimmer can also be used to control, to some degree, the heat produced by the lamps. There was no objectionable glare at any degree of brilliance with the 100-W lamps, and the highlight effect on the speaker's face and shoulders was more than satisfactory.

The two columns located approximately in the center of the area, as can be seen on the floor plan, were thought to be a great problem to the architect. The columns offered a possible obstruction to the field of vision between the seated audience and the speaker. They were also thought to be unattractive. However, the electrical designer suggested paneling these columns to match the walls, and then highlighting them instead of trying to hide them.

Two ceiling-recessed downlights were mounted on two sides of each column, as shown on the drawings and in Fig. 5-6. This changed what was thought to be a hindrance into an attractive added effect. All four of these lighting fixtures were also controlled by one inexpensive rheostat dimmer.

At this stage, the new lighting design had greatly improved

both the appearance and the illumination levels of the area. Still, the very low ceiling left much to be desired—architecturally speaking.

In an attempt to improve the appearance of this low ceiling, the electrical designer specified a continuous cove along the ceiling line on three sides of the area. A continuous row of 40-W fluorescent strip-lighting fixtures were then specified to be mounted in this cove. Each side was controlled by a single-pole toggle switch. Not only did this addition provide a supplemental light source for still more versatility in desired effects, but these additional cove lighting fixtures gave the low ceiling the appearance of being much higher than it actually was. This, in turn, improved the overall appearance of the area. See Fig. 5-7.



Fig. 5-7 Illustration of cove lighting.

DEPARTMENT STORE

The owner's initial requirements for the electrical system in a recently constructed department store were brief but to the point. "The electrical system shall be designed to provide adequate and uninterrupted power supply for all equipment and devices which require electrical energy. The electrical system shall be simple, economical, and safe."

After attending several preliminary conferences with both the architects and owners present, obtaining all available architectural drawings, and getting a sales fixture layout, the lighting designer began the actual layout of the lighting system.

Modern practice requires the establishment of a minimum quantity of light throughout a given area, which is usually termed "general lighting." This lighting must be arranged so that the eye can function with ease and efficiency. Experienced judgment combined with lighting calculations enabled the designer to create the lighting layout as shown in Figs. 5-8 and 5-9. Notice that the overall lighting arrangement combines fluorescent and incandescent lighting fixtures in order to obtain the desired illumination levels, color quality, and effects. A single light source for this type of sales area would have been entirely inadequate.

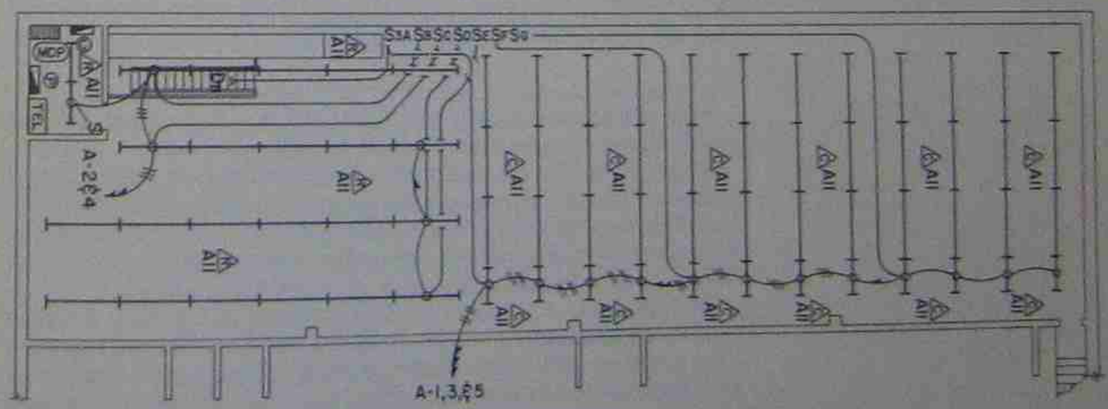


Fig. 5-8 Floor plan of the lighting layout for the mezzanine of a department store.

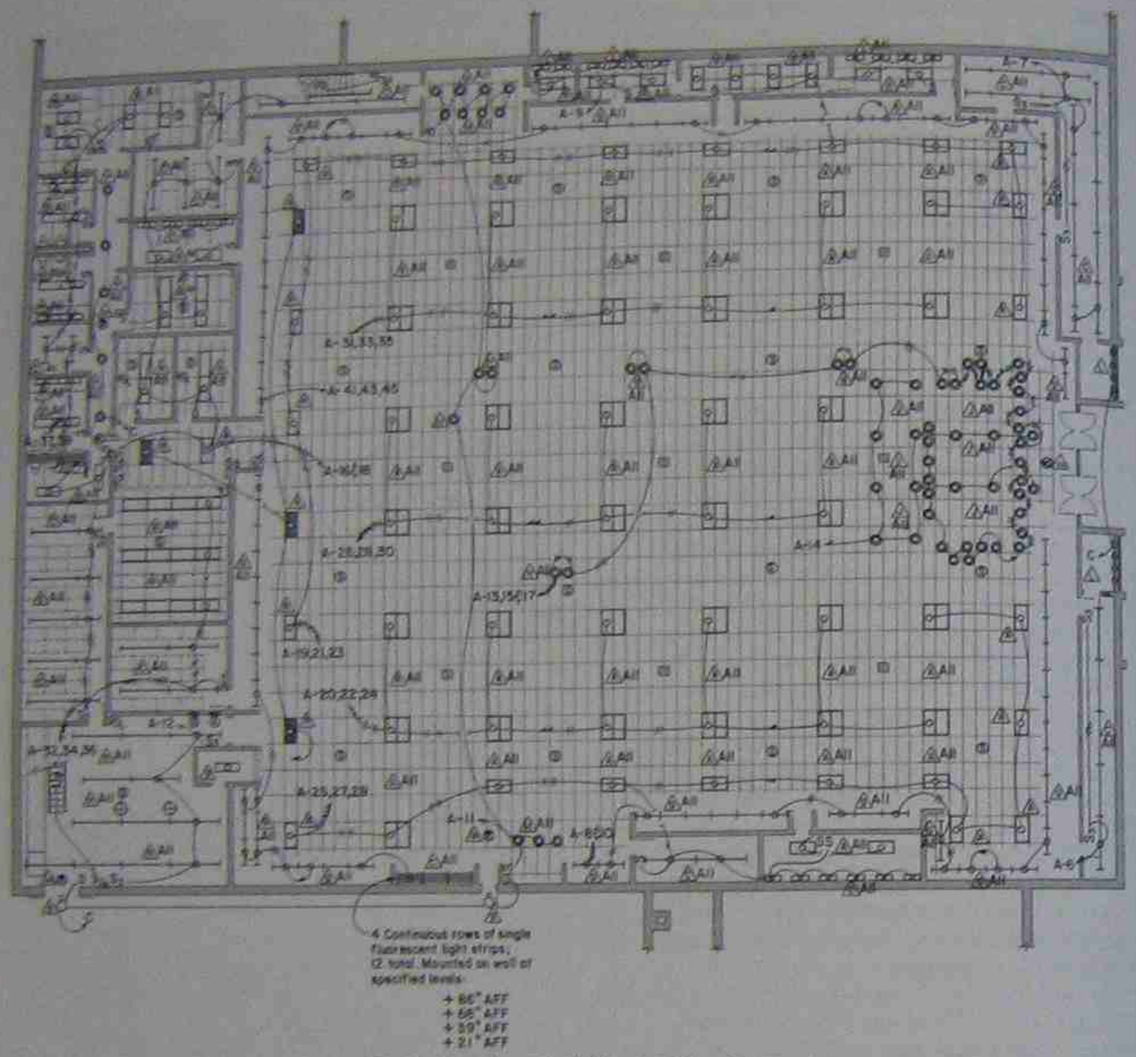


Fig. 5-9 Floor plan of the lighting layout for a department store.

The paragraphs to follow will explain the reasoning behind the designer's layout for this store building.

Recessed 2- by 4-ft, four-lamp lighting fixtures with acrylic lenses were used throughout the sales area for general lighting. The aim was to obtain a uniform level of illumination of not less than 65 fc throughout the entire area, at 30 in. above the floor.

It is apparent that the layout or location of lighting fixtures largely determines how uniformly the light will be distributed over an area, just as the location of sprinkler heads regulates water coverage in case of fire. The layout illustrated in Fig. 5-10 would have provided more uniform light distribution than the

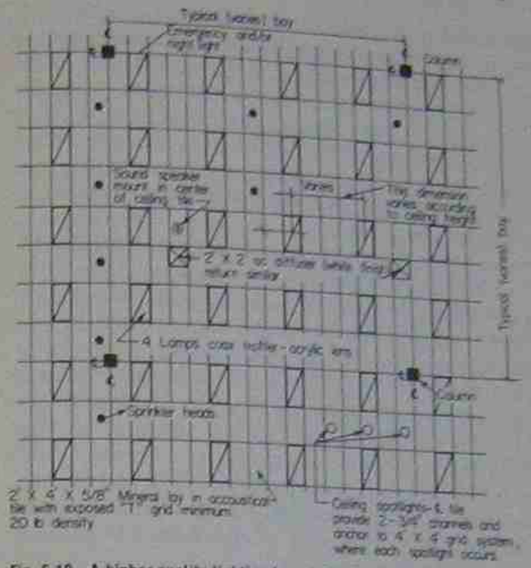


Fig. 5-10 A higher-quality lighting layout for Fig. 5-9. (NOTE. All 2- by 4-ft troffers must be supported by 12-gauge galvanized annealed wires from the top and secured to the structure above.)

layout used, but since one of the owner's requirements was economy, the layout actually used was the best compromise.

The design of the general lighting for this store was also governed by the arrangement of bays, columns, beams, and other architectural details; they required that the layout be fitted as symmetrically as possible to the interior but always kept within the limits of spacing directed by ceiling height or the heights at which lighting units could be mounted.

Again, recessed 2- by 4-ft fluorescent lighting fixtures with 100 percent acrylic low-brightness prismatic lenses were used in all office areas. However, in these areas, it was calculated that the maintained illumination level was 150 fc at 30 in. above the floor. The zonal cavity method was used for this calculation.

Lighting in stockrooms and receiving areas was designed to provide an illumination level of 50 fc maintained at 30 in. above the floor. Lighting fixtures in these areas were surface-mounted strips with exposed unshielded fluorescent tubes for economy.

The lighting layout in stairways, as well as in all alteration rooms, was arranged to maintain an illumination level of 100 fc. All lighting fixtures in these areas were acrylic-shielded fluorescents—surface-mounted in some locations and recessed in others.

In quite a few instances, surface-mounted strips with exposed unshielded fluorescent tubes have been used in corridors and stairways, and the lighting result has been unsatisfactory. The reason for this is that the high brightness of this type of lighting

fixture causes uncomfortable glare and poor, or no, diffusion.

Two successful methods are generally being used today in lighting corridors and stairways. One is to provide a good matte-white ceiling and to use totally indirect lighting (in some, the light sources are completely hidden); the other is to employ a light source of low brightness which in turn provides for high visual comfort. In stairways, the problem of changing lamps should also be considered when selecting either the type or the location of a lighting fixture.

The show windows near the main store entrance are illuminated to a level of 500 fc by utilizing high-intensity shielded and adjustable spotlighting fixtures. Two or more different light sources in these areas would have provided more versatility for displays, but again economy had to be considered.

All fitting rooms were provided with wall-mounted shielded fluorescent fixtures over the mirror in the dressing booths and a ceiling-mounted acrylic-shielded fluorescent fixture in the center of the fitting area.

Exit lights have stenciled faces and cast-aluminum bodies, and use fluorescent lamps. They are also designed to serve as emergency downlights, providing 5 fc of illumination at the door.

Note that no unshielded fluorescent fixture was installed in any area which would be visited by the public.

All incandescent lamps were either inside-frosted or silver bowl, as required. The fluorescent lamps in the sales area, beauty salon, fitting rooms, toilets, and hall as well as in storage rooms were standard warm white for color quality. Cool-white

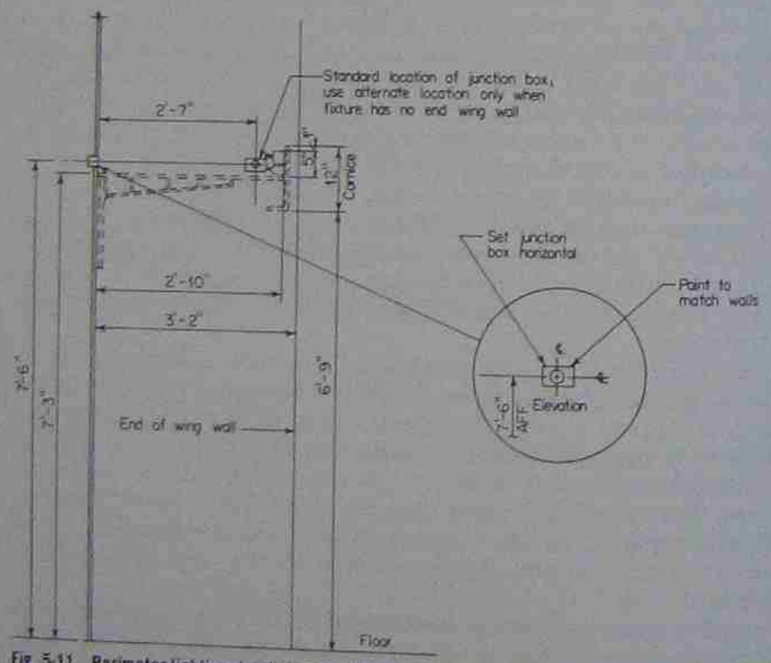


Fig. 5-11 Perimeter-lighting detail (valance lighting) showing alternative "J" box location where no end wall occurs. All equipment shown with broken lines is supplied by fixture contractor. Light fixture is supplied by electrical contractor.

fluorescent lamps were used in all offices, bulk-storage areas, alteration rooms, shipping and marking areas, and stairways. This specification, of course, was to provide the greatest number of lumens per watt.

Supplemental Lighting

The perimeter lighting shown in the floor plans in Figs. 5-8 and 5-9 and also in the detail in Fig. 5-11 served to highlight the merchandise shelves around the perimeter of the store. Although all these lamps were bare tubes, the light sources were not readily visible to the public.

The remaining filament (incandescent) lighting in the sales areas consisted of either recessed downlights or adjustable spots and were used for various merchandise displays as required by the store-fixture layout.

INDOOR VOLLEYBALL COURT

The alterations and additions to the Shenandoah Valley Detention Home in Staunton, Virginia, called for one indoor recreation area, the floor plan of which is illustrated in Fig. 5-12.

Each of the fifteen type "5" lighting fixtures contained a 250-W color-corrected mercury vapor lamp. This type of lighting fixture was also supplied with a lens guard to protect the fixture from damaging impacts caused by a misdirected volleyball.

The eight type "7" lighting fixtures also installed in this area were used for two purposes. One was to supplement the type "5" fixtures for greater lighting intensity; the other was to provide a light source should a power interruption occur, causing the MV fixtures to go out and take 10 to 15 minutes to restart. These type "7" lighting fixtures are surface-mounted, and each contains a 100-W incandescent lamp.

The type "7" fixtures were controlled by one single-pole switch near the entrance to the area, while the three circuits feeding the fifteen type "5" fixtures were controlled by a three-pole 20-A lighting contactor.

DIRT ACCUMULATION

Since this is the last chapter on lighting, the matter of dirt accumulation should be mentioned. No matter how carefully designed a lighting system may be with respect to type and size of lamp and lighting fixture, spacing of fixtures, etc., it must be kept clean if it is to remain in good operating condition.

Dust and dirt allowed to accumulate on reflecting surfaces of lighting equipment may, in the space of a month, decrease the light output from 20 to 30 percent.

The lighting designer can help alleviate the dirt problem by selecting appropriate lighting fixtures for the type of area in question. In addition to cleaning the lighting fixtures frequently, frequent painting and maintenance of the surroundings—walls, ceilings, etc.—will help keep the lighting efficiency near its original value. While most of the suggestions are usually out of the lighting designer's control, the designer can make certain that the owners are aware of the situation.

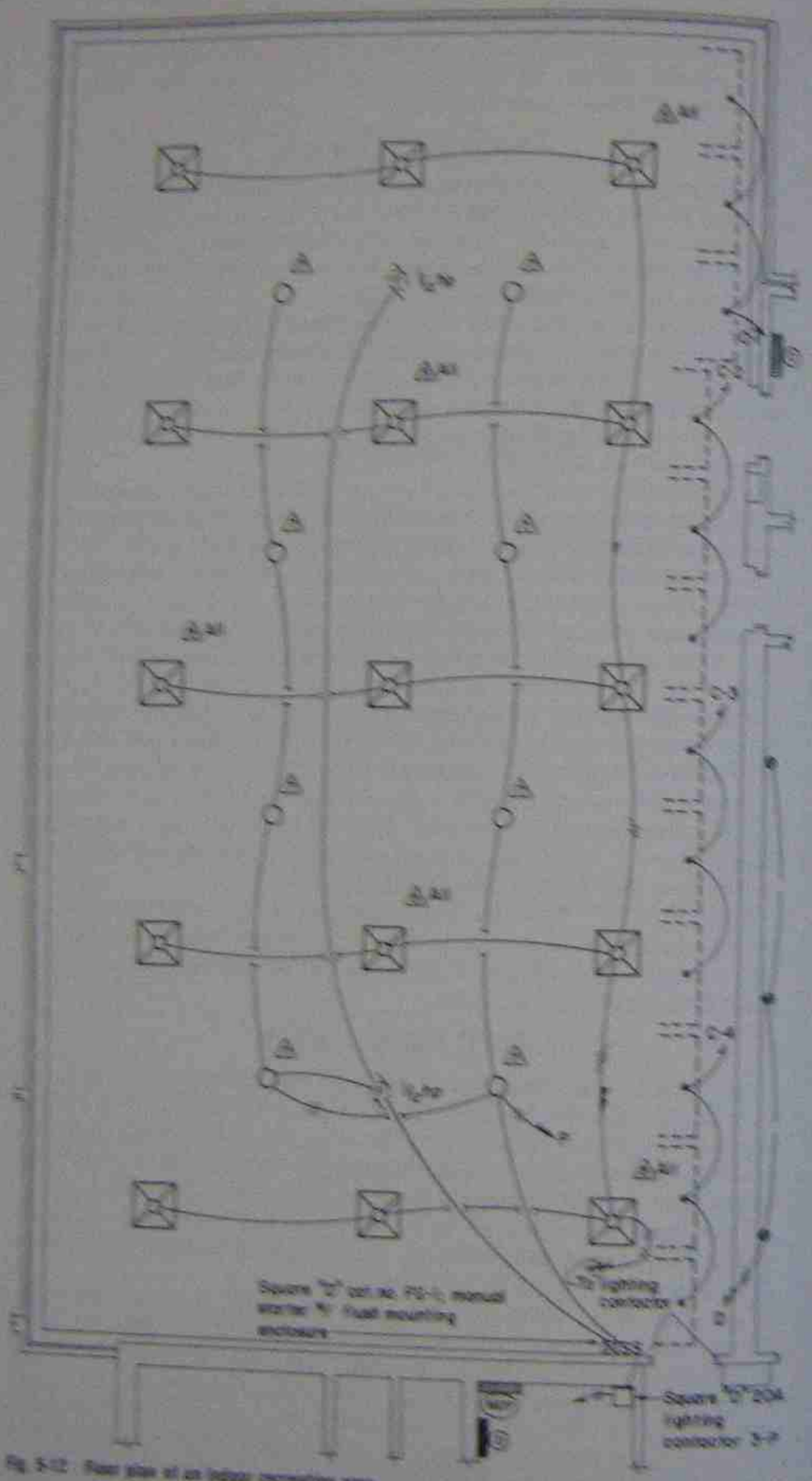


Fig. 5-22 Power plan of an indoor recreation area.

Chapter 6
Power Wiring for Convenience Outlets

The ordinary duplex receptacle or convenience outlet used in residences, stores, offices, and other buildings is the one electrical device most often used by the occupants. For this reason, it is designed to be one of the safest energy-transmitting devices manufactured. Since the early 1950s, the grounded receptacle has been mandatory on new construction and renovations under the National Electrical Code and was another step forward in further reducing electrical shock hazards.

Article 410-52(d) of the 1971 National Electrical Code states: "All 15- and 20-ampere attachment plugs and connectors shall be so constructed that there are no exposed current-carrying parts except the prongs, blade or pins. The cover for wire terminations shall be mechanically secured, or an integral part of the attachment plug or connector."

As of May 1, 1974, Underwriters' Laboratory is requiring that all plugs not of the dead-front construction type meet this

requirement by having the insulating disk secured in place. More stringent requirements can be expected in the future, and they may cover:

1. Wiring contacts
2. Strain relief
3. Impact resistance
4. Gripping configuration
5. Dead-front construction

In a commercial building, the plug receptacles or convenience outlets are usually placed on separate circuits and are not made a part of the general lighting circuit as is sometimes done in a residence. The Code states that a minimum of 180 W shall be allowed for this type of outlet. Therefore, since a duplex receptacle has two plugs, a minimum of 360 W shall be allowed for each duplex receptacle.

Most electrical designers round this figure off and allow 400 W for each duplex receptacle. This makes it easier to keep the figures in one's head while circuiting the outlets and allows a slight margin to ensure sufficient capacity.

The following floor plan (Fig. 6-1) shows a room with several duplex receptacles located at various intervals within the room. Assuming 20-A branch circuits, how many circuits will be required to feed all the receptacles?

First, find the number of receptacles that can be connected to a 20-A branch circuit.

$$\frac{120\ (\text{V}) \times 20\ (\text{A})}{400\ (\text{W per duplex receptacle})}$$

$$= 6\ (\text{number allowed on circuit})$$

Since there are twelve duplex receptacles in the area, they will require two branch circuits and may be circuited as shown in Fig. 6-2.

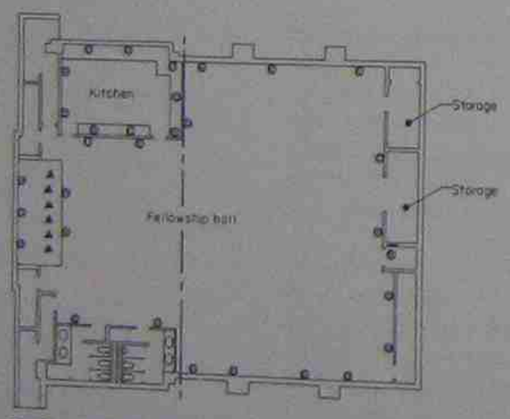


Fig. 6-1 Floor plan showing a room with duplex receptacles located at various intervals.

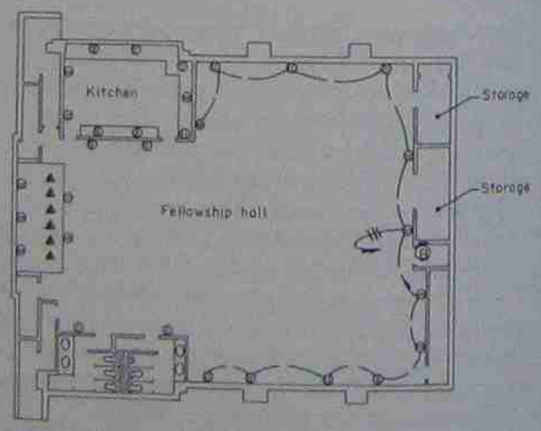


Fig. 6-2 Circuiting of the receptacles shown in Fig. 6-1.

MULTIOUTLET ASSEMBLIES

The National Electrical Code defines a *multioutlet assembly* as a type of surface or flush raceway designed to hold conductors and plug receptacles, assembled in the field or at the factory. "Plugmold" is one of several brand names of multioutlet assemblies available, and is a product of The Wiremold Co.

The Code further states that where fixed multioutlet assemblies are employed, each five feet or fraction thereof of each separate and continuous length shall be considered as one outlet of not less than 180-W capacity, except in locations where a number of appliances are likely to be used simultaneously, when each foot or fraction thereof shall be considered as an outlet of not less than 180 W.

The floor plan shown in Fig. 6-3 gives an example of multioutlet assemblies used in a commercial store area. Multioutlet assemblies were used because several television sets and small appliances were to be demonstrated in these areas. However, multioutlet assemblies are not limited to such locations only, but are also practical anywhere that convenience receptacles are desired fairly close together.

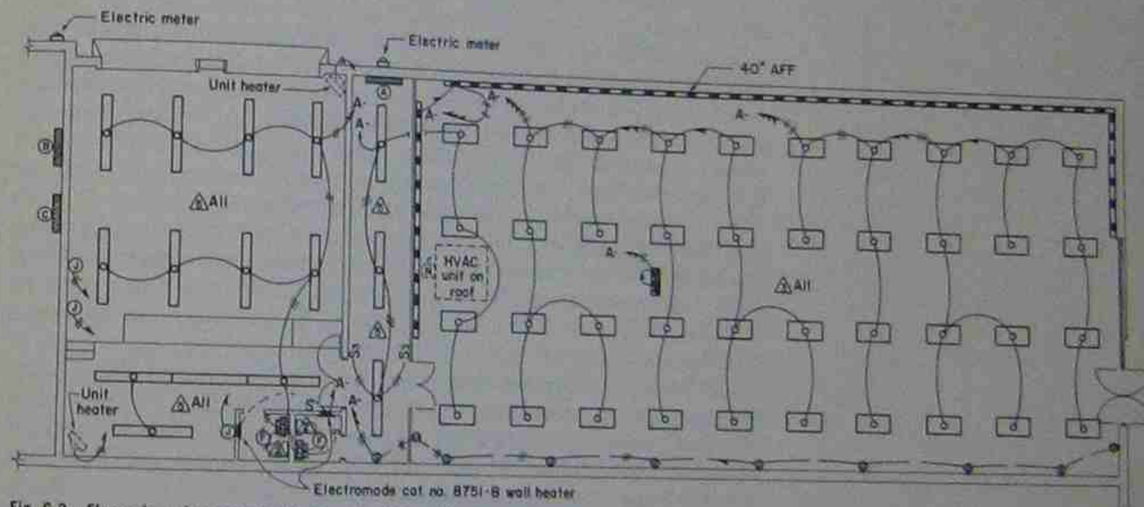


Fig. 6-3 Floor plan of a commercial store showing multioutlet assemblies.

SMALL-APPLIANCE BRANCH CIRCUITS AND RECEPTACLES

The National Electrical Code states that for small-appliance outlets, two or more 20-A branch circuits shall be provided, and "such circuits shall have no other outlets" connected. On these circuits, No. 12 AWG wire must be used to carry the required 20-A load; 1.5 kW is the figure used when calculating residential appliance circuits.

In addition to the two 20-A circuits required for appliances used in the kitchen, pantry, family room, dining room, or break-

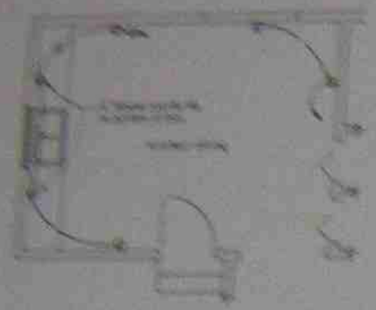


Fig. 8-4 Partial floor plan of a residence.

foot area, the Code requires that "at least one 20-A branch circuit shall be provided for laundry receptacles." This is required because automatic washers draw a large amount of current during certain cycles of their operation. The amount of current drawn from irons is also large, and such appliance circuits will lessen the danger of overloading circuits.

The kitchen floor plan of the residence in Fig. 8-4 shows six duplex receptacles. In accordance with the Code, two circuits would have been sufficient to feed these receptacles, i.e., three outlets on each circuit. However, to provide greater insurance of sufficient capacity for the many small appliances used in the kitchen today, the designer used three 20-A circuits (two outlets on a circuit) to feed these six receptacles.

The receptacle provided for the portable dishwasher was fed by one 20-A circuit because a large amount of current is drawn by this one appliance. The single receptacle for this circuit is also rated at 20 A since the Code states that "a single receptacle installed on an individual branch circuit shall have a rating of not less than the rating of the branch circuit."

The receptacle provided for the garbage disposal was again fed by a single circuit, this time at a 15-A rating. Again, to comply with the Code, a receptacle with a rating of 15 A was used.

Receptacles in the remaining areas of the home are located so that no point along the floor line in any wall space is more than 6 ft from an outlet in that space. Where the sliding glass door extends to the floor, it is not possible to install receptacles in this glass; thus, outlets were installed on each side of the door so that a 6-ft extension cord within the space of the sliding door would reach one of these outlets.

In situations where sliding glass doors or windows extend to the floor and they are more than 12 ft wide, some means other than conventional wall-mounted receptacles must be used to comply with the National Electrical Code. The use of floor outlets is one way to solve this problem.

The bedroom receptacles are split-wired so that the top plug of the receptacle is always energized while all the bottom plugs may be switched on and off by means of a single-pole switch near each door. This enables table lamps to be plugged into the bottom plug and provides a means of controlling them. Such items as clocks, radios, etc., may be connected to the top plug and will remain "hot" all the time.

It is recommended that one convenience outlet be placed in hallways, regardless of their size. In larger hallways, one outlet should be provided for every 15 ft (linear) of hallway. Such outlets are normally used for vacuum cleaners, floor polishers, table lamps, etc.

The National Electrical Code does not specify the maximum number of receptacle outlets to be connected to each circuit in residential applications. However, it is good practice never to load a circuit to more than 80 percent of its current-carrying capacity. In the case of a 15-A circuit at 120 V, this would be $15 \times 120 \times 0.8 = 1.44$ kW. Still it is difficult to predetermine just what will be connected to these outlets in actual use. In residential applications, more designers allow 300 W per duplex receptacle unless it is provided for a known usage. This means four or five outlets per circuit if it is provided with a 15-A overcurrent protective device. If this figure is used in designing residential electrical systems, the end result will be a well-designed branch circuit with minimal voltage drop.

Other electricians and designers figure 1½ A per duplex receptacle; this method allows a maximum of ten outlets per circuit. Even by this method, common sense indicates that certain outlets will not use 1½ A. These would include outlets for clocks, night-lights, etc.

If such low-wattage items are known to be connected to the circuit, the designer would be justified in increasing the maximum number of ten outlets to possibly twelve outlets per circuit. The reverse is also true. For example, if outlets were to be installed over a home workbench where it is known that heavy power tools will be used, the designer will most certainly provide outlets and circuits to handle this load. The outlets and circuits will probably be similar to those installed in the kitchen or laundry area.

The only problem with allowing for small wattage loads such as night-lights and clocks is that the load may change in the future. The night-light may be removed from a bedroom outlet and a window air conditioner may be connected. This is why most designers like to play it safe and allow 300 W minimum for each duplex receptacle.

In laying out receptacle outlets for residential applications, the first step is to provide outlets for known usages such as washer, dryer, dishwasher, workbench outlets, bedside outlets, etc. The information can usually be obtained from the architect, owners, and /or interior decorator. Once the outlets are located for the known requirements, other outlets should be located so that no point along the floor line in any wall space is more than 6 ft from an outlet in that space.

Circuiting of the outlets should be such that all home runs are as short as possible, and all looping between outlets should also be made as short as possible. But on any given electrical installation, there are many different combinations or groupings of outlets into circuits—all of which will be technically correct; the problem is to determine quickly the route which will conserve the most wire and in turn keep voltage drop to a minimum.

The floor plan of a small branch bank is shown in Fig. 8-5. This drawing is titled "Main Floor Plan—Power" to indicate that all power wiring is shown on this plan while the plan showing the lighting layout will be titled "Main Floor Plan—Lighting." On all drawings of electrical systems, except those of warehouses and similar projects where very little electrical work will be required, it is best to use separate floor plans for power and lighting. This enables the drawing to be more easily read by the workers installing the electrical system.

Notice that the designer has laid out the majority of the duplex receptacles in this branch bank in groups of four; that is, the four receptacles in each office are fed by one circuit, and

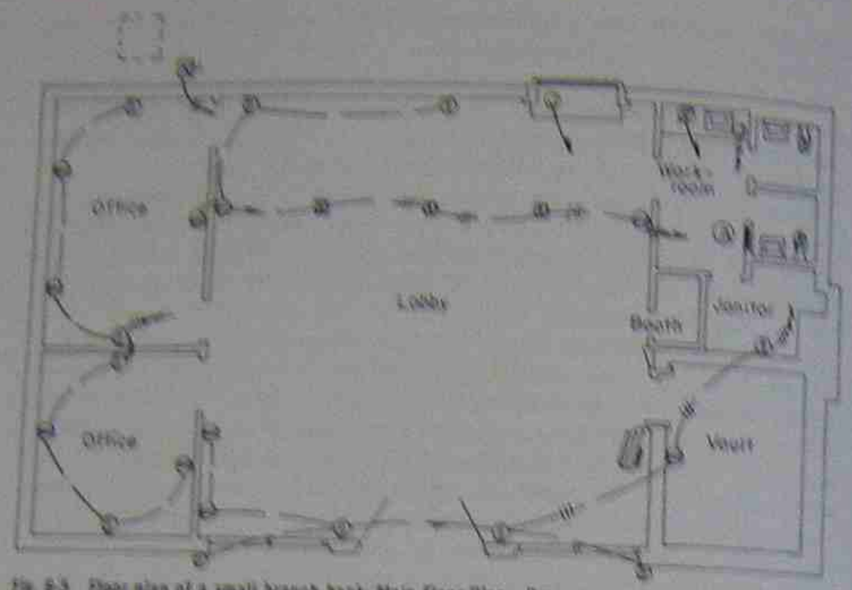


Fig. 6-5 Floor plan of a small branch bank: Main Floor Plan – Power.

then both circuits are run to the panelboard "A" in one conduit using a common neutral.

All the duplex receptacles in the lobby area are also run in groups of four, picking up the two outside outlets at the front entrance in the process. All these circuits are again run to the panelboard, using a common neutral for each two circuits. In a three-phase, four-wire, wye-connected service, most designers try to make all home runs consist of three circuits and a common neutral, but this particular bank is using a three-phase, four-wire, delta-connected service where the high leg cannot be used for 120-V loads.

The duplex receptacle over the countertop in the workroom is indicated by the standard receptacle symbol with a slash through it. This outlet is connected to a separate circuit because the bank personnel will use it for a 1,000-W coffeemaker. The junction box adjacent to this outlet feeds a small electric water heater under the counter.

The junction box shown in the cutout section off the lobby area feeds a prefabricated drive-in unit, while the nonfusible disconnect with a three-wire circuit, located outside the building, is provided for a condensing unit which is indicated by a broken-line square.

In general, most electrical designers lay out convenience outlets for commercial applications in much the same manner as for residential; that is, they locate outlets for known needs first, then provide additional outlets so that no point along any usable floor line is more than 6 ft from any outlet. Although this is not a Code requirement, it is good practice.

Common sense, however, will normally dictate the number and location of outlets in most commercial applications. Common sense and good judgment will come with experience, but in the meantime, the new designer should look at existing

installations, ask questions concerning these existing outlets, and then attempt an original design.

Figure 6-6 shows another floor plan: a laundry building used at a nursing home. Again, the drawing is labeled "Main Floor Plan – Power" and is drawn to a scale of ⅛ in. = 1 ft 0 in.

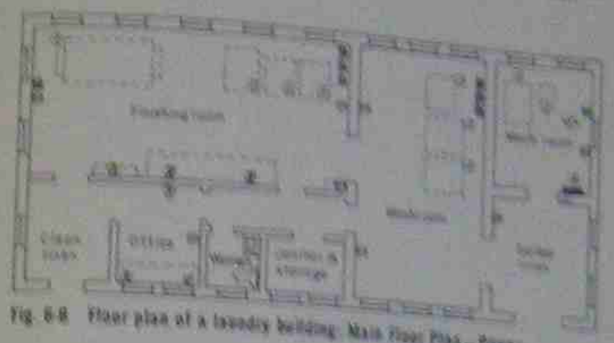


Fig. 6-6 Floor plan of a laundry building: Main Floor Plan – Power.

Each of the junction boxes – indicated by a circle with the letter J inside – contains separate feeders for various pieces of equipment with known loads. The duplex receptacle in the mechanical room is for maintenance purposes, that is, to connect drop cords, hand power tools, etc. The one duplex receptacle in the soiled-linen room and the two receptacles in the washroom were provided for convenience. They will probably be used for vacuum cleaners or similar loads, and therefore all three will be connected to one circuit.

If one goes to the finishing room from the washroom, the duplex receptacle on the left immediately beyond the entrance of the finishing room is provided for a water cooler. The receptacle on the right beyond the entrance, as well as that on the opposite wall, is for convenience. The two outlets over the workbench are for electric clothes- or linen-mending tools, and the one next to the bench is for a sewing machine.

The three duplex receptacles in the office are fed by one separate circuit. The symbol consisting of an open triangle with a slash indicates a telephone outlet above the countertop.

A floor plan titled "Main Banking Level – Power" is shown in Fig. 6-7 and is drawn to a scale of ⅛ in. = 1 ft 0 in.

On this drawing, conventional wall-mounted duplex receptacles are indicated by the usual symbol. The floor receptacles, however, are indicated by a circle with a dot inside. Floor-mounted telephone outlets are indicated by a circle enclosing a shaded triangle.

If one enters the vestibule from the outside, there is one duplex receptacle in the small lobby to the right to provide power for a water cooler; it is fed by one circuit – L-19. The "L-19" indicates that the home run goes to panel L (shown in the opposite vestibule) and that this particular circuit is connected to circuit 19 within the panelboard.

The two floor outlets in the vault-officer area, as well as the single floor outlet mounted under the lobby desk, are connected

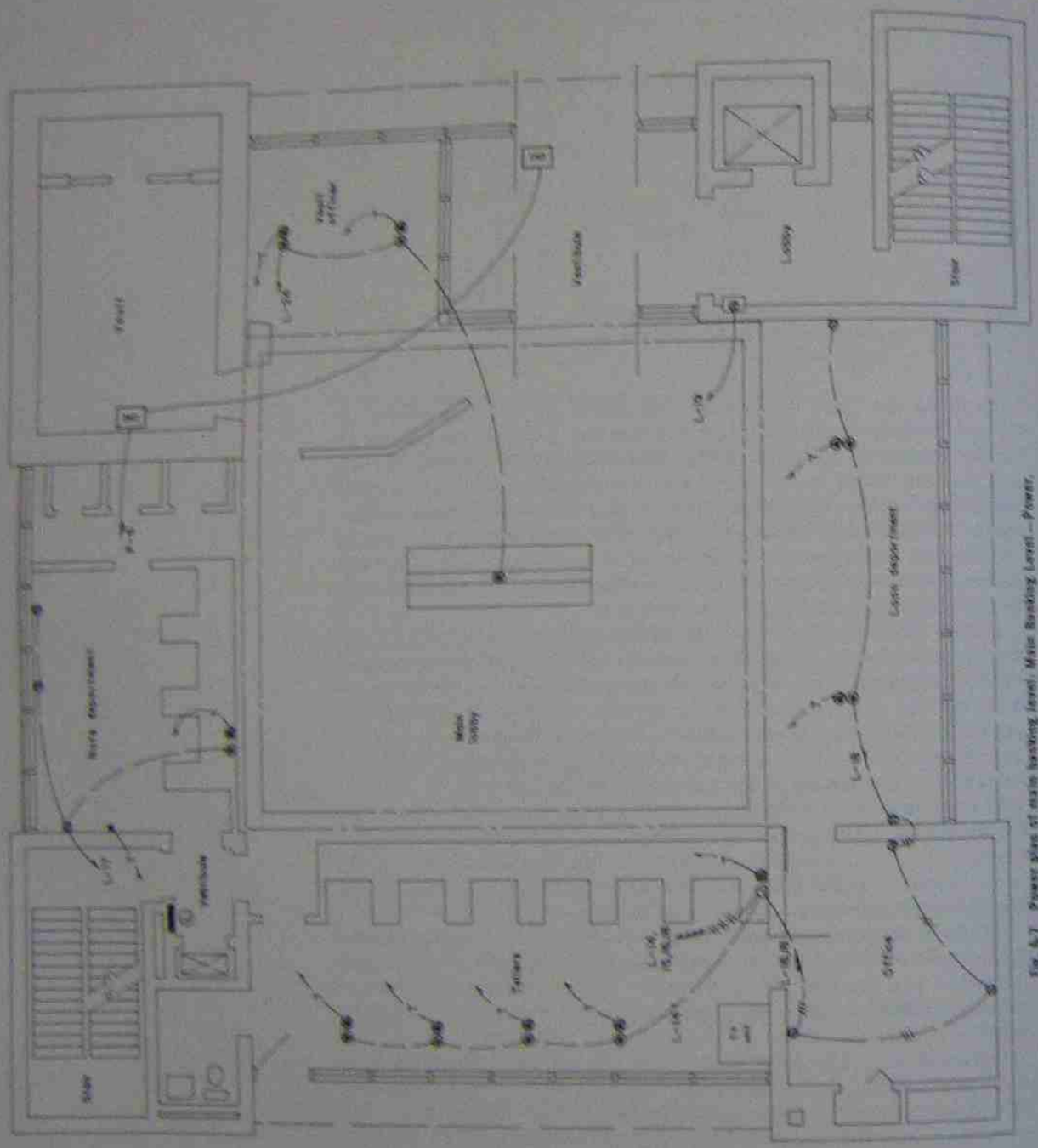
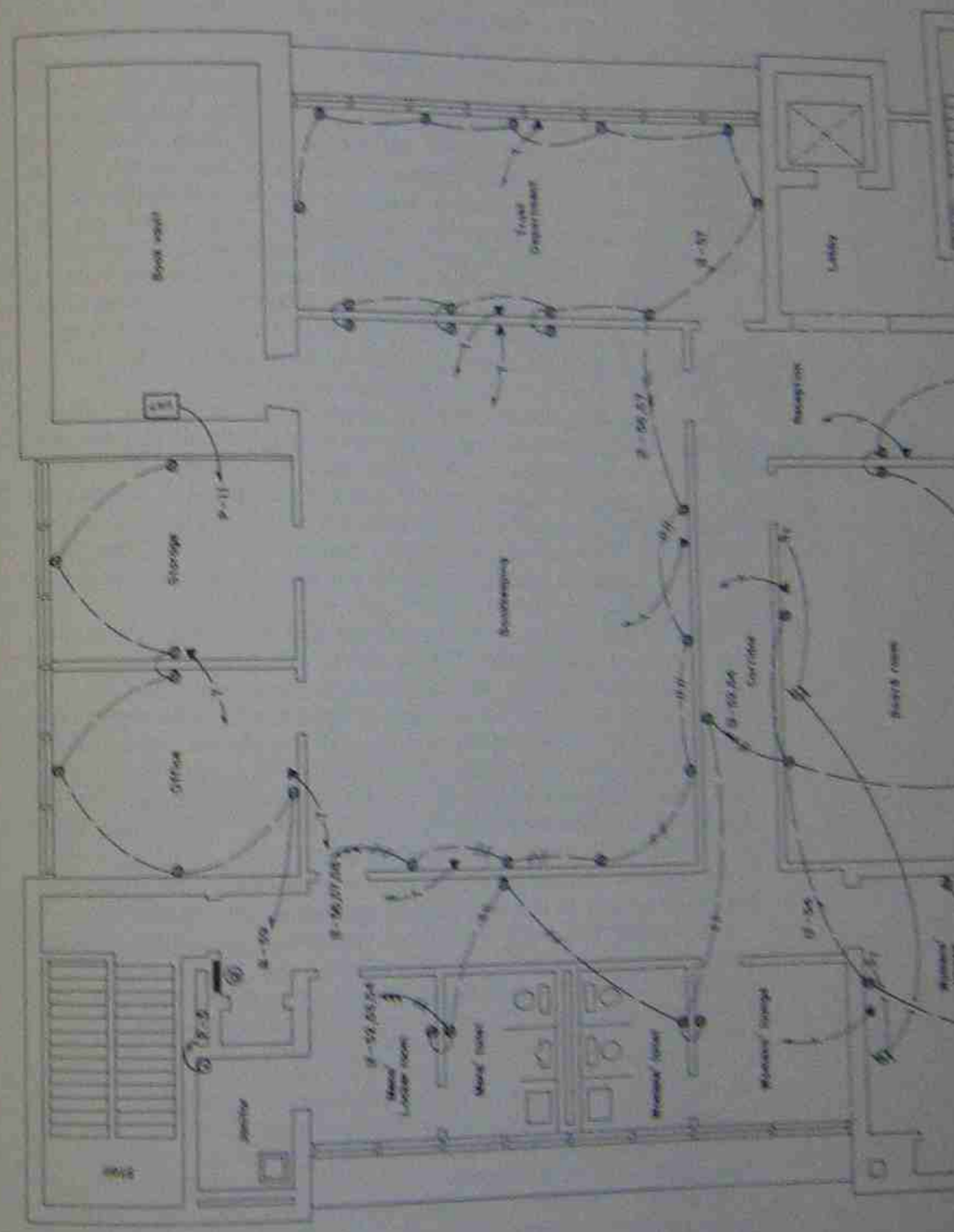


Fig. 6.7 Power plan of main banking level: Main Banking Level – Power.



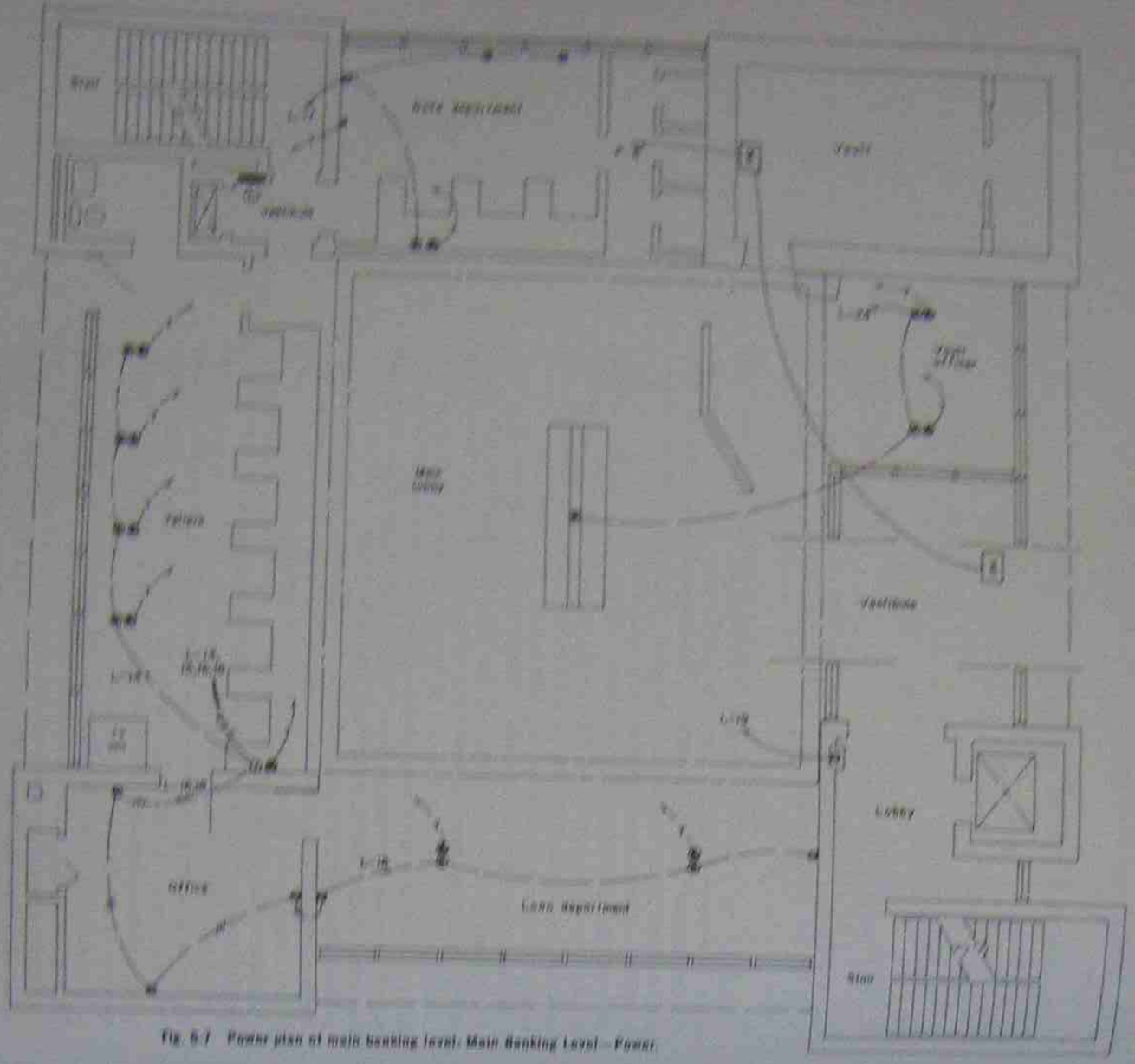


Fig. 5.7 Power plan of main banking level: Main Banking Level – Power

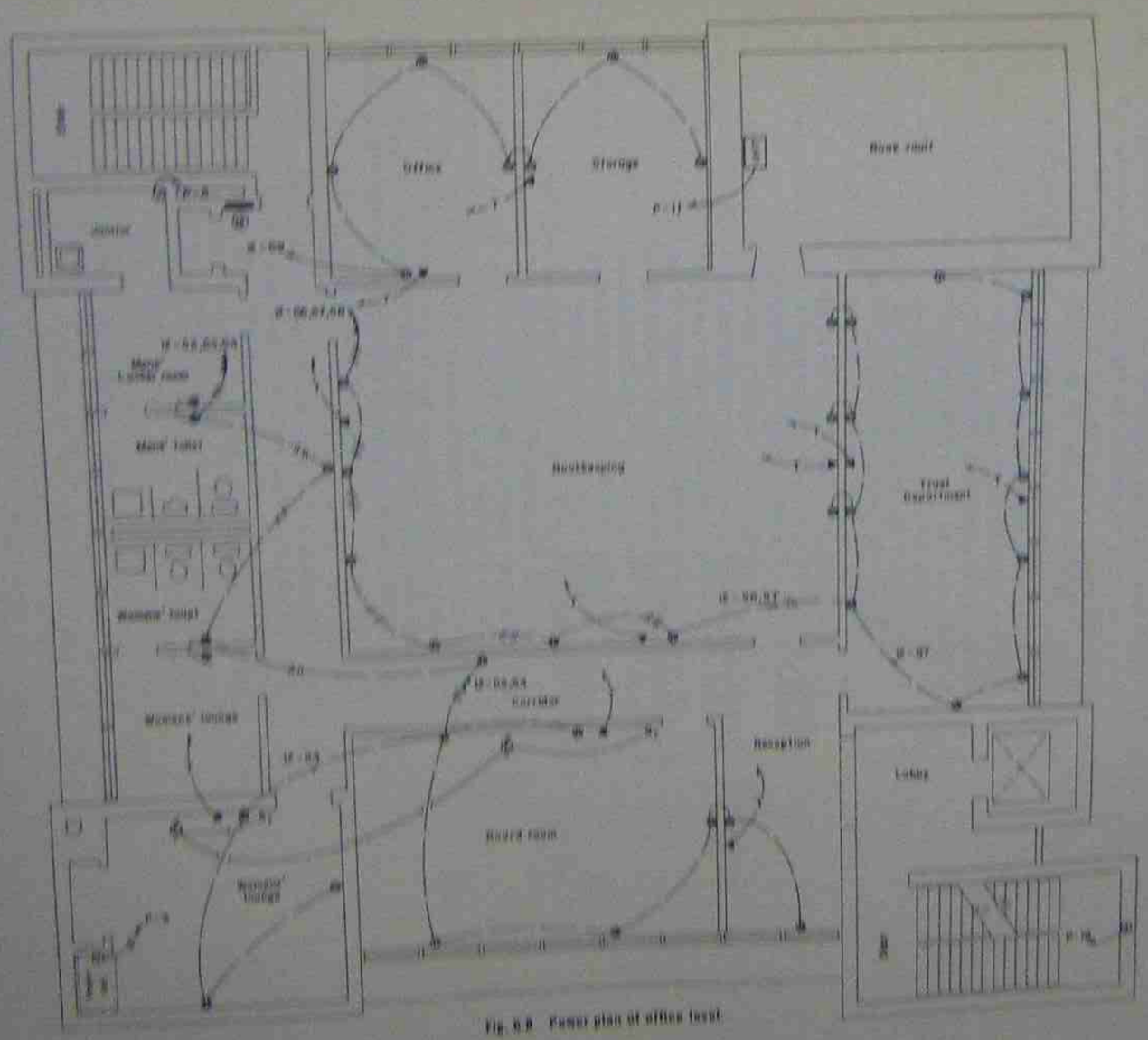


Fig. 5.8 Power plan of office level

to one circuit that also runs to panel L, but this time it is connected to circuit 24.

All other floor- and wall-mounted receptacles are connected to circuits and run to panel L. The two wall-mounted duplex receptacles and the three floor receptacles in the loading department area, as well as the receptacles in the adjacent office and boiler area, run to a junction box before a home run is run to panel L. Since there are four circuits in this home run, six conductors must be provided, because on a three-phase, 4-wire wye-connected service only three circuits may be installed on a common neutral (this would consist of four wires—three hot wires and a neutral). If another circuit is pulled in the same raceway, such as in our case, another hot wire and another neutral are required. Thus, six conductors are required, as indicated by the six slash marks in the circuit on the drawings.

The circuit designated P-6 in Fig. 6-7 feeds the blower motors in unit heater 1 (UH1) and unit heater 2 (UH2). Each telephone circuit home run consists of a ¾-in. empty conduit with a galvanized pull wire in each; this may be designated either in the symbol list or in the written specifications.

Three wall-mounted duplex receptacles and one floor-mounted receptacle in the note department are all fed on one circuit running to panel L, as shown, and connected to circuit 17.

Although the designer did not specify an outlet in the stairs or vestibule, one would be advisable for use by the janitor for connecting floor polishers, vacuum cleaners, and the like. Also an outlet near the sink in the lavatory may be useful for those who may want to use an electric shaver.

Another level of the bank just described is shown in Fig. 6-8. On this level (designated Office Level) all duplex receptacles and telephone outlets are wall-mounted. Since most of the outlets were provided for low-power-consuming electronic calculators, up to seven duplex receptacles are shown on a circuit.

The telephone outlets are again fed by an empty ¾-in. conduit with a galvanized pull wire. The pull wire is to enable the telephone company personnel to more easily "fish" their telephone cables through the empty conduit.

All circuits on this level run to panelboard L2, and are numbered according to the designated circuits on the panel.

The junction box with a separate two-wire circuit (208 V) is for a combination sink-refrigerator-cooking unit. Another circuit is required to feed the two exhaust fans shown on the drawing, one in the board room and the other in the women's lounge.

Chapter 7
Power Wiring for Special Outlets

The electric motor provides a means of converting electrical energy into mechanical energy and is classified according to:

1. Size, in horsepower
2. Type of application
3. Electrical characteristics
4. Mechanical protection
5. Type of cooling
6. Speed and speed control

Electric motors range in size from small, fractional-horsepower 120-V motors to very large, high-voltage synchronous motors. They are designed for light or heavy duty and also for general-purpose, definite-purpose, or special-purpose types of application. Electrical characteristics will include voltage, frequency, alternating or direct current, type of wiring, and phase (in the case of ac motors). Mechanical protection and type of cooling usually refer to the motor housing, that is, open machine, protected machine, dripproof machine, splashproof machine, totally enclosed machine, explosionproof totally enclosed fan-cooled machine, etc.

Starting and speed-control equipment varies from simple thermal tumbler switches to large, switch-gear-type controllers. The type of controller depends basically upon the motor to be controlled, the type of control circuit, and the location of the controller. Usually the controller is mounted adjacent to the motor or in its immediate vicinity. Sometimes, however, the controller may be located some distance away, e.g., in a motor-control center. The control center may consist of a group of individual motor controllers or a factory-built self-contained unit having all the motor controllers installed in it.

Motor controllers are available for manual or automatic operation, either at the controller or at a point remote from the controller and the motor. Any number of remote push-button stations may be used with automatic controllers.

When a disconnecting means is required for the motor, it may be a separate externally operated switch, or it may be combined in the same enclosure as the controller. In some instances the motor circuit disconnecting means may serve as the motor disconnect.

The garbage disposal shown by symbol and notation on the floor plan in Fig. 7-1 is rated at 7.5 A at 120 V. A separate 15-A, 120-V branch circuit is shown going to panel A from the junction box provided for connection purposes on the disposal unit. Most garbage-disposal units are powered by split-phase, 120-V motors of between ⅓- and ½-hp rating; and according to the National Electrical Code, running-overcurrent protection is required and must not exceed 125 percent of the full-load current rating of the motor.

The garbage-disposal unit shown in Fig. 7-1 was provided with a running-overcurrent protection by using a thermal protector ("heater") built into the unit. This thermal protector is of the manual-reset type. In other units, however, automatic resetting of the thermal protector is featured.

Where running-overcurrent protection is an integral part of the disposal unit, the electrical designer merely shows a circuit feeding the unit, and a regular toggle switch if needed for control. However, where running-overcurrent protection is not an integral part of the disposal unit, the designer must specify one such as that shown on the drawing in Fig. 7-2.



Fig. 7-1 Floor plan showing garbage disposal by symbol and notation.

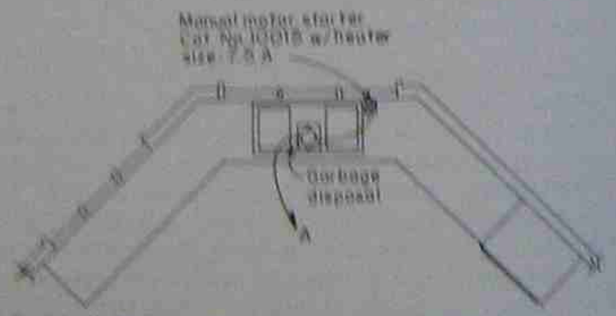


Fig. 7-2 Method of showing running-overcurrent protection for a garbage disposal unit on working drawings.

EXHAUST FANS

Exhaust fans are another type of motor-driven device that uses electric current for power. They may be equipped with an integral pull-chain switch for starting and stopping, or a separate wall switch may be used for control. When an automatic system of humidity control is desired, these fans may be controlled with a humidistat.

Single-speed or multispeed exhaust fans used for ventilating residential kitchens, bathrooms, utility rooms, or laundry rooms have a very small power demand and are usually connected to lighting circuits. Larger fans for commercial kitchens or industrial applications, however, require motors of several horsepower and usually are controlled by an elaborate motor control system.

The floor plan of the "Parking Level" of a bank building is shown in Fig. 7-3. The area labeled "Vest.," or vestibule, shows an exhaust fan (F) connected to panel P and controlled by a safety switch on a wall of this area. Note that this circuit is connected to circuit 10 of panel P since the home run is designated "P-10."

Power outlets in Fig. 7-3, other than duplex receptacles, include circuits feeding the blower fans for unit heaters UH3, UH4,

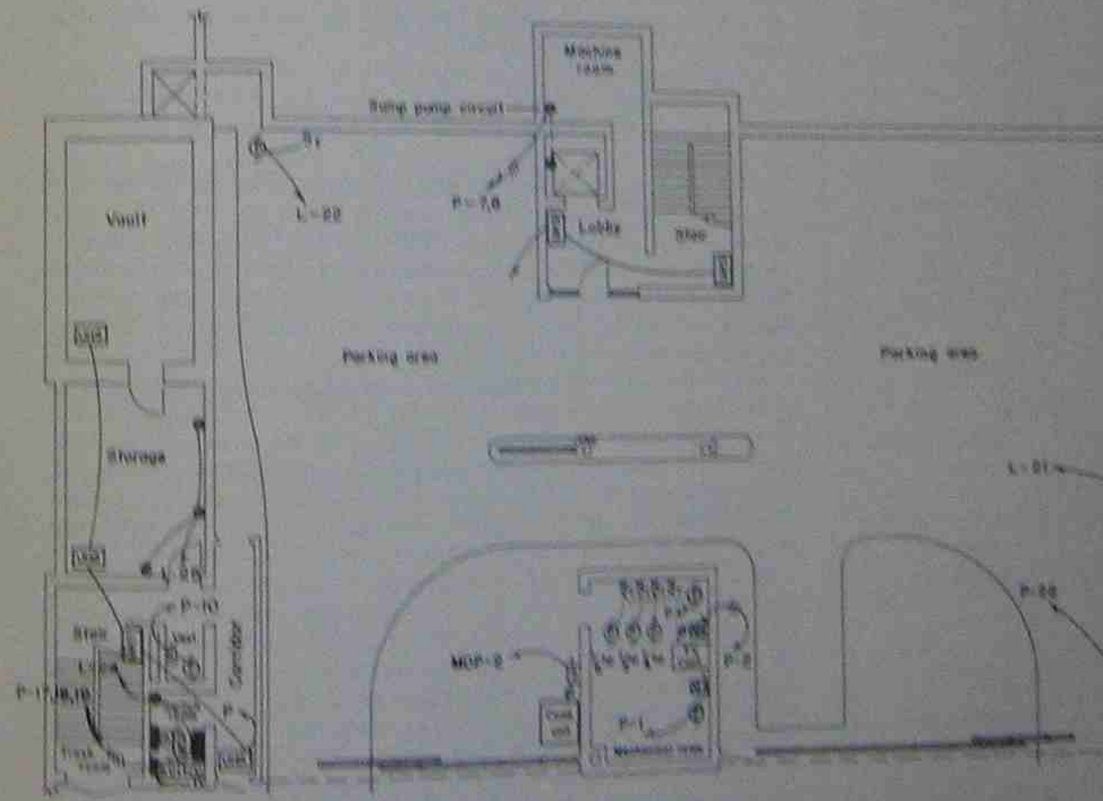


Fig. 7-3 Floor plan of the parking level of a bank building.

UH5, UH7, UH8, and UH9; a junction box connected to circuit L-21 for a telephone booth; a three-phase, 208-V, three-wire circuit (MDP-2) for a pad-mounted condensing unit; two other exhaust fans in the mechanical room (P-1 and P-2); a three-phase, 208-V, three-wire circuit for the closed-circuit television controls; a 120-V circuit feeding three small circulating pumps in the mechanical room; and another circulating pump (L-22) in another area.

All the circuits in Fig. 7-3, shown with solid lines, are to be installed concealed in the ceiling; those designated with a short dashed line are run in the ceiling or on the wall concealed, while those symbolized with the long dashed lines—such as shown for the receptacles in the storage area—are run concealed in the floor or slab.

A time clock used to control certain lights in the parking area is fed with three circuits connected to panel P, circuits 17, 18, and 19.

WATER HEATERS

Many water heaters used for residential and commercial applications require electric current for operation. The residential size may range from 1.2 to 4.5 kW, the smaller size at 120 V and all others at 240 V. Today the average residential electric water heater consists of a 52-gal tank with a maximum wattage of 4.5 kW. Depending upon the length of the circuit, the minimum wire size should be No. 10 AWG.

Water is heated in the storage tank by means of copper-clad electric heating elements which enter the side of the tank. These elements (usually two) project inward and are immersed in the water.

When two elements of 4.5 kW each are used in an electric water heater, the controls are usually wired so that only one element will operate at a time. That is, when the bottom thermostat calls for heat, the contacts close and allow current to flow through the heating element. Whether or not the upper thermostat is calling for heat, the contacts will not close as long as current flows in the lower element.

When the desired temperature is reached at the bottom thermostat, the contacts open and stop the flow of current. At this time, if the upper thermostat still calls for heat, the upper contacts will close and allow current to flow through this element. This method of control prevents the existence of a load of more than 4.5 kW. A wiring diagram showing the connections of the circuit just described is shown in Fig. 7-4.

In some cases it may be desirable to permit both the upper and the lower elements to become energized simultaneously should the thermostats indicate the need. This is true where a quick hot-water recovery is desired. In this case, two circuits capable of carrying the total amperage of each element should be provided; that is, each element will have its own circuit.

Each storage tank of a large commercial water heater may contain six or more elements with a rating of 20 kW or more. In such cases, the manufacturer's wiring diagram of the specific unit should be referred to before the electrical feeders are designed. The unit may require one large feeder, or it may require several smaller circuits for each element. One such wiring diagram is shown in Fig. 7-5.

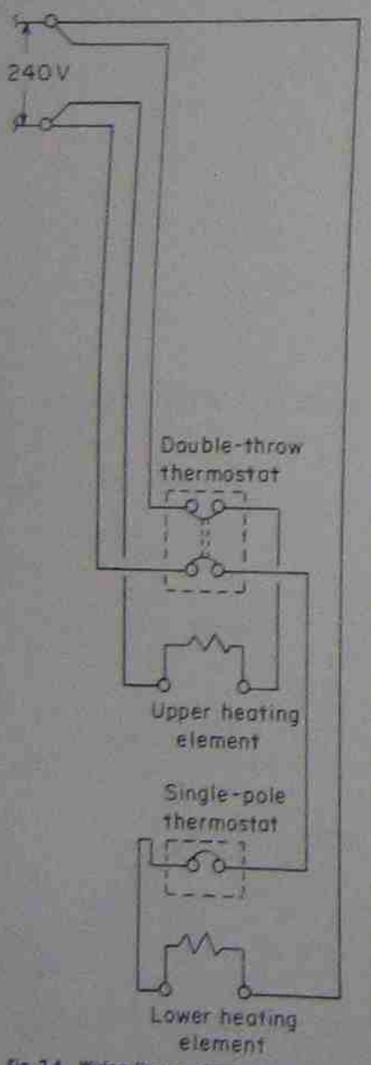


Fig. 7-4 Wiring diagram showing the connections for a water heater.

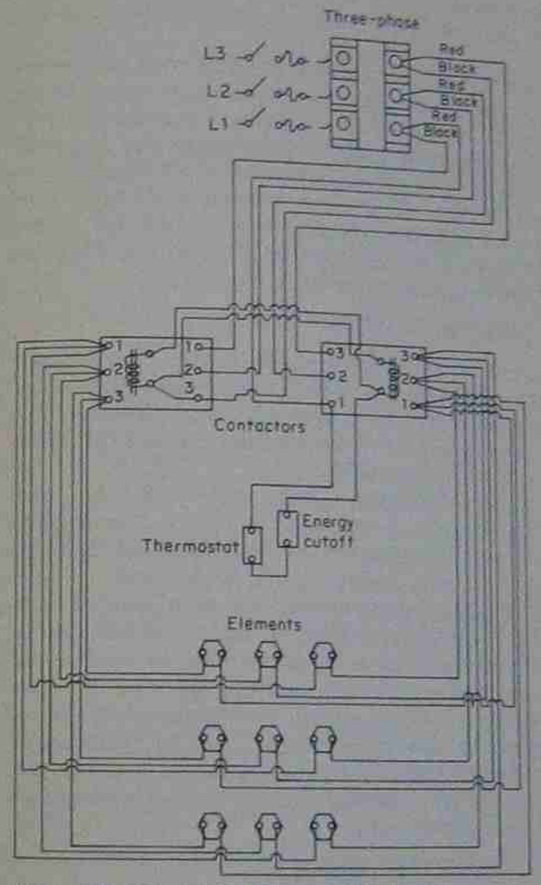


Fig. 7-5 Wiring diagram of a large commercial water heater.

CLOTHES-DRYER CIRCUITS

In addition to the receptacle circuits described in Chap. 6, most residences need circuits for special appliances of which the clothes dryer is one. The clothes-dryer circuit usually will be a 120/240-V, single-phase, three-wire circuit of No. 10 AWG wire, since most of the heating elements are 4.5 kW. A clothes-dryer circuit is shown in the residential floor plan in Fig. 7-6.

The clothes-dryer outlet in Fig. 7-6 indicates a 30-A, 250-V dryer receptacle. This is the most common method of providing electric power to clothes dryers. The dryer is then connected by plugging in a cord attached to the dryer.

Another method is to indicate a three-wire circuit run to the dryer location and then connected directly to a junction box on



Fig. 7-6 Method of showing clothes-dryer circuit on a residential floor plan.

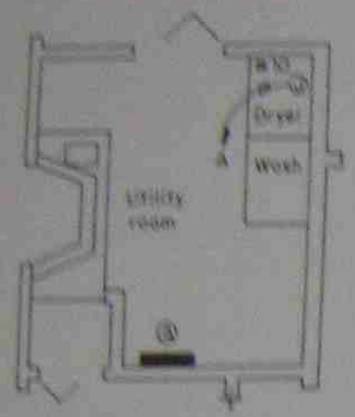


Fig. 7-7 Another method of indicating a three-wire clothes dryer circuit.

the dryer provided for that purpose. The plan view in Fig. 7-7 shows how this is indicated on a working drawing.

OVERHEAD GARAGE-DOOR OPENER

The motor symbols shown in the floor plan in Fig. 7-8 represent motors to operate the overhead garage door openers of this fire station.

Notice that a push button is located at each door to operate its respective door; that is, the three-button switch raises, stops, or lowers the door. Other push-button stations are also located in the console in the dispatch room and are connected in parallel with the one at each door, so that each door can be controlled from either location. An override switch is also provided in the console so that each group of doors may be raised simultaneously in case of an emergency. The wiring diagram for the control of these doors is shown in Fig. 7-9.

COOKING TOPS AND OVENS

The National Electrical Code permits both the cooking top and the wall-mounted oven to be connected to one circuit provided the circuit has ample capacity to serve both appliances. The diagram in Fig. 7-10 shows how this might be applied to a built-in cooking top and oven in a residence.

The No. 10 AWG tap conductors from the No. 6 AWG conductors must be as short as possible, that is, "no longer than necessary for servicing." Therefore two appliances of approximately 30-A rating each may be fed by one 50-A circuit.

However, since tapping or splicing the smaller-size conductors from the 50-A circuit will require extra junction boxes, cable or conduit connectors, and wire connectors, as well as additional labor for making the splices and connections, it is our opinion that it would be best to specify two separate 30-A circuits if the distance to the panelboard were of reasonable length. The two separate circuits would also offer greater protection in the event of a ground fault because of the lower-rated individual overcurrent protection.

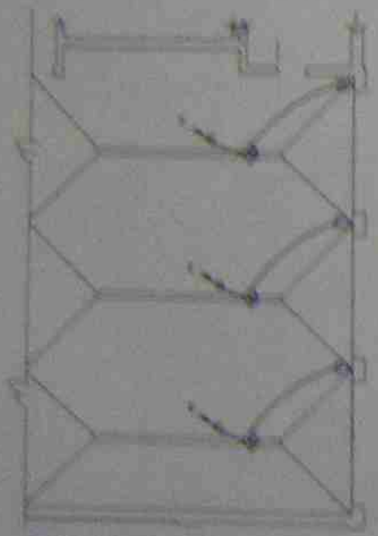


Fig. 7-8 Floor plan showing location of motors to operate overhead garage doors.

ELECTRIC RANGES

Single electric ranges are wired in much the manner of clothes dryers in that a single circuit (usually rated at 40–50 A) is run from the panel to a 250-V, 50-A "range receptacle." The electric range is then connected by means of a range cord, although the circuit can be connected directly to a junction box on the range provided for such a purpose. Figure 7-11 shows how a direct-connection circuit may be indicated on a working drawing, while Fig. 7-12 shows how the outlet would appear should a range receptacle be desired.

COMMERCIAL-KITCHEN POWER OUTLETS

Most commercial kitchens require a large number of electrical outlets to operate the various pieces of kitchen equipment, and because these outlets are special, a special way of showing the information on the electrical drawings is required.

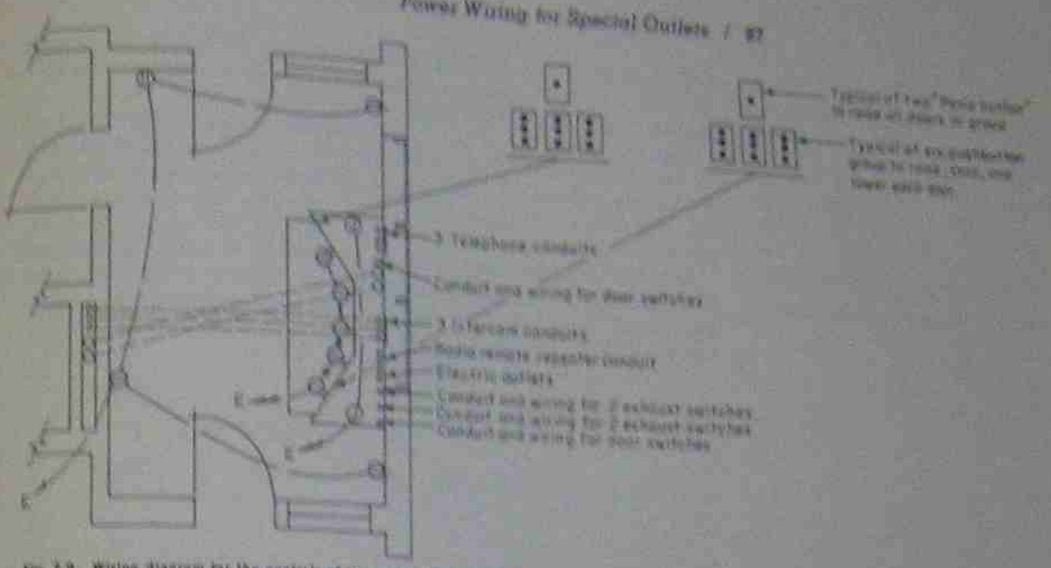


Fig. 7-9 Wiring diagram for the controls of the motors shown in Fig. 7-8. (NOTE: All wiring in console shall be run beneath floor. Use chase in wall directly behind console to run upward, provide and install one digital clock in console; flush-mounted 3½ × 6 × 4 in. deep. Allied Radio model ID-728-U.)

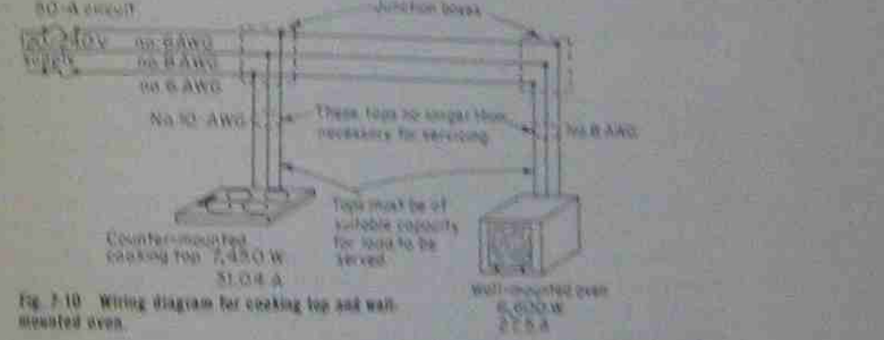


Fig. 7-10 Wiring diagram for cooking top and wall-mounted oven.



Fig. 7-11 Method of showing direct-connection circuit on a working drawing.

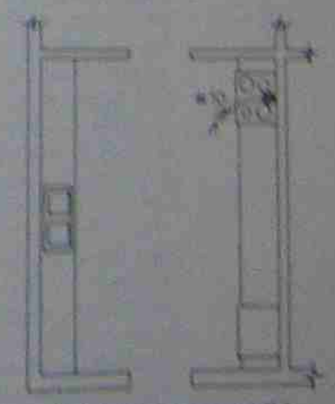


Fig. 7-12 Method of showing an outlet connection on a working drawing.



Fig. 7-13 Floor plan of a firehouse kitchen.

A floor plan of a kitchen is shown in Fig. 7-13. This particular kitchen is that of a firehouse and is used in relation to the adjacent meeting room for dinners and dances.

Because of the large number of outlets required in the kitchen in Fig. 7-13, the original drawing is too small to show all the necessary details of construction without becoming confusing. Therefore, the designer had the draftsman enlarge the floor plan to a scale of ¼ in. = 1 ft 0 in.; this is shown in Fig. 7-14.

After the kitchen floor plan was drawn to a larger scale and the pieces of kitchen equipment were drawn, each piece of equipment was given an identification number enclosed in a hexagon, as shown in Fig. 7-14.

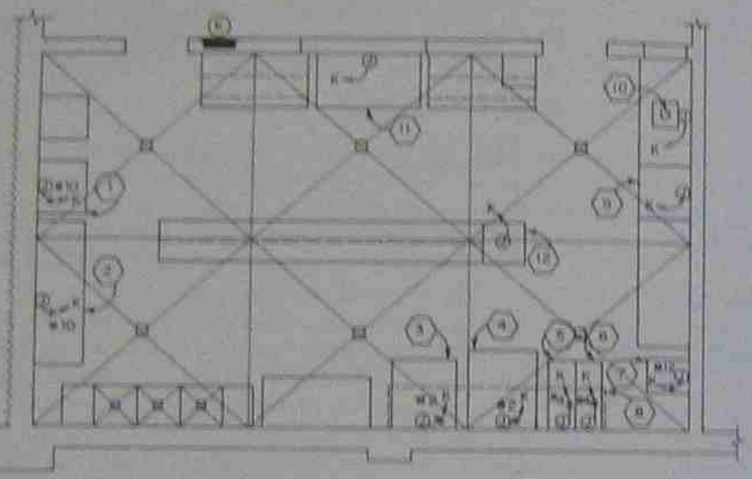


Fig. 7-14 Detailed floor plan of a firehouse kitchen.

Those pieces of kitchen equipment requiring electric power were provided with the symbol to indicate that a junction box or a direct connection is required. The written specifications accompanying the drawings instructed the contractor to verify exact requirements with the kitchen-equipment supplier, that is, the mounting height of the outlets, etc.

From each junction box, a home run is indicated to panel K. The absence of slash marks indicates a circuit of two No. 12 AWG conductors. A circuit other than this is indicated by slash marks representing the number of conductors in the circuit, and the size of the conductors is indicated by a numeral directly adjacent to the slash marks.

The identifying numbers, the junction boxes with home runs, and panel K are also shown in the floor-plan view of the kitchen in Fig. 7-14. The drawing, however, still lacks some of the information required for the electrical installation. First, the contractor needs to know the name of each piece of equipment, the electrical load required for each, and the overcurrent protection required for each.

The kitchen equipment schedule shown in Fig. 7-15 is one method of conveying this information to the contractor.

Kitchen Equipment Schedule

Equip. no.	Designation	kW or HP	Volts	Connection			Furnished by	Remarks
				Wire	Conduit	OC		
1	Freezer	2 kW	120	#10	¾"	30A	Owner	Provide outlet
2	Refrigerator	1.7kW	120	#12	¾"	20A		Provide outlet
3	Range	12kW	208	#3	1¼"	60A		Direct connection
4	Oven	10kW	208	#3	1¼"	60A		Direct connection
5	Fryer #1	3.5kW	208	#8	1"	30A		Direct connection
6	Fryer #2	3.5kW	208	#8	1"	30A		Direct connection
7	Mixer	1Hp	208	#12	¾"	20A		Direct connection
8	Kitchen hood	1Hp	120	#12	¾"	20A		Provide outlet
9	Dishwasher	5kW	208	#12	¾"	20A		Direct connection
10	Disposall	1Hp	208	#12	¾"	20A		Direct connection
11	Hot food table		208	#10	¾"	30A		Provide outlet
12	Ice maker			#10	¾"	30A		Provide outlet

Fig. 7-15 Kitchen equipment schedule for Fig. 7-14.

The "Equip. no." column lists the identifying numbers of each piece of equipment shown in the floor-plan view in Fig. 7-14. The second column, "Designation," names the corresponding pieces of equipment, while the next five columns indicate the horsepower or kilowatts, volts, wire size, conduit size, and overcurrent protection, respectively. The next column indicates that all the pieces of equipment are furnished by others. The final column indicates the type of connection; that is, direct connection or outlet.

Therefore, the floor-plan view in Fig. 7-14 and the kitchen equipment schedule in Fig. 7-15, combined with the written specifications, leave little doubt as to the exact requirements for the electrical installation for the area. A panelboard schedule, shown elsewhere on the drawings, also indicates on which circuit each piece of equipment is connected, the trip amperes of each circuit breaker, and the type of frame required.

SCHEDULES

Since we have just described one type of kitchen equipment schedule, a word about schedules in general is warranted at this point.

A schedule is a systematic method of presenting notes or lists of equipment on a drawing in tabular form, and when properly organized, it is a powerful time-saving device for the draftsman and designer. A good schedule will also save valuable time for the specification writer as well as the worker on the job. For example, the kitchen equipment schedule shown in Fig. 7-15 lists all the information necessary for a correct installation.

Sometimes all the same information can be found in the written specifications of a project, but the workers do not always carry the specifications, whereas they usually do have constant access to the working drawings. Therefore, the schedule is an excellent means of providing essential information in a clear, concise, and accurate manner, allowing the workers to carry out their assignments in the least amount of time.

Other types of electrical schedules can be found in other chapters and in Appendix B of this book.

Chapter 8

Power Wiring for Heating, Ventilating, and Air Conditioning

Circuit requirements for HVAC (heating, ventilating, and air conditioning) equipment do not greatly differ from those for any other circuit or feeder, but the electrical designer must carefully study the manufacturer's wiring diagram for the equipment in question.

For example, an electric furnace may have a total rating of 24 kW. It would then be natural for the designer to calculate the circuit size as follows for a 208-V three-phase system:

$$\frac{24{,}000\ \text{W}}{\sqrt{3} \times 208\ \text{V}} \times 1.25 = 80.39\ \text{A}$$

Using this as a basis, the designer would specify a conductor rated at 80.39 A minimum. However, the resistance-type heaters in a furnace of this type will usually be connected in steps, that is, four electric heaters of 6 kW each. If one conductor is used for the feeder, another subpanel would have to be installed in

order to separately feed each of the four heaters. If the designer did not specify this, the electrical contractor would be entitled to an extra billing and would cost someone additional money.

Of course, the electric furnace may have its own built-in controls dividing the 80.3-A circuit into four subcircuits, but the information must be verified with the specifications furnished by the equipment manufacturer before the electrical design is made.

If the electric furnace under discussion required that the circuit be divided into four 30-A circuits, for example the designer could specify a 100-A subpanel near the furnace and then use three three-pole 30-A circuit breakers to feed the four electric resistance heaters. It may be best, in some cases, to run the four separate circuits from the original panel directly to the contactors controlling the heating elements. But, the point we are trying to make is that all circuits for HVAC equipment must be verified in order to ascertain the exact requirements.

RESIDENTIAL ELECTRIC HEATING SYSTEM

Residential electric heating units are available in baseboard, wall, floor-mounted, and ceiling heat cable—to name a few—and all are becoming very popular as a means of heating residential buildings. Some of the advantages of electric heat follow.

1. Electric heat is safer than combustible fuels.
2. It is quiet in operation.
3. The initial installation cost is usually lower since electric heat requires no chimneys, little if any storage space, and no fuel tanks.
4. It is the cleanest type of heat available.
5. Each room may have its own individual thermostat which enables the rooms to have variable temperatures to suit each occupant.

Electric heat may also be supplied by a duct system similar in every respect to a conventional oil, gas, or coal hot-air system except that the heat comes either from electric heating elements or a heat pump. When a ducted electric heating system is used, humidity control, air conditioning, and ventilation may also be combined with the system.

In studying the floor plan in Fig. 8-1, we find that there are three ventilating units in the bay area of a firehouse which must have power supplied. These units are actually installed on the roof above the bay area. Each unit consists of a steel housing designed to be mounted on a flat roof and a blower unit which is enclosed in the steel housing.

The blower unit is made up of a single-phase 208-V motor driving a propeller-type fan by means of a V-belt drive. This arrangement results in quieter operation than using a direct drive. A section of this fan, showing the internal construction as well as the electrical connecting box, can be seen in Fig. 8-2. The circuit is shown in the floor plan in Fig. 8-1 and is drawn to indicate a home run to panel P. By referring to the panelboard schedule for panel P, we can determine the type

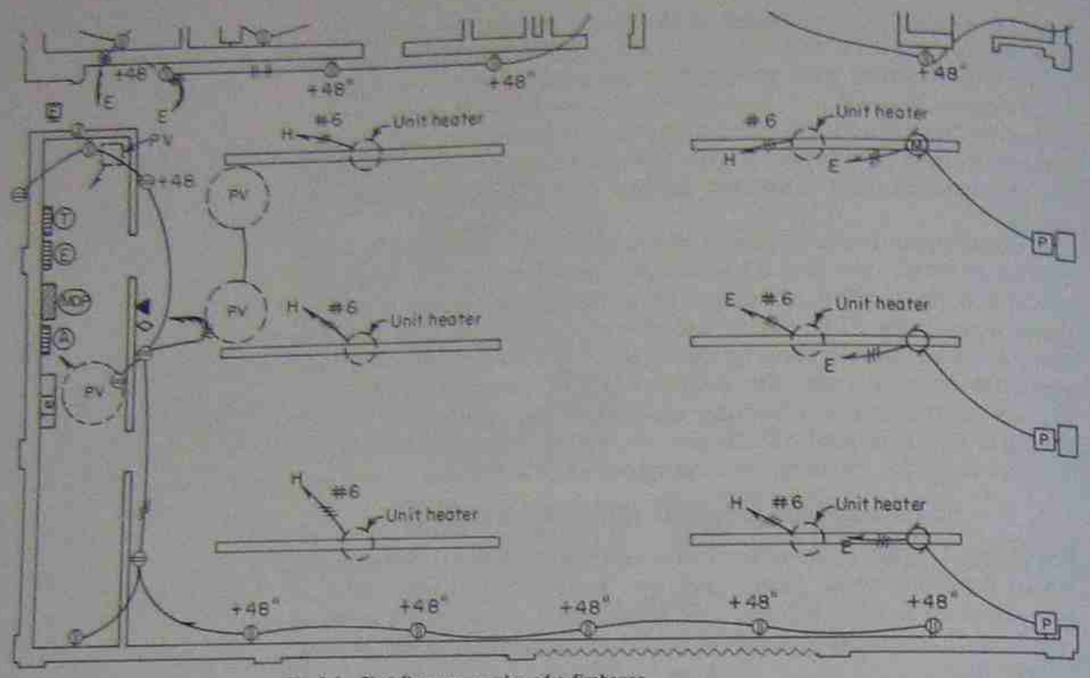


Fig. 8-1 First-floor power plan of a firehouse.

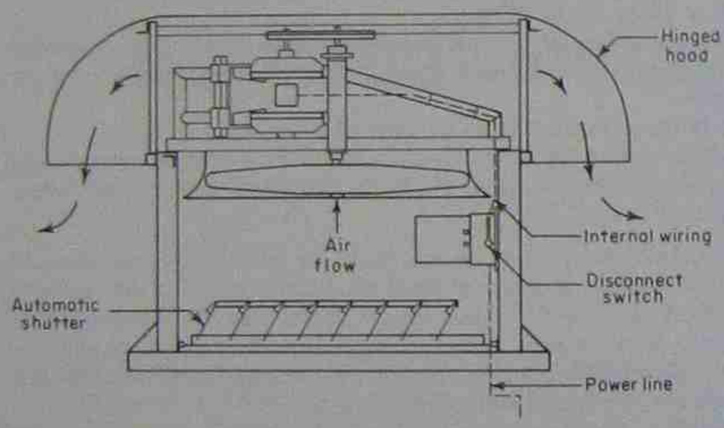


Fig. 8-2 Section of a ventilating fan showing electrical connections.

of circuit breaker provided for overcurrent protection; in this case, it is a two-pole, 20-A circuit breaker. The conductors consist of two No. 12 AWG wires in ½-in. conduit.

The power-riser diagram for this firehouse is shown in Fig. 8-3. Panel H and panel P—one located in the mechanical room and the other located on the mezzanine level—furnish an adequate power supply for all heating and cooling equipment such as electric unit heaters, condensing units, air-handling units, etc., all of which are shown on the floor plan in Fig. 8-1.

The unit heaters are three-phase, 208-V and are rated at 15 kW each. Therefore a 1-in. conduit containing three No. 6

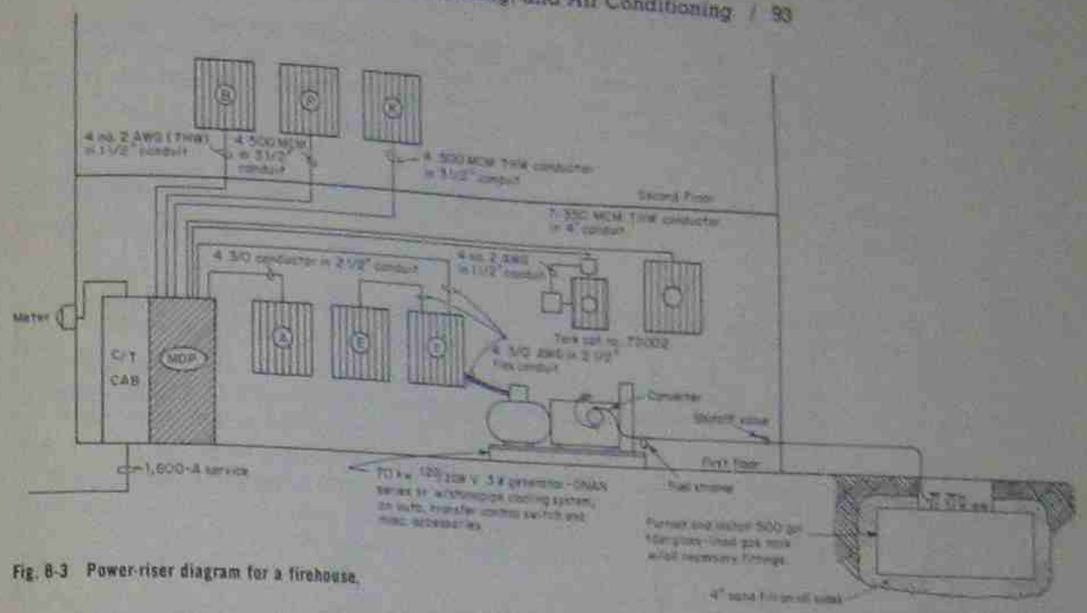


Fig. 8-3 Power-riser diagram for a firehouse.

AWG THW conductors was needed to feed each heater. As mentioned previously, all the unit heaters obtain their power from panel H with the exception of two. These two heaters are run to panel E, which is connected to the 70-kW emergency generator in case of a power failure. In the event that a power failure occurs, the generator controls will automatically start the generator and at the same time transfer the loads on panel E to the generator. While the two unit heaters on the emergency panel will not provide comfortable temperatures in the bay areas during extremely cold days, they will keep the temperature above freezing, which is very important in a building such as the one described.

Since most heating and cooling equipment is installed by a "mechanical" or heating and cooling contractor, the electrical plans only need to show the feeder circuits. Even the control wiring of the various pieces of heating and cooling equipment is usually the responsibility of the heating and cooling contractor and are therefore not shown on the electrical drawings.

Motor starters are items which have been confusing for both electrical contractors and heating and cooling contractors, in that the starters are usually furnished by the heating and cooling contractor, but are usually mounted and connected by the electrical contractor. The reasons are that the mechanical contractor should be responsible for obtaining the correct starter for the piece of equipment furnished; yet the mounting and wiring of the starter should be the electrical contractor's responsibility since experienced personnel should work on the voltages usually encountered in motor starter wiring—usually 240 to 480 V.

At times an electrical contractor will be responsible for the entire installation of an electric heating system such as the one

shown in the floor plans of a church-education building in Figs. 8-4 and 8-5. The reason is of course that no ductwork is involved in this installation, and the job is entirely related to the electrical industry.

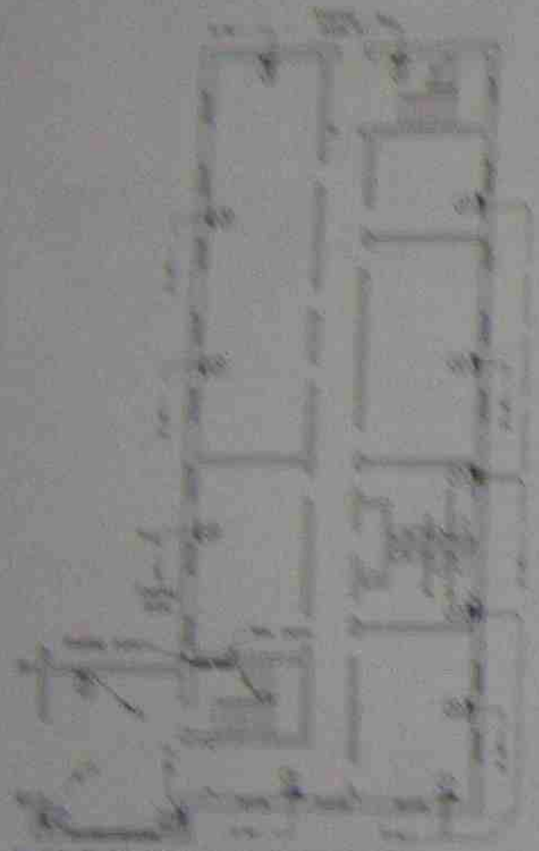


Fig. 8-4 Third-floor plan of a church-education building.

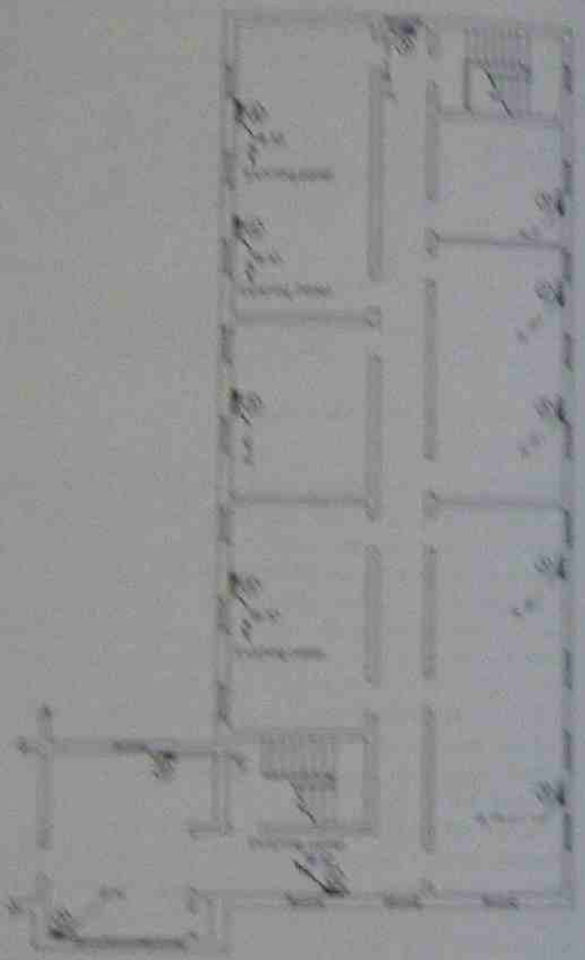


Fig. 8-5 Second-floor plan of a church-education building.

The first-floor plan in Fig. 8-4 shows several wall-mounted forced-air heaters indicated by the symbol ⓗ. An identifying number is also located at each heater. By referring to the electric heat schedule in Fig. 8-6, we see that the manufacturer, catalog number, dimensions, voltage, mounting, and wattage of each type can be found.

This is an existing building; therefore, to save labor, all wiring will be run exposed, with cutting and patching of existing structures.

To conceal as much of the wiring as possible, it was decided to run the circuits for the heaters on the first level in a trench

Mark	Manufacturer's designation	Dimensions	Volts	Mounting	Watts
A	Electromode cat. no. 1042(-) 3	9¾" x 6 1/4" x 3 1/4"	240/	Surface	1,000 Watts
B	Electromode cat. no. 1042(-) 4	9¾" x 6 1/4" x 3 1/4"	240/	Surface	1,500 Watts
C	Electromode cat. no. 1042(-) 5	9¾" x 6 1/4" x 3 1/4"			2,000 Watts
D	Electromode cat. no. 1042(-) 6	9¾" x 6 1/4" x 3 1/4"			2,500 Watts
E	Electromode cat. no. 1042(-) 8	9¾" x 6 1/4" x 3 1/4"			3,000 Watts

Fig. 8-6 Electric heat schedule.

outside of the building and to lead the cable through the wall at each heater. A note on the drawing reads as follows:

NOTE: All electric wall heaters on the first-floor level shall be fed with type H.F. cable run in a shallow trench outside of building. See detail on this sheet for construction.

The detail drawing appeared as shown in Fig. 8-7.

The second-floor plan shown in Fig. 8-5 required a slightly different method of feeding, since there was no place to conceal the cable because it was on the first floor. A note appeared on the drawing as follows:

NOTE: Electric wall heaters on second-floor level shall be fed by one 1½-in. conduit from panel 'F' up through corner of stairwell terminating in a 12- by 12- by 6-in. deep junction box with block cover. Run No. 500 Wiremold on wall surface from junction box to wall heater.

See detail in Fig. 8-8.

The panelboard schedule appears in Fig. 8-9.

Many electrical designers and contractors are required to calculate the heat loss in residences because more and more homes now utilize baseboard electric heaters as their only source of heat. Since there have been many methods previously described for calculating heat loss, it will not be covered in this chapter. However, a good reference for residential heat-loss calculations is the book Making Electrical Calculations by J. F.

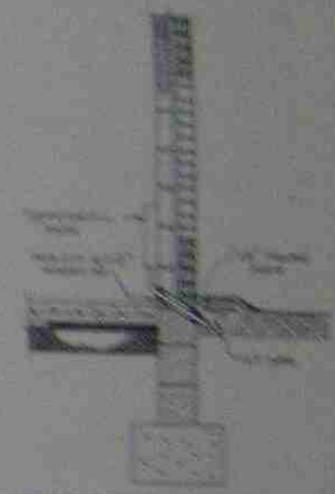


Fig. 8-7 Electric wall heating method of feeding cable in a shallow trench outside of building.

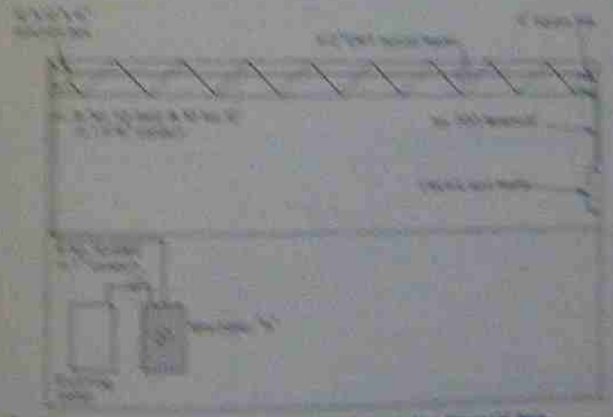


Fig. 8-8 Electric wall heating method of connecting Wiremold from a junction box to a wall heater.

Note: Panels not shown Fig. 8-5 have conduit feeders.

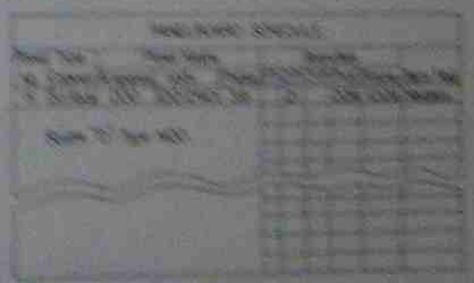


Fig. 8-9 Panelboard schedule.

McPartland, published in 1975 by *Electrical Construction and Maintenance* Magazine, New York.

Three working drawings using electric heat are shown in Figs. 8-10, 8-11, and 8-12. Related wiring, location of the heaters,

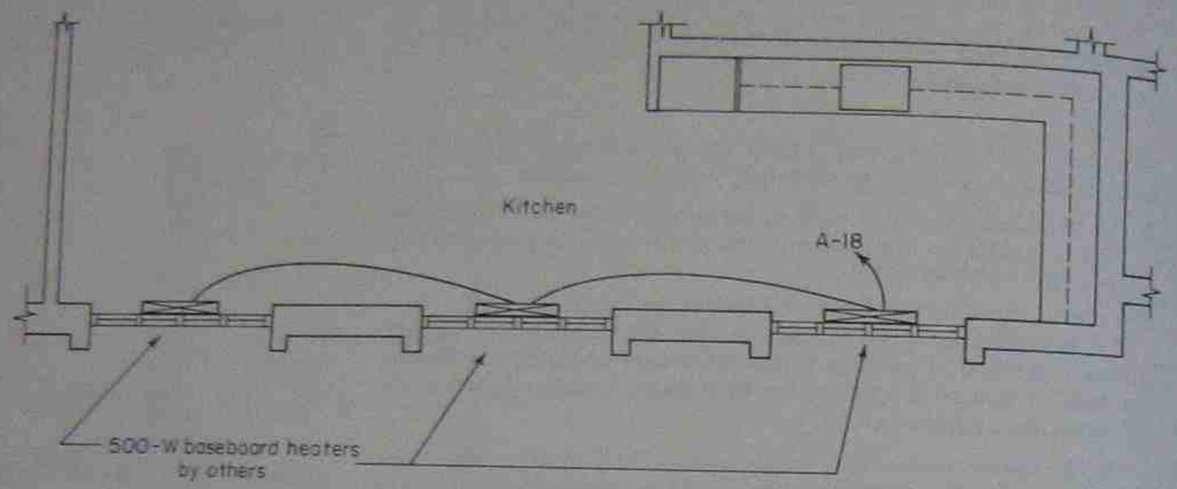


Fig. 8-10 How electric-heating equipment is shown on a working drawing.

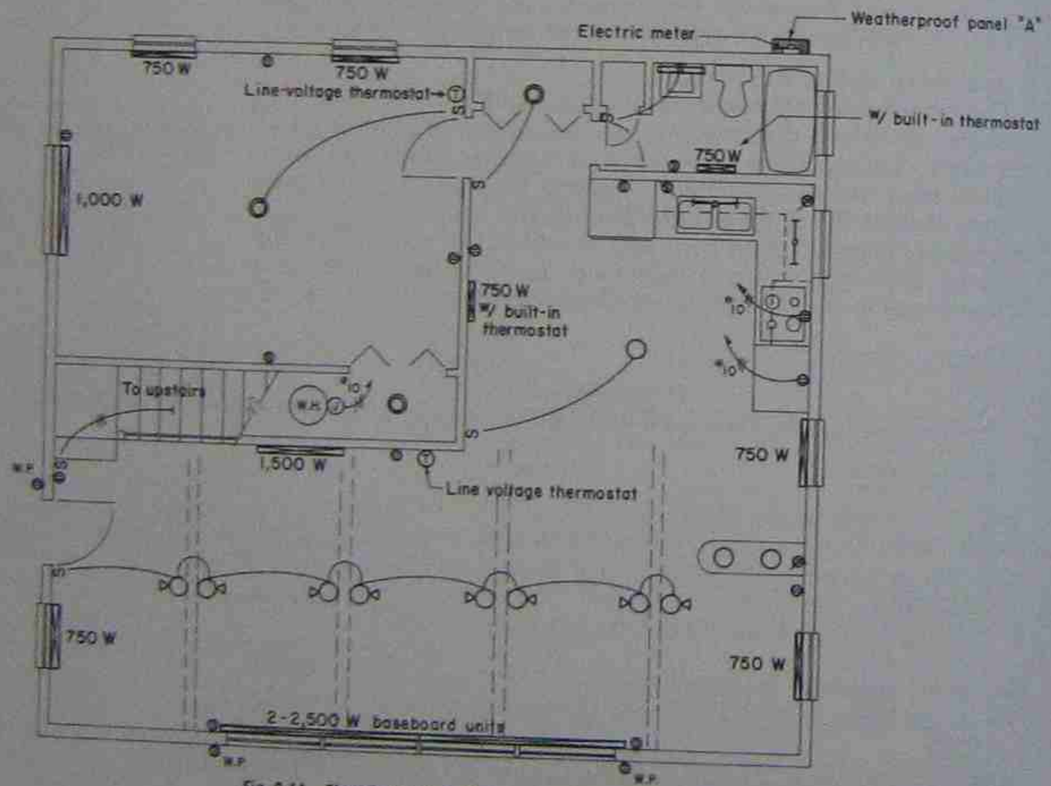
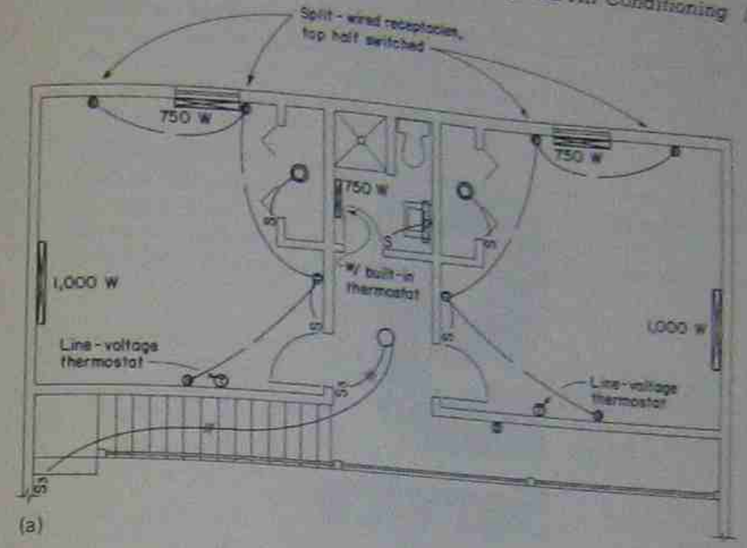
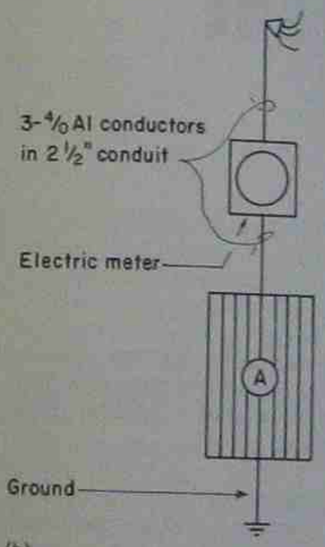


Fig. 8-11 Electric heating shown on a working drawing, first-floor plan.



(a)



Weatherproof 200-A I ϕ panel to contain:

1-15A ground fault protector for outside receptacles.
2-20A IP CB for appliance circuits.
3-15A IP CB for receptacles.
3-15A IP CB for lights.
1-30A 2P CB for cooking top.
1-30A 2P CB for oven.
1-30A 2P CB for water heater.
10-20A 2P CB for electric heat.
5-Spares

(b)

Fig. 8-12 (*a*) Electric heating shown on a working drawing, second-floor plan corresponding to plan in Fig. 8-11; (*b*) power-riser diagram for the entire building.

etc., are shown on the floor plan. The actual working drawings also used panelboard schedules and electric heat schedules to give further details of construction.

Chapter 9
Service Equipment

In the order of passage of electrical energy from the power company's lines to the point of first overcurrent protection and disconnecting means in the building, these are the following generally recognized sections of an electrical system:

Service Drop: The overhead conductors, through which electrical service is supplied, between the last power company pole and the point of their connection to the service facilities located at the building or other support used for the purpose

Service Entrance: All components between the point of termination of the overhead service drop or underground service lateral and the building main disconnecting device, with the exception of the power company's metering equipment

Service-Entrance Conductors: The conductors between the point of termination of the overhead service drop or underground service lateral and the main disconnecting device in the building

Service Lateral: The underground conductors, through which service is supplied, between the power company's distribution facilities and the first point of their connection to the building or area service facilities located at the building or other support used for the purpose

Service-Entrance Equipment: Provides overcurrent protection to the feeder and service conductors; provides a means of disconnecting the feeders from energized service conductors; and provides a means of measuring the energy used by the use of metering equipment

AVAILABLE VOLTAGES

The power company usually supplies alternating current at a frequency of 60 hertz (Hz), or cycles per second. The standard voltages which are normally available are listed in the following table.

Voltage	Phase	Wires
120/240	1	3
120/208	3	4 wye
120/240	3	4 delta
277/480	3	4 wye
2,400	3	3 delta
4,160	3	4 wye
12,470	3	4 wye
34,500	3	3

The availability of the above voltages is dependent upon the power company's available facilities, method of service, and the size and character of the customer's load.

Service for small lighting, heating, and power installations will normally be supplied as single-phase, 120/240-V, three-wire.

When three-phase service is required, 120/208-V or 277/480-V wye is usually preferred over delta as the "red-leg" phase of the delta prevents proper balancing of 120-V loads.

Three-phase service may also be made available at 2,400, 4,160, 12,470 and 34,500 V. Service at these voltages is for large power installations and is normally provided from an individual customer substation. When service is taken at 2,400 or 4,160 V, it is usually necessary for the consulting engineer to design the 15-kV class equipment, which includes underground cable, cutouts, arresters, primary breakers, primary terminations, transformer vaults, etc.

As mentioned previously, most services are delivered at 120/240-V single-phase or 102/208-V three-phase. However, 277/480-V services are quite common in the larger buildings today. In such cases, most of the power equipment, such as heating and cooling equipment, pumps, motors, etc., are rated for 480-V operation. Convenience receptacles, however, along with some possible lighting circuits, will require 120 V. In such instances, stepdown transformers are used to transform the voltage from 277/480 V of the primary circuit to 120/208 V for the

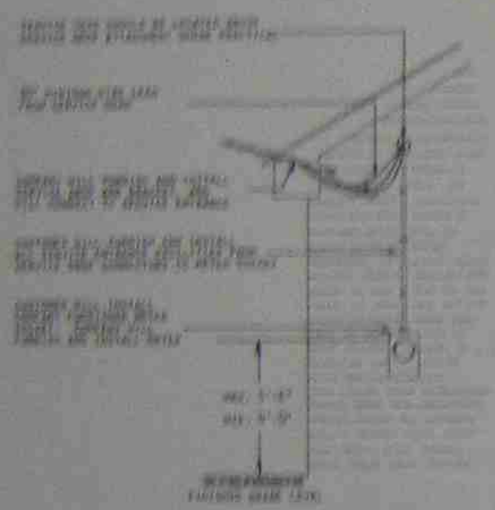
secondary section. These transformers are usually of the "dry" type, and the capacity or size will depend upon the load requirements.

Overhead Service Installations

A safe, substantial support is necessary for the power company's overhead service. When designing or specifying any electrical service, requirements set forth in the National Electrical Code must be followed as well as the requirements of the local power company.

Figures 9-1 through 9-11 show various overhead services and meter installations that are acceptable to most power companies. Other examples of services which are of a higher current-carrying capacity, as well as practical applications of all types, are given later in this chapter.

TYPICAL 200 AMP. OR LESS OVERHEAD SERVICE INSTALLATION



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   (d) [illegible]
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4. [illegible]

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Fig. 9-1

TYPICAL 200 AMP. OR LESS OVERHEAD SERVICE MAST INSTALLATION

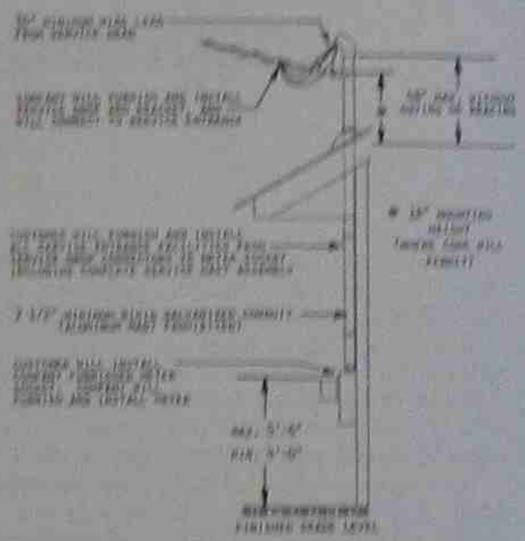

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Fig. 9-2

TYPICAL 200 AMP. OR LESS PERMANENT OVERHEAD SERVICE POLE (PERMANENT FEEDER)

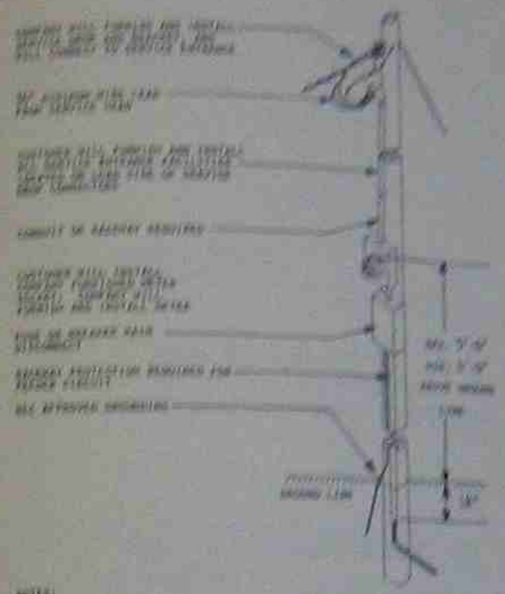

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Fig. 9-3

TYPICAL 200 AMP. OR LESS PERMANENT OVERHEAD SERVICE POLE (WEATHERPROOF POWER OUTLET)

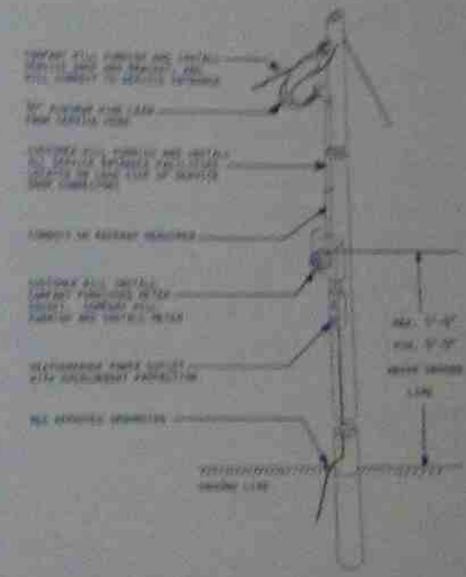

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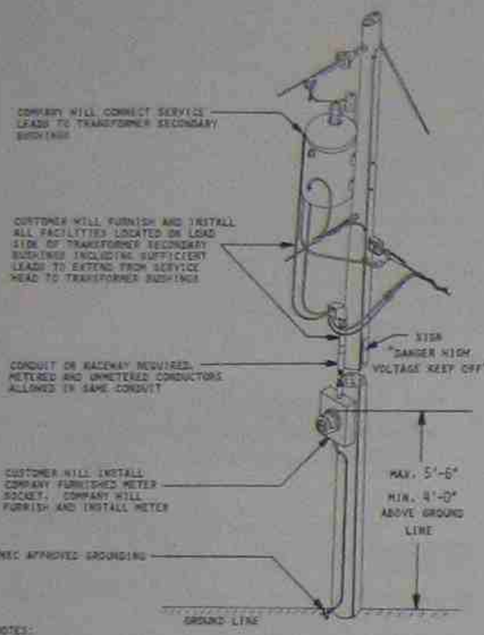
Fig. 9-4

LIBRARY

CENTRAL FARM POLE SERVICE



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY BEFORE INSTALLING CENTRAL FARM POLE SERVICE.
2. CUSTOMER MUST NOTIFY COMPANY AND OBTAIN ITS PERMISSION BEFORE PERFORMING ANY WORK ON FACILITIES LOCATED ON THIS POLE.
3. COMPANY WILL FURNISH AND INSTALL POLE WHEN NECESSARY TO SUPPORT TRANSFORMER.
4. NOT MORE THAN FIVE (5) CUSTOMER FEEDER CIRCUITS WILL BE PERMITTED ON COMPANY OWNED POLE. ALL FEEDER CIRCUITS MUST BE MULTIPLEX.
5. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.
6. WHEN LOAD EXCEEDS 200 AMP., METERING TRANSFORMERS WILL BE LOCATED AT TOP OF POLE WITH ALL METERING FACILITIES FURNISHED AND INSTALLED BY COMPANY.

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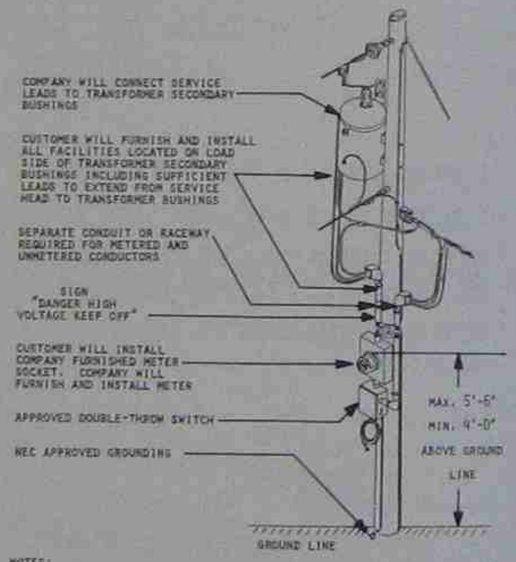
Fig. 9-5

200 AMP. OR LESS CENTRAL FARM POLE SERVICE (EMERGENCY STAND-BY GENERATOR FACILITIES)



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY BEFORE INSTALLING EMERGENCY STAND-BY GENERATOR FACILITIES AND MUST ALSO ENTER INTO A COMPANY INDEMNIFICATION AND SAVE-HARMLESS AGREEMENT.
2. ALL EMERGENCY STAND-BY GENERATOR FACILITIES MUST BE INSTALLED IN ACCORDANCE WITH APPLICABLE CODES AND BE SUBJECT TO COMPANY APPROVAL.
3. CUSTOMER MUST NOTIFY COMPANY AND OBTAIN ITS PERMISSION BEFORE PERFORMING ANY WORK ON FACILITIES LOCATED ON THIS POLE.
4. COMPANY WILL FURNISH AND INSTALL POLE WHEN NECESSARY TO SUPPORT TRANSFORMER.
5. NOT MORE THAN FIVE (5) CUSTOMER FEEDER CIRCUITS WILL BE PERMITTED ON COMPANY OWNED POLE. ALL FEEDER CIRCUITS MUST BE MULTIPLEX.
6. ALL CONDUITS MUST BE INSTALLED ON SAME SIDE OF POLE IN ORDER TO PROVIDE CLIMBING SPACE.
7. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

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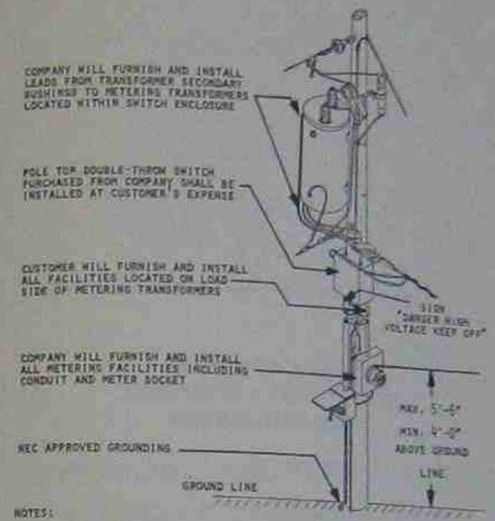
Fig. 9-6

400 AMP. CENTRAL FARM POLE SERVICE (EMERGENCY STAND-BY GENERATOR FACILITIES WITH POLE TOP SWITCH)



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY BEFORE INSTALLING EMERGENCY STAND-BY GENERATOR FACILITIES AND MUST ALSO ENTER INTO A COMPANY INDEMNIFICATION AND SAVE-HARMLESS AGREEMENT.
2. ALL EMERGENCY STAND-BY GENERATOR FACILITIES MUST BE INSTALLED IN ACCORDANCE WITH APPLICABLE CODES AND BE SUBJECT TO COMPANY APPROVAL.
3. CUSTOMER MUST NOTIFY COMPANY AND OBTAIN ITS PERMISSION BEFORE PERFORMING ANY WORK ON FACILITIES LOCATED ON THIS POLE.
4. DRAWING SHOWS USE OF POLE TOP SWITCH. CUSTOMER TO CONSULT COMPANY FOR ALTERNATE LOCATIONS.
5. MAINTENANCE OF POLE TOP SWITCH WILL BE PERFORMED BY COMPANY AT CUSTOMER'S EXPENSE.
6. COMPANY WILL FURNISH AND INSTALL POLE WHEN NECESSARY TO SUPPORT TRANSFORMER.
7. ALL CONDUITS AND CONTROL ROD MUST BE INSTALLED ON SAME SIDE OF POLE IN ORDER TO PROVIDE CLIMBING SPACE.
8. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

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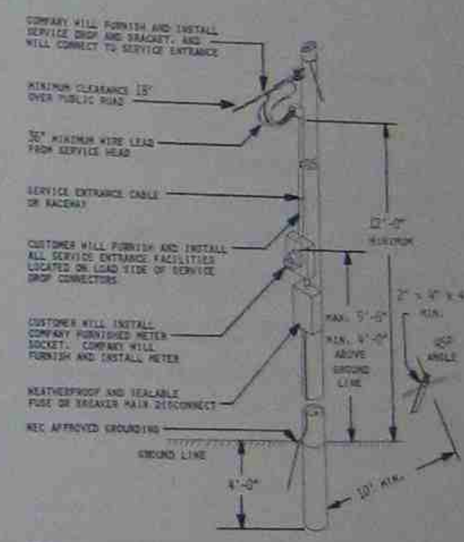
Fig. 9-7

TEMPORARY OVERHEAD SERVICE SUPPORT



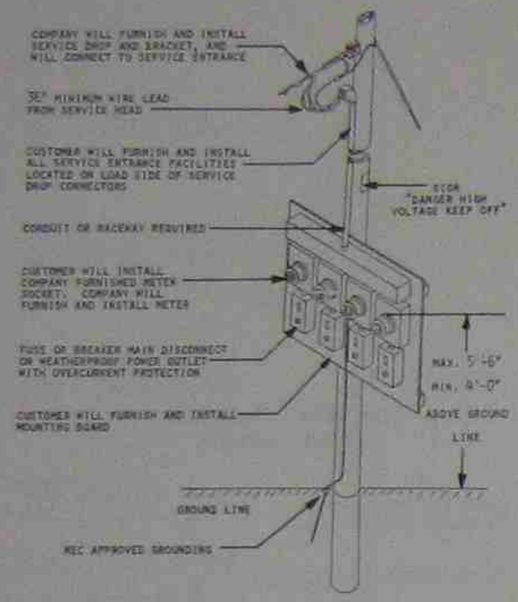
NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR LOCATION OF TEMPORARY SERVICE POLE OR SUPPORT) ALSO. CUSTOMER MUST PAY APPLICABLE CHARGES.
2. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
3. SERVICE POLE OR SUPPORT, FURNISHED AND INSTALLED BY CUSTOMER. REQUIREMENTS: 10' MINIMUM LENGTH CHEMICAL PRESERVATIVE TREATED POLE (MIN. CLASS 6, OR 4" DIAMETER AT TOP) OR 10' MINIMUM CONTINUOUS LENGTH OF 4" x 4" REDWOOD, OR OTHER CHEMICAL PRESERVATIVE TREATED POST FREE OF UNACCEPTABLE DEFECTS.
4. GUY WIRE FURNISHED AND INSTALLED BY CUSTOMER. IF COMPANY SERVICE DROP LENGTH EXCEEDS 50'. REQUIREMENTS: #8 GUM FENCE WIRE, OR #7 ALUMINUM CLOTHES LINE WIRE, OR TV TOWER GUY WIRE, INSTALLED AGAINST PULL OF SERVICE DROP. WOOD BRACING FOR POLE OR SUPPORT NOT ACCEPTABLE.
5. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.
6. COMPLETED CUSTOMER INSTALLATION SUBJECT TO COMPANY APPROVAL PRIOR TO CONNECTION.

(8/73)

Fig. 9-8

MOBILE HOME PARK SERVICE POLE/METER INSTALLATION



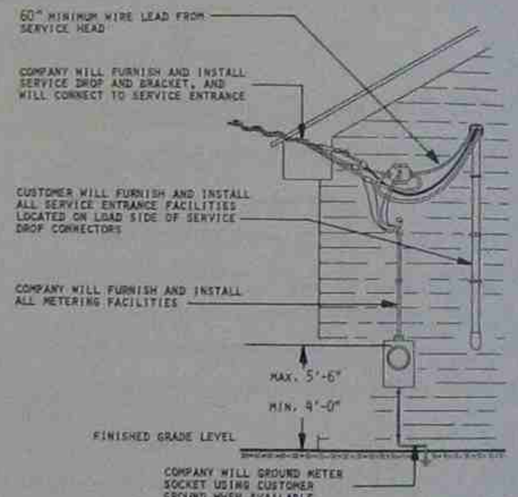
NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR METHOD OF SERVING MOBILE HOME PARK AND LOCATION OF SERVICE POLES.
2. CUSTOMER MUST NOTIFY COMPANY AND OBTAIN ITS PERMISSION BEFORE PERFORMING ANY WORK ON FACILITIES ON THIS POLE.
3. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
4. COMPANY WILL FURNISH AND INSTALL POLE WHEN A MINIMUM OF TWO (2) AND A MAXIMUM OF FOUR (4) METERS ARE INSTALLED ON THE POLE. A MOBILE HOME PARK SHOULD PREFERABLY BE DESIGNED TO SPECIFY FOUR METERS PER POLE.
5. FOUR-METER MOUNTING BOARD REQUIREMENTS: 80" WIDE, 48" HIGH, 3/4" THICK WITH 2"X 4" BATTENS; PAINTED AND SECURELY ATTACHED TO POLE WITH 1/2" THRU BOLTS.
6. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

(8/73)

Fig. 9-9

TYPICAL OVERHEAD TRANSFORMER - OPERATED METER INSTALLATION



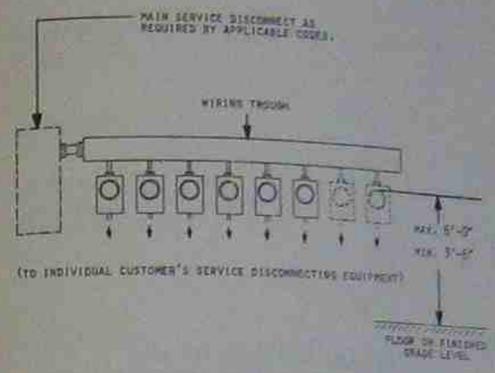
NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR POINT OF ATTACHMENT OF SERVICE DROP AND METER LOCATION.
2. CUSTOMER TO CONSULT COMPANY FOR THREE-PHASE, OR POLE MOUNTED, TRANSFORMER OPERATED METER INSTALLATION.
3. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
4. SERVICE DROP POINT OF ATTACHMENT MUST BE OF SUFFICIENT HEIGHT TO ALLOW FOLLOWING MINIMUM SERVICE DROP CLEARANCES:
   (a) TEN FEET (10') FOR MULTIPLEX SERVICES ABOVE SIDEWALKS AND FINISHED GRADES.
   (b) TWELVE FEET (12') FOR OPEN WIRE SERVICES ABOVE SIDEWALKS AND FINISHED GRADES.
   (c) TWELVE FEET (12') OVER RESIDENTIAL DRIVEWAYS.
   (d) EIGHTEEN FEET (18') OVER PUBLIC STREETS, ALLEYS, PUBLIC AND SHOPPING CENTER PARKING LOTS.
   (e) TWO FEET (2') CLEARANCE FROM TELEPHONE AND CATV WIRES AT MIDSPAN CROSSINGS.
5. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

(8/73)

Fig. 9-10

TYPICAL OVERHEAD MULTIPLE METER INSTALLATION



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR POINT OF ATTACHMENT OF SERVICE DROP AND METERING LOCATION.
2. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
3. THE CUSTOMER SHALL BE RESPONSIBLE FOR FURNISHING AND INSTALLING ALL SERVICE ENTRANCE WIRING AND FACILITIES FROM THE COMPANY'S SERVICE DROP TO THE METER SOCKETS.
4. CUSTOMER WILL INSTALL COMPANY FURNISHED METER SOCKETS.
5. COMPANY WILL FURNISH AND INSTALL METERS.
6. METERED CONDUCTORS SHALL NOT BE INSTALLED IN WIRING TROUGH(S).
7. CUSTOMER MAY INSTALL METER STACK OR METER TROUGH TYPE EQUIPMENT, SUBJECT TO COMPANY APPROVAL, IN LIEU OF COMPANY FURNISHED METER SOCKETS.
8. WHEN THE SERVICE ENTRANCE CONSISTS OF MORE THAN ONE SET OF CONDUCTORS, THE INDIVIDUAL LOADS MUST BE CONNECTED SO AS TO BE BALANCED AMONG ALL SETS OF CONDUCTORS.
9. WIRING TROUGH(S) AND MAIN SERVICE DISCONNECT SHALL BE SEALABLE AND SHALL ALSO BE WEATHERPROOF WHEN INSTALLED OUTDOORS.
10. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

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Fig. 9-11

Underground Services

Figures 9-12 through 9-15 show various underground service and meter installations accepted by most power companies. Other examples are also shown later in this chapter.

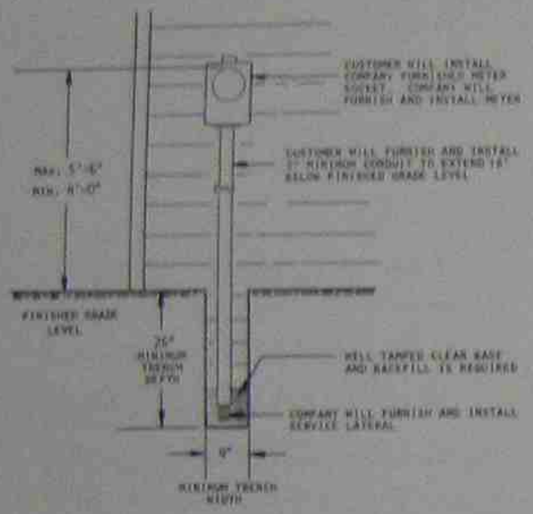
Service-entrance equipment will usually consist of either a factory-built switchboard with all switches, fuses, or circuit breakers, and, in some instances, the metering equipment built in, or an assembly of individual units of switches or circuit breakers, metering equipment, and auxiliary gutters.

In the design of service-entrance equipment, the following factors must be taken into consideration:

1. Service characteristics available from the power company
2. Total connected electrical load
3. Total demand of electrical load

4. Capacity for present and future requirements
5. Requirements of National Electrical Code, local ordinances, and local power company
6. Type and cost of equipment
7. Delivery date of equipment
8. Physical dimensions of equipment and space available in building

TYPICAL 200 AMP. OR LESS UNDERGROUND SERVICE INSTALLATION



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR POINT OF ATTACHMENT OF SERVICE LATERAL AND METER LOCATION) ALSO CUSTOMER MUST PAY ANY APPLICABLE CHARGES OR DEPOSITS ASSOCIATED WITH UNDERGROUND SERVICE BEFORE CONSTRUCTION IS BEGUN.
2. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
3. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

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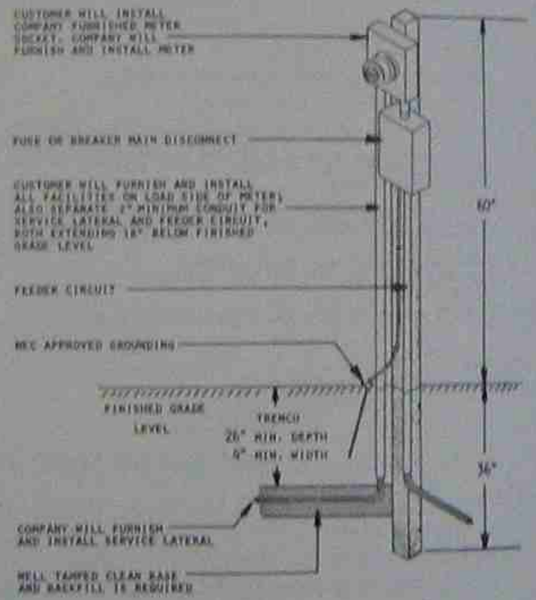
Fig. 9-12

TYPICAL 200 AMP. OR LESS PERMANENT UNDERGROUND SERVICE SUPPORT (PERMANENT FEEDER)



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR LOCATION OF SUCH SUPPORT REQUIRED WHEN INSTALLATION OF METER ON BUILDING NOT FEASIBLE (MOBILE HOME, ETC.)) ALSO CUSTOMER MUST PAY ANY APPLICABLE CHARGES OR DEPOSITS ASSOCIATED WITH UNDERGROUND SERVICE BEFORE CONSTRUCTION IS BEGUN.
2. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
3. CUSTOMER WILL FURNISH AND INSTALL A NOMINAL 6" x 6" x 8' REDWOOD OR OTHER CHEMICAL PRESERVATIVE TREATED POST OR OTHER COMPANY APPROVED SUPPORT.
4. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

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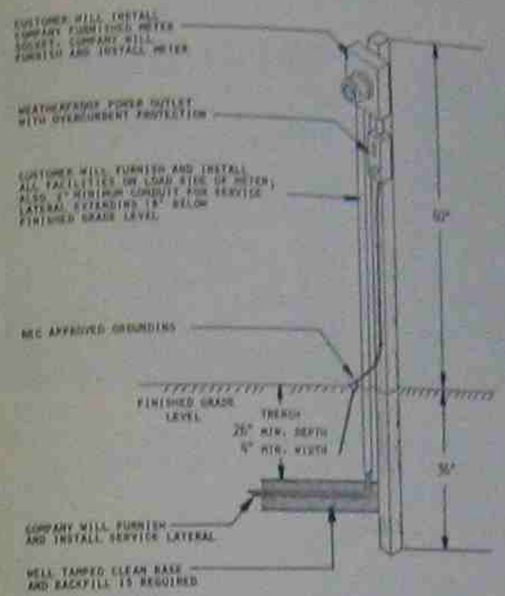
Fig. 9-13

TYPICAL 200 AMP. OR LESS PERMANENT UNDERGROUND SERVICE SUPPORT (WEATHERPROOF POWER OUTLET)



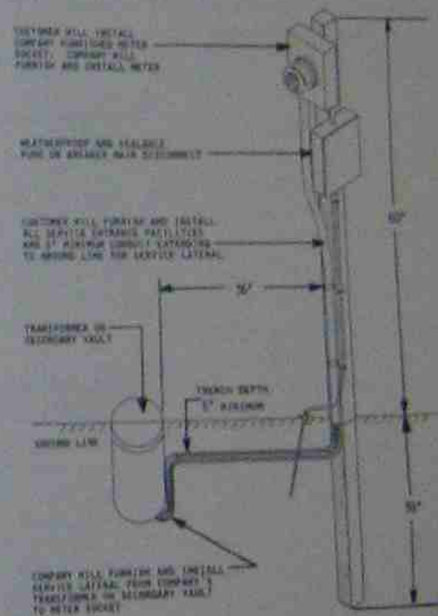
NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR LOCATION OF SUCH SUPPORT REQUIRED WHEN INSTALLATION OF METER ON BUILDING NOT FEASIBLE (MOBILE HOME, ETC.)) ALSO CUSTOMER MUST PAY ANY APPLICABLE CHARGES OR DEPOSITS ASSOCIATED WITH UNDERGROUND SERVICE BEFORE CONSTRUCTION IS BEGUN.
2. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
3. CUSTOMER WILL FURNISH AND INSTALL A NOMINAL 6" x 6" x 8' REDWOOD OR OTHER CHEMICAL PRESERVATIVE TREATED POST OR OTHER COMPANY APPROVED SUPPORT.
4. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

(8/73)

Fig. 9-14

TEMPORARY UNDERGROUND SERVICE SUPPORT



NOTES:

1. CUSTOMER MUST CONSULT WITH COMPANY FOR LOCATION OF TEMPORARY SERVICE POST OR SUPPORT. SUCH SUPPORT SHALL BE LOCATED WITHIN 24' OF COMPANY'S TRANSFORMER OR SECONDARY VAULT, OR FINAL METER LOCATION. CUSTOMER MUST PAY ANY APPLICABLE CHARGES.
2. ALL CUSTOMER WORK MUST BE COMPLETED AND REQUIRED INSPECTIONS BE OBTAINED BEFORE COMPANY WILL PROVIDE SERVICE.
3. CUSTOMER WILL FURNISH AND INSTALL A NOMINAL 6" x 6" x 8' REDWOOD OR OTHER CHEMICAL PRESERVATIVE TREATED POST OR OTHER COMPANY APPROVED SUPPORT. A TEMPORARY STANDARD POLE OR SUPPORT CAN BE USED PROVIDED APPLICANT REMOVES SUPPORT FOR UNDERGROUND SERVICE.
4. INHIBITOR COMPOUND SHALL BE USED ON ALL ALUMINUM WIRE TERMINATIONS.

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Fig. 9-15

Figures 9-16 through 9-18 show examples of various types of service-entrance equipment now in use. These should be compared to the drawings that follow in order to better visualize the riser diagrams such as Fig. 9-19 and plan views.



Fig. 9-16 Photograph of panelboard used in bank. See Fig. 9-20 for corresponding riser diagram.

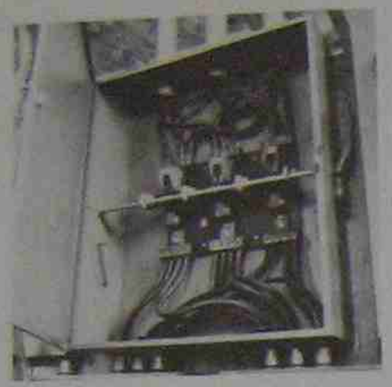


Fig. 9-17



Fig. 9-18

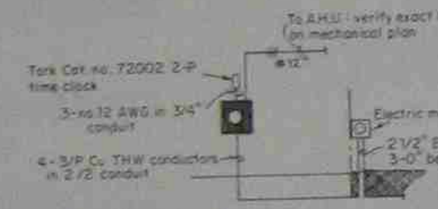


Fig. 9-19 Power-riser diagram.

PRACTICAL APPLICATIONS

The power-riser diagram shown in Fig. 9-20 was used on the plans for a branch bank, the floor plan of which was shown in

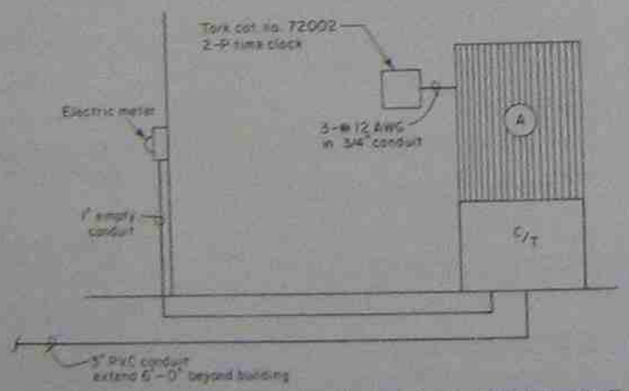


Fig. 9-20 Power-riser diagram used on the plans for the branch bank in Fig. 2-9.

Chapter 2. In analyzing this diagram, the following things are apparent:

1. A 3-in. PVC (plastic) conduit extends from 6 ft beyond the building to the C/T (current transformer) cabinet.
2. A 1-in. empty conduit runs from the C/T cabinet to the meter base mounted on the outside wall of the building. This conduit is for the power company's six meter wires from the current transformer.
3. Panel A is mounted above the C/T cabinet.
4. A two-pole time clock is mounted next to the panel and is fed with three No. 12 AWG conductors. This is to control the outside sign and building lights.

This power-riser diagram, in itself, is not sufficient to tell the electrical contractor exactly what is to be done. However, the written specifications along with the panelboard schedule (also on the drawings) will give all the necessary information. The panelboard schedule will give the manufacturer, voltage, amperage, and number and size of breakers required in panel A; the written specifications indicate that the local power company will pull the service lateral into the C/T cabinet which is also furnished and installed by the power company; the meter base, while furnished by the power company, is to be installed by the contractor along with the 1-in. empty conduit.

The power-riser diagram shown in Fig. 9-21 is very similar to

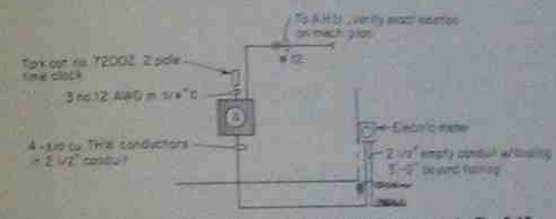


Fig. 9-21 A power-riser diagram similar to that shown in Fig. 9-19, except that more information is given directly on the riser diagram.

the diagram in Fig. 9-20 except that more information is given directly on the riser diagram. This riser diagram, when used in conjunction with the floor plans and the panelboard schedule shown in Fig. 9-22, eliminates the need for written specifications, provided that a note on the drawing states that "all work shall be done in accordance with the National Electrical Code."

Panel Board Schedule

Panel no.	Type Cabinet	Panel mains			Branches					Items fed
		Amperes	Volts	Phase	1P	2P	3P	First	Frame	
"A"	Flush	200a	120/240V	3ø 4W Δ	–	1	–	20 A	70A	Time clock
Square "D" NQOB w/main breaker					–	–	1	20 A	70A	A.H.U.
					–	1	–	30 A	70A	Meter fm
					–	–	1	30 A	70A	Cond unit
					–	–	1	30 A	70A	Lights
					5	–	–	20 A	70A	Heights
					10	–	–	30 A	70A	Spares
					5	–	–	30 A	70A	
					12	–	–	–	–	Provide only

Fig. 9-22 Panelboard schedule from which the power-riser diagram in Fig. 9-21 was taken.

Each electrical system is required to be grounded in the manner prescribed by the National Electrical Code, although the details of grounding rarely appear in the power-riser diagram; rather, a paragraph usually appears in the written specifications and may read as follows:

> *d.* GROUNDING: The electrical contractor shall properly ground the electrical system as required by the National Electrical Code. The ground wire for the service entrance shall be run in conduit and connected to the main water service and connected ahead of any valve or cutoff.

The paragraph above will serve in most cases, but the electrical designer should carefully coordinate all electrical drawings with the plumbing drawings and the plumbing contractor because PVC (plastic) water pipe may be specified, and would not provide a ground.

It is recommended that the electrical designer calculate and give exact details of the grounding system for each service entrance. Such details may appear in the specification, as, for example, in the following specification for a 200-A service entrance:

> Furnish and install a No. 4 AWG bare copper conductor in a ¾-in. rigid galvanized conduit from the neutral bus in the main distribution panel to a 1-in. or larger cold-water pipe in the mechanical room on the ground floor. Water-pipe connections shall be with an approved ground fitting that bonds both conduit and conductor to water pipe.

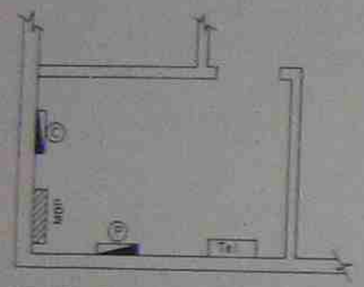


Fig. 9-23 Floor plan of an electrical equipment room.

The floor plan of an electrical equipment room for a department store is shown in Fig. 9-23. This room contains the main distribution panel, C/T cabinet, telephone cabinet, and other subpanels.

The corresponding power-riser diagram for this service entrance is shown in Fig. 9-24 and conveys the following information:

1. The service entrance consists of three 3½-in. conduits with four 500-MCM THW conductors in each, terminating in the C/T cabinet. This is rated for 1,200 A.

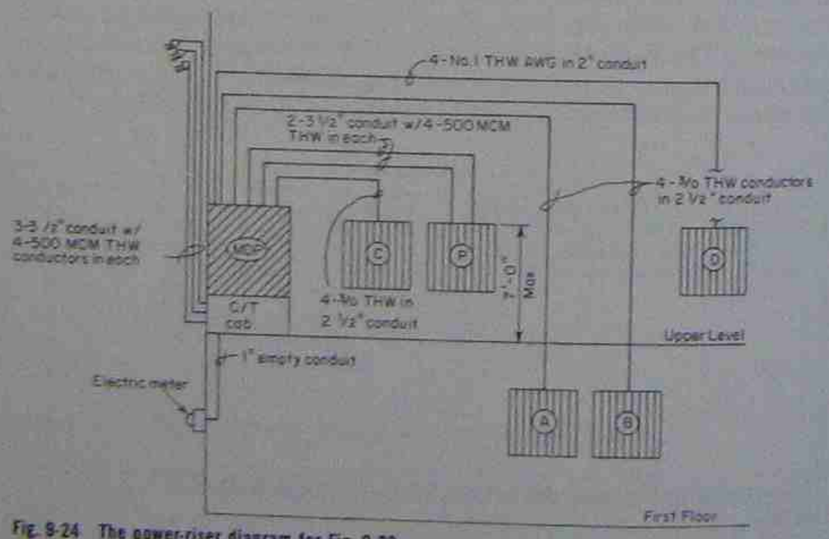


Fig. 9-24 The power-riser diagram for Fig. 9-23.

2. A 1-in. empty conduit runs from the C/T cabinet and terminates in a meter base mounted on the side of the building.
3. The main distribution panel is mounted over the C/T cabinet and is identified "MDP."
4. Panels A, B, C, D, and P are fed from the main distribution panel by feeders as indicated in the schedule. Details of each panel can be found in the panelboard schedules, elsewhere on the drawings.

The floor plan of a mechanical room for a three-story building is shown in Fig. 9-25. This room contains, besides mechanical

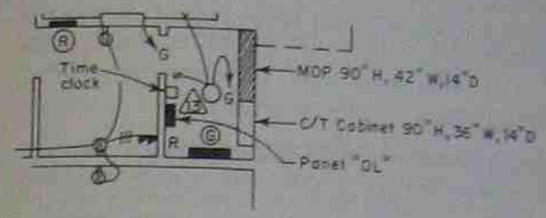


Fig. 9-25 Floor plan of a mechanical room.

equipment, the main distribution panel, C/T cabinet, emergency panel, panel P, panel OL, and a 100-A magnetic contactor for panel OL which is controlled by a time clock. The corresponding power-riser diagram is shown in Fig. 9-26; this shows

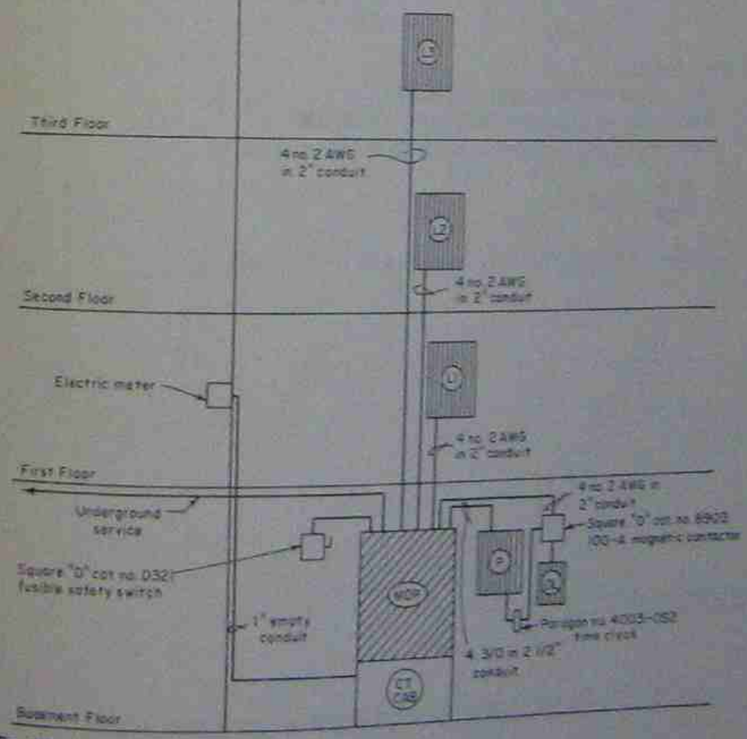


Fig. 9-26 Power-riser diagram for Fig. 9-25.

a schematic arrangement of all panels, feeders, and conduits as well as wire sizes for the power equipment illustrated.

RESIDENTIAL SERVICE-ENTRANCE EQUIPMENT

Several methods of sizing residential service entrances are given in Chap. 9, "Tables and Examples," of the National Electrical Code; one of them is very much as follows:

Example No. 1(b). Single-Family Dwelling.

Optional Calculation for One-Family Dwelling (Section 220-7)

Dwelling has a floor area of 1,500 sq ft exclusive of unoccupied cellar, unfinished attic, and open porches. It has a 12-kW range, a 2.5-kW water heater, a 1.2-kW dishwasher, 9 kW of electric space heating installed in five rooms, a 4.5-kW clothes dryer, and a 6-A 230-V room air-conditioning unit.

Air conditioner kW is $6 \times 230/1{,}000 = 1.38$ kW

1.38 kW is less than the connected load of 9 kW of space heating; therefore, the air-conditioner load need not be included in the service calculation [see Section 220-4(k)].

1,500 sq ft at 3 W	4.5 kW
Two 20-A appliance outlet circuits at 1,500 W each	3.0
Laundry circuit	1.5
Range (at nameplate rating)	12.0
Water heater	2.5
Dishwasher	1.2
Space heating	9.0
Clothes dryer	4.5
Total	38.2 kW

Calculations:

First 10 kW at 100 percent = 10.00 kW
Remainder at 40 percent $(28.2 \times 0.4) = 11.28$ kW
Calculated load for service size is 21.28 kW or 21,280 W.

$$\frac{21{,}280}{230} = 92.5 \text{ A}$$

Therefore, this dwelling may be served by a 100-A service.

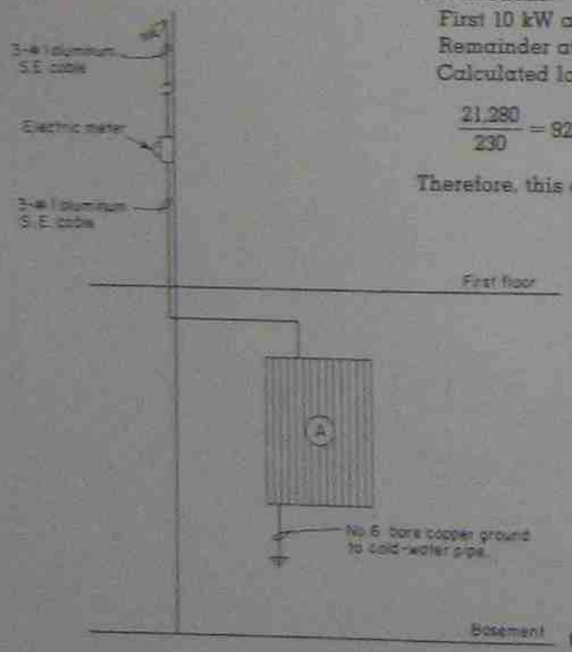


Fig. 9-27 A typical power-riser diagram for a residence.

A typical power-riser diagram which may be used on the working drawings for this residence is shown in Fig. 9-27; a typical panelboard schedule is shown in Fig. 9-28.

PANELBOARD SCHEDULE

Panel No.	Type Cabinet	Panel Mains Amperes	Volts	Phase	Branches 1P	2P	3P	Prot.	Frame	Item fed or remarks
A	Surface	100	120/240	1P, 3W	-	1	-	30A	70A	Clothes dryer
Square "D" type "QO" w/100A main					-	5	-	20A	70A	Space heating and water heater
					-	1	-	50A	70A	Range
					5	-	-	20A	70A	Appliances & ac unit
					6	-	-	15A	70A	Lighting & receptacles
					4	-	-	15A	70A	Spares

Fig. 9-28 A typical panelboard schedule for a residence.

HIGH-VOLTAGE SERVICE ENTRANCE

Figure 9-29 shows the site plan for a new building at a state institution. The existing transformer bank and primary service

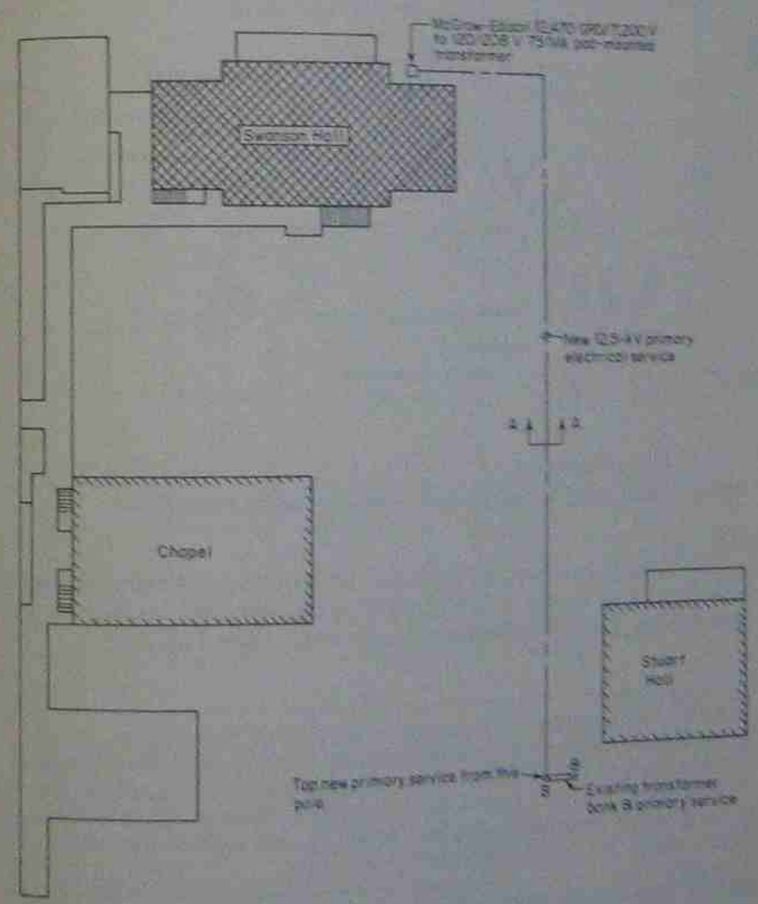


Fig. 9-29 Site plan of an institutional building.

are located in the lower right-hand corner of the drawing. The designer indicates that the new service is tapped on this pole and runs underground to the new pad-mounted transformer.

Section A-A showing the detail of the buried cable is illustrated in Fig. 9-30.



Fig. 9-30 Detail of the buried cable in the site plan in Fig. 9-29.

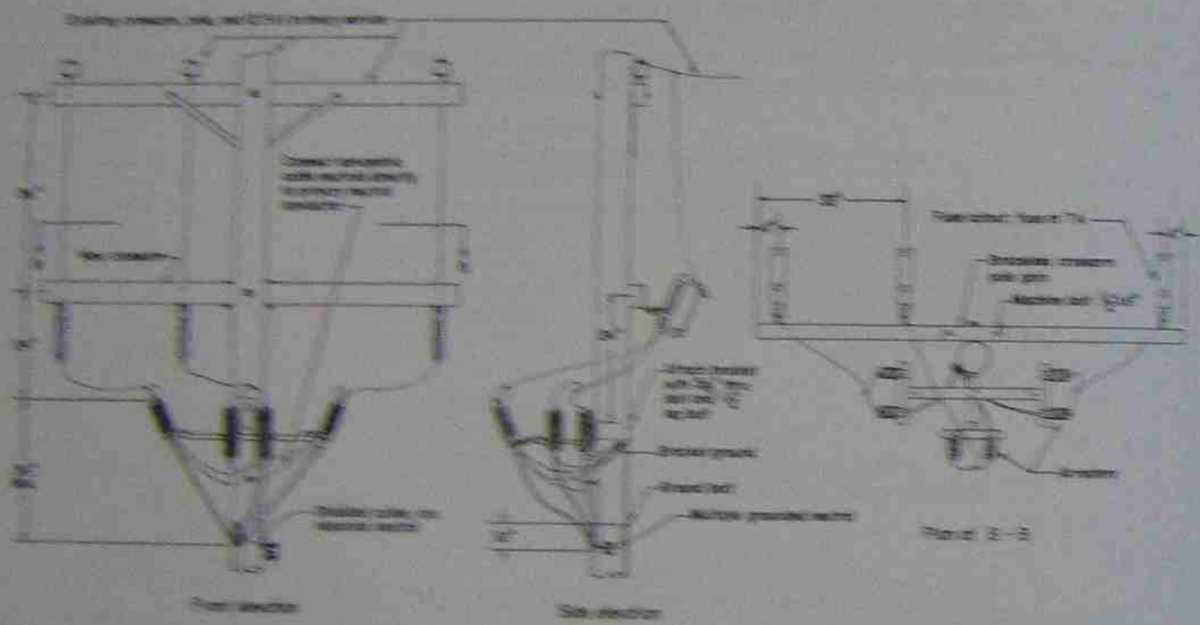


Fig. 9-31 Drawing showing the details involved in tapping the existing primary service.

The details involved in tapping the existing primary service are illustrated in Fig. 9-31. A note also appears on the drawings describing the underground primary cable. See Fig. 9-32.

NOTE: All high-voltage underground wiring shall be direct-burial, 15 kV, No. 4 alum. AWG, type 4A, 2 conductor-1-No. 2 alum. 4A, 7-strand phase conductor with extruded semiconducting cross-linked polyethylene strand shielding, 175 mils of crosslinked polyethylene insulation, 30 mils semiconducting polyethylene jacket and 1/-No. 14 AWG bare copper concentric neutral; min. depth shall be 42".

Fig. 9-32 Note on drawing describing the underground primary cable.

A power-riser diagram showing the secondary service-entrance equipment is shown in Fig. 9-33.

The transformer-pad detail is shown in Fig. 9-34, and notes pertaining to the entire installation are shown in Fig. 9-35.

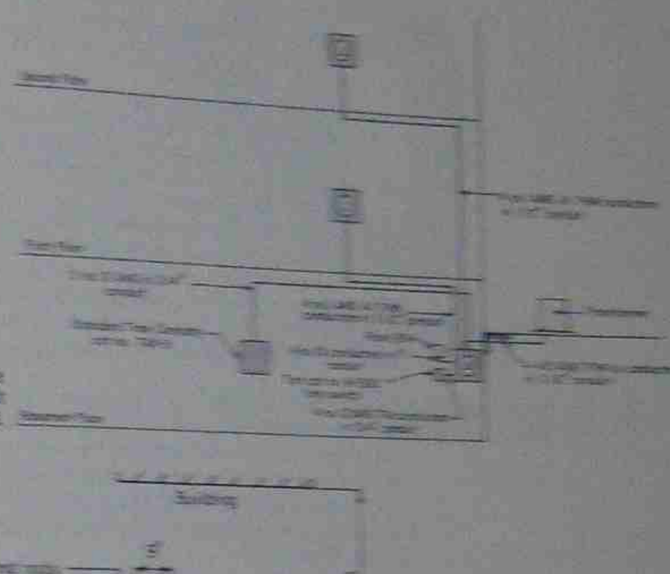


Fig. 9-33 Power-riser diagram showing the secondary-service-entrance equipment for this project.

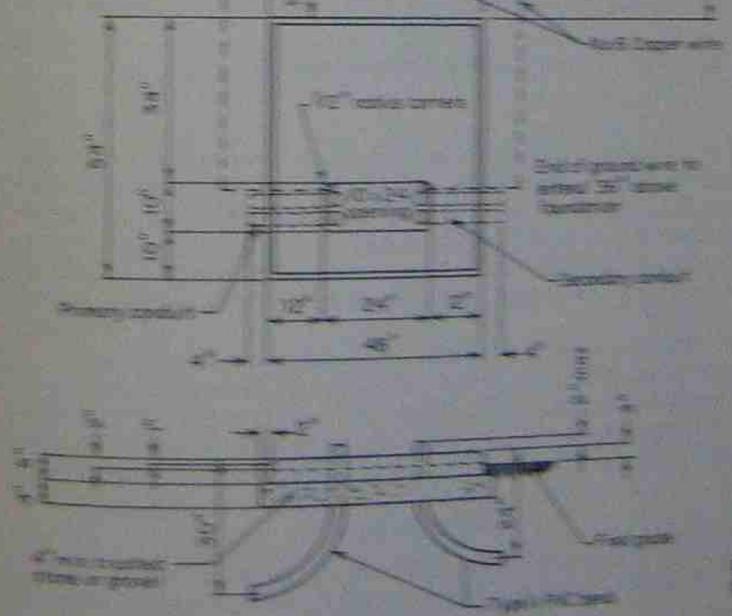


Fig. 9-34 Transformer pad for the project shown in Fig. 9-29.

Underground Distribution Notes

1. To avoid physical obstructions and to provide adequate space separation for fire protection, the following are minimum clearances for locating transformer foundations: (For physical location see TD 2150-2)
   10 ft from window (along wall horizontally)
   10 ft below window (vertically)
   5 ft from building or other structure
   10 ft from door or entrance (along wall)
   10 ft from fire escape
   10 ft from ventilating ducts
2. Concrete pad may be poured in place or may be precast.
3. Install all conduits before placing pad. Conduits should not be placed under the section of the pad supporting the transformer so that the original ground will not be disturbed.
4. Conduit shall be rigid polyvinyl chloride.
5. Thoroughly compact the crushed stone or gravel.
6. To prevent water migration from concrete, place a waterproof membrane on crushed stone or gravel before placing concrete.
7. Backfill shall be clean granular soil, free of large stones and perishable material. All backfill shall be spread and compacted in maximum layers of 8 inches.
8. Where damage to the transformer by vehicles is possible, the transformer shall be protected by an appropriate barrier.
9. Seal all spare conduits and openings to prevent the entry of rodents and animals into the transformer compartment.
10. If conduit extends into building it must be sealed at the building end to prevent gas from entering the building through the conduit. Use Aqua Seal Stk. No. 594006.
11. Concrete to develop 3000 psi at 28 days' age, contain a minimum of 5.5 bags of cement per cu. yd. and a maximum of 6 gal. of water per 94-pound bag of cement, and conform to ASTM designation C-94.
12. Cement to be I of I-A and meeting ASTM designation C-150 and C-175, respectively.
13. Reinforcing steel shall conform to ASTM designation A615, Grade 60.

Fig. 9-35 Notes on the working drawings pertaining to the entire installation.

Chapter 10
Panelboard and Feeders

Branch-circuit control and overcurrent protection must be provided for all circuits and the power-consuming devices connected to them. Protective devices, such as fuses, circuit breakers, and relays, are usually grouped together at one centralized location (or more) in order to keep the length of the branch-circuit raceways at a practical minimum length for operating efficiency.

These protective devices are usually factory-assembled and installed in a metal housing, the entire assembly being commonly called a panelboard or "panel." The number and sizes of the overcurrent protective devices vary in accordance with requirements for lighting and power of the branch-circuit wiring system.

PANELBOARDS

On electrical drawings, a panelboard is usually indicated by a solid rectangle for surface-mounted panelboards such as



Fig. 10-1 Method of indicating a surface-mounted panelboard on working drawings.



Fig. 10-2 Method of indicating flush-mounted panelboard on working drawings.

shown in Fig. 10-1 and a solid rectangle with a "flange" for a flush-mounted panelboard as shown in Fig. 10-2. A mark is also used to identify each panelboard on the drawings: Fig. 10-1 is identified by a circle with the letter P, and Fig. 10-2 with the letter L.

The following material is a guide to various types of panelboards as furnished by one manufacturer.

Type CHP Panelboard

This type of panelboard utilizes the plug-in type of branch-circuit breaker for lighting and appliance branch circuits. Figure 10-3 shows typical wiring diagrams for both single- and three-phase panels, while Fig. 10-4 shows the approximate cabinet dimensions.

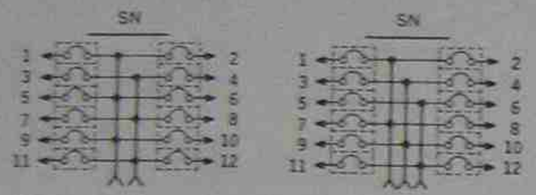
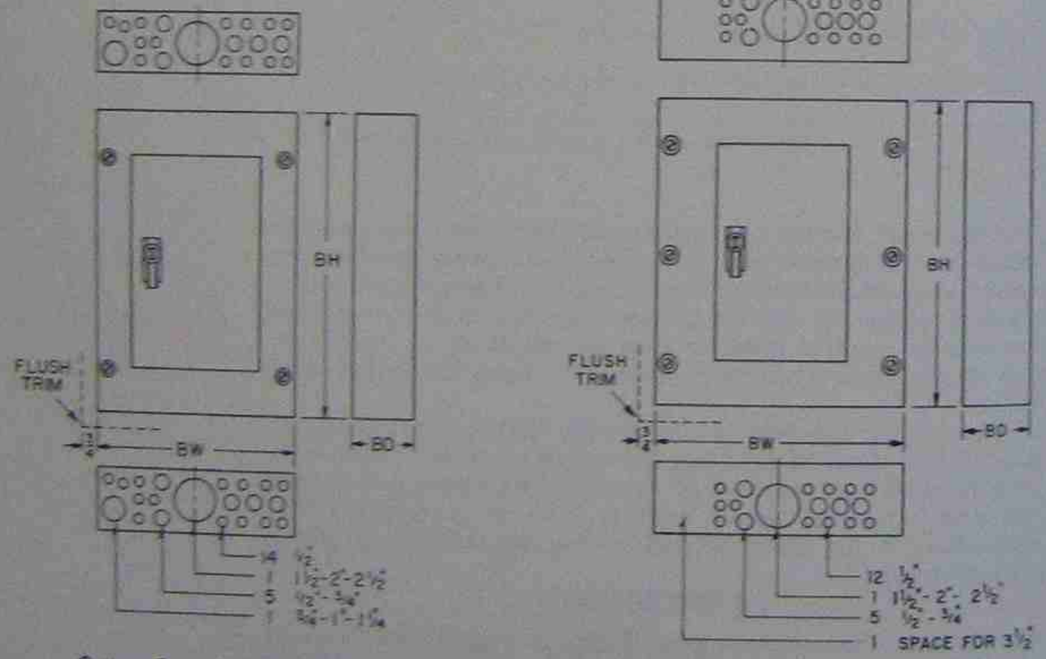


Fig. 10-3 Typical wiring diagrams for both single- and three-phase panels. (*By permission of Cutler-Hammer.*)



Type CHB Panelboard

This type of panel is very similar to type CHP except that it is constructed for bolt-in-type circuit breakers for use on lighting and appliance branch circuits. The wiring diagram and physical dimensions shown for the CHP-type panel in Figs. 10-3 and 10-4 will also suffice for type CHB panelboards.

Type NA1B and NH1B Panelboards

This type of panelboard uses bolt-in-type EA-frame circuit breakers for lighting and appliance branch circuits. This type is designed for use with 277/480-V service and from 100- to 400-A capacity. Branch breakers are available as single-, two-, or three-pole types.

Type NDP and NHDP Panelboards

For use with 120/240-V or 120/208-V service using bolt-in-type EA-frame or EH-frame circuit breakers for power branch circuits. The NHDP panelboard is also available for use with 277/480-V service with the same types of frame. A suggested method of designing an electrical system for use with this type of panelboard is to make a sketch of the panelboard as shown in Fig. 10-5 (right).

List amperage capacity of all components, that is, neutral, main lugs, or current breaker and panel. If the total X-unit spaces required exceeds 33, lay out two or more panelboards. If these panels need to be cabled together, include subfeed lugs or circuit breaker.

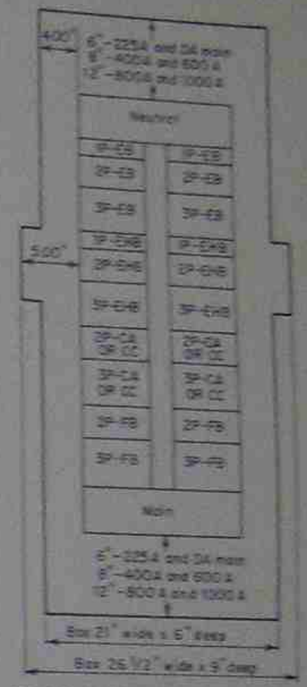


Fig. 10-5 Sketch used for designing NDP and NHDP panelboards.

Fig. 10-4 (On facing page and below) Approximate cabinet dimensions of single- and three-phase panels. (*By permission of Cutler-Hammer.*)

With Main Lugs Only					With Circuit-Breaker Main				
Number of poles	Main, A	Dimensions, inches			Number of poles	Main, A and C.B. type	Dimensions, inches		
		Wide BW	High BH	Deep BD			Wide BW	High BH	Deep BD
Single-phase-three-wire									
8–20	125	15	19 1/2	4 1/8	8–10	50 EA	15	25	4 1/8
20–30	225	15	29	4 1/8	12–30	100 EA	15	28	4 1/8
32–42	225	15	34	4 1/8	20–30	225 QCC	15	38	4 1/8
54	225	15	42 1/2	4 1/8	32–42	225 QCC	15	42 1/2	4 1/8
					20–42	225 JA	21	48 1/4	6
					54	225 QCC	21	54 1/4	6
					54	225 JA	21	58 1/2	6
Three-phase-four-wire									
8–18	125	15	19 1/2	4 1/8	8–12	50 EA	15	25	4 1/8
20–30	125	15	29	4 1/8	14–18	100 EA	15	28	4 1/8
30–42	225	15	34	4 1/8	20–30	100 EA	15	38	4 1/8
54	225	15	42 1/2	4 1/8	30–42	225 QCC	15	42 1/2	4 1/8
					30–42	225 JA	21	48 1/4	6
					54	225 QCC	21	54 1/4	6
					54	225 JA	21	58 1/2	6

NOTE: (Applies to panels standard in the 15" wide box.) When conduit larger than 2 1/2" is to be used, or if more gutter space is desired, a 21" wide by 6" deep box of approximately the same height will be provided at no charge, upon request. Not available in unassembled panels.

3,000 AMP. INTERRUPTING CAPACITY SAFETYBREAKERS

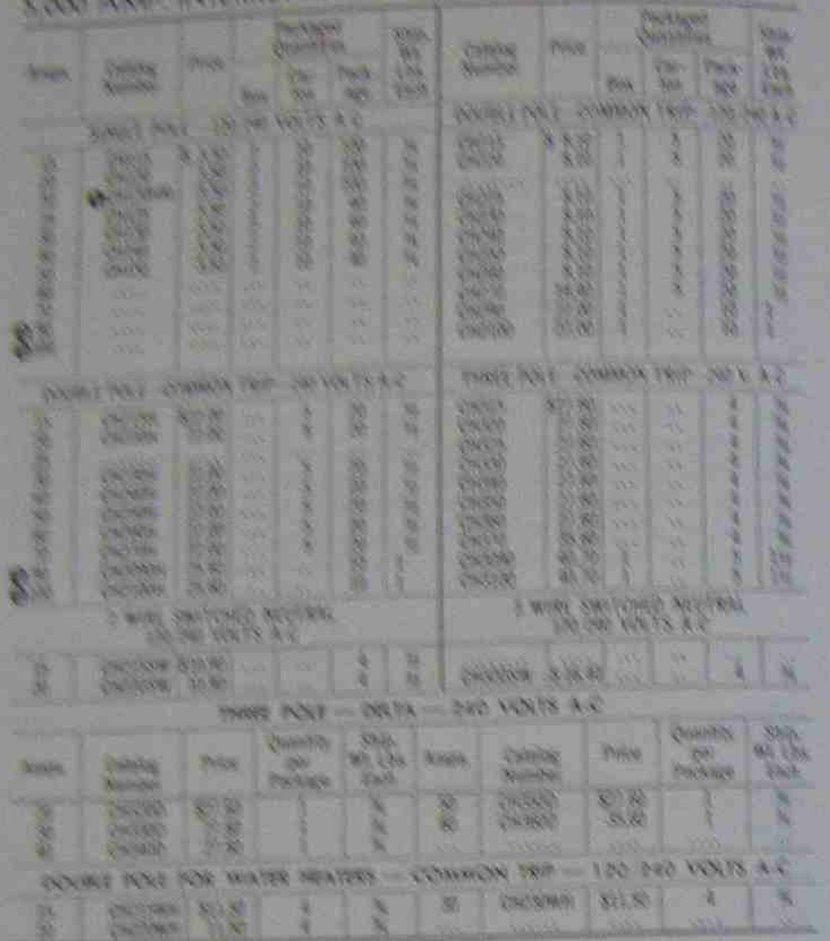


Fig. 10-6 Table of circuit breakers available.

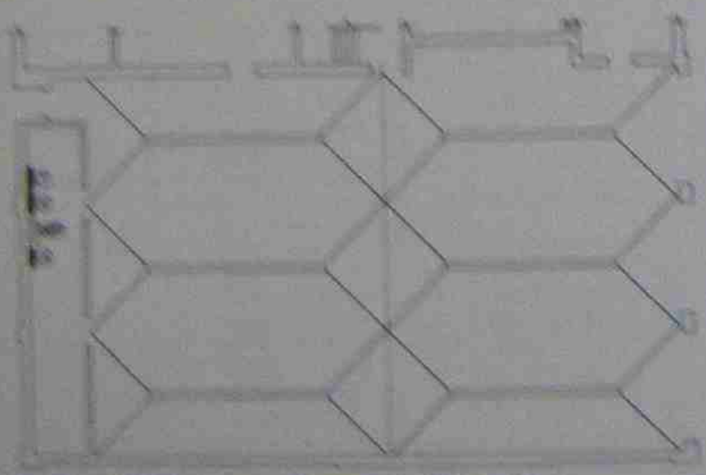


Fig. 10-7 Method of locating panelboards on a typical floor plan.

The labeled sketch should then be used for a neat drawing on the working drawings of the project, for example, in the power-riser diagram.

Type CDP Panelboard

This type of panelboard also uses bolt-in circuit breakers for power branch circuits and feeder distribution in ratings from 15 through 1,200 A. The maximum voltage rating for dc power is 250 V; ac power rates up to 600 V. The table in Fig. 10-8 gives the various circuit breakers available together with related information.

METHOD OF SHOWING PANELBOARDS ON WORKING DRAWINGS

Panelboards usually are shown on all floor plans of buildings as well as in a power-riser diagram. The panels are first located on the floor plan as shown in Fig. 10-7. This enables the estimator to accurately calculate the length of the panel feeders as well as the branch circuits to them. Each panel (as can be seen in Fig. 10-7) is given an identifying letter or number to which reference can be made.

A panelboard schedule should be provided on the working drawings or in the specifications to relay the following information:

1. Panel identification
2. Type cabinet (surface- or flush-mounted)
3. Panel mains
   a. Amperage rating
   b. Voltage
   c. Phase
4. Number of circuit breakers including number of poles, trip amperage, frame type, etc.
5. Items fed or remarks

A typical panelboard schedule is shown in Fig. 10-8.

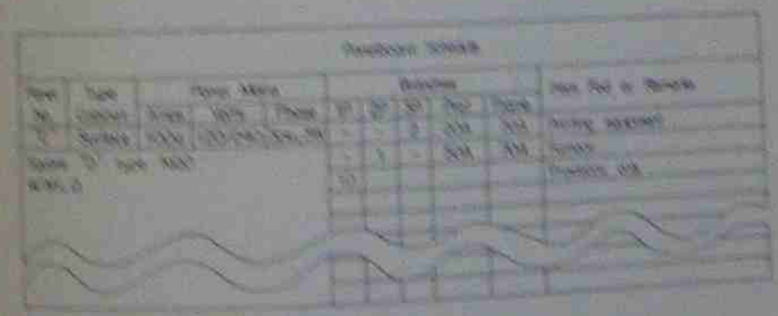


Fig. 10-8 Typical panelboard schedule.

Most working drawings also include a power-riser diagram to indicate how each panel is fed, that is, the number and size of conductors and the size of the conduit enclosing the conductors. A typical power-riser diagram is shown in Fig. 10-9.



Fig. 10-9 Typical power-riser diagram.

FEEDER AND PLUG-IN DUCT

The modern approach to flexible power distribution in industrial electrical systems tends to carry feeder conductors in troughs or trays or to use bus bars enclosed in either a ventilated or a nonventilated duct from the source of supply to points within the system where distribution of electric power is needed.

Bus ducts provide for fast initial installation and are also very fast and convenient for adding on electrical feeders at a later date. Straight ducts are manufactured in 1½-, 3-, 5-, 6-, and 10-ft lengths. These are bolted together by means of bolt bus bar joints. Numerous fittings are also available as can be seen in Fig. 10-10.

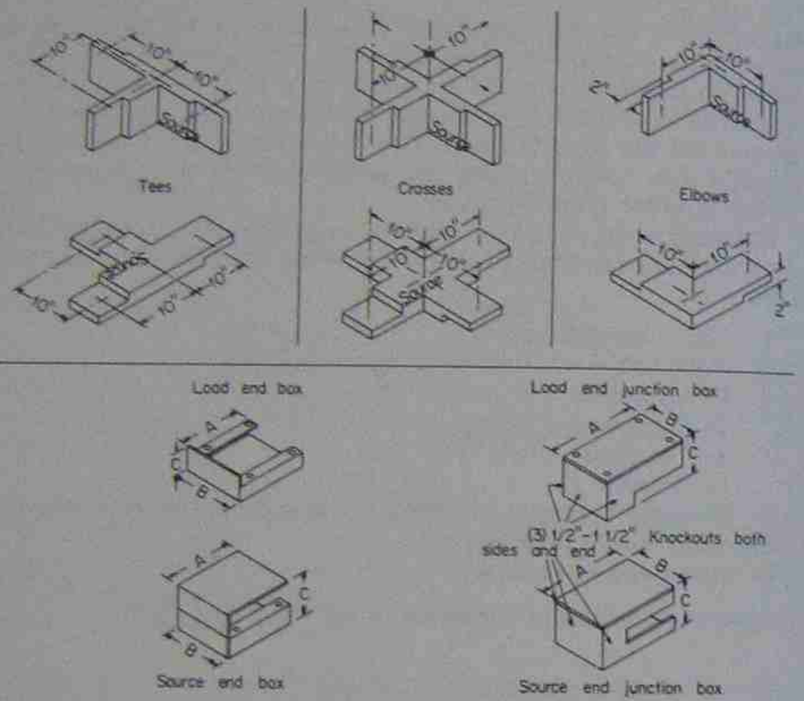


Fig. 10-10 Numerous fittings are available for use with feeder duct. (*By permission of Cutler-Hammer.*)

Fitting	Number of poles								
	3-, 4-, and 5-Pole			6- and 7-Pole			8- through 13-Pole		
	A, in.	B, in.	C, in.	A, in.	B, in.	C, in.	A, in.	B, in.	C, in.
Load end box	6¼	6 1/16	2	10¾	7 9/16	7	18	7 9/16	7
Source end box	6¼	6 1/16	2	10¾	7 9/16	7	18	7 9/16	7
Load end junction box	10¾	6 1/16	4	10¾	7 9/16	7	18	7 9/16	7
Source end junction box	10¾	6 1/16	4	10¾	7 9/16	7	18	7 9/16	7

The broad array of feeder and plug-in duct types and standardized fittings will satisfy almost any low-voltage requirement for local circuit protection and control. Plug-in devices—fused, fused disconnect switches, circuit breakers,

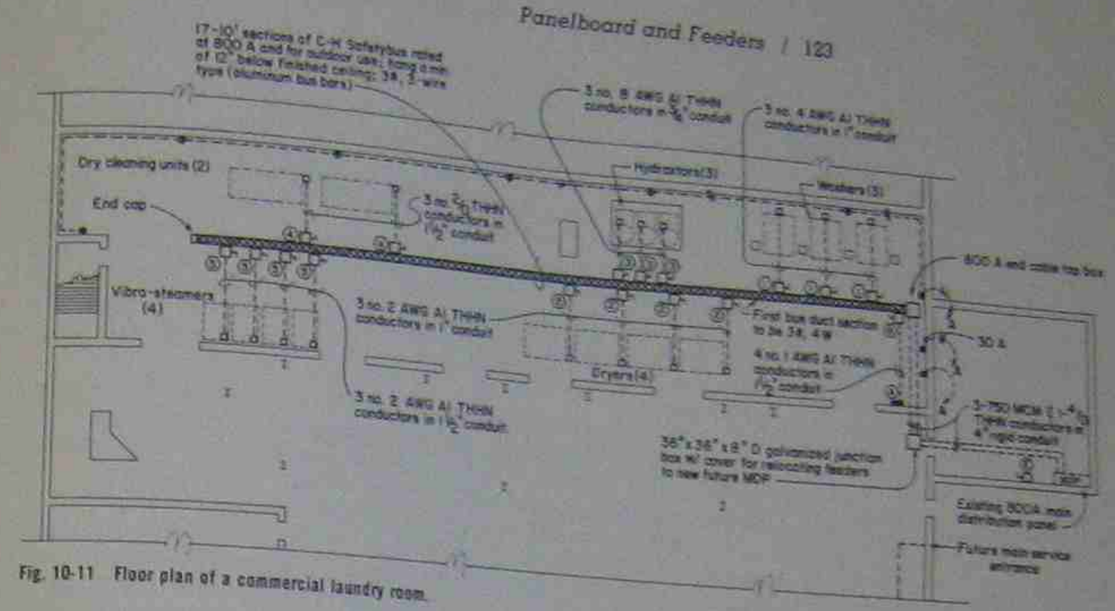


Fig. 10-11 Floor plan of a commercial laundry room.

transformers, etc.—are readily available with feature rating and characteristics to match nearly any load condition.

A carefully planned network of bus ducts is necessary to provide maximum economy, flexibility, and low voltage-drop characteristics. Also because of physical limitations and electrical requirements, each design of a bus-duct system requires a customized solution. The following project will show the reader how one simple bus-duct system was designed and will apply—basically—to most bus-duct systems.

PROBLEM

A uniform-rental service required that a laundry room be supplied with electrical power to operate sixteen 240-V machines, a reasonable number of convenience outlets, and lighting for this area as well as for a small office space above. The basic floor plan is shown in Fig. 10-11.

1. Since branch-circuit wiring was the major item, the designer determined that in no instance should a machine or other load be more than 30 ft away from the main bus duct. Therefore, an end cable-tap box was located at one end of the area which was closest to the main power source. The total demand for this area was calculated to be 800 A. Therefore, two 4-in. conduits were run from the main power source to the end cable-tap box, each containing three 750-MCM THHN cables and one 4/0 aluminum conductor.
2. Eight 10-ft sections of bus duct were then specified to be attached to the end cable-tap box and to run along the approximate center of the area. Since taps were required all along this bus duct, the plug-in type was used throughout. However, in instances where a sizable run is required before taps are necessary, feeder-type ducts should be used from the power source out to the area where plug-in (branch-circuit) convenience is

required. This is because the price-per-foot cost of feeder duct is less than the plug-in type.

3. Note that, in the drawing in Fig. 10-11, the bus duct runs over aisles. This provides easy access to the duct and reduces installation costs as well as maintenance expense.

4. It was determined that the 800-A system would be the most satisfactory and most practical for other areas within the plant; if one ampere size is standard throughout the plant, any later modification of the system can be readily made without a lot of additional expense. If additional ducts need to be added or if part of the system must be disassembled and moved to a new location, all components can be reapplied with very little planning.

5. Although this is not required in the project under consideration, if extensive runs are needed, it might be advisable to install more runs on closer centers to obtain better blanket coverage and reduce the branch-circuit wiring costs.

6. Since there are more than six distribution circuits in this system (not shown in Fig. 10-11), a main was required on the main distribution panel. However, where possible, try to arrange a system so that there are no more than six distribution circuits. With this consideration, according to the National Electrical Code no main breaker or service switch is required.

7. Notice that lighting panel A is also fed from the bus duct, eliminating the cost of an additional feeder from the main distribution center. Always check the advantages of connecting lighting in with the bus-feeder system. It is usually more economical to install a four-wire system and tap the lighting panels directly off the bus duct. In our example, the main service is 120/240 V, so no further modification was necessary for the lighting. When a 480-V service is required for the main bus duct, dry-type transformers are available which attach directly to the bus duct for 120-V loads.

8. For greater installation economy, the bus duct in our example was mounted edgewise because installation procedures are quicker, the edgewise hangers are more economical, and the costs in general are lower.

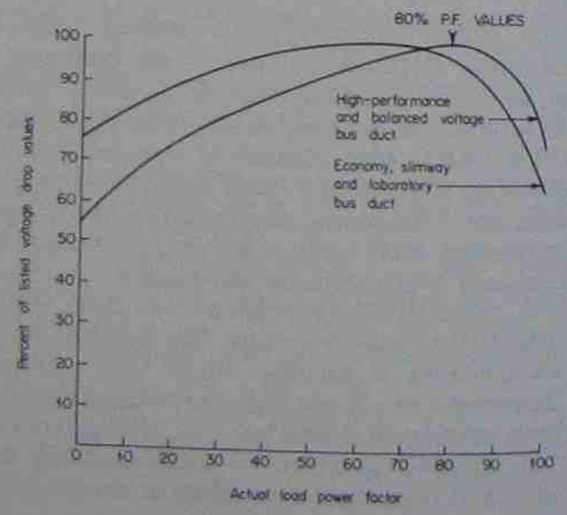


Fig. 10-12 Graph showing voltage-drop and power-factor figures.

Switch Schedule

Switch Type	Manufacturer's Description	Volts	Amperes	Prot	Conduit Size	Conductors No.	Conductors Size	Remarks
1	Cutler–Hammer cat no CP2HD 323	240	100	60A	1"	3	No 4	Verify exact connection details
2	cat no CP2HD 323		100	90A	1"	3	No 2	
3	cat no CP2HD 32		30	25A	3/4"	3	No 8	
4	cat no CP2HD 324		200	125A	1 1/2"	3	2/0	
5	cat no CP2HD 323		100	90A	1 1/2"	3	2/0	
6	cat no CP2HD 423		100	100A	1 1/2"	4	No 1	

Fig. 10-13 Schedule to identify switches used on bus duct.

PLANNING THE SYSTEM

A duct system can be planned easily and quickly in most cases. The basic factors necessary to electrically plan and execute a compatible, efficient, and economical system include:

1. Determine connected-load and future-growth requirements.
2. Determine the load demand and duty cycles of the various loads.
3. Calculate voltage drop.
4. Calculate power factors.

Factors 1 and 2 are acquired from the owners or equipment suppliers.

The voltage drop can be calculated by the following formula:

$$\text{Maximum voltage drop per 100 ft} \times \frac{\text{actual load amperage}}{\text{rated amperage}} \times \frac{\text{percentage drop}}{@\ \text{worst power factor}} = \text{voltage drop per 100 ft}$$

The graph in Fig. 10-12 will aid the designer in voltage-drop and power-factor calculations.

EXAMPLE

A copper bus duct rated at 800 A is installed with a load of 400 A (demand) at 0.60 power factor. Voltage drop (2.8) × 400 load A/800 rated A × percent of voltage drop at appropriate power factor (0.93) = 1.3 V per 100 ft. Therefore the complete voltage drop over a 500-ft run would be 6.5 V.

In our example in Fig. 10-11, plug-in taps are required adjacent to each piece of machinery and at the lighting panel; these switches are indicated by the symbol ◯, with an identification number at each. A schedule is then shown on the working drawing to exactly identify each switch. This schedule is shown in Fig. 10-13.

Chapter 11

Special Electrical Systems

REMOTE-CONTROL SYSTEMS FOR LIGHTING CIRCUITS

Remote-Control Relay Switching

Relays were developed several years ago to meet the demands for more convenient and reliable control of industrial, commercial, and residential equipment. The relays permitted more flexible control for residential lighting, and low voltage and low current in the control circuit provided for added safety.

The basic circuit of a remote-control wiring system is as shown in Fig. 11-1.

The split-coil type of relay, as shown in Fig. 11-1, permits positive control for ON and OFF. The relay can be located near the lighting load, or installed in centrally located distribution panel boxes, depending on the application.

Because no power flows through the control circuits and low voltage is used for all switch and relay wiring, it is possible to

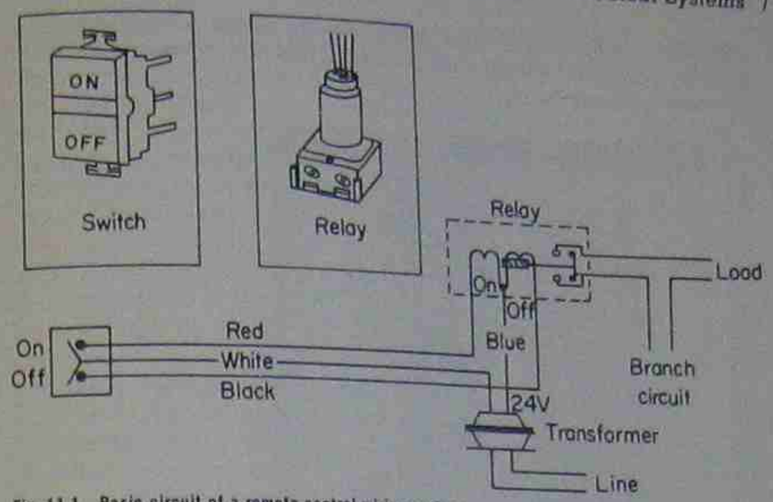


Fig. 11-1 Basic circuit of a remote-control wiring system.



Fig. 11-2 Typical 24-V transformer used for the power supply in remote-control systems.

place the controls at a great distance from the source or load, thus offering many advantages through this modern system of wiring.

System Components

Power Source. A single-main power source is used to provide the correct voltage for operation of all relays in a remote-control system. The power supply usually consists of a pulse-type transformer, a selenium rectifier, and an electrolytic capacitor. Input voltage is 120 or 277 V while the momentary output voltage occurring when a switch is pressed is 24 V. This power supply is usually mounted on one of the relay cabinets, but it may be installed at other locations, such as at the service entrance, if required for a particular application. Figure 11-2 shows a typical transformer used for the power supply in remote-control systems.

Relay. The relay normally used in residential remote-control systems is a mechanical latching type with a single coil. Momentary impulses from the power supply alternately open and close the contacts in the load circuit. Each relay may control several outlets if desired, but a single switch may not control more than one relay. See Fig. 11-3.

Switches. One basic type of switch, the single-pole, double-throw, momentary-contact push button, does the work of single-pole, double-pole, three-way, and four-way switches used in conventional wiring—and with less wiring. Pressing the ON position of the switch energizes the related relay and closes the circuit to the load; pressing the OFF position of the switch again energizes the relay and opens the circuit to the load. One type of remote-control switch does not have "on-off" designations, but with each touch of the push button, the relay alternately opens and closes. Figure 11-4 shows one type of remote-control switch.



Fig. 11-3 Remote-control relay.



Fig. 11-4 Remote-control switch.

Figure 11-A which was supplied by Electro Systems Inc. shows a typical relay cabinet, local switch connections and control wiring.

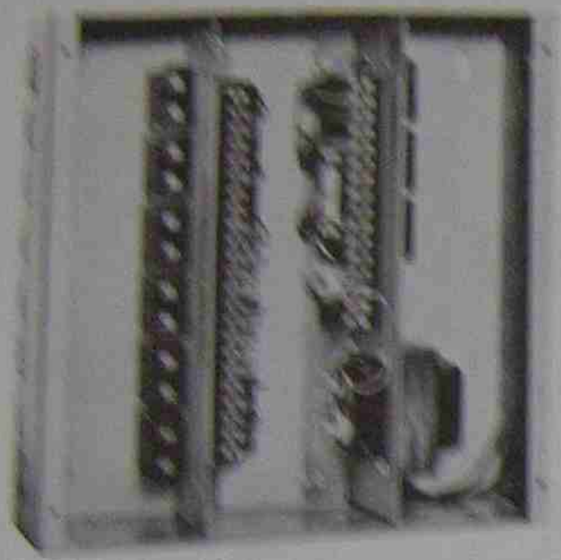


Fig. 11-A Relay cabinet

Master-Selector Switch. Where many circuits must be controlled from one convenient location, master-selector switches as shown in Fig. 11-B perform the necessary functions of selecting only those circuits wanted.



Fig. 11-B Master-selector switch

A "dial-type" master-selector switch for 10 circuits permits individual control of the circuits alternately, by pressing and then sweeping off circuits, master control is accomplished.

Multi-Master Control Units. Multi-master master-control units are used to turn on or off up to 25 individual circuits, when three units are connected, the pressing of a single master switch can control any number of circuits depending on the number of changing is accomplished by having the last position of the first unit wired to start the second unit, the last position of the second unit wired to start the third unit, and so on. These units can be activated by photoelectric cell relays for automated lighting control.

Combining Remote Control with Dimmer. Sometimes it is desirable to dim certain lighting fixtures which are controlled by a remote control system. This is accomplished by wiring a dimmer, between the relay and the fixture as shown in the wiring diagram in Fig. 11-C. The dimmer adjusts the intensity of the light, and the remote controls turn it on or off.

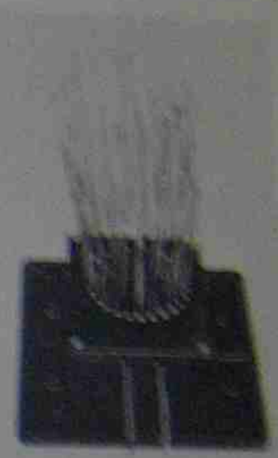


Fig. 11-C Multi-Master, 25 control unit.



Fig. 11-C Master-circuit connection one to control, multi-control, with dimmer.

LOW-VOLTAGE CONTROLS

Low-voltage controls offer a safe, quiet means of switching electricity that is not possible to obtain with conventional switching methods and that have provided a new freedom in the design and use of circuit control.

With a low-voltage control system, it is practical for the designer to provide all or a number over-all-room multiple-switch control of individual electrical circuits to create a new level in convenience for the user. Master-control centers also provide for remote control in the operation of multiple circuits from one or more locations and give visual indication of the use of each circuit. This capability in controlling lighting systems allows the electrical designer greater latitude in providing his or her clients with the convenience desired.

The following discussion indicates several applications possible with low-voltage control and was supplied by Touch-Plate Electro-Systems Inc.

Visual Aids to Schools

A variety of visual aids such as blackboards, flip charts, projection screens, etc., can be illuminated by supplementary and one fixed lamp, each connected to a master-control center at the instructor's position. Lights can be controlled as required during instruc-

Figure 11-5, which was supplied by Electro Systems, Inc., shows a typical relay cabinet, local switch connections, and related wiring.

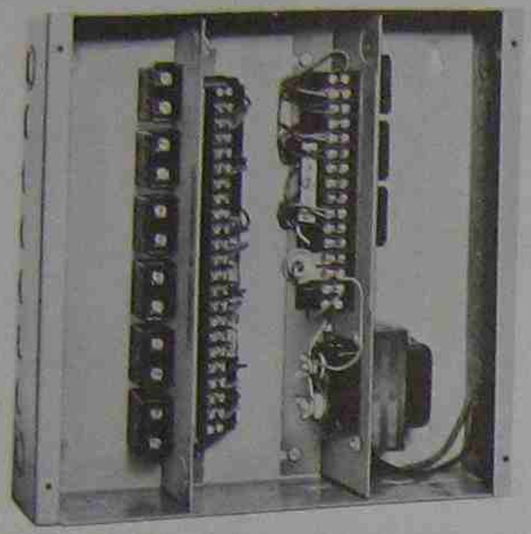


Fig. 11-5 Typical relay cabinet.

Master-Selector Switch. Where many circuits must be controlled from one convenient location, master-selector switches as shown in Fig. 11-6 perform the necessary functions of selecting only those circuits wanted.

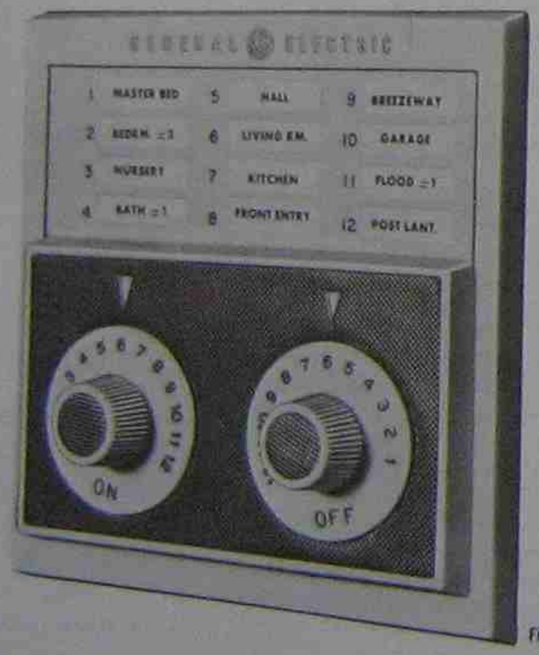


Fig. 11-6 Master-selector switch.

A "dial-type" master-selector switch for 12 circuits permits individual control of the circuits; alternatively, by pressing and then sweeping all circuits, master control is accomplished.

Motor-Master Control Units. Motor-driven master-control units are used to turn on or off up to 25 individual circuits; when these units are cascaded, the pressing of a single master switch can control any number of circuits, depending on the number of Motor-Master units (Fig. 11-7) that are ganged together. Ganging is accomplished by having the last position of the first unit wired to start the second unit, the last position on the second unit wired to start the third unit, and so on. These units can be activated by photoelectric cell relays, for automated lighting control.

Combining Remote Controls with Dimmers. Sometimes it is desirable to dim certain lighting fixtures which are controlled by a remote-control system. This is accomplished by wiring a dimmer between the relay and the fixture, as shown in the wiring diagram in Fig. 11-8. The dimmer adjusts the intensity of the light, and the remote controls turn it on or off.

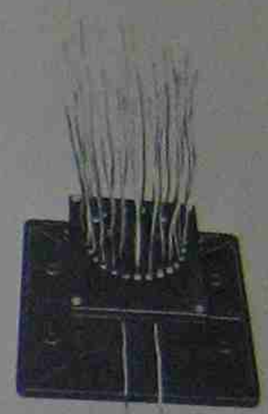


Fig. 11-7 Motor-Master (R) control unit.

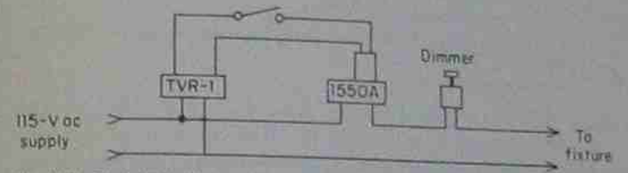


Fig. 11-8 Control-circuit connections used for combining remote controls with dimmers.

LOW-VOLTAGE CONTROLS

Low-voltage controls offer a safe, quiet means of switching electricity that is not possible to obtain with conventional switching methods, and they have provided a new freedom in the design and use of circuit control.

With a low-voltage control system, it is practical for the designer to provide—at a nominal cost—sufficient multiple-switch control of individual electrical circuits to create a new level in convenience for the user. Master-control centers also provide for remote control in the operation of multiple circuits from one or more locations and give visual indication of the use of each circuit. This capability in controlling lighting systems allows the electrical designer unusual latitude in providing his or her clients with the convenience desired.

The following discussion indicates several applications possible with low-voltage control and was supplied by Touch-Plate, Electro-Systems, Inc.

Visual Aids for Schools

A variety of visual aids, such as blackboards, flip charts, maps, etc., can be illuminated by supplemental spot and flood lamps, each connected to a master-control center at the instructor's podium. Lights can be controlled, as required, during instruc-

tion so that the desired visual aid can be highlighted. A wiring diagram for this application is shown in Fig. 11-9.

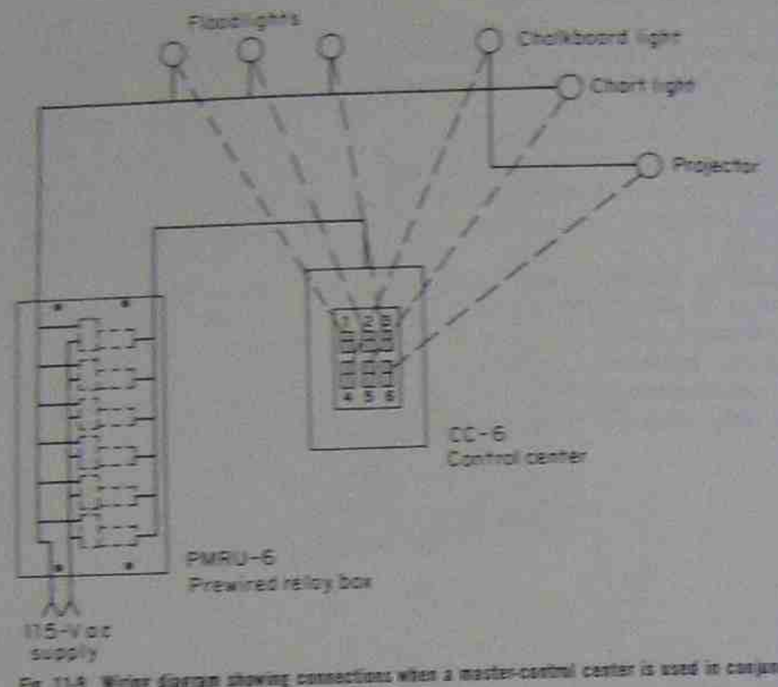


Fig. 11-9 Wiring diagram showing connections when a master-control center is used in conjunction with low-voltage relays for visual aids in schools.

Fail-Safe Alarm System

The purpose of this type of alarm is to alert the bank manager or security office when any one of the teller stations is in need of assistance, without sounding a general alarm.

Figure 11-10 shows the wiring diagram for a possible solution. Momentary contact switches are installed at each teller station and are wired with low-voltage wire to control centers in the offices of the manager and/or security officer. The control centers show at a glance the source of the warning. A bell or buzzer may also be installed which can be turned off by key as action is taken.

Industrial Application

PROBLEM

Lack of switch points owing to high ceilings and open truss construction. Attendant made rounds, turning out unused but sometimes necessary lights.

SOLUTION

A low-voltage remote-control system was installed. Number 18 AWG wire was strung along girders, reaching previously inaccessible switching points. Larger areas could now have zone control. Control panels at main entries revealed which

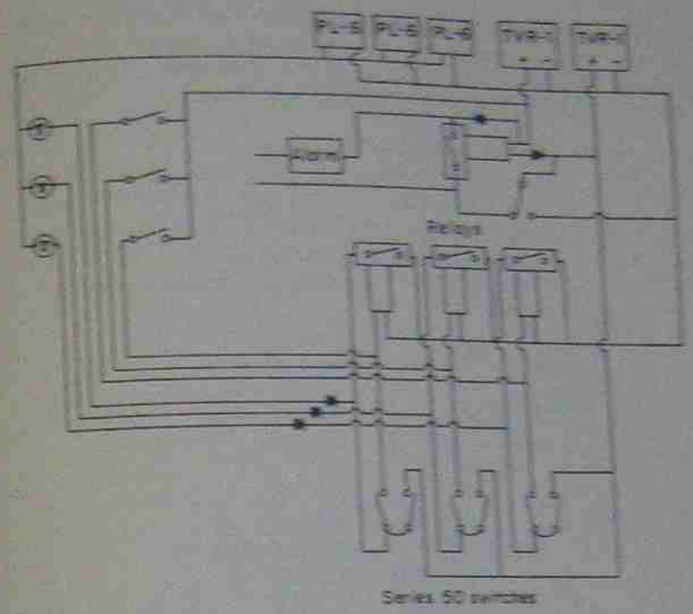


Fig. 11-10 Example of remote-control circuits used for security purposes.

lights were burning and gave fingertip control, thus reducing operating cost. See Fig. 11-11 for the wiring diagram.

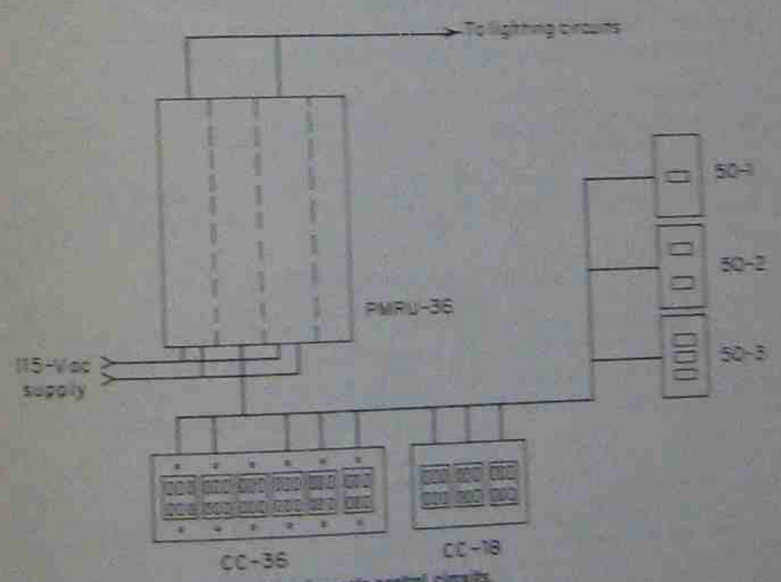


Fig. 11-11 Industrial application of remote-control circuits.

Motel Management

A low-voltage master-control center installed in a motel office and also in the supply room can save much time in determining

which rooms are ready for occupancy. (See Fig. 11-12.) As soon as maid service is completed, the office is signaled from the supply room. When guests check out, the manager signals for maid service, maintaining a constant readiness and flow of work.

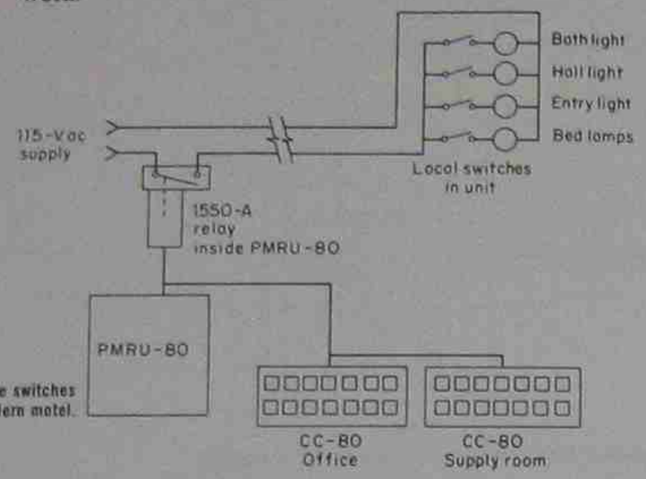
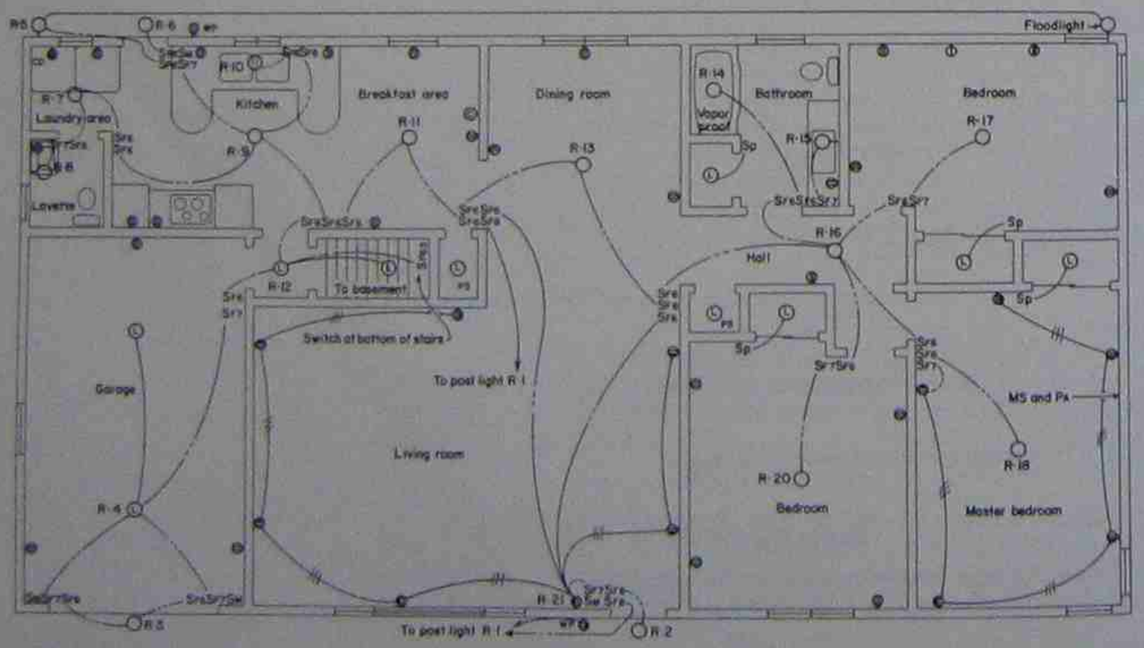


Fig. 11-12 Low-voltage switches used in a modern motel.

Home Protection

Floodlights are installed at the eaves of a house. These, along with entrance lighting fixtures and three landscape lighting circuits, were connected to a master-control panel in the master bedroom. When there are sounds or visitors in the night, occupants can instantly light up the entire property. See Fig. 11-13.



Nurse Call System

When it is necessary to alert the nursing-station supervisor that a patient has called for assistance, a low-voltage switch at the patient's bed can be used to turn on a corridor light outside the room as well as a light in the master-control center at the duty station. If it is wired to a wall switch at the door in the patient's room, the light at the control center will remain on until the patient receives attention. Then the light can be turned off by the wall switch in the patient's room. Figure 11-14 shows a wiring diagram of such a system.

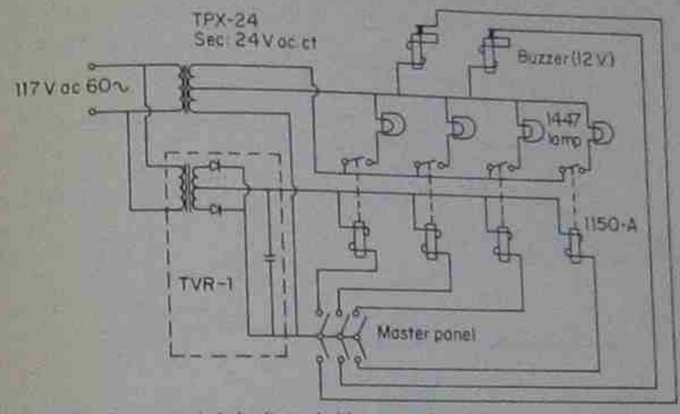


Fig. 11-14 Remote-control circuits used with a nurse-call system.

Nursing Homes

Low-voltage switches can provide ample, easy-to-handle switching for lights in nursing homes so that elderly patients need not walk in darkness or risk shock from wiring. In addition, master-control centers can provide zone lighting, allowing entire areas to be lit at once in case of emergencies. See Fig. 11-15.

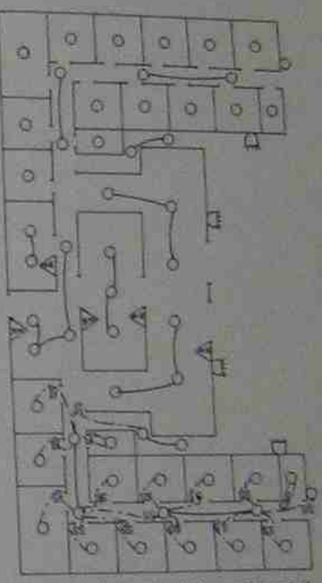


Fig. 11-15 Application of the remote-control circuit used in a nursing home.

Travel Trailers and Yachts

When space limitations are a problem, low-voltage switching is very practical, since the 18-gauge wire requires a minimum of space in the raceways and only a ½-in. depth is necessary for the switches. Because switch legs carry low voltage, danger of

Fig. 11-13 (Facing page) Remote-control circuits used for home protection. This layout shows a deluxe wiring system employing the use of multipoint switching that permits turning on room lights from every doorway, switch-controlled split receptacles in living room and master bedroom, master-selector switch at the bedside. Selected lights and receptacles are also controlled from two Motor-Master units not shown. It has been designed to provide protection control, turning on perimeter lights to floodlight the grounds, as well as lighting selected rooms from the master bedside. Pressing a single button S_M at any entrance, or the 12th position of the master-selector switch, starts the Motor-Master for ON control of the selected lights to provide a pathway of light through the house, or the OFF side for turning off the lights in and around the house. And here is downright convenience, a switch-controlled outdoor weatherproof split receptacle that lets the homeowner turn the decorative Christmas lights on and off from two handy indoor locations. Any portion of this layout can be used as a guide in laying out a General Electric remote-control installation to meet requirements specified by the architect, builder, or home-buyer. (NOTE: Be sure to specify pilot-type relays for pilot-light switches.)

fire and personal injury is kept to a minimum. Figure 11-16 shows a wiring diagram for such a system.

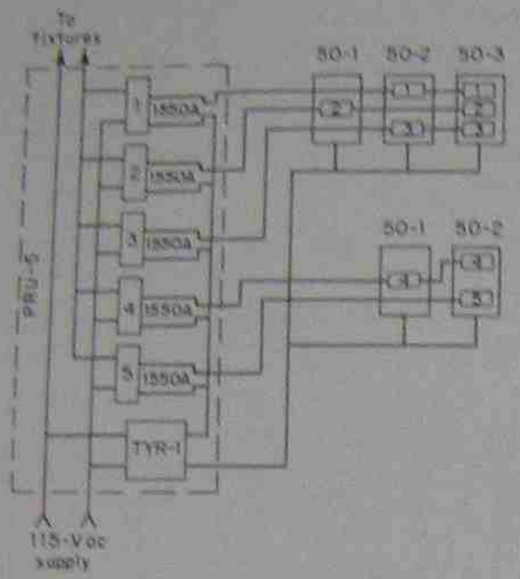


Fig. 11-16 Use of remote control in travel trailers and yachts.

Office Use

Should a large firm need to know where its key personnel are at all times, low-voltage master-control panels installed in each office and activity area can be wired into a similar panel at the receptionist's desk. By assigning a color to each person and a number to each room, it is possible to tell at a glance where each person is at any given moment. It is also possible to know who is in a particular office. See Fig. 11-17.

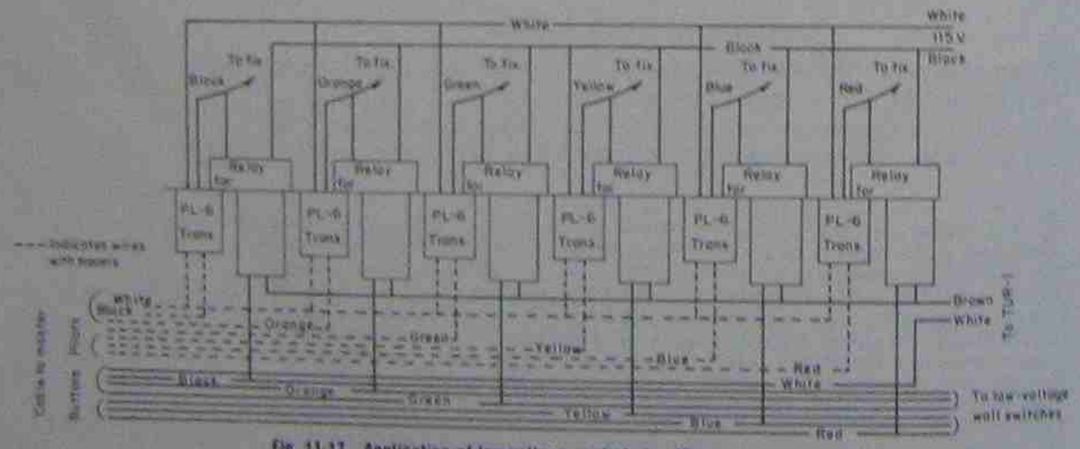


Fig. 11-17 Application of low-voltage controls in office areas to locate personnel.

Modular Housing

PROBLEM

Exterior walls were precast. Thin, interior wall-partitions were designed to be rearranged as changing space needs dictated.

SOLUTION

Conduit and outlet boxes were installed in the precast sections. All interior sections were wired with double runs of low-voltage wire so that low-voltage switches could be installed at either side of the panel, however it was placed. Multibutton master-control centers provided maximum control of all circuits. See Fig. 11-18.

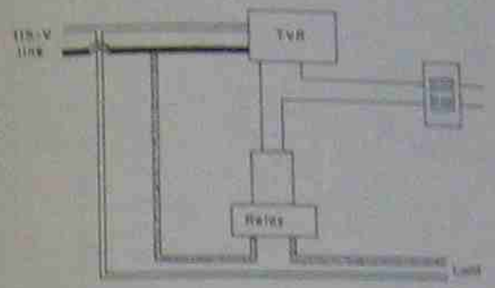


Fig. 11-18 Use of low-voltage controls in modular housing.

Restaurants

Sometimes it is desirable for restaurant managers to know instantly when a specific table anywhere in the restaurant becomes available for seating, without a lot of leg work.

A lighted scale model of the restaurant floor plan could be wired in parallel with master-control centers at two serving stations. The moment a table is cleared, the waiter pushes a button on his panel, signaling the manager that the table is ready. See Fig. 11-19.

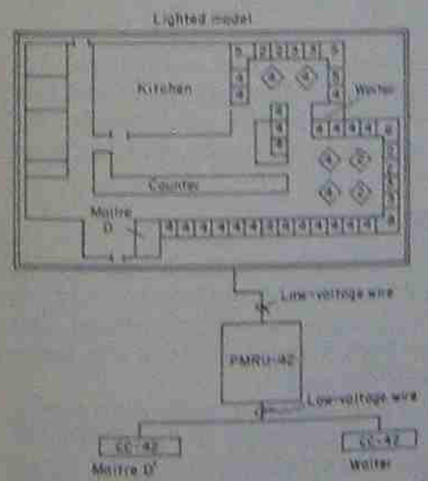


Fig. 11-19 Use of low-voltage controls in restaurants.

Figure 11-20 shows the floor plan of a typical residence using low-voltage switching for all lighting control.

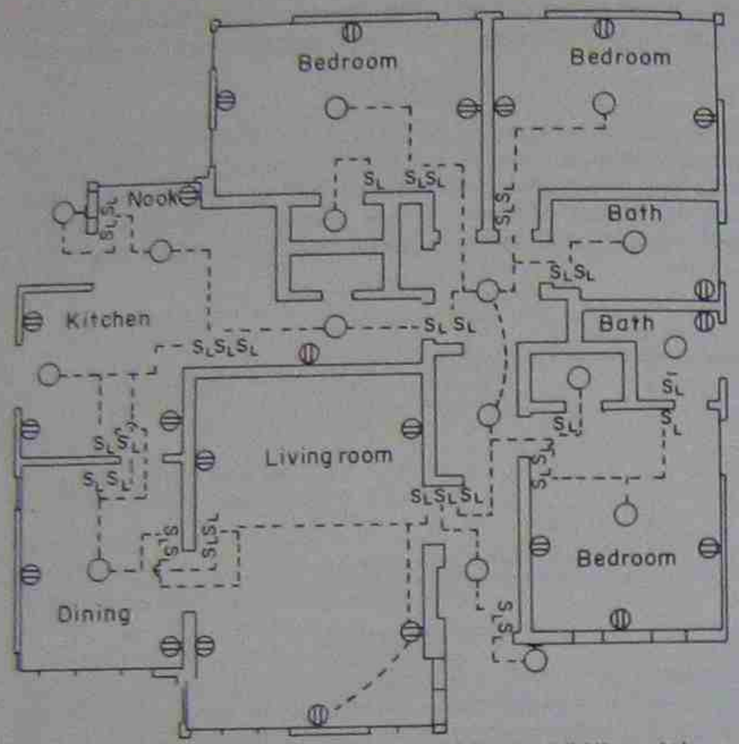


Fig. 11-20 Floor plan of residence using low-voltage switching for all lighting controls.

Figure 11-21 illustrates a typical relay cabinet and local switch connections for a typical low-voltage control system.

SIGNAL AND COMMUNICATION SYSTEMS

The field of electric signaling and communications is a very broad one, covering everything from simple residential door chimes to elaborate building-alarm and detector systems. For this reason, this chapter will not deal at length with any one branch of this field; rather it will touch briefly upon practically all branches with which the electrical designer will come in contact.

Electric Chime Systems

One of the simplest and most common electric signal systems is the residential door-chime system. Such a system contains a low-voltage source, a push button, wire, and set of chimes. The quality of the chimes will range from a one-note device to those which "play" lengthy melodies.

The wiring diagram in Fig. 11-22 shows a typical two-note chime controlled at two locations. One button, at the main entrance, will sound the two notes when pushed, while the other button, at the rear door, will sound only one note when pushed.

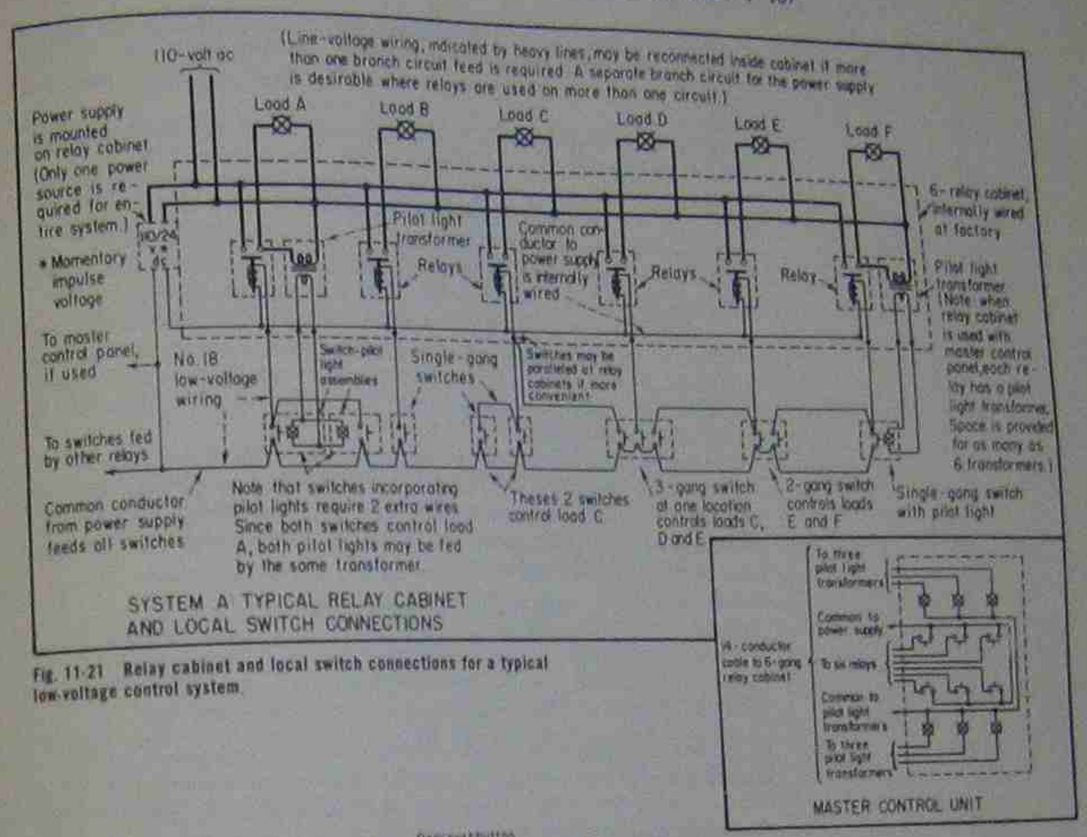


Fig. 11-21 Relay cabinet and local switch connections for a typical low-voltage control system.

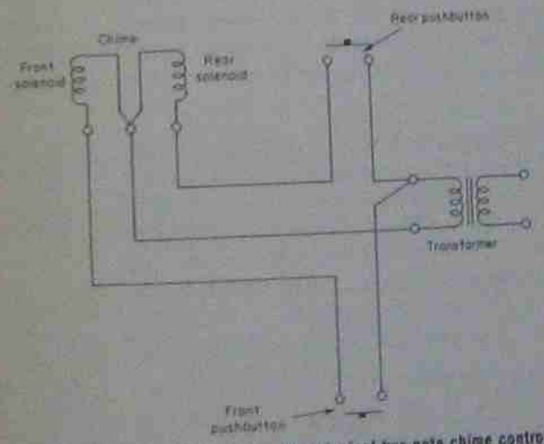


Fig. 11-22 Wiring diagram showing a typical two-note chime control at two locations.

Fire-Alarm Systems

All fire-alarm systems fall into four basic types:

1. Noncoded
2. Master-coded
3. Selective-coded
4. Dual-coded

Each of these four types has several functional features, so that an electrical designer can design a specific system to the client's needs within local and state fire codes, statutes, and regulations.

In a noncoded system, an alarm signal is sounded continuously until manually or automatically turned off.

In a master-coded system, a common-coded alarm signal is sounded for not less than three rounds. The same code is sounded regardless of the alarm-initiating device activated.

In a selective-coded system, a unique coded alarm is sounded for each firebox or fire zone on the protected premises.

In a dual-coded system, a unique coded alarm is sounded for each firebox or fire zone to notify the owner's personnel of the location of the fire, while noncoded or common-coded alarm signals are sounded separately to notify other occupants to evacuate the building.

The most difficult aspect of applying fire-alarm systems is the selection of the basic system along with the functional features required by different occupancies. The following chart simplifies this selection process, for the chart reads easily yet covers 64 standard systems.

GUIDE CHART FOR FIRE-ALARM SYSTEMS

Type of system	General alarm annunciation			Presignal annunciation		
	None	"A" type	"D" type	None	"A" type	"D" type
Noncoded systems	N-1 N-2	NA-1 NA-2	ND-1 ND-2	NM-1 NM-2	NAM-1 NAM-2	NDM-1 NDM-2
Common-coded systems	C-1 C-2	CA-1 CA-2	CD-1 CD-2	CM-1 CM-2	CAM-1 CAM-2	CDM-1 CDM-2
Selective-coded systems:						
Series noninterfering, successive	S-1 S-2	— —	— —	SM-1 SM-2	— —	— —
Positive noninterfering, successive	P-1 P-2	— —	PD-1 PD-2	PM-1 PM-2	— —	PDM-1 PDM-2
Zone-coded	— —	ZA-1 ZA-2	ZD-1 ZD-2	— —	ZAM-1 ZAM-2	ZDM-1 ZDM-2
Dual-coded systems:						
Noncode + series noninterfering, successive	NS-1 NS-2	— —	— —	— —	— —	— —
Noncode + positive noninterfering, successive	NP-1 NP-2	— —	NPD-1 NPD-2	— —	— —	— —
Noncoded + zone-coded	— —	NZA-1 NZA-2	NZD-1 NZD-2	— —	— —	— —
Common-coded + series noninterfering, successive	CS-1 CS-2	— —	— —	— —	— —	— —
Common-coded + positive noninterfering, successive	CP-1 CP-2	— —	CPD-1 CPD-2	— —	— —	— —
Common-coded + zone coded	— —	CZA-1 CZA-2	CZD-1 CZD-2	— —	— —	— —

The system numbers used in the preceding table consist of up to three alphabetical characters followed by the suffix 1 or 2.

The alphabetical characters denote:

N. A no-code system.

M. A multialarm or presignal system where the initial operation of any manual or automatic alarm-initiating device sounds an alarm on certain primary alarm signals. Authorized personnel with special keys may initiate a general-evacuation alarm from any manual firebox. On automatic fire-alarm systems, auxiliarized city fireboxes (if used) are tripped on the first alarm, and general-evacuation alarms are all noncoded.

C. A common-code or master-code system.

S. A selective-code system using coded fireboxes in which all fireboxes are in one common wired loop, and the coded firebox nearest the control unit has precedence on the loop. This is commonly called series noninterfering, and successive.

P. A selective-code system using coded fireboxes in which all fireboxes are on one common wired loop and arranged so that only one code at a time can sound even if two or more fireboxes are activated simultaneously. This prevents confusion resulting from incomplete, lost, or mutilated codes. This is commonly referred to as positive, noninterfering, and successive.

Z. A selective-code system using noncoded fireboxes or automatic devices that are point-wired to the control unit and with the coding done with the control unit. All codes sound in a positive, noninterfering, and successive manner as described for the P systems. All Z systems are furnished with annunciators in the control unit.

A. An annunciator feature on some systems in which each alarm zone illuminates a backlighted window. In addition, each alarm-zone window has an adjacent trouble window that lights in the event of an "open" condition on its associated alarm-zone wiring. Two lamps are used in the alarm window and one lamp in the trouble window. A flashing alarm-lamp feature is available with the A-line annunciators.

D. An annunciator feature on some systems in which each alarm zone illuminates a backlighted window. Two lamps are used in parallel so that the window can be read even if one lamp is burned out.

The suffixes 1 and 2 have to do with the alarm-signal circuits:

1 Alarm-signal operating voltages derived from the primary power source of 120 V ac

2 Alarm-signal voltage of 24 V dc derived from a transformer and rectifier isolated from the 120 V ac

Individual system descriptions are available from the manufacturer.

Fire-Alarm System Applications

Nursing Home. Figure 11-23 shows a partial floor plan of a nursing home. This portion of the floor plan shows the fire-alarm panel, smoke detectors (SD), striking stations, gongs

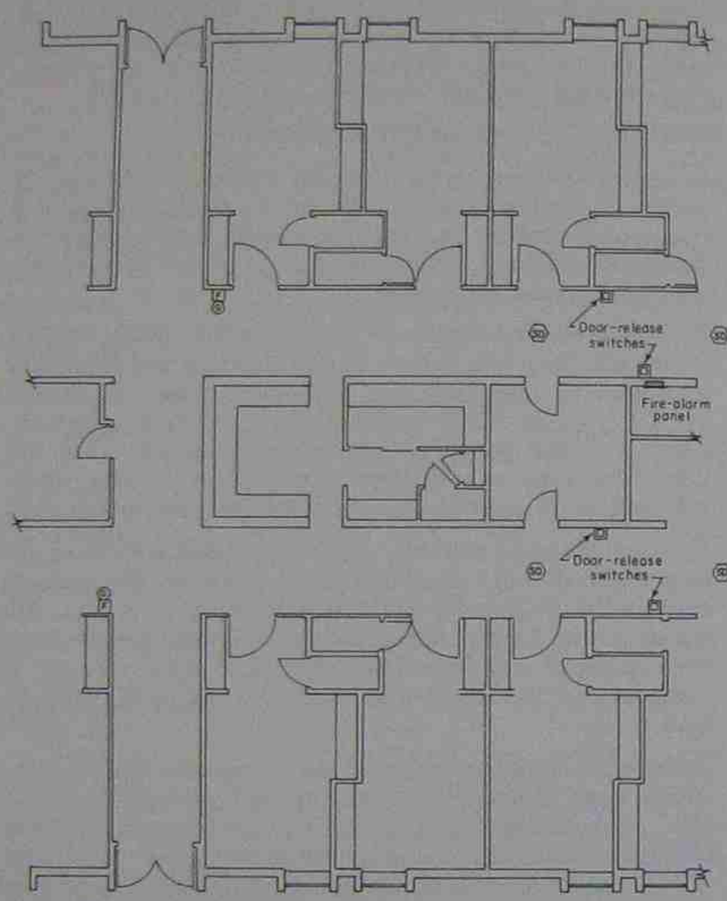


Fig. 11-23 Partial floor plan of nursing home.

(bells), and magnetic door-release switches. The fire-alarm riser diagram in Fig. 11-24 shows all devices connected to this system, along with the wiring of each.

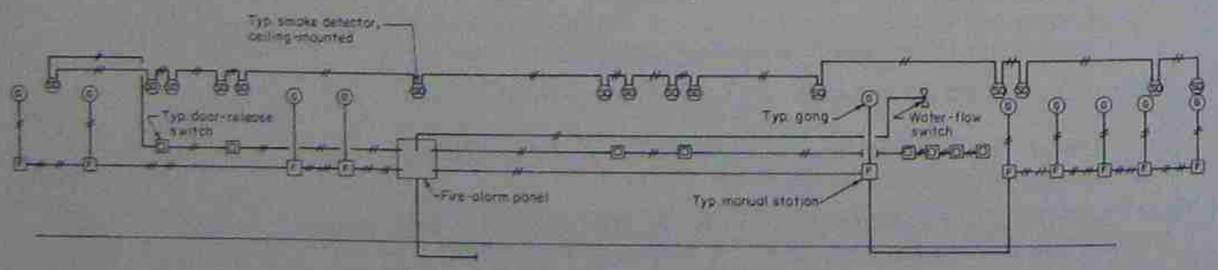


Fig. 11-24 Fire-alarm system riser diagram.

Basically, if any smoke detector senses smoke, or if any manual striking station is operated, all bells within the building will ring, indicating a fire. At the same time, the magnetic door switches will release the smoke doors to help block smoke and/or drafts. This system is also connected to a water-flow switch on the sprinkler system, so that if any of the sprinkler valves are activated, causing a flow of water in the system, the fire-alarm system will again go into operation energizing all bells and closing smoke doors.

Public Building. The floor plan of a county courthouse is shown in Fig. 11-25. The fire-alarm panel is located in the mechanical room on another floor, but all striking stations, bells, door-

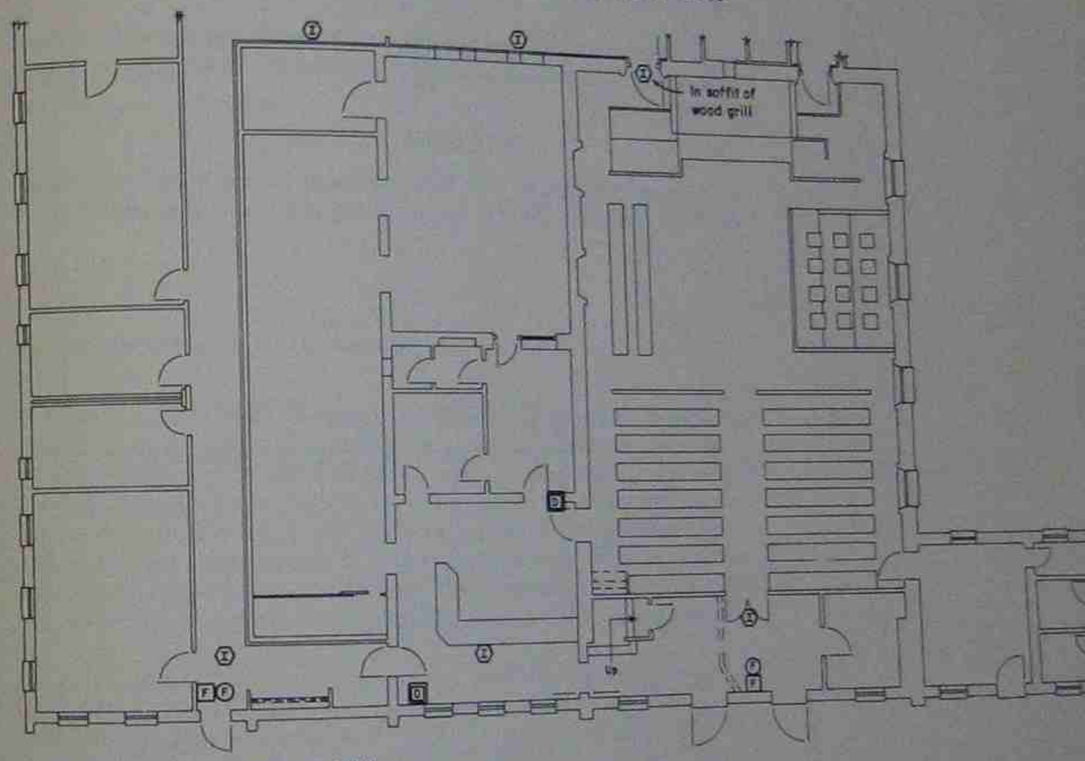


Fig. 11-25 Floor plan of a courthouse building.

release switches, and ionization smoke detectors are shown on this plan and operate in the same manner as the system described for the nursing home. A few differences, however, should be noted and can be seen by referring to the related fire-alarm riser diagram in Fig. 11-26.

1. There is no sprinkler system in this building, and therefore no water-flow switch was used.
2. A magnetic contactor was supplied on each of the three air-handling units used for air-conditioning purposes. When any part of the fire-alarm system is activated, either manually or automatically, all fans are automatically shut down to stop the flow of air within the building. This action keeps the spread of fire to a minimum.

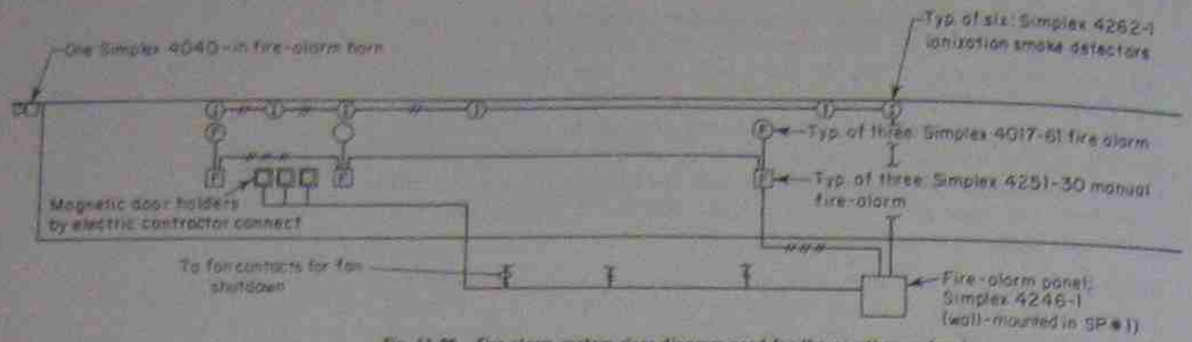


Fig. 11-26 Fire-alarm system riser diagram used for the courthouse drawings.

3. The ionization smoke detectors are more sensitive than the conventional smoke detectors used on the nursing home project.

INTERCOM SYSTEMS

A local rescue squad unit recently built an addition onto their existing building. During the planning stages of this addition, it

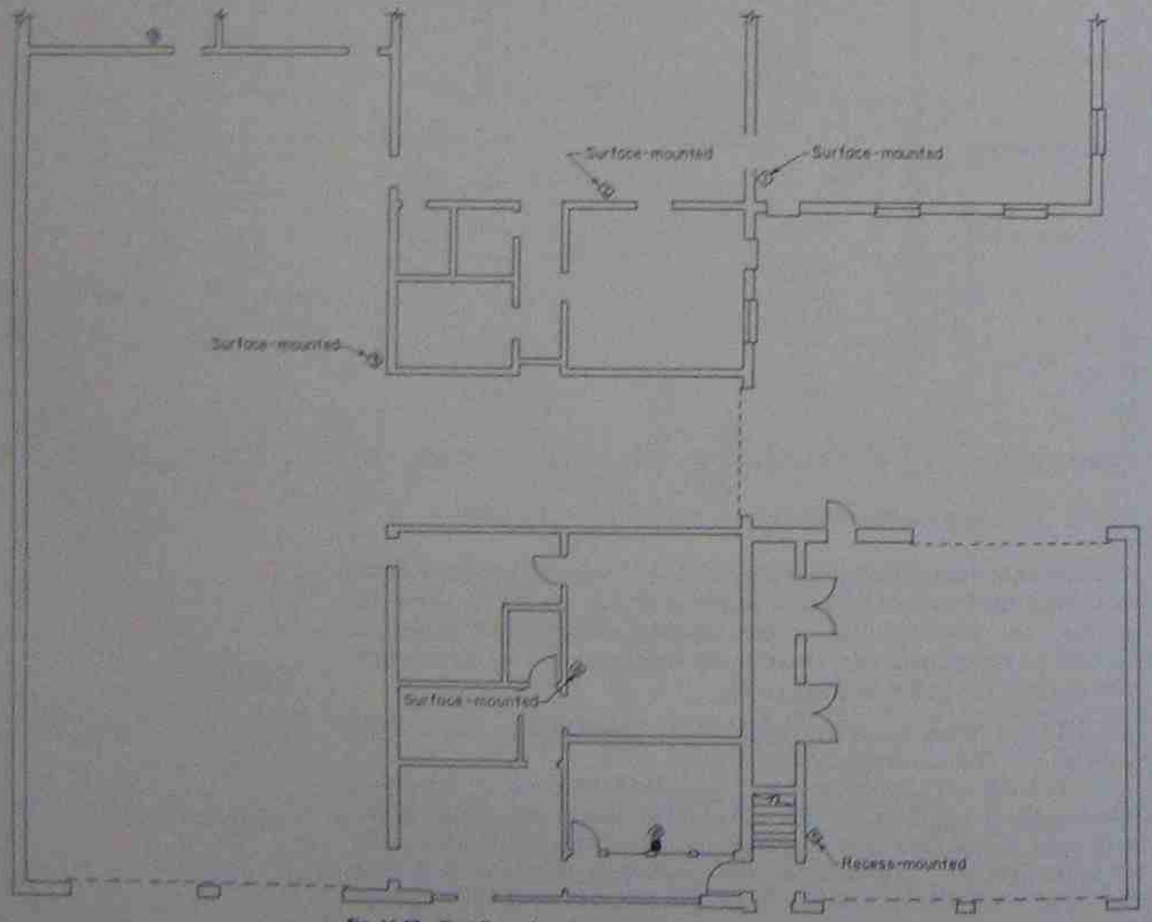


Fig. 11-27 First-floor plan of a rescue-squad building.

was decided to install a new intercom system throughout the building. The system was to be designed so that the dispatcher could talk or listen to the stations within the building either individually or simultaneously and so that any one station could call and talk with the dispatcher or any other individual station within the building.

Figures 11-27 and 11-28 show the floor plans of the building under consideration. All stations are indicated by a diamond-shaped symbol with the station number in each.

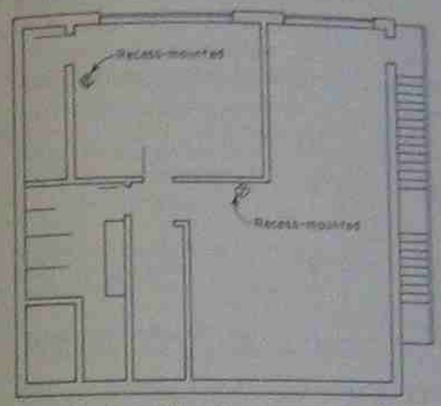


Fig. 11-28 Second-floor plan of a rescue-squad building.

The intercom-riser diagram in Fig. 11-29 gives a schematic diagram of all the stations as well as the related wiring, conduit sizes, etc. The manufacturer and catalog number of each device are also indicated on this riser diagram along with other notes, in order to facilitate the installation of the system.

A detailed description of the system should also appear in the written specifications in case the contractor wishes to substitute another brand of equipment.

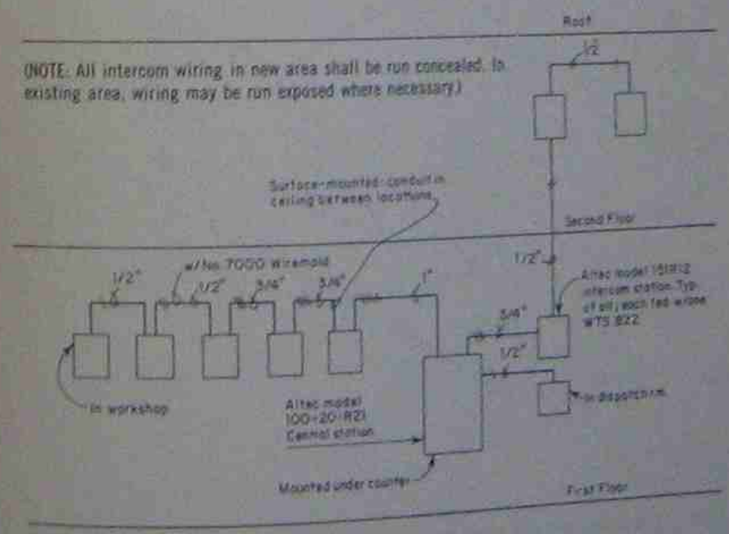


Fig. 11-29 Intercom-riser diagram.

TELEPHONE SYSTEMS

A partial floor plan of a branch bank is shown in Fig. 11-31 below. The wall-mounted telephone outlets are designated by a shaded triangle; three are shown in the illustration. Four floor-mounted telephone outlets are also shown in the teller area and are designated by a shaded triangle and enclosed in a square.

Although it is not shown on the floor plan, a telephone cabinet is located in the mechanical room of this building. The written specifications describe the type of outlet box to be used for each of the two outlet types and the telephone-riser diagram (see Fig. 11-30) shows that a ¾-in. empty conduit with a pull wire in each runs from each telephone outlet and terminates in the telephone cabinet.

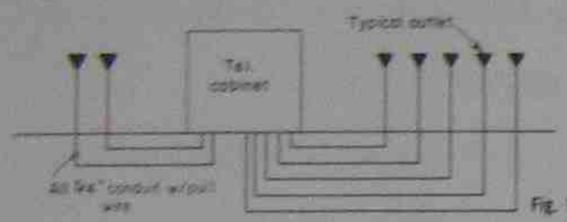


Fig. 11-30 Telephone-riser diagram.

The local telephone company is responsible for installing the telephone cabinet as well as pulling the required cable to each telephone outlet within the building.

BANK ALARM SYSTEMS

Figure 11-31 also shows various outlets for the bank security system such as camera junction boxes, smoke detectors, sound

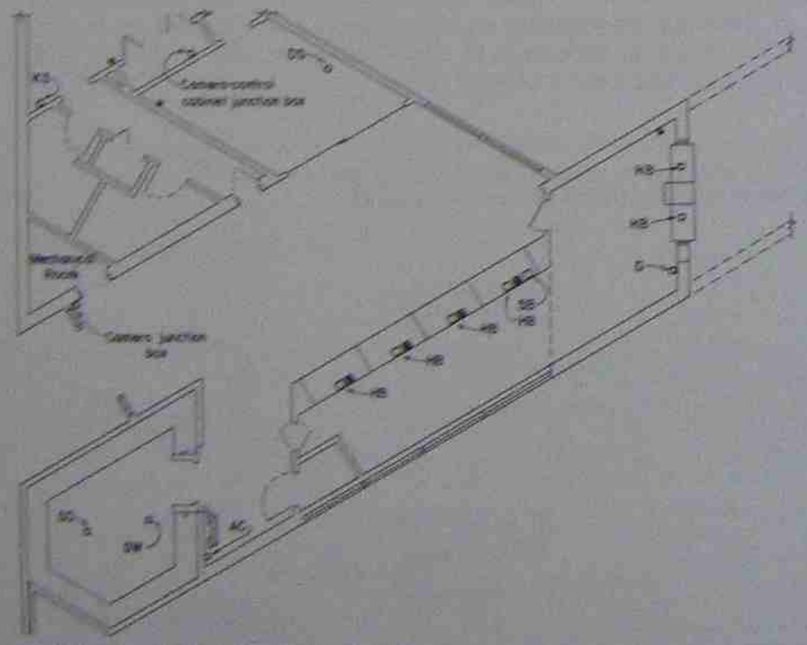


Fig. 11-31 A partial floor plan of a branch bank.

receivers, alarm buttons, etc. They are shown on the floor plan only to indicate the approximate location of each. Details of wiring are not shown in this drawing, but the riser diagram in Fig. 11-32 indicates clearly how each outlet is to be installed.

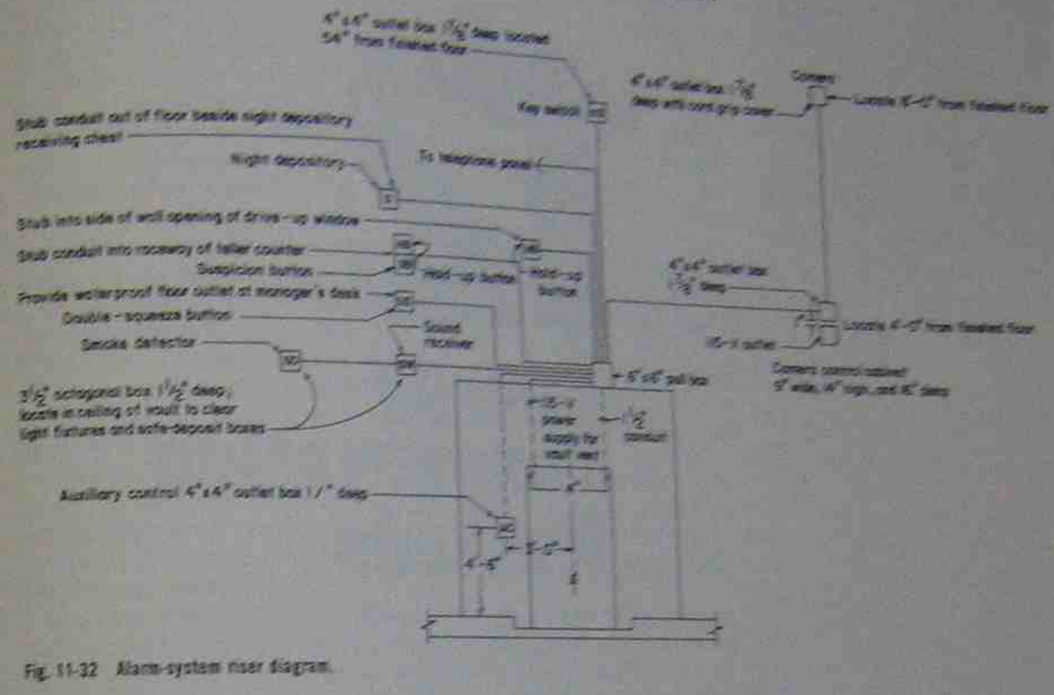


Fig. 11-32 Alarm-system riser diagram.

Chapter 12

Energy-Conservation Methods

Conservation of our natural resources through wise and efficient use of energy has now become a matter of great importance to everyone. This does not mean that the use of these resources must be stopped—returning us to the life-style of our ancestors—but it does mean that there is no place for wasteful use of energy. Everyone must strive to use available energy resources more wisely and with greater efficiency.

This new era has clearly defined the electrical engineer's role in the immediate future—to design electrical systems which will permit the use of electrical energy wisely; to see to it that these systems are installed as specified; and to instruct the system users on its proper and most efficient operation.

The following paragraphs describe various methods—employed by consulting engineers, contractors, and users—which have helped to conserve electrical energy. The use of any or all of these techniques is highly recommended whenever it is practical. Judgment must be used in each individual application to determine the feasibility of each technique.

INCANDESCENT LAMPS

Incandescent lamps should be installed only in areas where their use will be of short duration. Such areas may include clothes closets and small storage closets, janitors' closets, infrequently used storage areas, or places where the use of a more efficient light source would be impractical.

Higher-wattage general-service lamps are more efficient than lamps of a lower wattage. One 200-W lamp, for example, produces 4,010 lm as compared to 3,500 lm from two 100-W lamps. Therefore, the designer should strive to specify lighting fixtures which will handle the higher-wattage lamps. For example, the lighting fixture shown in Fig. 12-1 contains two 75-W lamps. The same style of fixture is manufactured to handle one 150-W lamp with about 15 percent increase in lamp lumen output—a much better choice when trying to conserve energy.



Fig. 12-1 Illustration of a two-lamp fixture.

General-service incandescent lamps are more efficient than extended-service lamps, but at the cost of a shorter lamp life. Where the replacement of lamps causes no large problem, it is recommended that all incandescent lamps specified be of the general-service type; hard-to-reach fixtures, however, should be lamped with extended-service lamps.

If wall-wash fixtures must be used for accent lighting, try to select fluorescent or HID lighting fixtures. The color quality of certain HID and fluorescent lamps closely matches that of incandescent lamps and with a much higher efficiency (more lumens per watt).

Existing wall-wash fixtures containing incandescent lamps can be controlled by a timer switch or flasher control to turn the lights off and on at desired intervals. We have found that an interval of five seconds is about right for most applications—that is, on for five seconds, then off for five seconds. This will cut the energy consumed by 50 percent. Any duration shorter than 5 seconds becomes annoying to most, and the effect is lost for intervals longer than five seconds.

This interval delay of lighting may possibly be useful for applications other than wall-wash fixtures. In fact, for sign lighting, it would be more beneficial than a constant light since a flashing light (at short intervals) creates both light and motion which attract attention better than a constant light.

When the user leaves a room which will not be occupied again for several hours or until the next day, the lamps should, of course, be turned off unless safety reasons dictate otherwise. However, energy will not be saved by turning the lights off if the user will be returning to the room in a few minutes.

Any lighting fixture—incandescent included—should be cleaned frequently for maximum efficiency. Higher fixture efficiency will mean fewer fixtures and lamps and less wattage and wasted energy.

In rooms utilizing several incandescent fixtures for illumination, switch on the fixtures by rows because it is usually unnecessary to turn on every light in the room when natural daylight is available.

Since daylight intensity varies, switching off fixtures may not

always be the way to conserve energy. Dimming the lights, however, may be another possibility. Incandescent lamps become very versatile tools when they are equipped with a dimming-control device; moreover, energy is saved by reducing the lamp output. Now practically all lamps, including fluorescent and HID, may be dimmed, with the possibility of conserving energy.

Since conductor and circuit-breaker sizes need not be modified by use of dimmers, existing lighting circuits are readily adaptable to dimming systems.

In addition to helping to conserve energy and lowering operating costs, dimming systems are ideal for providing security lighting and allowing selective variation in illumination levels for other multifunction areas where the lighting needs cannot always be predicted.

More emphasis should be placed on the visual task in an area than on general illumination. For example, if it is desired to have 70 fc of illumination on a desk in a small office, one fluorescent fixture mounted directly above the desk will give approximately 70 fc on the desk top while the rest of the room may average only 30 fc. However, this should not be too annoying, and almost 200 W of energy will be saved in the process.

Fluorescent Lighting

Again more concentration should be placed on the visual task than on general illumination. The floor plan of a small branch bank is shown in Fig. 12-2. Notice that sufficient, even illumination is provided in the teller areas, but in the general lobby area uneven lighting was provided and the footcandle level varied from 20 to 70 fc. However, this gave a "warm" atmosphere within the lobby, and less energy was used than would have been if the entire lobby had been lighted to an average of 50 fc.

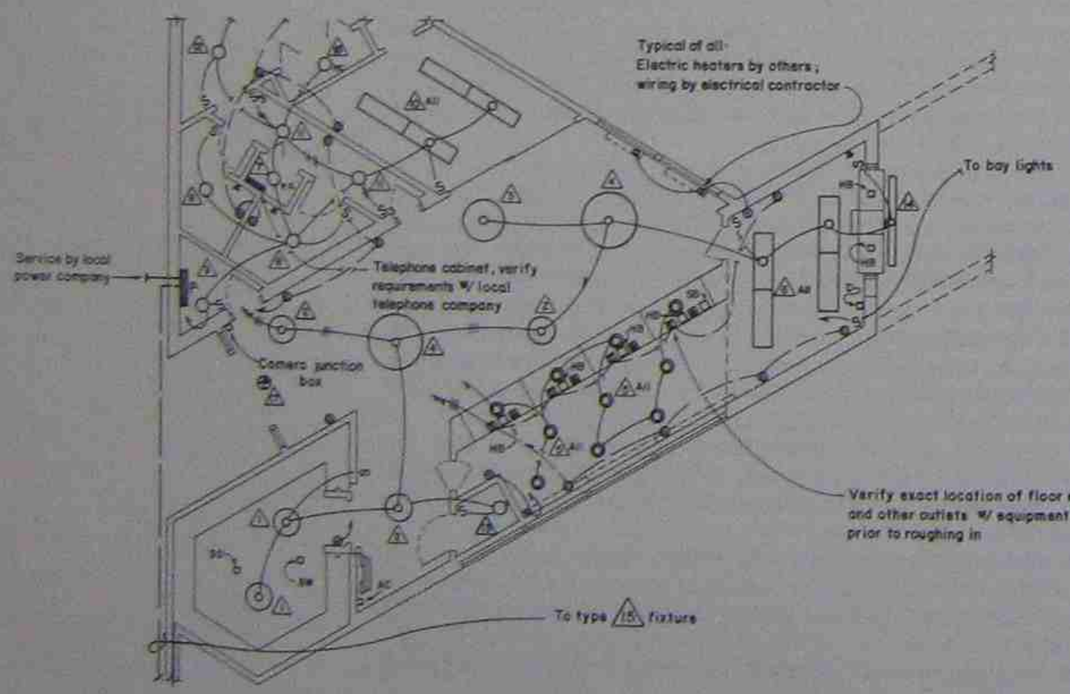


Fig. 12-2 Floor plan of a small branch bank.

Fluorescent fixtures should be substituted wherever possible for incandescent lighting. The photograph in Fig. 12-3 shows an office building corridor where two-tube fluorescent fixtures had just been installed to replace recessed incandescent fixtures using single 100-W lamps. The two 20-W fluorescent lamps in the new fixtures give more lumens at half the energy of the 100-W incandescent fixtures.



Fig. 12-3 An office building corridor in which two-tube fluorescent fixtures have just been installed to replace recessed incandescent fixtures using a 100-W lamp in each.

Wherever practical, four-tube fluorescent fixtures should be controlled so that each ballast is switched separately. Thus, either the two inside tubes or the two outside tubes may be controlled independently. Besides offering more versatility in lighting control, half of the lamps may be out when full brilliance is not required—thus saving energy. Figure 12-4 illustrates how this switching arrangement is shown on an electrical working drawing.

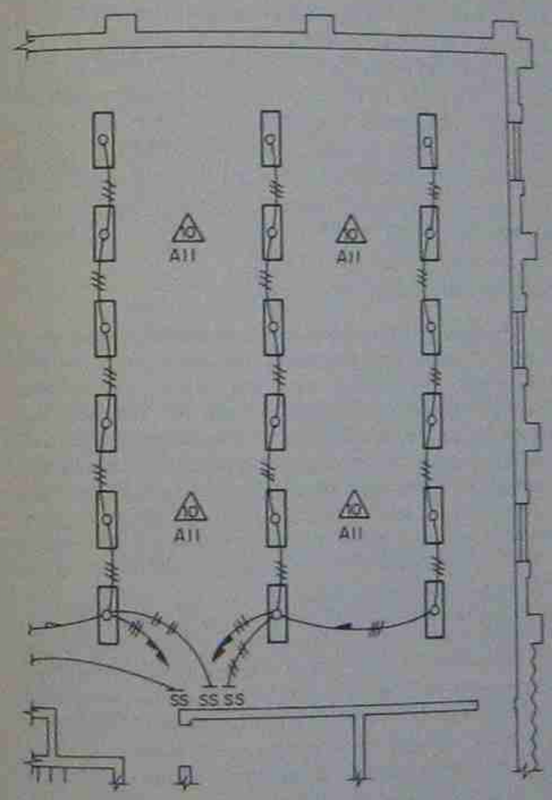


Fig. 12-4 Method used to show individual ballast switching on the working drawings.

"HEAT OF LIGHT"

Utilization of air-handling lighting fixtures is increasingly applied in a growing number of buildings and is now the preferred lighting design in many commercial structures.

Sometimes referred to as "heat of light," such fixtures utilize the heat of light as a by-product in the air-conditioning design. While saving energy in heating a building, this type of lighting fixture also has other advantages, since the removal of heat within the lighting fixture safeguards against excessive heat buildup, which can otherwise act to reduce light output and accelerate the degradation of electrical components and fixture finish materials.

Because of the cooler lamp chambers, this heat-of-light system permits higher lighting levels (up to 24 percent more light) with little or no increase in conditioned-air requirements. The result is fewer fixtures required for the visual task as well as saving in electrical energy.

Another benefit of heat of light is that it reduces the overall load on the air-conditioning equipment—another saving in energy use.

DAYLIGHTING

In the early part of this century, a distinguished French engineer by the name of Pierre Arthuys began experiments which resulted in the apparatus known as the Arthel heliostat.

A description of this sun-tapping device was published in *The Passing Show*, London (May 15, 1937). It was reportedly used to illuminate a large café in Brussels, the office building of the *Intransigeant* in Paris, the office building of the HAVOS news agency in Marseilles, the central post office at Amsterdam, and several other large offices and apartment buildings in France, Belgium, the Netherlands, North Africa, and London. All were apparently installed between 1933 and 1937.

Following is a description of heliostat use:

> A huge multistory office building located in the business section of a familiar city stands lifeless in the cool morning hours before sunrise. The outline of a motionless apparatus, resembling a large mirror, can be seen on the roof as it stands out against the brighter moonlit sky. Suddenly the warmth of the first rays of morning sun strikes an ultra-sensitive thermostat located near the apparatus. This energizes an electric motor which swings the westward-facing mirror quickly over to the east. From that point the mirror is pivoted by a second motor, controlled by three other sun-operated thermostats, until the solar image is reflected in the center of the steel mirror. Then, almost instantaneously, every room in the huge building is showered with bright, diffused sunlight.
>
> Above the mobile mirror is a large fixed mirror facing downward at an angle over a square shaft in the center of the building. The rays from the mobile mirror reflect on the fixed mirror, which deflects them in a powerful 32,000-candlepower beam straight down the shaft to the basement. Narrow shafts of light are collected from this main beam and reflected by mirrors from room to room through small apertures at ceiling level on each floor. Regardless of how far the rays must travel, there is no loss of light intensity.
>
> If the sun is obscured by a passing cloud, the thermostat stops the motor, at the same time switching on the auxiliary electric lighting in the rooms below. When the sun comes out again, the starter-motor again goes into action, swinging the mirror forward until it catches up with the new position of the sun, which in turn switches off the electric lights in the rooms below.
>
> General illumination within the rooms is provided by the rays of the sun passing through diffused glass panels in the ceiling while direct beams are focused at will on desks and similar seeing tasks.
>
> This sun-tapping apparatus comes complete with several ingenious accessories. An automatic mirror-wiper prevents the upturned mirror from getting grimy. A motor-operated arm automatically sponges and polishes the mirror once a day as it swings from west to east to catch the morning sun. A pilot-thermostat controls the mirror motor, causing it to move at the same speed as the sun.

Full-time use of electrical energy offered a less expensive method of lighting buildings initially, however, and so the heliostat lost ground and was eventually discarded. It was determined, however, that this heliostat offered a saving in electrical energy of between 35 and 80 percent, depending upon the latitude in which it was used, and it may be wise for engineers to take another look at this apparatus which tapped our first light source—the sun.

While the control of daylighting is seldom within the engineer's realm of responsibility, there are certain control elements which he or she can provide.

1. Provide brightness control to prevent excessive brightness ratios.
2. Make such suggestions to the person designing the daylighting system (usually the architect) as will benefit the lighting. Such suggestions may include:
   a. Avoidance of direct sunlight
   b. Use of light reflected from the ground outside rather than the sky
   c. Use of high windows with clear glazing for deeper room illumination
   d. The use of lighting-control glass of various types for an even distribution of light

The amount of daylighting is never predictable because of the various weather conditions. For this reason, care should be taken to properly control (switch and dim) the supplemental electrical lighting fixtures which will function under a varied set of conditions.

HIGH-INTENSITY DISCHARGE (HID) LIGHTING

The increasing use of high-intensity discharge lamps for other interior lighting than industrial applications is being reported daily. Of course, there is also increasing use of HID lamps in exterior and industrial applications since the lamps have always been particularly well suited for the two latter applications.

Many developments have contributed to this increased interest in HID lamps for nonindustrial interior lighting application:

1. Great progress has been made in improving the color quality of mercury lamps to the extent that such lamps are now superior to cool-white fluorescent lamps (in some cases). The cool-white fluorescent lamp has been the number-one light source for use in commercial buildings for a number of years.

2. HID lamp life and efficiency have continually increased. For example, a new 1,000-W high-pressure sodium lamp has an initial efficiency of 130 lm per W with an average rated life of 8,000 hr on a 10-hr-per-start basis.
3. A greater range of available lamp sizes has also contributed to the increasing popularity of the HID lamp.

The use of HID lamps can be one of the greatest aids in reducing the consumption of electrical energy for lighting; some methods are as follows.

A relatively new metal halide lamp can now be operated in most indoor mercury lamp sockets and would be a good choice for many applications where the replacing of existing mercury lamps is necessary. A changeover to the higher-efficiency metal halide lamp, according to the manufacturer, will permit owners to get at least 50 percent more light initially than would be possible with mercury lamps of the same wattage. This means that the same amount of original light can be had with fewer lighting fixtures which in turn would reduce the consumption of electrical energy.

At this writing, a new 250-W high-pressure sodium lamp has also been developed for use in lamp sockets designed for 400-W mercury vapor lamps. It is claimed that this lamp will produce more initial lumens than the mercury lamp and at an obviously lower wattage.

Utility companies should use this lamp to replace old existing mercury lamps as the need arises, since this use alone would add up to a tremendous saving in electrical energy.

Those areas now using 500-W incandescent lamps as the chief light source can be dramatically improved by switching to mercury lighting. For example, if fifty 500-W incandescent lamps are needed to light a large warehouse, the incandescent fixtures could be replaced with 250-W mercury fixtures. This new system would consume only half as much energy as the incandescent lamps and still give about one-third more light output; in addition, the new mercury lamps would last about three times as long as the incandescent lamps.

Existing mercury systems can be improved by replacing inefficient mercury lamps with a relatively new type known as the Multi-Vapor. This lamp gives from 50 to 300 percent more light output than regular mercury lamps of the same wattage. Relamping existing areas with this more efficient lamp type means fewer lamps and fixtures. And a more efficient system consumes fewer watts, too.

DIRT ACCUMULATION

Dirt accumulation can severely reduce lighting levels, as can old lamps because they produce nowhere near their initial output. The usual 70 percent maintenance factor used in lighting calculations can be increased to 90 percent if commitment is made to group relamping at minimum-cost-of-light intervals, along with frequent cleanings. This can save both money and energy on the order of 20 to 40 percent.

The cases are endless, but it is now obvious that the electrical engineer or lighting designer is faced with the big task of providing sufficient light with less wasted energy. Yet we must learn to grow and progress while meeting the terms of the energy situation.

Appendix A

Electrical Specifications

The electrical specifications presented in this appendix have been successfully used for numerous commercial projects where the electrical contract has been under $100,000. Few, if any, problems have been encountered with the proper interpretation.

All projects presented in this book used this specification as a basis for the final bid specifications. Modifications are of course necessary, but this specification should be adequate for any conventional commercial electrical project, provided such items as lighting-fixture schedules, panelboard schedules, etc., are shown on the drawings.

HOW TO USE THE SPECIFICATION

1. The designer or specification writer must first become thoroughly familiar with the project: wiring methods, electrical characteristics of the electrical service, size of service, type of heating and cooling system, special equipment, emergency electrical equipment, etc.
2. The entire "master specification" is then laid out in front of the writer for review. A copy of all working drawings is also kept close at hand for reference as the master specification is being read.
3. The specification writer then begins to read the master specification, deleting any words or paragraphs not related to the given project or adding items which are necessary for the project.
4. After the master specification has been modified for the project in question, the rough drafts are usually given to a typist for retyping. This revised version is then reproduced to obtain the number of copies required for the construction documents.

EXAMPLE

The project described throughout this book as "The First National Bank–Stanley Branch" will serve to demonstrate the procedure used to write a specification. Prior to compiling the master specification as described later in this appendix, a specification for a branch bank would take at least two days to write. Using the master specification, two hours is sufficient time to get the specification ready for retyping. The following procedure is used by the designer to write the specification for the branch bank.

1. Since the designer had made all calculations, laid out all work for the draftsmen, and checked all requirements with the local utility companies, she or he was familar with the entire project prior to writing the specifications.
2. A folder containing the master specification was laid out on the work table along with a set of electrical drawings. Pads and work pencils completed the "tools" for the procedure.

3. Section 16A, General Provisions (below), was read first, and it was determined that the entire section would remain unchanged for this project.
4. Section 16B, Basic Materials and Workmanship (page 159), was the next section to be read. The designer found that it was necessary to make some changes in this section, and they were made as follows. A paragraph (number 16) was added to this section to allow for the use of armored cable; it read as follows:

> Armored cable type AC (BX) may be used in place of EMT or rigid conduit in all wood-framed partitions and ceilings where permitted by the latest edition of the National Electrical Code.

5. Section 16D was the next section to be read. It was determined that this section could remain unchanged except for subparagraph "a" under paragraph 7, "Distribution Panelboard–Fusible Switch (MDP)." A note was attached to this sheet to notify the typist to delete subparagraph "a" and change all letters after this. Therefore subparagraph "b" was changed to subparagraph "a"; subparagraph "c" became subparagraph "b," etc.
6. Section 16E, Lighting Fixtures and Lamps, remained unchanged.
7. Section 16F, Special Systems, also remained unchanged.
8. Since there were no underfloor ducts in this system, Section 16G, Underfloor Electrical Distribution System, was deleted completely.
9. The panelboard schedules were placed on the drawings for this project, and there was no need for section 16H in the specifications. Therefore, this section was deleted also.
10. There was no emergency standby electrical service nor any fire-alarm system for this project, and sections 16I and 16J were also deleted.

This completed the specifications for the project. The few sheets which had to be modified were finished and then these sheets along with the remaining sheets were sent to the offset printing room for printing.

DIVISION 16–ELECTRICAL

Section 16A–General Provisions

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE–GENERAL REQUIREMENTS" apply to this Division.
2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the architect.
3. SCOPE OF THE WORK
   a. The scope of the work consists of the furnishing and installing of complete electrical systems–exterior and interior–including miscellaneous systems. The Electrical Contractor shall provide all supervision, labor, materials, equipment, machinery, and any and all other items necessary to complete the systems. The Electrical Contractor shall note that all items of equipment are specified in the singular; however, the Contractor shall provide and install the number of items of equipment as indicated on the drawings and as required for complete systems.

b. It is the intention of the Specifications and Drawings to call for finished work, tested, and ready for operation.

c. Any apparatus, appliance, material, or work not shown on drawings but mentioned in the specifications, or vice versa, or any incidental accessories necessary to make the work complete and perfect in all respects and ready for operation, even if not particularly specified, shall be furnished, delivered, and installed by the Contractor without additional expense to the Owner.

d. Minor details not usually shown or specified, but necessary for proper installation and operation, shall be included in the Contractor's estimate, the same as if herein specified or shown.

e. With submission of bid, the Electrical Contractor shall give written notice to the Architect of any materials or apparatus believed inadequate or unsuitable, in violation of laws, ordinances, rules, and any necessary items or work omitted. In the absence of such written notice, it is mutually agreed that the Contractor has included the cost of all required items in his proposal, and that he will be responsible for the approved satisfactory functioning of the entire system without extra compensation.

4. ELECTRICAL DRAWINGS

a. The Electrical drawings are diagrammatic and indicate the general arrangement of fixtures, equipment, and work included in the contract. Consult the Architectural drawings and details for exact location of fixtures and equipment; where same are not definitely located, obtain this information from the Architect.

b. The Contractor shall follow drawings in laying out work and check drawings of other trades to verify spaces in which work will be installed. Maintain maximum headroom and space conditions at all points. Where headroom or space conditions appear inadequate, the Architect shall be notified before proceeding with installation.

c. If directed by the Architect, the Contractor shall, without extra charge, make reasonable modifications in the layout as needed to prevent conflict with work of other trades or for proper execution of the work.

5. CODES, PERMITS, AND FEES

a. The Contractor shall give all necessary notices, including electric and telephone utilities, obtain all permits, and pay all government taxes, fees, and other costs, including utility connections or extensions, in connection with his work; file all necessary plans, prepare all documents, and obtain all necessary approvals of all governmental departments having jurisdiction; obtain all required certificates of inspection for his work and deliver same to the Architect before request for acceptance and final payment for the work.

b. The Contractor shall include in the work, without extra cost to the Owner, any labor, materials, services, apparatus, drawings (in addition to contract drawings and documents) in order to comply with all applicable laws, ordinances, rules, and regulations, whether or not shown on drawings and/or specified.

c. Work and materials shall conform to the latest rules of the National Board of Fire Underwriters' Code, Regulations of the State Fire Marshal, and with applicable local codes and with all prevailing rules and regulations pertaining to adequate protection and/or guarding of any moving parts, or otherwise hazardous conditions. Nothing in these specifications shall be construed to permit work not conforming to the most stringent of applicable codes.

d. The National Electrical Code, the local electric code, and the electrical requirements as established by the State and Local Fire Marshal, and rules and regulations of the power company serving the project, are hereby made part of this specification. Should any changes be necessary in the drawings or specifications to make the work comply with these requirements, the Electrical Contractor shall notify the Architect.

6. SHOP DRAWINGS

a. The Electrical Contractor shall submit five (5) copies of the shop drawings to the Architect for approval within thirty (30) days after the award of the general contract. If such a schedule cannot be met, the Electrical Contractor may request in writing for an extension of time to the Architect. If the Electrical Contractor does not submit shop drawings in the prescribed time, the Architect has the right to select the equipment.

b. Shop drawings shall be submitted on all major pieces of electrical equipment, including service-entrance equipment, lighting fixtures, panelboards, switches, wiring devices and plates, and equipment for miscellaneous systems. Each item of equipment proposed shall be a standard catalog product of an established manufacturer. The shop drawing shall give complete information on the proposed equipment. Each item of the shop drawings shall be properly labeled, indicating *the intended service of the material*, the job name, and Electrical Contractor's name.

c. The shop drawings shall be neatly bound in five (5) sets and submitted to the Architect with a letter of transmittal. The letter of transmittal shall list each item submitted along with the manufacturer's name.

d. Approval rendered on shop drawings shall not be considered as a guarantee of measurements or building conditions. Where drawings are approved, said approval does not mean that drawings have been checked in detail; said approval does not in any way relieve the Contractor from his responsibility, or necessity of furnishing material or performing work as required by the contract drawings and specifications.

7. COOPERATION WITH OTHER TRADES

a. The Electrical Contractor shall give full cooperation to other trades and shall furnish (in writing, with copies to the Architect) any information necessary to permit the work of all trades to be installed satisfactorily and with least possible interference or delay.

b. Where the work of the Electrical Contractor will be installed in close proximity to work of other trades, or where there is evidence that the work of the Electrical Contractor will interfere with the work of other trades, he shall assist in work-

ing out space conditions to make a satisfactory adjustment. If so directed by the Architect, the Electrical Contractor shall prepare composite working drawings and sections at a suitable scale clearly showing other trades. If the Electrical Contractor installs his work before coordinating with work of other trades, he shall make necessary changes in his work to correct the condition without extra charge.

c. The complexity of equipment and the variation between equipment manufacturers require complete coordination of all trades. The Contractor, who offers, for consideration, substitutes of equal products of reliable manufacturers, has to be responsible for all changes that affect his installation and the installation and equipment of other trades. All systems and their associated controls must be completely installed, connected, and operating to the satisfaction of the Architect prior to final acceptance and contract payment.

8. TEMPORARY ELECTRICAL SERVICE

a. The Electrical Contractor shall be responsible for all arrangements and costs for providing, at the site, temporary electrical metering, main switches, and distribution panels as required for construction purposes. The distribution panels shall be located at a central point designated by the Architect. The General Contractor shall indicate prior to installation whether three-phase or single-phase service is required.

9. ELECTRICAL CONNECTIONS

a. The Electrical Contractor shall provide and install power wiring to all motors and electrical equipment complete and ready for operation including disconnect switches and fuses. Starters, relays, and accessories shall be furnished by others unless otherwise noted, but shall be installed by the Electrical Contractor. This Contractor shall be responsible for checking the shop drawings of the equipment manufacturer to obtain the exact location of the electrical rough-in and connections for equipment installed.

b. The Mechanical Contractor will furnish and install all temperature-control wiring and all interlock wiring unless otherwise noted.

c. It shall be the responsibility of the Electrical Contractor to check all motors for proper rotation.

10. AS-BUILT DRAWINGS

a. The Electrical Contractor shall maintain accurate records of all deviations in work as actually installed from work indicated on the drawings. On completion of the project, two (2) complete sets of marked-up prints shall be delivered to the Architect.

11. INSPECTION AND CERTIFICATES

a. On the completion of the entire installation, the approval of the Architect and Owner shall be secured, covering the installation throughout. The Contractor shall obtain and pay for Certificate of Approval from the public authorities having jurisdiction. A final inspection certificate shall be submitted to the Architect prior to final payment. Any and all costs incurred for fees shall be paid by the Contractor.

12. TESTS

a. The right is reserved to inspect and test any portion of the equipment and/or materials during the progress of its erection. The Contractor shall test all wiring and connections for continuity and grounds, before connecting any fixtures or equipment.

b. The Contractor shall test the entire system in the presence of the Architect or his engineer when the work is finally completed, to ensure that all portions are free from short circuits or grounds. All equipment necessary to conduct these tests shall be furnished at the Contractor's expense.

13. EQUIVALENTS

a. When material or equipment is mentioned by name, it shall form the basis of the Contract. When approved by the Architect in writing, other material and equipment may be used in place of those specified, but written application for such substitutions shall be made to the Architect as described in the Bidding Documents. The difference in cost of substitute material or equipment shall be given when making such request. Approval of substitute is, of course, contingent on same meeting specified requirements and being of such design and dimensions as to comply with space requirements.

14. GUARANTEE

a. The Electrical Contractor shall guarantee, by his acceptance of the Contract, that all work installed will be free from defects in workmanship and materials. If during the period of one year, or as otherwise specified, from date of Certificate of Completion and acceptance of work, any such defects in workmanship, materials, or performance appear, the Contractor shall, without cost to the Owner, remedy such defects within a reasonable time to be specified in notice from the Architect. In default, the Owner may have such work done and charge cost to Contractor.

Section 16B—Basic Materials and Workmanship

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. CONDUIT MATERIAL AND WORKMANSHIP

a. General The Electrical Contractor shall install a complete raceway system as shown on the drawings and stated in other sections of the specifications. All material used in the raceway system shall be new and the proper material for the job. Conduit, couplings, and connectors shall be a product of a reputable manufacturer equal to conduit as manufactured by Triangle Conduit and Cable or National Electric.

b. Conduit installation

(1) Conduit shall be of ample size to permit the ready insertion and withdrawal of conductors without abrasion. All joints shall be cut square, reamed smooth, and drawn up tight.

(2) Concealed conduits shall be on run in as direct a manner and with as long a bend as possible. Exposed con-

duit shall be run parallel to or at right angles with the lines of the building. All bends shall be made with standard ells, conduit bent to a radius not less than shown in NEC, or screw-jointed conduit fittings. All bends shall be free of dents or flattening. Not more than the equivalent of four quarter-bends shall be used in any run between terminals and cabinets, or between outlets and junction or pull boxes.
(3) Conduits shall be continuous from outlet to outlet and from outlet to cabinets, or junction or pull boxes, and shall enter and be secured at all boxes in such a manner that each system shall be electrically continuous throughout.
(4) A No. 14 galvanized iron or steel fish wire shall be left in all conduits in which the permanent wiring is not installed.
(5) Where conduits cross building joints, furnish and install O.Z. Electric Manufacturing Company expansion fittings for contraction, expansion, and settlement.
(6) Open ends shall be capped with approved manufactured conduit seals as soon as installed and kept capped until ready to install conductors.
(7) Conduit shall be securely fastened to all sheet metal outlets, junction, and pull boxes with galvanized lock-nuts and bushings, care being observed to see that the full-number threads project through to permit the bushings to be drawn tight against the end of conduit, after which the lock-nut shall be made up sufficiently tight to draw the bushings into firm electrical contact with the box.
(8) For all flush-mounted panels there shall be provided and installed 1¼-in. empty conduit up through the wall and turned out above the ceiling and one 1¼-in. empty conduit down to space below floor except where slab in on grade.

c. *Conduit hangers and supports*
(1) Conduit throughout the project shall be securely and rigidly supported to the building structure in a neat and workmanlike manner, and wherever possible, parallel runs of horizontal conduit shall be grouped together on adjustable trapeze hangers. Support spacing shall not be more than eight (8) feet.
(2) Exposed conduit shall be supported by one-hole malleable iron straps, two-hole straps, suitable beam clamps, or split-ring conduit hanger with support rod.
(3) Single conduit 1¼ inches and larger run concealed horizontally shall be supported by suitable beam clamps or split-ring conduit hangers with support rod. Multiple runs of conduit shall be grouped together on trapeze hangers where possible. Vertical runs shall be supported by steel riser clamps.
(4) Conduit one inch and smaller run concealed above a ceiling may be supported directly to the building structure with strap hangers or No. 14 gauge galvanized wire provided the support spacing does not exceed four (4) feet.

4. OUTLET BOXES
a. *General*
(1) Before locating the outlet boxes, check all of the architectural drawings for type of construction and to make sure

that there is no conflict with other equipment. The outlet boxes shall be symmetrically located according to room layout and shall not interfere with other work or equipment. Also note any detail of the outlets shown on the drawings.
(2) Outlet boxes shall be made of galvanized sheet steel unless otherwise noted or required by the NEC and shall be of the proper code size for the required number of conductors. Outlet boxes shall be a minimum of four (4) inches square unless specifically noted on the drawings with the exception that a box containing only two current-carrying conductors may be smaller. The outlet boxes shall be complete with the approved type of connectors and required accessories.
(3) The outlet boxes shall be complete with raised device covers as required to accept device installed. All outlet boxes must be securely fastened in position with the exposed edge of the raised device cover set flush with the finished surface. Approved factory-made knockout seals shall be installed where knockouts are not intact. Galvanized outlet boxes shall be manufactured by Raco, Steel City, Appleton, or approved equal.
(4) Outlet boxes for exposed work shall be handy boxes with handy box covers unless otherwise noted.
(5) Outlet boxes located on the exterior in damp or wet locations or as otherwise noted shall be threaded cast-aluminum device boxes such as Crouse Hinds type FS or FD.

b. *Receptacle outlet boxes:* Wall receptacles shall be mounted approximately 18 inches above the finished floor (AFF) unless otherwise noted. When the receptacle is mounted in a masonry wall, the bottom of the outlet box shall be in line with the bottom of a masonry unit. Receptacles for electric water coolers shall be installed behind the coolers in accordance with manufacturer's recommendations. All receptacle outlet boxes shall be equipped with grounding lead which shall be connected to grounding terminal of the device.

c. *Switch outlet boxes:* Wall switches shall be mounted approximately 54 inches above the finished floor (AFF) unless otherwise noted. When the switch is mounted in a masonry wall, the bottom of the outlet box shall be in line with the bottom of a masonry unit. Where more than two switches are located, the switches shall be mounted in a gang outlet box with gang cover. Dimmer switches shall be individually mounted unless otherwise noted. Switches with pilot lights, switches with overload motor protection, and other special switches that will not conveniently fit under gang wall plates may be individually mounted.

d. *Lighting-fixture outlet boxes:* The lighting-fixture outlet boxes shall be furnished with the necessary accessories to install the fixture. The supports must be such as not to depend on the outlet box supporting the fixture. The supports for the lighting fixture shall be independent of the ceiling system. All ceiling outlet boxes shall be equipped with raised circular cover plates with edge set flush with surface of finished ceiling.

5. PULL BOXES
   a. Pull boxes shall be installed at all necessary points, whether indicated on the drawings or not, to prevent injury to the insulation or other damage that might result from pulling resistance for other reasons necessary to proper installation. Pull box locations shall be approved by the Architect prior to installation. Minimum dimensions shall be not less than NEC requirements and shall be increased if necessary for practical reasons or where required to fit a job condition.
   b. All pull boxes shall be constructed of galvanized sheet steel, code gauge, except that no less than 12 gauge shall be used for any box.
   c. Where boxes are used in connection with exposed conduit, plain covers attached to the box with a suitable number of countersunk flathead machine screws may be used.
   d. Where so indicated, certain pull boxes shall be provided with barriers. These pull boxes shall have a single cover plate, and the barriers shall be of the same gauge as the pull box.
   e. Each circuit in pull box shall be marked with a tag guide denoting panels to which they connect.
   f. Exposed pull boxes will not be permitted in the public spaces.
6. WIREWAYS OR WIRE TROUGHS
   a. Wireways shall be used where indicated on the drawings and for mounting groups of switches and/or starters. Wireways shall be the standard manufactured product of a company regularly producing wireway and shall not be a local shop-assembled unit. Wireway shall be of the hinged-cover type, Underwriters' listed, and of sizes indicated or as required by NEC. Finish shall be medium light-gray enamel over rust inhibitor. Wireways shall be of raintight construction where required. Wireways shall be General Electric type HS or approved equal.
7. CONDUCTOR MATERIAL AND WORKMANSHIP
   a. *General*
      (1) The Electrical Contractor shall provide and install a complete wiring system as shown on the drawing or specifications herein. All conductors used in the wiring system shall be soft-drawn copper wire having a conductivity of not less than 98 percent of that of pure copper, with 600-volt rating, unless otherwise noted. Wire shall be as manufactured by General Cable, Triangle, or approved equal.
      (2) The wire shall be delivered to the site in its original unbroken packages, plainly marked or tagged as follows: (a) Underwriters' labels; (b) size, kind, and insulation of the wire; (c) name of manufacturing company and the trade name of the wire.
   b. *Conductor workmanship*
      (1) Install conductors in all raceways as required, unless otherwise noted, in a neat and workmanlike manner. Telephone conduits and empty conduits, as noted, shall have a No. 14 gauge galvanized pull wire left in place for future use.
      (2) Conductors shall be color-coded in accordance with the National Electrical Code. Mains, feeders, and subfeeders shall be tagged in all pull, junction, and outlet boxes and in the gutter of panels with approved code type wire markers.
      (3) No lubricant other than powdered soapstone or approved pulling compound may be used to pull conductors.
      (4) At least eight (8) inches of slack wire shall be left in every outlet box whether it be in use or left for future use.
      (5) All conductors and connections shall test free of grounds, shorts, and opens before turning the job over to the Owner.
8. LUGS, TAPS, AND SPLICES
   a. Joints on branch circuits shall occur only where such circuits divide and shall consist of one through circuit to which shall be spliced the branch from the circuit. In no case shall joints in branch circuits be left for the fixture hanger to make. No splices shall be made in conductor except at outlet boxes, junction boxes, or splice boxes.
      (1) All joints or splices for No. 10 AWG or smaller wire shall be made with UL-approved wire nuts or compression-type connectors.
      (2) All joints or splices for No. 8 AWG or larger wire shall be made with a mechanical compression connector. After the conductors have been made mechanically and electrically secure, the entire joint or splice shall be covered with Scotch No. 33 tape or approved equal to make the insulation of the joint or splice equal to the insulation of the conductors. The connector shall be UL approved.
9. ACCESS DOORS
   a. The Electrical Contractor shall furnish to the lather the access doors as shown on the drawings or required for access to junction boxes, etc. The doors shall be 12-inch-square, unless otherwise noted, hinged metal doors with metal frames.
   b. Door and frame shall be not lighter than 16-gauge sheet steel. The access door shall be of the flush type with screwdriver latching device. The frame shall be constructed so that it can be secured to building material as required. The access doors shall be Milcor or equal. Access door and location shall meet the approval of the Architect.
10. FUSES
    a. Fuses manufactured by Buss or Shawmut shall be furnished and installed as required. Motor protection fuses shall be dual-element.
11. CUTTING AND PATCHING
    a. On new work the Electrical Contractor shall furnish sketches to the General Contractor showing the locations and sizes of all openings and chases, and furnish and locate all sleeves and inserts required for the installation of the electrical work before the walls, floors, and roof are built. The Electrical Contractor shall be responsible for the cost of cutting and patching where any electrical items were not installed or where incorrectly sized or located. The Contractor shall do all drilling required for the installation of his hangers.
    b. On alterations and additions to existing projects, the Electrical Contractor shall be responsible for the cost of all cutting and patching, unless otherwise noted.
    c. No structural members shall be cut without the approval of the Architect, and all such cutting shall be done in a manner

directed by him. All patching shall be performed in a neat and workmanlike manner acceptable to the Architect.

12. EXCAVATION AND BACKFILLING

a. The Electrical Contractor shall be responsible for excavation, backfill, tamping, shoring, bracing, pumping, street cuts, repairing of finished surface, and all protection for safety of persons and property as required for installing a complete electrical system. All excavation and backfill shall conform to the Architectural Section of the specifications.

b. Excavation shall be made in a manner to provide a uniform bearing for conduit. Where rock is encountered, excavate three (3) inches below conduit grade and fill with gravel to grade.

c. After required test and inspections, backfill the ditch and tamp. The first foot above the conduit shall be hand-backfilled with rockfree clean earth. The backfill in the ditches on the exterior and interior of the building shall be tamped to 90 percent. The Electrical Contractor shall be responsible for any ditches that go down.

13. EQUIPMENT AND INSTALLATION WORKMANSHIP

a. All equipment and material shall be new and shall bear the manufacturer's name and trade name. The equipment and material shall be essentially the standard product of a manufacturer regularly engaged in the production of the required type of equipment and shall be the manufacturer's latest approved design.

b. The Electrical Contractor shall receive and properly store the equipment and material pertaining to the electrical work. The equipment shall be tightly covered and protected against dirt, water, chemical or mechanical injury, and theft. The manufacturer's directions shall be followed completely in the delivery, storage, protection, and installation of all equipment and materials.

c. The Electrical Contractor shall provide and install all items necessary for the complete installation of the equipment as recommended or as required by the manufacturer of the equipment or required by local code without additional cost to the Owner, regardless of whether the items are shown on the plans or covered in the specifications.

d. It shall be the responsibility of the Electrical Contractor to clean the electrical equipment, make necessary adjustments, and place the equipment into operation before turning equipment over to the Owner. Any paint that was scratched during construction shall be "touched-up" with factory-color paint to the satisfaction of the Architect. Any items that were damaged during construction shall be replaced.

14. CONCRETE PADS, SUPPORTS, AND ENCASEMENT

a. The Electrical Contractor shall be responsible for all concrete pads, supports, piers, bases, foundations, and encasement required for the electrical equipment and conduit. The concrete pads for the electrical equipment shall be six (6) inches larger all around than the base of the equipment and a minimum of four (4) inches thick unless specifically indicated otherwise.

15. WATERPROOFING

a. The Electrical Contractor shall provide all flashing, caulking, and sleeves required where his items pass through the outside walls or roof. The waterproofing of the openings shall be made absolutely watertight. The method of installation shall conform to the requirements of Division 7, "Moisture Control," and/or meet the approval of the Architect.

Section 16C—Service-Entrance System

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. SERVICE ENTRANCE

a. General: The Electrical Contractor shall provide and install a complete service-entrance system as shown on the drawings or as required for a complete system. All material and workmanship shall conform with Section 16B of the specifications, National Electrical Code, and the local electric code. The electric service entrance shall conform to the requirements and regulations of the electric utility serving the project.

b. Electric utility charge: The Electrical Contractor shall make all arrangements with the electric utility and pay all charges made by the electric utility for permanent electric service to the project. In the event that the charges of the electric utility are not available at the time the project is bid, the Electrical Contractor shall qualify his bid to notify the Owner that such charges are not included.

c. Metering: The Electrical Contractor shall provide and install raceway, install current transformer cabinet, and/or meter trim, for metering facilities as required by the electric utility serving the project. The electric utility will provide the meter installation including meter, current transformers, and connections.

d. Grounding: The Electrical Contractor shall properly ground the electrical system as required by the National Electrical Code. The ground wire for the service entrance shall be run in conduit and made to the main water service and connected ahead of any valve or cutoff.

e. Conduit: The conduit used for service entrance shall be galvanized rigid steel conduit unless otherwise noted on drawings.

f. Conductors: Conductors for the service entrance shall be copper type RHW or THW rated at 75°C unless otherwise noted. The conductors indicated on the drawings are based on copper. Conductors with a size of No. 1/0 and larger may be aluminum, provided the size of the conductor is increased to have the same current-carrying capacity as the copper conductors (or more). Also, the conduit size shall be increased accordingly.

Section 16D—Electrical Distribution System

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the architect.
3. FEEDERS AND BRANCH CIRCUITS
   a. General: The Electrical Contractor shall provide and install a complete electrical distribution system as shown on the drawings or as required for a complete system. All materials and workmanship shall conform with Section 16B of the Specifications, National Electrical Code, and the local electric code.
   b. Conduit materials:
   (1) Rigid conduit (heavy wall): Rigid conduit shall be galvanized rigid steel conduit with a minimum size of ¾ inch unless otherwise noted. Rigid steel conduit shall be installed for the following services and locations: service entrance, underground in contact with earth, in concrete slab, panel feeders, exterior of building walls, motor feeders over 10 hp, electrical equipment feeders over 10 kW, "wet" locations, and as required by the National Electrical Code and local codes.
   (2) Electrical metallic tubing (EMT): Electrical metallic tubing shall be galvanized steel with a minimum size of ¾ inch. Electrical metallic tubing shall be used in all locations not otherwise specified for rigid or flexible conduit and where not in violation of the National Electrical Code.
   (3) Flexible metal conduit: Flexible metal conduit shall be galvanized steel. Flexible metal conduit located in wet locations shall be the Liquid-Tight type. Flexible metal conduit may be used in place of EMT where completely accessible, such as above removable acoustical tile ceilings and for exposed work in unfinished spaces.
   (4) A short piece of flexible metal conduit shall be used for the connection to all motors and vibrating equipment, connection between recessed light fixtures and junction box, and as otherwise noted, provided the use meets the requirements of the National Code and local codes. The flexible metal conduit shall be the type approved for continuous grounding.
   c. Conductor material:
   (1) The conductor material shall be as follows, unless otherwise noted:
      (*a*) *Feeders:* Shall be Type RHW or THW rated at 75°C.
      (*b*) *Branch Circuits:* Shall be Type THW rated at 75°C, except that branch circuits with conductor sizes of No. 10 and smaller in dry locations may be Type TW rated at 60°C.
      (*c*) *Special Locations:* Conductors in special locations such as range hoods, lighting fixtures, etc., shall be as required by the National Electrical Code, local code, or as otherwise noted.
   (2) No conductor shall be smaller than No. 12 wire, except for the control wiring and as stated in other sections of the Specifications or on the drawings. Wiring to switches shall not be considered as control wiring.
   (3) Conductors indicated on the drawings are based on copper. Panel, motor, and electrical equipment feeders with a size of No. 1/0 and larger may be aluminum, provided the size of the conductor is increased to have the same current-carrying capacity as the copper conductors (or more). Also, the conduit sizes shall be increased accordingly.
   (4) All conductors with the size of No. 8 or larger shall be stranded.
   (5) All lighting and receptacle branch circuits in excess of 100 linear feet shall be increased one size to prevent excessive voltage drop.
4. SAFETY SWITCHES (FSS) (NFSS)
   a. General: Furnish and install safety switches as indicated on the drawings or as required. All safety switches shall be *NEMA General Duty Type* and Underwriters' Laboratories Listed. The switches shall be Fused Safety Switches (FSS) or Nonfused Safety Switches (NFSS) as shown on the drawings or required.
   b. Switches: Switches shall have a quick-make and quick-break operating handle and mechanism which shall be an integral part of the box. Padlocking provisions shall be provided for padlocking in the OFF position with at least three padlocks. Switches shall be horsepower rated for 250 volts ac or dc as required. Lugs shall be UL-listed for copper and aluminum cable.
   c. Enclosures: Switches shall be furnished in NEMA 1 general-purpose enclosures with knockouts unless otherwise noted or required. Switches located on the exterior of the building or in "wet" locations shall have NEMA 3R enclosures (WP).
   d. Installation: The safety switches shall be securely mounted in accordance with the NEC. The Contractor shall provide all mounting materials. Install fuses in the FSS. The fuses shall be dual-element on motor circuits.
   e. Manufacturer: Square "D," General Electric, Cutler-Hammer, or Westinghouse.
5. PANELBOARDS – CIRCUIT BREAKER
   a. General: Furnish and install circuit-breaker panelboards as indicated in the panelboard schedule and where shown on the drawings. The panelboard shall be dead-front safety type equipped with molded-case circuit breakers and shall be the type as listed in the panelboard schedule. Service-entrance panelboards shall include a full-capacity box bonding strap and be approved for service entrance. The acceptable manufacturers of the panelboards are Square "D," General Electric, Cutler-Hammer, and Westinghouse provided they are fully equal to the type listed on the drawings. The panelboard shall be listed by Underwriters' Laboratories and bear the UL label.
   b. Circuit breakers: Provide molded-case circuit breakers of frame, trip rating, and interrupting capacity as shown on the schedule. Also, provide the number of spaces for future circuit breakers as shown in the schedule. The circuit breakers shall be quick-make, quick-break, thermal-magnetic, trip-indicating, and have common trip on all multipole breakers with internal tie mechanism.
   c. Panelboard bus assembly: Bus bar connections to the branch circuit breakers shall be the "phase-sequence" type. Single-phase three-wire panelboard bussing shall be such that

any two adjacent single-pole breakers are connected to opposite polarities in such a manner that two-pole breakers can be installed in any location. Three-phase four-wire bussing shall be such that any three adjacent single-pole breakers are individually connected to each of the three different phases in such a manner that two or three-pole breakers can be installed at any location. All current-carrying parts of the bus assembly shall be plated. Mains ratings shall be as shown in the panelboard schedule on the plans. Provide solid neutral (S/N) assembly when required.

d. Wiring terminals: Terminals for feeder conductors to the panelboard mains and neutral shall be suitable for the type of conductor specified. Terminals for branch-circuit wiring, both breaker and neutral, shall be suitable for the type of conductor specified.

e. Cabinets and fronts: The panelboard bus assembly shall be enclosed in a steel cabinet. The size of the wiring gutters and gauge of steel shall be in accordance with NEMA Standards. The box shall be fabricated from galvanized steel or equivalent rust-resistant steel. Fronts shall include door and have flush, brushed stainless steel, spring-loaded door pulls. The flush lock shall not protrude beyond the front of the door. All panelboard locks shall be keyed alike. Fronts shall not be removable with door in the locked position.

f. Directory: On the inside of the door of each cabinet, provide a typewritten directory which will indicate the location of the equipment or outlets supplied by each circuit. The directory shall be mounted in a metal frame with a nonbreakable transparent cover. The panelboard designation shall be typed on the directory card and panel designation stenciled in 1½-inch-high letters on the inside of the door.

g. Panelboard installation:

(1) Before installing panelboards, check all the architectural drawings for possible conflict of space, and adjust the location of the panelboard to prevent such conflict with other items.

(2) When the panelboard is recessed into a wall serving an area with accessible ceiling space, provide and install an empty conduit system for future wiring. A 1¼-inch conduit shall be stubbed into the ceiling space above the panelboard and under the panelboard if such accessible ceiling space exists.

(3) The panelboards shall be mounted in accordance with Article 373 of the NEC. The Electrical Contractor shall furnish all material for mounting the panelboards.

6. WIRING DEVICES

a. General: The wiring devices specified below with Arrow Hart numbers may also be the equivalent wiring device as manufactured by Bryant Electric, Harvey Hubbell, or Pass & Seymour. All other items shall be as specified.

b. Wall switches: Where more than one flush wall switch is indicated in the same location, the switches shall be mounted in gangs under a common plate.

(1) Single-pole — AH#1991
(2) Three-way — AH#1993
(3) Four-way — AH#1994
(4) Switch with pilot light — AH#2393-R
(5) Motor switch—surface — AH#6908
(6) Motor switch—flush — AH#6908-F

c. Receptacles:

(1) Duplex
(2) Clock outlet — AH#8739
(3) Weatherproof — AH#5708
(4) Floor receptacles: Steel City Series 600 floor box with bronze edge ring, floor plate P-60-1, bronze carpet plate, and service fitting SFH-40-RG. — AH#5735-F
(5) Floor outlet for telephone and alarm: Steel City Series 600 floor box with bronze edge ring, floor plate P-60-1, bronze carpet plate, and service fitting SFL-10.

d. Wall plate: Stainless steel wall plates with satin finish minimum 0.030 inch shall be provided for all outlets and switches.

7. DISTRIBUTION PANELBOARD—FUSIBLE SWITCH (MDP)

a. General: Furnish and install distribution and power panelboards as indicated in the panelboard schedule and where shown on the drawings. Panelboards shall be dead-front safety type, equipped with quick-make, quick-break fusible branch switches, and approved for service entrance. The acceptable manufacturers of the panelboard are Square "D," General Electric, Cutler-Hammer, and Westinghouse provided they are fully equal to the type listed on the drawings. The panelboard shall be listed by Underwriters' Laboratories and bear the UL label.

b. Fusible switches: All fusible branch switches shall be quick-make, quick-break, with visible blades and dual horsepower ratings. Switch handles shall physically indicate ON and OFF positions. Such handles shall also be able to accept three padlocks having heavy-duty industrial-type shackles. Covers shall be interlocked with the switch handles to prevent opening in the ON position. A means shall be provided to allow authorized personnel to release the interlock for inspection purposes when a switch is ON. A cardholder, providing circuit identification, shall be mounted on each branch switch. Switches shall be provided with Bussman Fusetron fuses or as noted on the drawings.

c. Bussing assembly: Panelboard bus structure and main lugs or main switch shall have current ratings as shown on the panelboard schedule. The bus structure shall accommodate plug-on or bolted branch switches and motor starters as indicated in the panelboard schedule without modification to the bus assembly. Provide solid neutral (S/N) assembly when required.

d. Equipment rating: Switches and panelboard bus structure shall safely and without failure withstand short circuits on the systems capable of delivering up to 50,000 amperes RMS symmetrical, unless otherwise noted.

e. Cabinet: Panelboard assembly shall be enclosed in a steel

cabinet. The rigidity and gauge of steel is to be as specified in UL Standard for cabinets. The size of wiring gutters shall be in accordance with UL Standard. Cabinets shall be equipped with a front door and have fully concealed, self-aligning trim clamps. Fronts shall be full-finished steel with rust-inhibiting primer and baked enamel finish.

f. Wiring terminals: Terminals for feeder conductors to the panelboard mains and neutral shall be suitable for the type of conductor specified. Terminals for branch circuit wiring, both breaker and neutral, shall be suitable for the type of conductor specified.

g. Panelboard installation: Before installing panelboards, check all of the Architectural drawings for possible conflict of space and adjust the location of the panelboard to prevent such conflict with other items. The panelboards shall be mounted in accordance with the NEC. The Electrical Contractor shall furnish all material for mounting the panelboards.

Section 16E – Lighting Fixtures and Lamps

1. Portions of the sections of the documents designated by the letters A, B, and C and "DIVISION ONE – GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. LIGHTING FIXTURES

a. General: The Electrical Contractor shall furnish, install, and connect all lighting fixtures to the building wiring system unless otherwise noted.

b. Fixture type: The fixture for each location is indicated by type letter. Refer to fixture schedule on the drawings for each type, manufacturer, catalog number, and type of mounting.

c. Fluorescent ballasts: All fluorescent fixtures shall have ETL CBM high power factor, quiet-operating, Class A sound-rated, thermally protected Class P cool-rated ballast with UL approval. Ballasts shall be as manufactured by General Electric, Advance, Jefferson or approved equal. The ballasts shall be subject to a two (2) year manufacturer's guarantee. Guarantee shall be filed with the Owner.

d. Shop drawings:

(1) Shop drawings for lighting fixtures shall indicate each type together with manufacturer's name and catalog number, complete photometric data compiled by an independent testing laboratory, and type of lamp(s) to be installed. No fixtures shall be delivered to the job until approved by the Architect.

(2) If the Electrical Contractor submits shop drawings on a fixture for approval other than those specified, he shall also submit a sample fixture when requested by the Architect. The sample fixture will be returned to the Electrical Contractor. The decision of the Architect shall be final.

e. Coordination: It shall be the responsibility of the Electrical Contractor to coordinate with the ceiling contractor and the General Contractor in order that the proper type of fixture be furnished to match the ceiling suspension system being installed or building construction material.

4. LAMPS

a. The Electrical Contractor shall furnish and install lamps in all fixtures as indicated on the drawings or as required. Fluorescent lamps shall be standard cool white, and incandescent lamps shall be inside frosted unless otherwise noted on the drawings.

b. Lamps shall be manufactured by General Electric, Westinghouse, or Sylvania.

Section 16F – Special Systems

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE – GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. TELEPHONE RACEWAY SYSTEMS

a. General: The Electrical Contractor shall provide and install empty raceway, outlet boxes, pull boxes, and associated equipment required for a complete telephone system as indicated on the drawings and specified herein. All materials and workmanship shall conform with Section 16B of the Specifications. All wiring shall be installed by the local telephone company. The entire installation shall be in accordance with the requirements of the local telephone company.

b. Rigid conduit (heavy wall): Rigid conduit shall be installed in the following locations: Service entrance, underground in contact with earth, in concrete slab and "wet" locations.

c. Electric metallic conduit (EMT): Electric metallic tubing shall be used in all locations not otherwise specified to be rigid conduit.

d. Outlets: Telephone wall outlets shall consist of a 4-inch two-gang outlet box, raised device cover, and a telephone device plate of the same material as the receptacle device plates. The conduit shall extend from the outlet to the designated telephone space unless otherwise noted.

e. Pull wire: The Electrical Contractor shall install a No. 14 gauge galvanized pull wire in the raceway system for future use.

f. Mounting heights: The wall outlets shall be mounted at approximately the following heights unless otherwise noted on the drawings or required by the telephone company: Desk Phones – 18 inches AFF; Wall Phone – 58 inches AFF; Telephone Booth – 7 feet-6 inches AFF.

g. Floor outlets: See wiring devices, Section 16D. Verify exact location with Architect.

4. EMERGENCY LIGHTING SYSTEM

a. The Electrical Contractor shall provide and install a complete emergency lighting system as indicated on the drawings and specified herein. The system shall originate on the line side of the service-entrance main switch, through overcurrent protective equipment to each exit light fixture and each fixture

designated as being "emergency light." The switch shall be pointed red. The Contractor shall be responsible for verification with local governing authorities of the proper letter and background colors of exit-light fixtures before purchase of same. The entire installation shall be in accordance with the National Electrical Code, the local electric code, and the fire-protection department having authority in the local jurisdiction.

Section 16E—Underfloor Electrical Distribution System

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. UNDERFLOOR DUCT SYSTEM

a. Furnish and install, as shown on plans, an electrical underfloor distribution system as manufactured by Walker-Parkersburg. This system shall consist of No. 4 ducts for telephone and No. 2 ducts for power service together with the necessary junction boxes, couplings, supports, adapters, and headers to form a complete installation, made watertight with sealing compound.

b. Duct: Shall be manufactured from No. 14 gauge steel and finished with a UL-approved corrosion-resistant coating. Number 2 Duct for power service shall be 3⅛ × 1¼ inches with threaded 2-inch IPS inserts spaced on two-foot centers. Number 4 Duct for telephone service shall be 6⅛ × 1⅛ inches with two-inch IPS inserts on two-foot centers.

c. Junction boxes: Shall be Cat. No. 226-S with finish similar to duct. Cat. No. 226-S-LS Tile Holders shall be furnished with depth as required for installation in floor finish specified. All boxes shall be carefully leveled with the tops flush with the finished concrete floor.

d. Supports: All ducts shall be accurately aligned and leveled with the top of the inserts at 1/16 inch to ⅛ inch below the finished concrete floor. They shall be held in place during the pour by Cat. No. S-224 supports, spaced at five-foot intervals.

e. Markers: Cat. No. 418-F and No. 418-N markers shall be placed in the first insert at all dead ends, on each side of partitions, and at the first insert adjacent to the junction box.

4. SERVICE FITTINGS—UNIT PRICE

a. Provide a unit price for installing floor receptacles in the underfloor duct system. The unit price shall include: (1) One Walker-Parkersburg No. 518 RLEDFSG-G service fitting with adapters, locking nipples, or supports as required; (2) Duplex outlet as specified; and (3) the floor receptacle shall be installed at the locations as directed by the Owner complete including the wiring from the receptacle to the panel with a maximum of six receptacles per circuit.

b. Provide a unit price for installing a Walker-Parkersburg No. 518 RLG telephone service fitting with adapters, locking nipple, or support as required.

5. SERVICE FITTINGS SHOWN ON THE DRAWINGS

Shall be as specified above and shall be part of the Contract Price.

Section 16F—Panelboard Schedules

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. Refer to drawings for panelboard schedules.

Section 16I—Emergency Standby Service

1. Portions of the sections of the Documents designated by the letters A, B, and C and DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. EMERGENCY SYSTEM

a. General: The Electrical Contractor shall furnish and install a complete emergency lighting and power system, as shown on the plans, including necessary standby power equipment, control accessories, feeders, panels, branch circuits, and outlets as noted. All wiring shall be of the sizes indicated on the drawings and shall conform to the provisions of the NEC and all other local regulations covering this type of installation.

b. Generator: Furnish and install, where indicated on the drawings, an emergency standby engine-generator set rated as shown on the drawings. It shall be cushion-mounted on a heavy steel base and be free from torsional vibration. The engine shall operate satisfactorily on fuel specified. The engine shall have a 12-volt battery, a 12-volt starting motor, and a charging generator with automatic charging-rate regulator and shall also be equipped with low oil pressure, high water temperature, and automatic overspeed safety shutdown devices.

c. Instrument panel: The instrument panel on the standby unit shall contain engine oil-pressure and water-temperature indicators, battery charge-rate ammeter, start and stop buttons for manual operation of unit, manual reset circuit breaker, voltage regulator, ammeter with phase-selector switch, running-time and frequency meters.

d. Control panel: The wall-mounted control panel shall contain the necessary control equipment to automatically start the standby generator set when the line voltage drops to 70 percent of normal value, transfer the load to the generator, and retransfer the load back to normal source when voltage is restored to 90 percent normal. The enclosed panel shall contain an electrically operated, mechanically held remote switch, automatic engine-starting relays, and a cranking limiter to open the starting circuit after about 45 seconds.

e. The emergency standby generator shall be Onan, Caterpillar, or Kato/Igbi.

Section 16J—Signals and Communications

1. Portions of the sections of the Documents designated by the letters A, B, and C and "DIVISION ONE—GENERAL REQUIREMENTS" apply to this Division.

2. Consult the Index to be certain that set of Documents and Specifications is complete. Report omissions or discrepancies to the Architect.

3. FIRE-ALARM SYSTEM

a. Furnish and install a Fire-Alarm System as manufactured by Simplex and described in these specifications and indicated on the drawings. The system is to be wired and installed in accordance with the manufacturer's specifications and left in first-class operating condition.

b. Operation: At each stairway, exit, and other locations shown on the plans, there shall be a noncoded fire-alarm station. At each location, where shown, there shall be a bell or horn. Operating any station shall cause all sounding devices to operate continuously until the fire-alarm station has been restored to normal. It shall also be possible for those in authority to transmit a test signal from any station. The stations and sounding devices shall be connected to a control panel which shall permit a small supervisory current to pass through the entire system. A trouble bell shall also be provided and shall sound continuously in the event of failure of the main power-supply source or a ground fault of its installation wiring circuit.

c. Equipment: Install where shown a flush noncoded manual fire-alarm station. Flush stations shall mount on standard outlet boxes with single-gang cover.

(1) Install where shown on plans an underdome vibrating bell. Size and number of signals to be located so that they may be heard by all occupants of the building.

(2) Install where shown a closed-circuit fire-alarm control panel in flush wall-type steel cabinet equipped with hinged door and with lock and keys. Panel shall contain all necessary relays, meters, resistances, thermal cutout, terminals, and fuses for the control and supervision of the system. Panel shall contain number of bell and station circuits required. A trouble bell shall be provided for external connections.

(3) All interior wiring shall be in strict accordance with NFPA Codes 70 and 72 and all local electrical codes applying. Size and number of wires shall be in accordance with wiring diagram supplied by manufacturer of fire-alarm system.

(4) The Electrical Contractor shall provide and install smoke detectors, wiring and connections to magnetic door latches, and flow switches. The fire-alarm panel shall be factory-wired to accept these and any other devices specified herein or as shown on the drawings.

Appendix B

Using a Calculator

Many electrical engineers and designers in the past have rated the slide rule as one of their most important instruments, since it helped reduce long minutes of paper-and-pencil calculations to a few simple manipulations of the "slip-stick" and "runner." While the slide rule has proved indispensable since its invention in the 1850s, there is now something faster, more versatile, more compact, more accurate, and better able to solve today's engineering problems. It is the electronic pocket calculator.

It is not the purpose of this appendix to explain the fundamentals of electronic calculator operation, since this information may readily be obtained from the handbooks accompanying these devices and since practically anyone can master the modern operations of an electronic calculator in a single evening. On the other hand, this appendix will explain how to make specific basic electrical calculations. Actual directions will be given for pressing the required keys in each case.

A selected number of examples have been chosen. These are basic; by no means do they attempt to cover all possible uses of the calculator. Other examples solvable by the same processes will readily occur to the reader.

We find that the type of electronic calculator possessed by most electrical designers is an inexpensive device costing less than $100. Our discussion, therefore, will be limited to that type. However, any calculator capable of adding, subtracting, multiplying, and dividing may be employed, except for problems involving reciprocals and square roots.

Ohm's Law (dc)

1. To find resistance when current and voltage are known:

   A. Key in voltage value.
   B. Press the division key.
   C. Key in current value.
   D. Read answer displayed.

   Example: voltage = 120 V
   current = 2 A

   A. Key in voltage. [1] [2] [0]
   B. Press the division key. [÷]
   C. Key in current value. [2]
   D. See display (ohms). [60.00]

2. To find current when resistance and voltage are known:

   A. Key in voltage value.
   B. Press the division key. [÷]
   C. Key in resistance value.
   D. [illegible] displayed.

3. To find voltage when current and resistance are known:

A. Key in current value.
B. Press the multiplication key. [×]
C. Key in resistance value.
D. See answer (voltage) displayed.

4. To determine value of cathode resistor for any tube:

A. Key in desired grid-bias voltage.
B. Press the division key. [÷]
C. Key in tube plate-current value.
D. See answer displayed.

5. To determine value of grid resistor for a VHF power amplifier tube:

A. Key in desired dc grid-voltage value.
B. Press the division key. [÷]
C. Key in recommended dc grid-current value.
D. See answer displayed.

Ohm's Law (ac)

6. In order to find current when reactance (or impedance) and voltage are known:

A. Key in voltage value.
B. Press the division key. [÷]
C. Key in reactance (or impedance) value.
D. Press the [=] key and read current value.

7. To find the voltage of a circuit when current and reactance (or impedance) are known:

A. Key in current value.
B. Press the multiplication key. [×]
C. Key in reactance (or impedance) value.
D. Press [=] key and read the voltage value.

8. If it is desired to find impedance (or reactance) when voltage and current are known:

A. Key in voltage value.
B. Press the division key. [÷]
C. Key in current value.
D. Press the [=] key and read impedance (or reactance) on the panel.

DC Power

9. In order to find the power in watts when current and voltage are known:

A. Key in current value.
B. Press the multiplication key. [×]
C. Key in voltage value.
D. Press [=] key and read the answer (watts) on the panel.

10. To find the power in watts when current value and resistance are known on calculators with the square key [x^2]:

A. Key in the current value.
B. Press the square key. [x^2]
C. Press the multiplication key. [×]
D. Key in the resistance value.
E. Press the [=] key and read the answer on the panel.

11. In order to find the power in watts when the voltage and resistance are known on calculators with the square key [x^2]:

A. Key in the voltage value.
B. Press the square key. [x^2]
C. Press division key. [÷]
D. Key in resistance value.
E. Press the [=] key and read the answer on the panel.

For use on machines that have no square key, problems with squared factors may be solved as follows:

A. Key in current value.
B. Press multiplication key. [×]
C. Key in current value again.
D. Press the multiplication key. [×]
E. Key in the resistance value.
F. Press the [=] key and read the answer on the panel.

AC Power

12. In order to find the power in watts in an ac circuit when current, voltage, and power factors are known:

A. Key in the current value.
B. Press multiplication key. [×]
C. Key in voltage value.
D. Press multiplication key. [×]
E. Key in power factor.
F. Press the [=] key and read the answer on the panel.

13. To find reactive power value in watts (voltamperes, VA) when current and impedance are known on calculators with square key [x^2]:

A. Key in current value.
B. Press the square key. [x^2]
C. Press multiplication key. [×]
D. Key in impedance value.
E. Press the [=] key and read the answer on the panel.

14. To find reactive power value in VA when voltage and impedance are known:

A. Key in the voltage value.
B. Press the square key. [x^2]
C. Press the division key. [÷]
D. Key in impedance value.
E. Press the [=] key and read the answer in watts on the panel.

AC Conversions

15. In order to determine effective (RMS) value of alternating current or voltage from peak value:

A. Key in voltage value or peak current.
B. Press the multiplication key. ☒
C. Press the division key. ☐
D. Key in [illegible].
E. Press the ☐ key and read effective (RMS) value on the panel.

16. To determine the average value of alternating current or voltage from peak value:

A. Key in peak current or voltage value.
B. Press the multiplication key. ☒
C. Key in [illegible].
D. Press the ☐ key and read average value on the panel.

17. To determine peak value of alternating current or voltage from effective (RMS) value:

A. Key in effective (RMS) value.
B. Press the multiplication key. ☒
C. Key in [illegible].
D. Press the ☐ key and read peak value on the panel.

18. To determine peak value of alternating current or voltage from average value:

A. Key in average value.
B. Press the multiplication key. ☒
C. Key in [illegible].
D. Press the ☐ key and read peak value on the panel.

19. When the effective (RMS) value of alternating current is desired or voltage from average value:

A. Key in average value.
B. Press the multiplication key. ☒
C. Key in [illegible].
D. Press the ☐ key and read peak value on the panel.

20. To determine average value of alternating current or voltage from effective (RMS) value:

A. Key in effective (RMS) value.
B. Press the multiplication key. ☒
C. Key in [illegible].
D. Press the ☐ key and read average on the panel.

Reactance

21. If it is desired to know the reactance of a coil of negligible resistance when inductance and operating frequency are known:

A. Key in [illegible].
B. Press the multiplication key. ☒
C. Key in frequency.
D. Press the multiplication key. ☒
E. Key in inductance value.
F. Press the ☐ key and read reactance on the panel.

22. To find the reactance of a coil of negligible resistance or of a capacitor when the line voltage is known as well as the current through it:

A. Key in voltage value.
B. Press the division key. ☐
C. Key in current value.
D. Press the ☐ key and read reactance on the panel.

23. To find the reactance of a capacitor when capacitance and operating frequency are known:

A. Key in [illegible].
B. Press the multiplication key. ☒
C. Key in frequency.
D. Press the multiplication key. ☒
E. Key in capacitance.
F. Press the ☐ key and read reactance on the panel.

Unlike the slide rule, the use of the electronic calculator automatically places the decimal point in the answer. Therefore, when using the calculator, it is not necessary for users to keep before them a mental image of the proceeding arithmetic in the sense that they visualize the working of the example on paper.

It is recommended that the readers first become familiar with the particular type of electronic calculator they plan to use. Then substitute actual values in the preceding examples in order to become familiar with the procedures involved in the calculations.

A. Key in voltage value or peak current.
B. Press the multiplication key. ⊠
C. Press the division key. ⊟
D. Key in 0.707.
E. Press the ⊟ key and read effective (RMS) value on the panel.

16. To determine the average value of alternating current or voltage from peak value:

A. Key in peak current or voltage value.
B. Press the multiplication key. ⊠
C. Key in 0.636.
D. Press the ⊟ key and read average value on the panel.

17. To determine peak value of alternating current or voltage from effective (RMS) value:

A. Key in effective (RMS) value.
B. Press the multiplication key. ⊠
C. Key in 1.414.
D. Press the ⊟ key and read peak value on the panel.

18. To determine peak value of alternating current or voltage from average value:

A. Key in average value.
B. Press the multiplication key. ⊠
C. Key in 1.57.
D. Press the ⊟ key and read peak value on the panel.

19. When the effective (RMS) value of alternating current is desired or voltage from average value:

A. Key in average value.
B. Press the multiplication key. ⊠
C. Key in 1.11.
D. Press the ⊟ key and read peak value on the panel.

20. To determine average value of alternating current or voltage from effective (RMS) value:

A. Key in effective (RMS) value.
B. Press the multiplication key. ⊠
C. Key in 0.9.
D. Press the ⊟ key and read average on the panel.

Reactance

21. If it is desired to know the reactance of a coil of negligible resistance when inductance and operating frequency are known:

A. Key in 6.28.
B. Press the multiplication key. ⊠
C. Key in frequency.
D. Press the multiplication key. ⊠
E. Key in inductance value.
F. Press the ⊟ key and read reactance on the panel.

22. To find the reactance of a coil of negligible resistance or of a capacitor when the line voltage is known as well as the current through it:

A. Key in voltage value.
B. Press the division key. ⊟
C. Key in current value.
D. Press the ⊟ key and read reactance on the panel.

23. To find the reactance of a capacitor when capacitance and operating frequency are known:

A. Key in 6.28.
B. Press the multiplication key. ⊠
C. Key in frequency.
D. Press the multiplication key. ⊠
E. Key in capacitance.
F. Press the ⊟ key and read reactance on the panel.

Unlike the slide rule, the use of the electronic calculator automatically places the decimal point in the answer. Therefore, when using the calculator, it is not necessary for users to keep before them a mental image of the proceeding arithmetic in the sense that they visualize the working of the example on paper.

It is recommended that the readers first become familiar with the particular type of electronic calculator they plan to use. Then substitute actual values in the preceding examples in order to become familiar with the procedures involved in the calculations.

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About the Author

John E. Traister began work as an apprentice electrician between college semesters in 1956. He obtained his Master Electrician's License in 1963, at which time he organized an electrical contracting business which he operated until 1968. Since that time he has worked as an electrical designer and chief electrical designer for consulting engineering firms, one of the most recent being Engineering Associates, Ltd. Mr. Traister has written dozens of articles for trade and professional journals in addition to eight books.

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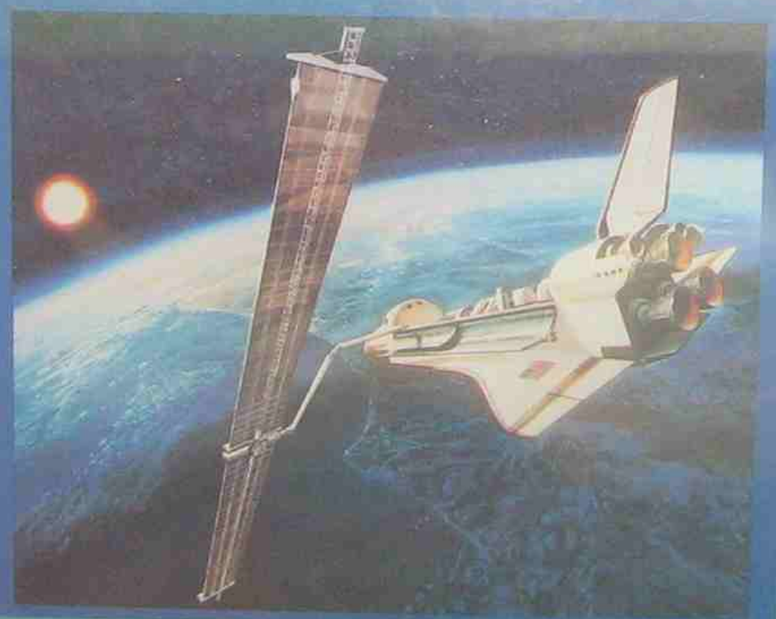

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POWER TECHNOLOGY

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10. What is the formula for calculating horsepower?
11. How much horsepower does an engine on a grain elevator deliver if it can load 705 pounds (3137 newtons) of corn into a 25-foot (7.6-meter) storage bin in 55 seconds?

Unit 2 Safety and Power Technology

OBJECTIVES After completing this unit, the student should be able to:

- Explain how personal attitudes toward safety affect other people.
- List rules for storing gasoline.
- Name safety precautions for gasoline use.
- List safety rules for operating power equipment.
- Identify the proper fire extinguisher to be used with each class of fire.
- State how carbon monoxide is produced.
- List the effect that carbon monoxide has on the body.
- State rules for the safe use of hand tools.

The maintenance, operation, repair and testing which are involved in a study of power technology requires that careful and constant emphasis be placed on safety. It is beyond the scope of this unit to deal with the particular safety considerations of each different prime mover and its vast number of applications. Instead, this unit deals with safety considerations in several common areas: safety attitudes, safety with gasoline, fires, carbon monoxide safety, safety with basic hand tools, safety with basic machines and applicances, and safety with small gasoline engines.

Specific safety information is included in later units as it applies. However, it is useful to review this unit before beginning laboratory experiences.

SAFETY ATTITUDES

Safety is important to every student, both as an individual and as a member of a community. The machine age brought many safety hazards. In transportation alone millions of power-driven vehicles presented a number of hazards. Industrial, construction, and scientific employees work with the tools of power technology every day. There are also many hazards in the home – power appliances, household machines, fire, boiling liquids, electricity, and so forth. Considering these hazards, it is necessary that an emphasis on safety begin early in childhood and continue throughout life.

Accidents can be compiled into statistics. Accidents can be measured in terms of frequency, probability, medical costs, and time lost from work. This information can serve a useful purpose in identifying hazards and in developing safety programs.

On an individual basis, the statistical approach loses all of its importance. How can a number or a dollar sign be put on the personal cost and human suffering that result when accidents occur? People do not like to think of the unpleasantness of an accident happening to them. Fortunately, most try to

protect themselves and those close to them from hazardous situations and accidents.

People must consider both their own safety, and the safety of others. Each person's actions and safety attitudes do have an effect on other individuals. Sometimes the effect is slow and indirect, such as parents' carelessness becoming part of their children's safety standards. At other times, the effect on others is direct, such as a head-on collision on the highway caused by an irresponsible driver. The point is that in power safety, individuals are responsible for themselves as well as for the safety of others.

Students should consider the safety aspect of every activity in which they engage. Most basic safety approaches to prime movers and machines are similar and the knowledge gained from one situation can be applied to another. Safety is never sacrificed for the sake of speed or expediency. It should have priority over everything else. How a person operates a machine can reveal that person's entire safety code. It can also indicate personal qualities or deficiencies.

Learning safety by trial and error alone is not enough. The safety considerations of each situation must be studied. A defensive attitude of, "if this happens, what might the result be?" must be a part of a person's overall judgment. Some safety is common sense. However, many safety requirements must be learned from machinery instruction booklets and repair manuals. To ensure personal safety as well as safety for others, the operator must know specific information that applies to the particular prime mover and its uses.

SAFETY WITH GASOLINE

Understanding the nature of gasoline and its safe use is very important. Gasoline is used as a common item in many households. The presence of this liquid, which is more powerful than TNT, is readily accepted. Many people have become too casual about this volatile and explosive liquid.

Gasoline is around the home (in the garage, toolshed, or barn) largely because the use of small gasoline engines has become so widespread. Lawn mowers, garden tractors, snow throwers, go-carts, utility vehicles, motorbikes, outboard motors, and chain saws need gasoline for operation.

Unfortunately, accidents do happen. It is estimated that every year several hundred persons lose their lives due to accidents involving gasoline and other flammable liquids. In addition, several million dollars of property damage is caused by such accidents.

The volatility of gasoline is the characteristic that makes it such an ideal fuel. This same characteristic is also the prime danger. Gasoline can vaporize and explode in a closed or nonventilated room just as it can in the engine. A concentration of one to seven cubic feet of gasoline vapor per 100 cubic feet of air represents a flammable condition. Any spark or flame can touch off gasoline as a fire or explosion.

Gasoline should not be stored inside the home – it is too dangerous. It should be kept in a garage, toolhouse, or some other outside building. Storage in the basement is dangerous as a gas can could be tipped over. If the seal was imperfect, gasoline would leak out and begin to vaporize. Given certain circumstances, the whole basement could blow up – triggered by the flame from a furnace or water heater or from the arc of an electric switch.

Many states have recognized the hazards of gasoline around the home and are developing safety regulations that help to protect the public. The proper use of storage containers

is one important area. Ideal storage is in a red metal can clearly labeled GASOLINE. Red is a universal color indicating danger. A metal can, such as shown in figure 2-1, will not break if it is accidentally dropped or struck. Follow these rules for the storage of gasoline:

- Store gasoline in an approved metal container.
- Store gasoline in an outbuilding – not inside the home.
- Do not store gasoline during the off season. It is too dangerous to have around.
- Do not allow small children to have access to the gasoline supply.
- Store gasoline away from flames, excessive heat, sparks caused by static electricity, sparks caused by electrical contacts, or sparks caused by mechanical contact.
- Have the proper portable fire extinguisher available for use if needed.

Gasoline should be regarded as dangerous; using it safely involves decisions and judgments. Furthermore, gasoline should be regarded as fuel for gasoline engines and not as a handy all-purpose solvent, cleaner, or fire starter. Again, the volatility and explosive nature of gasoline make it unsuitable for any type of general household use. Gasoline used as a cleaning agent for paint brushes or to cut grease creates real safety hazards. Accidental ignition can occur while the gasoline is being used. Also, disposing of the dirty gasoline may be hazardous.

Never use gasoline to start a fire. The result may be a fire or explosion much larger than the intended size resulting in injury to the person with the gasoline.



Fig. 2-1 Gasoline properly labeled and stored in proper container

Observe these precautions when using gasoline:

- Always regard gasoline as dangerous.
- Use gasoline only as a fuel for engines or devices where its use is clearly intended.
- Never smoke cigarettes, pipes, or cigars around gasoline.
- Never fill the tank of a hot engine or a running engine if the tank and engine are at all close to each other. Gasoline splashed on a hot engine can ignite or explode.

- When pouring gasoline from a container to the tank, reduce the possibility of a static electricity spark by having metal-to-metal contact. A metal spout held against the tank opening is good to use. A funnel that contacts both the container and the tank is also safe. Pouring gasoline through a chamois may present a static electricity hazard.

FIRES

An understanding of fires and fire extinguishers is very useful, figure 2-2. Most fires fall into one of three categories:

Class A – Wood, cloth, paper, rubbish

Class B – Oil, gasoline, grease, paint

Class C – Electrical equipment



Fig. 2-2 Using a fire extinguisher

Class A Fires

Class A fires are the most common type of fire. Extinguishing Class A fires consists of quenching the burning material and reducing the temperature below that of combustion. Some extinguishing methods also have a smothering effect on the fire.

The Class A fire can be effectively fought with water from a fire hose, garden hose, or a water-base extinguisher. The water stream should be directed at the base of the fire first, then back and forth following the flames upward.

The dry chemical extinguisher is the most common extinguisher used in the home, office, or shop. Dry chemical extinguishers are effective in fighting almost all types of fires (Class A, B, or C). These extinguishers expel a chemical that interrupts and smothers the fire.

Class B Fires

Class B fires involve burning liquids such as gasoline, oil, paint, thinners, solvents, etc. Careless or unknowing action against Class B fires can place the fire fighter in great danger. Burning liquids such as gasoline are unpredictable; they can explode into a ball of fire as well as burn. The basic extinguishing technique is to cut off the oxygen supply which feeds the burning liquid and interrupt the flame without splashing the burning liquid around. Dry chemical extinguishers are suitable for fighting Class B fires.

Carbon dioxide (CO_2) extinguishers contain carbon dioxide under high pressure; they also are used to extinguish Class B fires. Carbon dioxide does not support combustion and, therefore, has the effect of smothering the flame. The extinguisher should be used with a slow sweeping action that travels from side to side, working to the back of the flame area. The discharge horn of the extinguisher becomes very cold during discharge and so should not be touched. Another hazard is that using the extinguisher in a small room may decrease the oxygen supply which is dangerous to the fire fighter.

Foam fire extinguishers discharge a water-base foam that can smother the fire. When using a foam extinguisher on Class B fires, direct the foam at the back of the fire allowing the foam to spread onto the flame area. This minimizes the possibility of splashing the flaming liquid of an open container fire.

Class C Fires

Class C fires involve electrical equipment. Water-base extinguishing materials are not suitable for putting out Class C fires. Water on or around an electrical fire creates a shock hazard. If the electrical energy can be completely and positively shut off, the fire is no longer considered a Class C fire. The method used to extinguish the fire then depends on the material that is burning. For example, shorted wires in an electrical outlet may be arcing and causing insulation to smolder. If the fire has spread to the wooden walls and if the electric current is turned off, the burning walls are considered a Class A fire. A dry chemical extinguisher would be suitable for both the electrical fire and the wood fire. Using water would be hazardous unless the electricity had been shut off. If the electrical energy cannot be completely shut off, the fire must be fought with carbon dioxide extinguishers, dry chemical extinguishers, or vaporizing liquid extinguishers.

CARBON MONOXIDE SAFETY

The hazard of carbon monoxide is very real. Carbon monoxide (CO) is a poison that is colorless, odorless and tasteless. It is a killer that is responsible for more poisoning deaths than any other deadly poison.

Carbon monoxide is the result of incomplete combustion of solid, liquid, or gaseous fuels of a carbonaceous nature. At home the gas may be present due to an improperly adjusted hot water heater. In industry carbon monoxide can be found with kilns, oven stoves, foundries, smelters, mines, forges, and in the distillation of coal and wood, to list a few. However, it also exists in a much more common circumstance – the exhaust gases of all internal combustion engines from lawn mowers to automobiles. When an engine is in operation, carbon monoxide is produced. Knowledge about this poison and how to eliminate or minimize the danger is an important topic for everyone.

The action of this poison on the human body can be quite rapid. The hemoglobin of the blood has a great attraction for CO, three hundred times greater than that for oxygen. When the CO is combined with the hemoglobin, it has the effect of reducing the amount of hemoglobin available to carry oxygen to the body tissues. If large amounts of CO combine with the hemoglobin, the body becomes starved for oxygen and literally suffocates.

Ventilation is of prime importance in preventing carbon monoxide poisoning, figure 2-3. Unburned gases and exhaust must be carried away as effectively as possible by using chimneys, ventilation systems, and exhaust systems, figure 2-4. These systems must be efficient because even small amounts of

the gas can cause a dulling of the senses, which indicates danger.

Carbon monoxide in exhaust gas can get inside an automobile in several ways: through a defective exhaust system – tail pipe, muffler, or manifold; or through rusted-out or defective floor panels. If there is excessive CO around the automobile due to faulty exhausting or a poorly tuned engine, it can come in through an open window.

Knowing the symptoms of carbon monoxide poisoning and heeding their warnings could be a life-and-death matter. These symptoms include a tightness across the forehead followed by throbbing temples, weariness, weakness, headache, dizziness, nausea, decrease in muscle control, increased pulse rate, and increased rate of respiration. If anyone has these symptoms while riding in a car, the car should be stopped and the person should get some fresh air.



Fig. 2-4 Using an exhaust system to carry away carbon monoxide

If a person is discovered who has passed out from carbon monoxide poisoning, remove the victim to the fresh air immediately. If breathing has stopped or if the victim is only gasping occasionally, begin artificial respiration at once. Also, have someone call a doctor and/or emergency squad.

To prevent carbon monoxide poisoning, follow these rules:

- Do not drive an auto with all the windows closed if a carbon monoxide leak is suspected.
- Do not operate internal combustion engines in closed spaces such as garages or small rooms, unless the space is equipped with an exhaust system.
- Keep carbon monoxide producing engines and devices tuned or adjusted properly in order to reduce the output of CO gas.

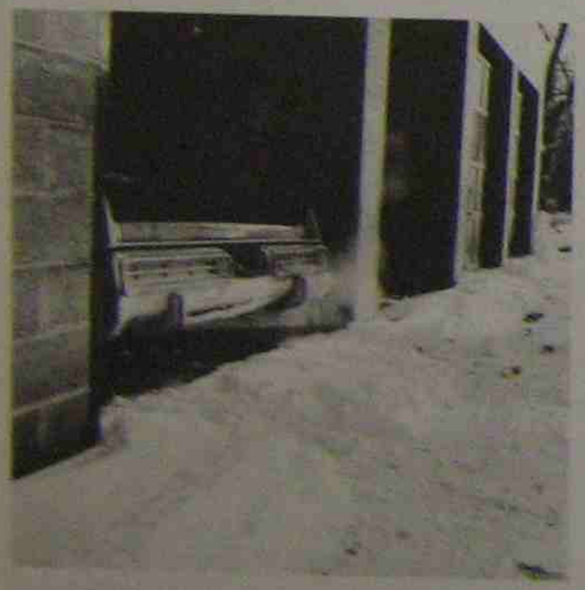


Fig. 2-3 Ventilation is of prime importance in preventing carbon monoxide poisoning

- Do not sit in parked cars with the engine running.
- Remember the importance of properly working ventilation and exhaust systems.

SAFETY WITH BASIC HAND TOOLS

Tools should be treated with respect and should be well cared for. They should be stored in a way that will protect their vital surfaces, cutting edges, and true surfaces. A wall tool panel with individual hangers or holding devices for each tool is ideal since the tools are easily seen, ready for use, and well protected. Tools carelessly thrown in a drawer can scratch, dull, or damage each other and are a hazard to the person who is looking for the right tool.

When tools must be carried in a toolbox, they should have individual compartments, if possible. If the box lacks individual compartments, the more sensitive tools and those with cutting edges should be wrapped in cloth.

Moisture and the rusting that results is a problem. If tools get wet, wipe them dry before storing. Also, the possibility of rusting can be lessened by wiping the tools with a slightly oily rag. If a tool picks up dirt during use, wipe it clean before putting it away.

The basic rules for the safe use of hand tools are:

- Use tools that are in good condition and well sharpened. A dull tool is inefficient and is more likely to slip during use.
- Use the correct tool for the job and use it as it should be used. The incorrect use of tools causes many accidents.

In some operations, hand tools can present the hazard of flying metal chips. A misstruck nail may fly across the room. Even a hammer can be dangerous. Especially dangerous are chipping operations with a cold chisel. All struck tools such as chisels and punches can mushroom out at the end over a period of use, figure 2-5. The ends should be dressed on a grinder to eliminate the possibility of tool chips breaking and flying from the tool when it is hit. Hammers can chip if they are struck side blows or glancing blows; hammers should strike the work with their full face. figure 2-6. Safety glasses should be worn whenever there is a possibility of flying chips or breakage. Grinding operations are especially hazardous and safety glasses should always be worn when grinding.

When properly used, a wrench is a safe tool. However, if used incorrectly, the wrench can be dangerous. Be certain to use the exact size wrench for the nut or bolt to prevent slipping or damage to the flats of the nut or bolt. If an adjustable wrench is used, place it tightly against the flats of the nut or bolt and be sure that the direction of force places the major strain on the fixed jaw and not on the movable jaw, figure 2-7. Be sure

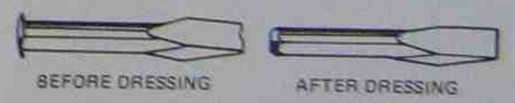


Fig. 2-5 All struck tools should be properly dressed on the ends

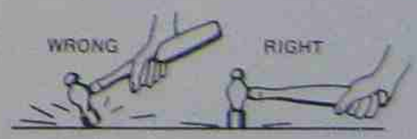
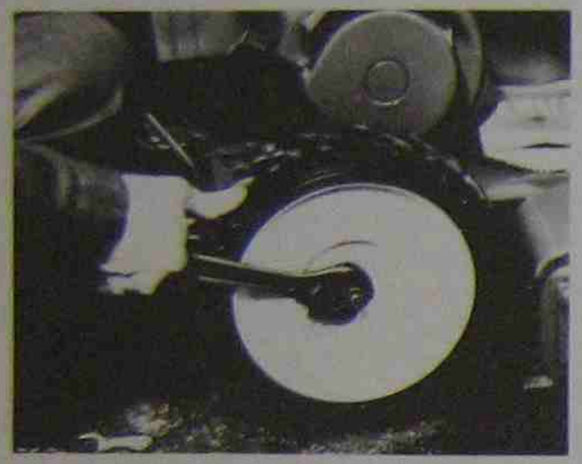
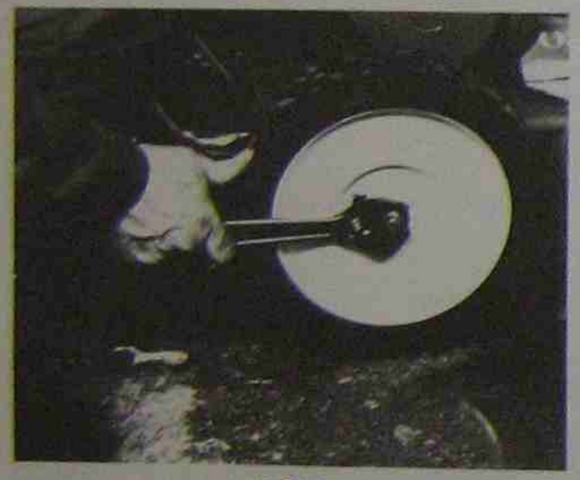


Fig. 2-6 The hammer face should strike the work with its full, flat face



WRONG



RIGHT

Fig. 2-7 Use an adjustable wrench so the strain is on the fixed jaw

to pull the wrench toward you; never push it. Pushing can be dangerous; the nut or bolt may suddenly loosen, or the tool may slip causing the user to be injured.

Screwdrivers are probably the most misused of all common tools. The list of abuses ranges from using it to open paint cans to using it as a wrenching bar. The tool is intended to be used for tightening or loosening various types of screws; its tip must be preserved for this purpose. Use a screwdriver that is the correct size, figure 2-8. It should fit the screw slot snugly in width; the blade should be as wide as the slot is long. Have several sizes of screwdrivers in a tool assortment. It is a poor practice to hold the work in one hand in such a manner that a slip would send the screwdriver into the palm of the hand. All small or irregularly shaped pieces should be held securely in a vise. Screwdrivers, pliers, or other tools that are used for electrical or electronic work should have insulated handles, figure 2-9.

Files are rarely sold with handles attached but they should be so equipped. The tang is



TOO SMALL



CORRECT SIZE

Fig 2-8 Use the correct size screwdriver for the job

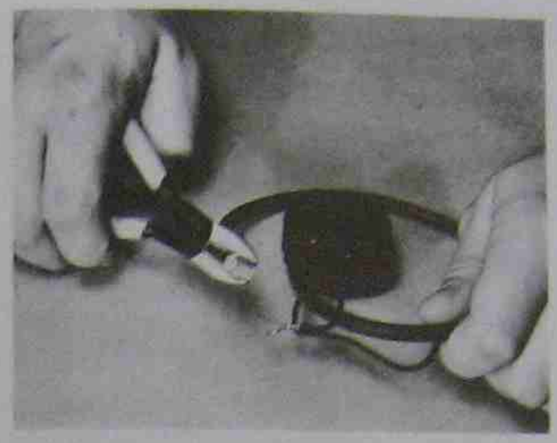


Fig. 2-9 Tools used in electrical and electronic work should have insulated handles

fairly sharp and can cut or puncture the hand if the file suddenly hits an obstruction. The brittle nature of files makes them a poor choice and dangerous as a pry bar; do not use them for this purpose.

SAFETY WITH BASIC MACHINES AND EQUIPMENT

Safe use of basic household machines, equipment, and appliances during normal use, adjustment, and repair is important to all, figures 2-10 and 2-11. Reference is made to power hand tools; power tools; appliances such as stoves, refrigerators, dishwashers, clothes driers, washing machines, air conditioners, electronic equipment such as television sets, record players, and radios; powered hobby or sports equipment; small home appliances for kitchen or personal use; and so forth. Several common rules should be followed when using these machines:

- Before attempting to adjust or repair a machine, always unplug or disconnect the machine or device from the electrical power source. Be certain that someone else does not accidentally reconnect or plug in the machine while you are working on it. If the power source is in a remote location, tag the source "Do not connect. Equipment under repair."
- Before attempting to adjust or repair machines driven by engines, stop the engine, disengage the clutch, and remove the spark plug lead to eliminate the possibility of accidentally restarting the engine.
- Be sure to ground electrical equipment that requires grounding. Use the three-prong plug on portable tools or devices and properly ground the convenience outlet.



Fig. 2-10 This man is practicing proper safety techniques while using a filament trimmer. Note the heavy work clothes, rugged shoes, safety glasses and hardhat. (Courtesy of Toro Company)

- Keep loose clothing away from rotating parts that could grab the cloth and thereby pull the operator into the machine.
- Protect eyes with safety glasses if there is any chance of flying chips or breakage.
- Thoroughly guard all belts, pulleys, chains, gears, etc. Do not remove these guards or allow them to be removed by others.
- Study the instructions that come with the machine. Be certain that the operating principles and the safety precautions are understood before operating or repairing the machine.
- Use the machine only in the manner and for the purpose for which it was designed.
- During adjustment and repair, retighten all nuts, bolts, and screws securely.
- Unless qualified to be there, keep away from high voltage areas in electronic equipment.
- Do not pull a lawn mower – push it. If a person falls while pulling the mower, it may be pulled over the body.
- Inspect the lawn for rocks, sticks, wire and other foreign objects that can be converted into projectiles by the mower blade.
- Allow only a responsible person to operate a power mower.
- Small children should be kept away from the mowing area.

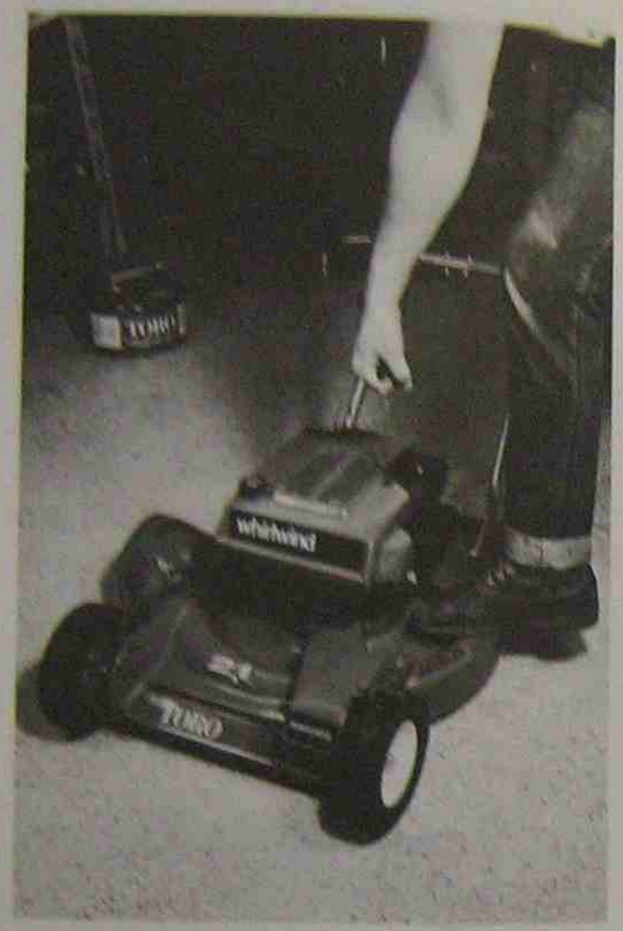


Fig. 2-11 Keep feet away from the blade when starting the mower

- Do not use a riding lawn mower as a play vehicle.
- Keep self-propelled lawn mowers under full control.
- Never leave a mower running unattended.
- Wear safety glasses while mowing.

REVIEW QUESTIONS

1. Name two factors that contribute to the safe operation of an engine.
2. What characteristics of gasoline makes it such a dangerous liquid?
3. List four rules for storing gasoline.
4. List three precautions to follow when using gasoline.
5. What type of extinguishers are best for putting out gasoline fires?
6. How is carbon monoxide produced? What is its effect on the body?
7. State two rules for the safe use of hand tools.
8. List six safety rules for operating power lawn mowers.

SECTION 2
THE SMALL GASOLINE ENGINE

Unit 3 Construction of the Small Gasoline Engine

OBJECTIVES After completing this unit, the student should be able to:

- Identify the basic parts of an engine and explain how they work together.
- Explain the principles of the four-stroke cycle.
- Explain the principles of the two-stroke cycle.
- Explain the differences in the construction of four-stroke cycle and two-stroke cycle engines.

The internal combustion engine is classified as a *heat* engine; its power is produced by burning a fuel. The energy stored in the fuel is released when it is burned. *Internal combustion* means that the fuel is burned inside the engine itself. The most common fuel is gasoline. If gasoline is to burn inside the engine, there must be oxygen present to support the combustion. Therefore, the fuel needs to be a mixture of gasoline and air. When ignited, a fuel mixture of gasoline and air burns rapidly; it almost explodes. The engine is designed to harness this energy.

The engine contains a cylindrical area commonly called the *cylinder* that is open at both ends. The top of the cylinder is covered with a tightly bolted-down plate called the *cylinder head*. The cylinder contains a *piston*, which is a cylindrical part that fits the cylinder with little clearance. The piston is free to slide up and down within the cylinder. The air/fuel mixture is brought into the cylinder, then the piston moves up and compresses it into a small space called the combustion chamber. The *combustion chamber* is the area where the fuel is burned; it usually consists of a cavity in the cylinder head and perhaps the uppermost part of the cylinder. When the fuel is ignited and burns, tremendous pressure builds up. This pressure forces the piston back down the

cylinder; thus the untamed energy of combustion is harnessed to become useful mechanical energy. The basic motion within the engine is that of the piston sliding up and down the cylinder, a *reciprocating* motion.

There are still many problems, however. How can the up-and-down motion of the piston be converted into useful rotary motion? How can exhaust gases be removed? How can new fuel mixture be brought into the combustion chamber? Studying the engine's basic parts can help answer these questions.

BASIC ENGINE PARTS

The internal combustion engine parts discussed here are those of the four-stroke cycle gasoline engine, the most common type. The most essential of these parts are briefly listed.

- *Cylinder:* hollow; stationary; piston moves up and down within the cylinder.
- *Piston:* fits snugly into the cylinder but still can be moved up and down.
- *Connecting rod:* connects the piston and the crankshaft.
- *Crankshaft:* converts reciprocating motion into more useful rotary motion.
- *Crankcase:* the body of the engine; it contains most of the engine's moving parts.
- *Valves:* "doors" for admitting fuel mixture and releasing exhaust.

Figure 3-1 shows the basic parts of two-cycle and four-cycle engines. Cross sections of two small gas engines are shown in figures 3-2 and 3-3.

Cylinder

The cylinder is a finely machined part which can be thought of as the upper part

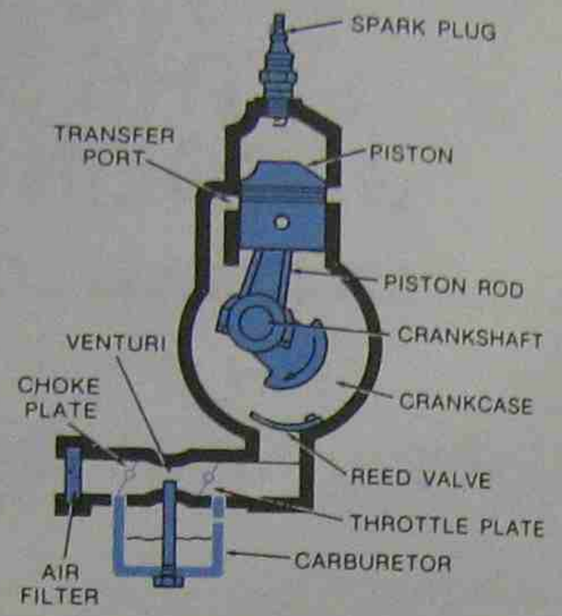


Fig. 3-1 Basic parts of two-cycle and four-cycle engines

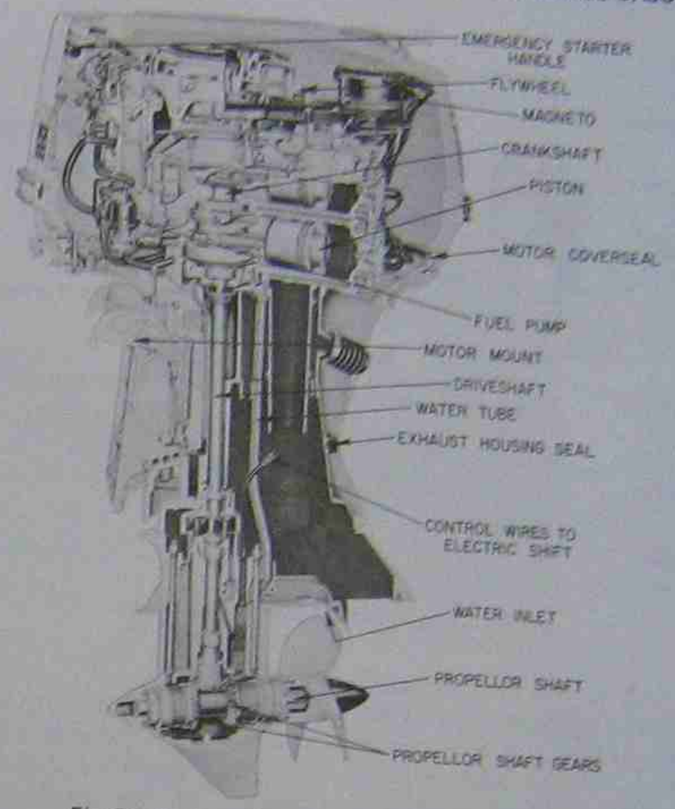


Fig. 3-2 Cross section of an outboard motor (Courtesy Johnson Company)

of the crankcase. The piston slides up and down in the cylinder. The fit is close; the piston is only a few thousandths of an inch smaller in diameter than the cylinder.

Light duty aluminum engines often use the aluminum engine block for the cylinder. However, some aluminum engines have a cast iron cylinder sleeve cast into the engine and the two are inseparable. A cast iron engine has a cast iron block for the cylinder. Some engines have a chrome-plated cylinder.

In engine specifications, the diameter or width across the top of the cylinder is referred to as the *bore* of the engine; this is an important measurement. Figure 3-4 shows four different cylinder arrangements.

Cylinder Head

The cylinder head forms the top of the combustion chamber and is exposed to great heat and pressure. This is where the action is – the few cubic inches made up by the top of the piston, the upper cylinder walls and the cylinder head.

The cylinder head must be tightly bolted to the cylinder. It is important to tighten all cyl-

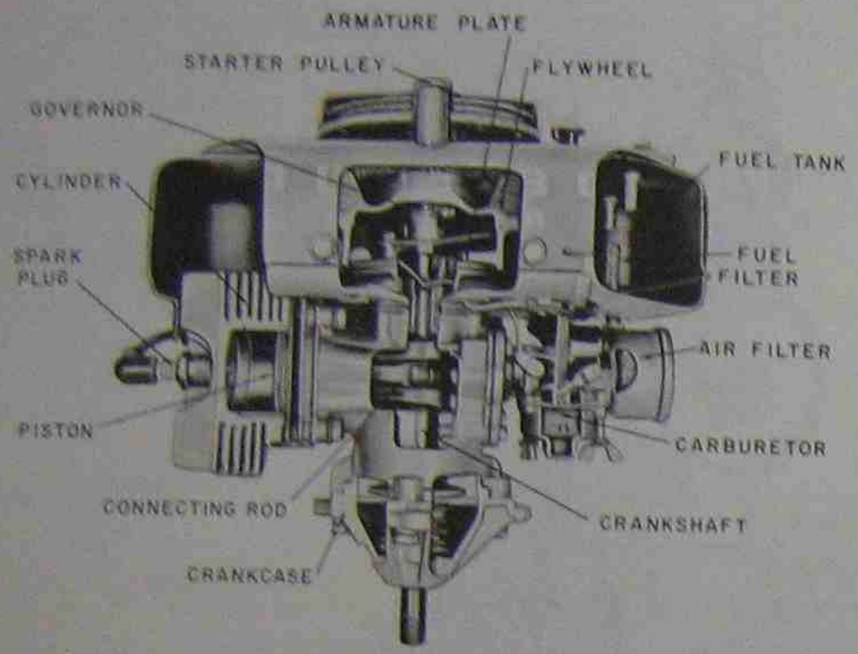


Fig. 3-3 Cross section of a lawn mower engine

inder head bolts with an even pressure and in their correct order so that uneven stress is not set up in the cylinder walls, figure 3-5. Such stress can distort the cylinder walls or warp the cylinder head. The cylinder head also contains the threaded hole for the spark plug.

Cylinder Head Gasket

A gasket between the two metal surfaces makes an airtight seal, figure 3–6. Gaskets are made of relatively soft material such as fiber, soft metal, cork, asbestos, and rubber. Cylinder head gaskets must be able to hold the high pressure of combustion without blowing out and they must be heat resistant.

There are many engines that have the cylinder and the cylinder head cast as one piece, therefore, there are no gaskets or head bolts. A threaded spark plug hole is still located at the top of the cylinder head. Many small two-cycle engines use this design.

Piston

The piston slides up and down in the cylinder. It is the only part of the combustion chamber that is free to move when the pressure of the rapidly burning fuel mixture is applied. The piston can be made of cast iron, steel, or aluminum alloy; aluminum is commonly used for small engines because of its light weight and its ability to conduct heat away rapidly.

There must be clearance between the cylinder wall and the piston to prevent excessive wear. The piston is 0.003 to 0.004 of an inch smaller in diameter on the thrust sides. To check this clearance, a special flat feeler gauge is necessary.

The piston top, or crown, may be flat, convex, concave, or many other shapes. Manufacturers select the shape that causes turbulence of the fuel mixture in the combustion chamber and promotes smooth burning of the

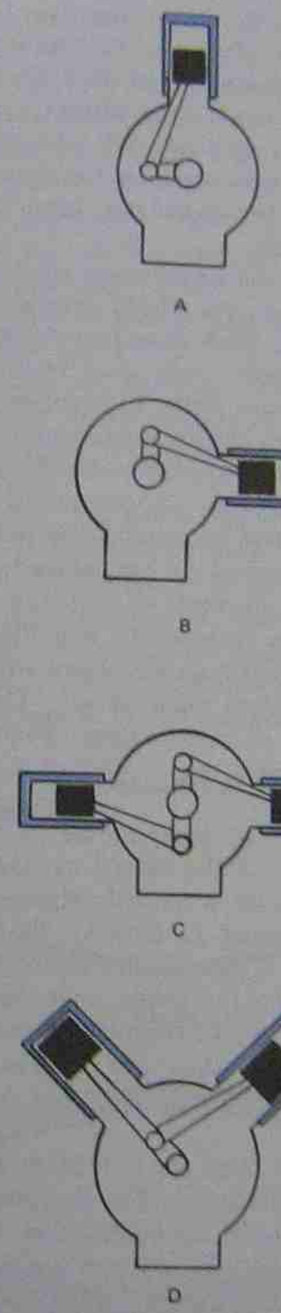


Fig. 3-4 Cylinder arrangement: (A) vertical, (B) horizontal, (C) opposed, and (D) V-type

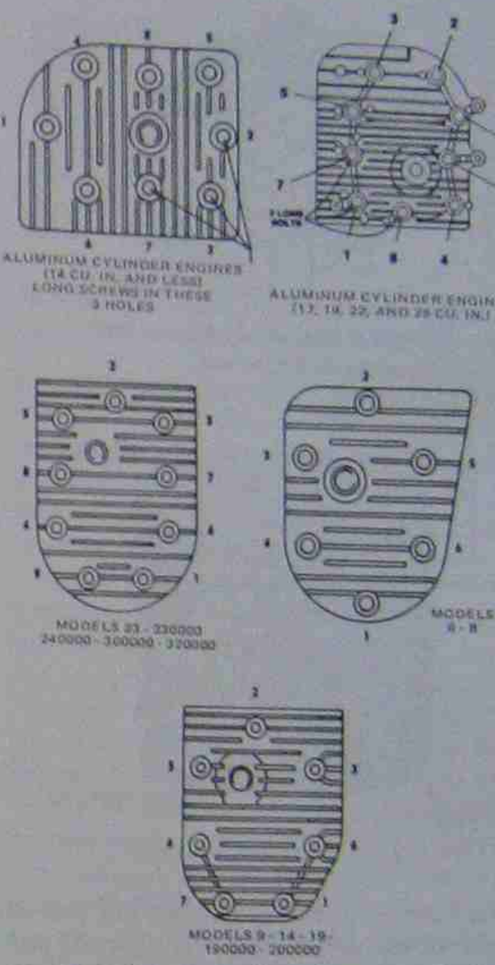


Fig. 3-5 Cylinder heads. Note the sequence for tightening the head bolts. (Courtesy Briggs and Stratton)

fuel mixture. The piston has machined grooves near the top to accommodate the piston rings, figure 3-7. To provide for expansion, some pistons are *cam ground* (not perfectly round), or have a vertical slot cut up the side.

The distance the piston moves up and down is called the *stroke*. The uppermost point of the piston's travel is called its *top*

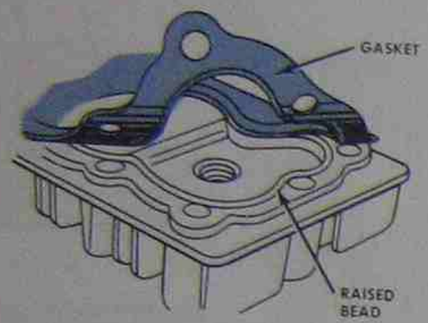


Fig. 3-6 The cylinder head gasket provides an airtight seal.

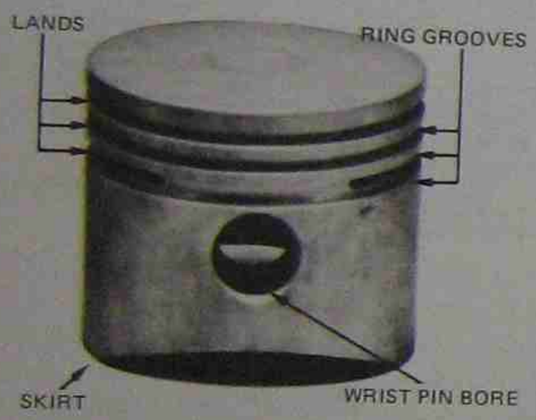


Fig. 3-7 The parts of a piston

dead center (TDC) position. The lowest point of the piston's travel is called its *bottom dead center* (BDC). Therefore, stroke is the distance between TDC and BDC.

Piston Rings

Piston rings provide a tight seal between the piston and the cylinder wall. Without the piston rings much of the force of combustion would escape between the piston and cylinder walls into the crankcase. The piston rings mainly act as a power seal, ensuring that a maximum amount of the combustion pressure is used in forcing the piston down the cylinder. Since the piston rings are between the piston and cylinder wall, there is a small area of metal sliding against the cylinder wall. Therefore, the piston rings reduce friction and the accompanying heat and wear that are caused by friction. Another function of the piston ring is to control the lubrication of the cylinder wall.

The job of the piston rings might appear simple. However, the piston rings may have to work under harsh conditions such as (1) distorted cylinder walls due to improper tightening of head bolts, (2) cylinder out of round, (3) worn or scored cylinder walls, (4) worn piston, and (5) conditions of expansion due to intense heat. The important job of providing a power seal can become difficult if the engine is worn or has been abused.

Piston rings are made of cast iron or steel and are finely machined. Sometimes the surfaces of piston rings are plated with other metals to improve their action. There are many designs of piston rings. Some rings, especially oil rings, may consist of more than one piece.

Blow-by and oil pumping are two serious problems that can be caused by bad piston rings, a bad piston, a warped cylinder, distortion, and/or scoring. In *blow-by*, the pressure of combustion is great enough to break the oil seal provided by the piston rings. When this happens, the gases of combustion force their way into the crankcase. The result is a loss in engine power and contamination of the crankcase oil.

Piston rings that are not fitted properly may start pumping oil. This pumping action leads to fouling in the combustion chamber, excessive oil consumption, and poor combustion characteristics. The rings have a side clearance which can cause a pumping action as the piston moves up and down if the piston

and rings become worn.

A piston usually has three or four piston rings. Some have only one ring. The top piston ring is a compression ring, figure 3-8. This pounds on the cylinder wall. The ring has a clearance in its groove: it can move slightly up and down and expand slightly in and out. The second ring from the top is also a compression ring. These two rings form the power seal. The second ring serves two purposes. The upper half helps with compression control and the lower outside edge acts as a scraper for oil control. In small engines, the second ring is commonly referred to as a scraper ring.

The third ring down (and fourth is one is present), is an oil control ring, figure 3-9. The job of this piston ring is to control the lubrication of the cylinder wall. These rings spread the correct amount of oil on the cylinder wall, scraping the excess from the wall and returning it to the crankcase. The rings

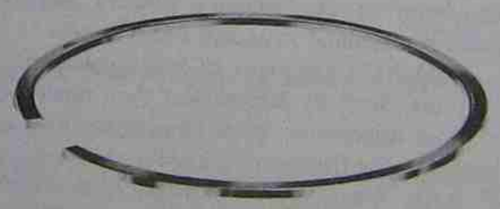


Fig. 3-8 Compression ring



Fig. 3-9 Oil control ring

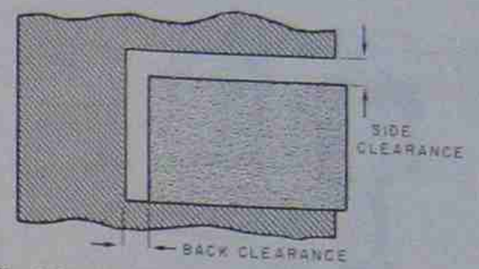


Fig. 3-10 Cross section showing a piston ring in its groove. Notice back clearance and side clearance.

are slotted and grooves are cut into the piston behind the ring. This enables much of the excess oil to be scraped through the piston and it then drips back into the crankcase. It should be noted that compression rings have a secondary function of oil control.

Two clearances (or tolerances) that are important in piston rings are end-gap and piston ring side groove clearance. The end gap is the space between the ends of the piston ring, measured with a flat feeler gauge when the ring is in the cylinder. The gap must be large enough to allow for expansion due to heat but not so large that power loss due to blow-by will result. Often 0.004 inch is allowed for each inch of piston diameter (top ring), and 0.003 inch is allowed for rings under the top ring. Since the second and third rings are exposed to less heat their allowance can be smaller.

Side clearance or ring groove clearance is also provided for heat expansion, figure 3-10. Often 0.0025 inch is allowed for the top ring and 0.003 inch is allowed on the second and third rings.

Piston Pin or Wrist Pin

The piston pin is a precision ground steel pin that connects the piston and the connecting rod, figure 3-11. This pin can be solid or

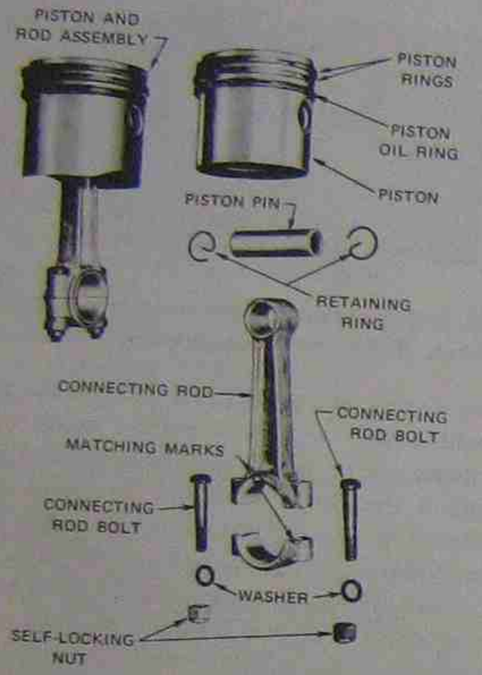


Fig. 3-11 Piston, piston pin, connecting rod, and associated parts for free-floating piston assembly (Courtesy Tecumseh Products Company)

hollow; the hollow piston pin has the advantage of being lighter in weight. Because piston pins are subjected to heavy shocks when combustion takes place, high-tensile strength steel is used. To keep noise at a minimum, the piston pin fits to a very close tolerance in the connecting rod. The piston pin does not rotate. It has a rocking motion similar to the action of the wrist when the wrist is moved back and forth, hence the name *wrist pin*. Heavy shocks, close tolerances, and the rocking motion make the lubrication of this part difficult. In most engines, lubricating oil is squirted or splashed on it.

Connecting Rod

The connecting rod connects the piston (with the aid of the piston pin) and the crankshaft, figure 3-12. Many small engines have cast aluminum connecting rods; larger engines can have steel connecting rods. Generally, the cross section of the connecting rod is an I-beam shape for strength. The lower end of the connecting rod is fitted with a cap. Both the lower end and the cap are accurately machined to form a perfect circle. This cap is bolted to the rod, encircling the connecting rod bearing surface on the crankshaft. Many connecting rods are fitted with replaceable bearings surfaces called rod bearings or inserts. These are used especially on heavy-duty or more expensive engines.

Crankshaft

The crankshaft is the vital part that converts the reciprocating motion of the piston into rotary motion. One end of the crankshaft has a provision for power takeoff (connecting accessory to use engine's power) and the other is machined to accept the flywheel.

Crankshafts are made of high-quality steel; they are carefully forged and then machined to close tolerances. Their bearing surfaces are large because they must accept a great amount of force. Since they revolve at high speeds, they must be well balanced. Figure 3-13 is an example of a single-throw crankshaft.

Figure 3-14 shows two types of small engine designs. Engines designed with *vertical* crankshafts are shown in figure 3-15. Vertical crankshafts are excellent for applications such as rotary power lawn mowers where the blade is bolted directly to the end of the crankshaft. Most wheeled applications such as motorbikes and go-carts use *horizontal* crankshaft engines which enable the power

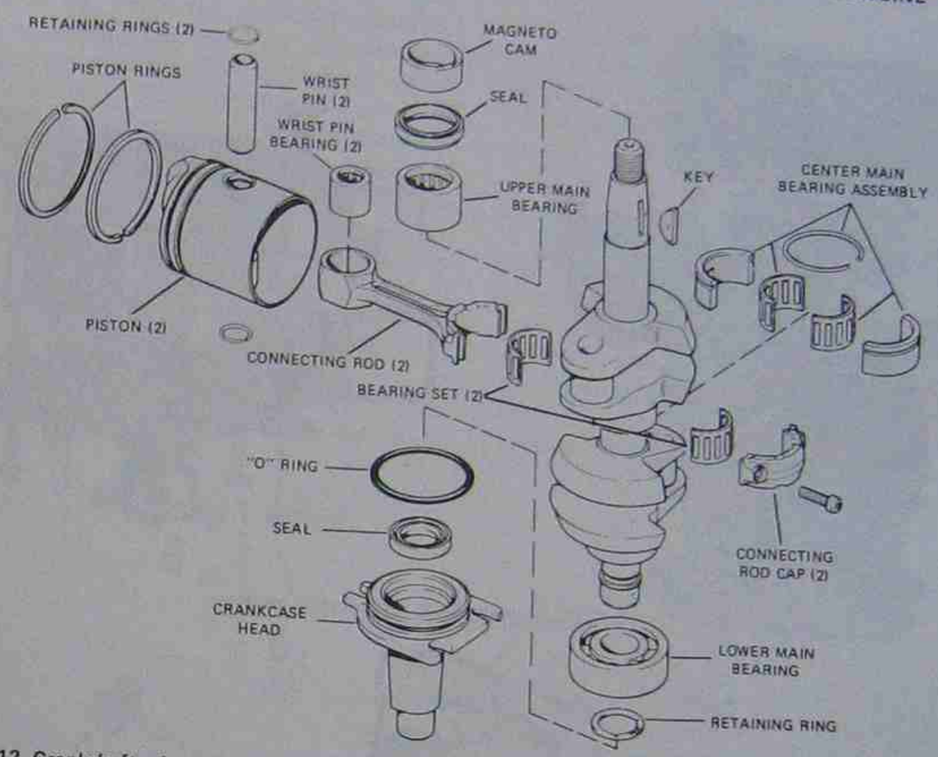


Fig. 3-12 Crankshaft, pistons, and connecting rod components – two-cycle, two-cylinder engine (note crankshaft)

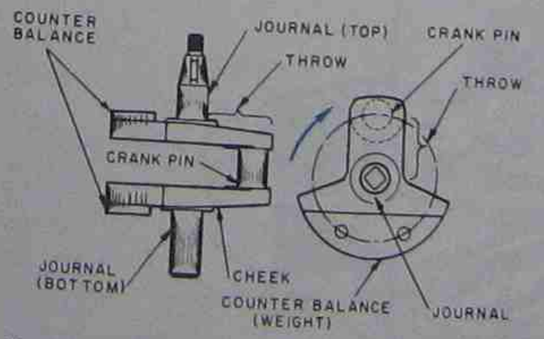


Fig. 3-13 Single-throw crankshaft: one crank pin for one cylinder

to be delivered to an axle through belts or chains. Multiposition engines such as chain saws are another variation. The crankshafts themselves are much the same but other changes in engine design are necessary to meet the requirements of crankshaft position. An engine can have clockwise or counterclockwise crankshaft rotation, depending upon its application and design.

Crankcase

The crankcase is the body of the engine. It houses the crankshaft and has main bearing

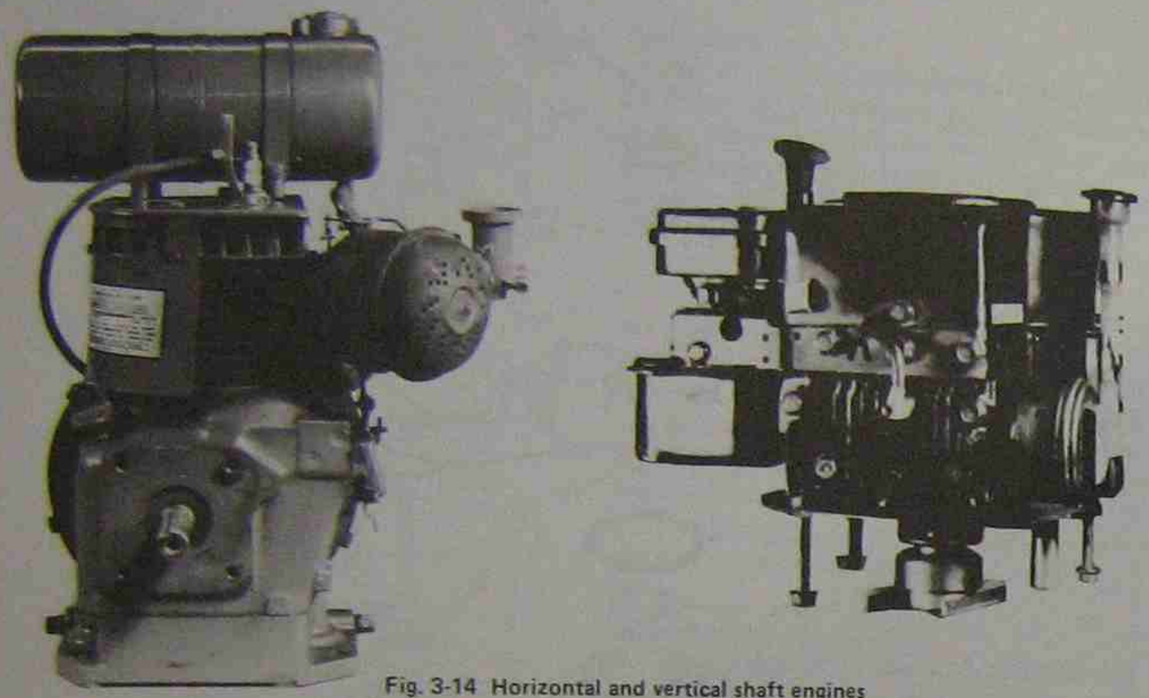


Fig. 3-14 Horizontal and vertical shaft engines

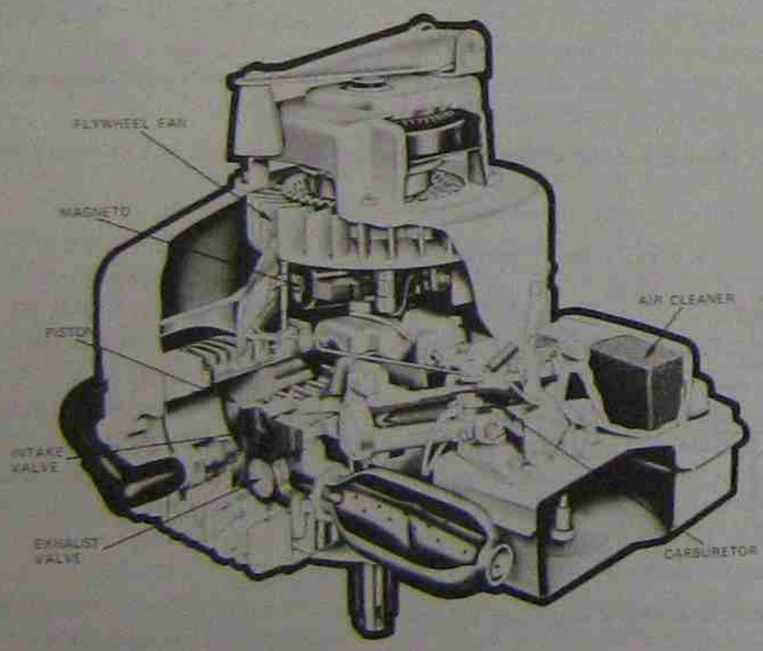


Fig. 3-15 Four-cycle engine with vertical shaft

surfaces on which the crankshaft revolves. The connecting rod, cam gear, camshaft, and lubrication mechanism are also located within the crankcase. The cylinder and bottom of the piston are exposed to the crankcase. On four-cycle engines a reservoir of oil is found within the crankcase. This lubricating oil is splashed, pumped, or squirted onto all the moving parts located in the crankcase. Figure 3-16 shows the components of a short block assembly (crankcase and its associated parts). A single-cylinder engine is illustrated in figure 3-17.

Generally the crankcase is made of cast aluminum for engines that are for light duty and especially where a lightweight engine is needed. Medium duty engines are die cast aluminum with a cast iron sleeve pressed into the aluminum. Crankcases for heavy duty engines are usually made of cast iron.

Flywheel

The flywheel is mounted on the tapered end of the crankshaft. A *key* keeps the two parts solidly together and they revolve as one part, figure 3-18. The key is also called a *shear pin* which acts as a safety device to protect the crankshaft in case of a sudden impact. (The slot that the key fits into is called the *keyway*.) The flywheel is found on all recipro-

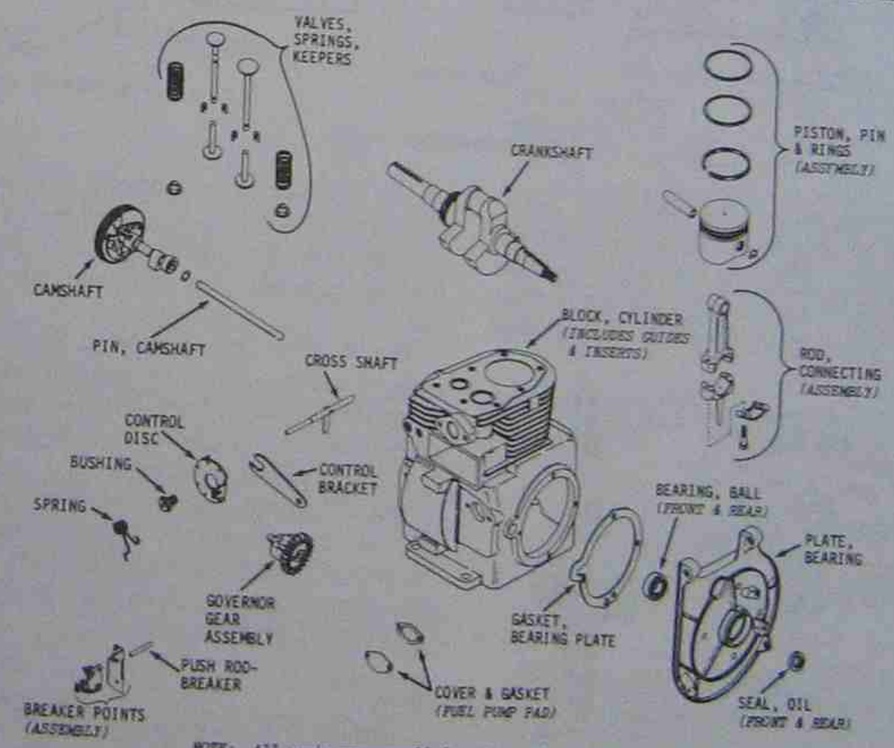


Fig. 3-16 Components of a short block assembly

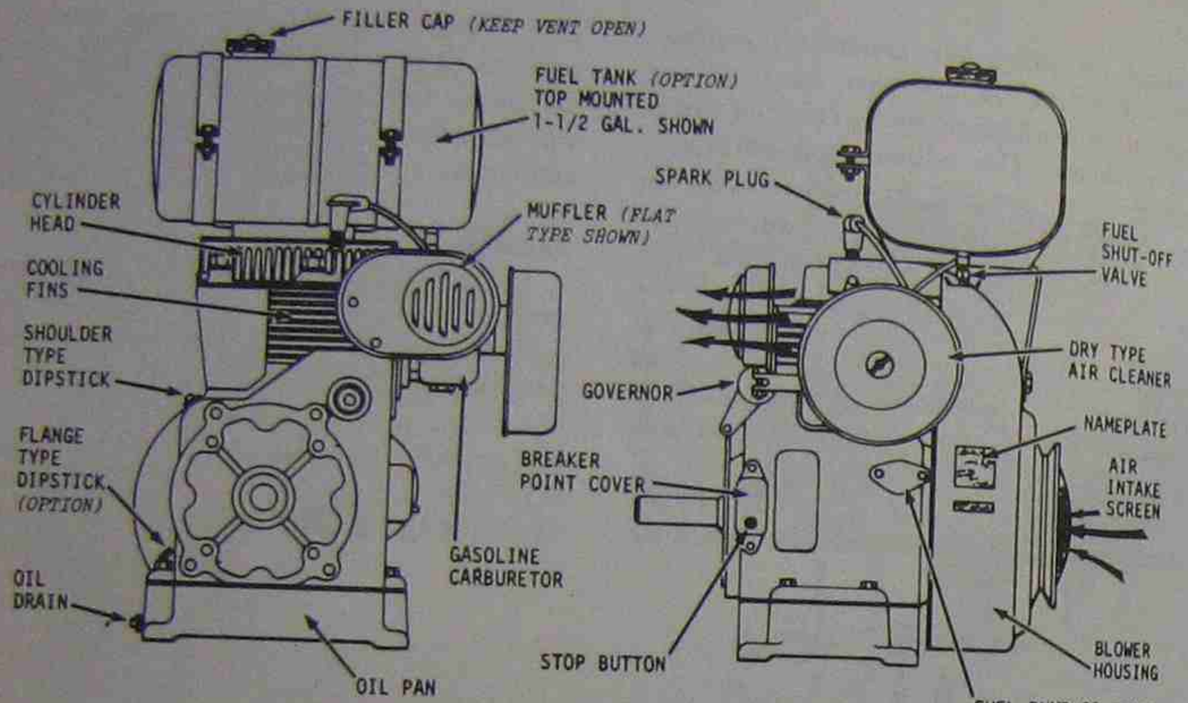


Fig. 3-17 Single-cylinder engine

cating piston engines. It is relatively heavy and helps to smooth out the operation of the engine. That is, after the force of combustion has pushed the piston down, the momentum of the flywheel helps to move the piston back up the cylinder. This tends to minimize or eliminate sudden jolts of power during combustion. The more cylinders the engine has, the less important this smoothing out action becomes.

The flywheel can also be a part of the engine's cooling system by having air vanes to scoop air as the flywheel revolves. This air is channeled across the hot engine by the cover or shroud, to carry away heat.

Most flywheels on small gasoline engines are part of the ignition systems; they have permanent magnets mounted in them. These permanent magnets are an essential part of the magneto ignition system.

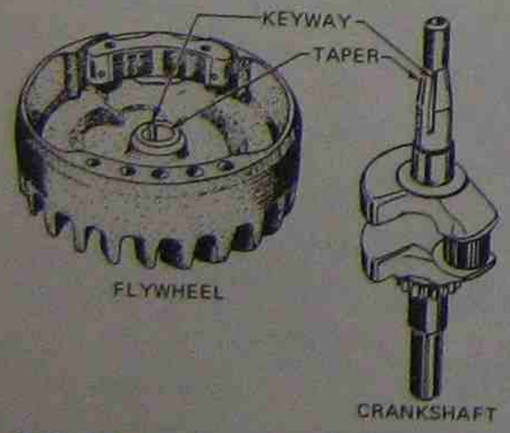


Fig. 3-18 A key locks the flywheel and crankshaft together

Valves

Figure 3-19 shows the parts of a valve. The most common valves are called *poppet valves*. With these valves, exhaust gases can be removed from the combustion chamber and new fuel mixture can be brought in. To accomplish this, the valve actually pops open and snaps closed. In the normal four-cycle combustion chamber there are two valves – one to let the exhaust out (exhaust valve) and one to allow the air/fuel mixture to come in (intake valve).

The two valves may look almost identical, but they are different. The exhaust valve must be designed to take an extreme amount of punishment and still function perfectly. Not only is it subjected to the normal heat of combustion (about 4500°F), but when it opens, the hot exhaust gases rush by it. When the valve returns to its seat, a small area touches, making it difficult for the valve's heat to be conducted away. This rugged valve opens and closes 1800 times a minute if the engine is operating at 3600 rpm. Exhaust valves are made from special heat-resisting alloys.

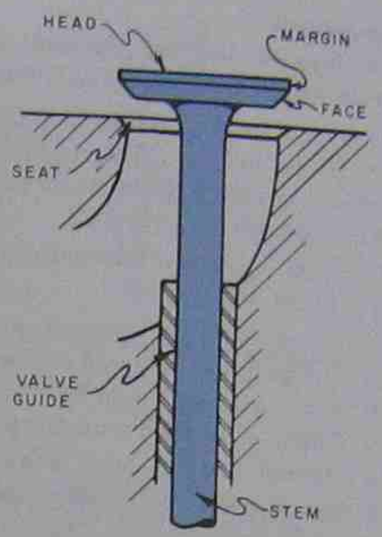


Fig. 3-19 A valve

Valves can be made to rotate a bit each time they open and close. This action tends to prevent deposits from building up at the valve seat and margin. In addition, rotation provides for even wear and exposure to temperatures which greatly increases the life of the valves, figure 3-20.

Intake values operate in the same manner as exhaust values except they are not subjected to the extreme heat conditions. Each time they open new fuel mixture rushes by, helping to cool the intake valve.

Operation of the valve requires the help of associated parts – the valve train and camshaft, figure 3-21. The valve train consists of the valve (intake or exhaust), valve spring, tappet or valve lifter, and cam. The valve spring closes the valve, holding it tightly against its seat. The valve lifter rides on the cam; there is a small clearance between it and the valve stem. Some valve lifter clearances are adjustable especially on larger and more expensive engines. The cam or lobe pushes up on the valve lifter; it, in turn, pushes up on the valve stem. The valve opens when the high spot on the cam lobe is reached. The opening and closing of the valves must be carefully timed in order to get the exhaust out at the correct time and the new fuel mixture in at the correct time.

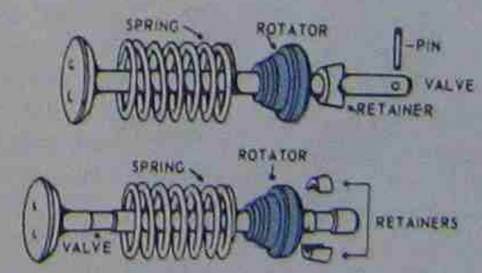


Fig. 3-20 "Rotocap" provides for even wear and long valve life

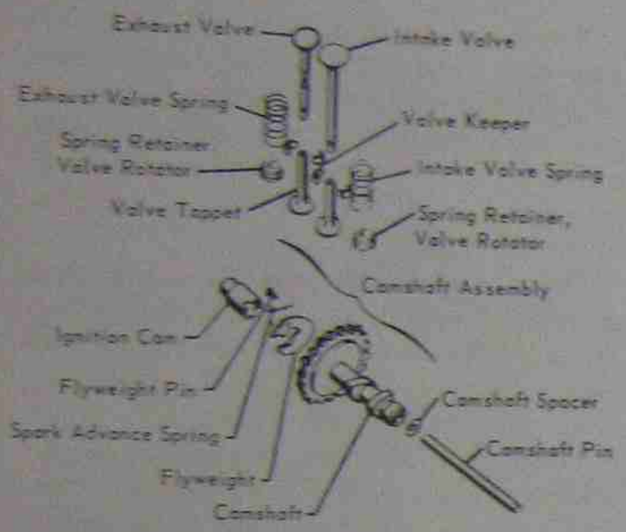


Fig. 3-21 Complete valve train and camshaft assembly

Valve Arrangement

Engines may be designed and built with one of several valve arrangements, as follows:

- *The L-head:* both valves open up on one side of the cylinder. This is the most common arrangement in small gasoline engines, figures 3-22 and 3-23.
- *The I-head:* both valves open down over the cylinder, figure 3-24.
- *The F-head:* one valve opens up and one valve opens down; both are on the same side of the cylinder, figure 3-25.
- *The T-head:* one valve is on one side of the cylinder and the other valve is on the opposite side; both valves open up, figure 3-26.



Fig. 3-22 L-head design used for most four-stroke cycle small engines

Camshaft

The camshaft and its associated parts control the opening and closing of the valves. The cams on this shaft are egg-shaped. As they revolve, their noses cause the valves to open and close. A tappet rides on each cam. When the nose of the cam comes under the tappet, the valve is pushed open admitting new fuel mixture or allowing exhaust to escape, depending on which valve is opened.

The camshaft is driven by the crankshaft. On four-cycle engines, the camshaft operates

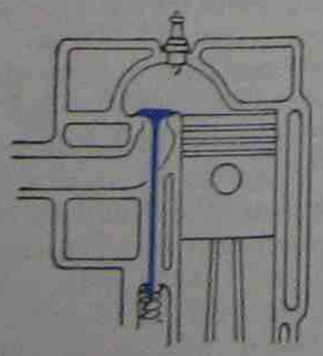


Fig. 3-23 L-head valve arrangement

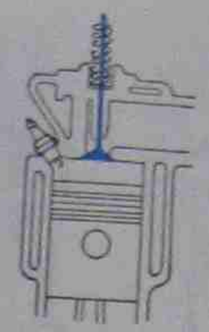


Fig. 3-24 I-head valve arrangement

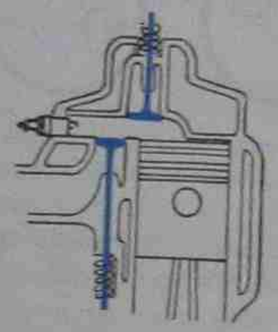


Fig. 3-25 F-head valve arrangement

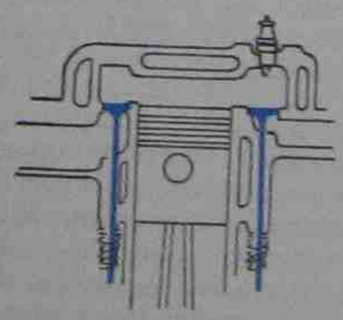


Fig. 3-26 T-head valve arrangement

at one-half the crankshaft speed. (If the engine is operating at 3400 rpm, the camshaft revolves at 1700 rpm.) The crankshaft and camshaft must be in perfect synchronization. Therefore, most engines have timing marks stamped or cut into the gears to ensure the correct reassembly of the gears, figure 3-27.

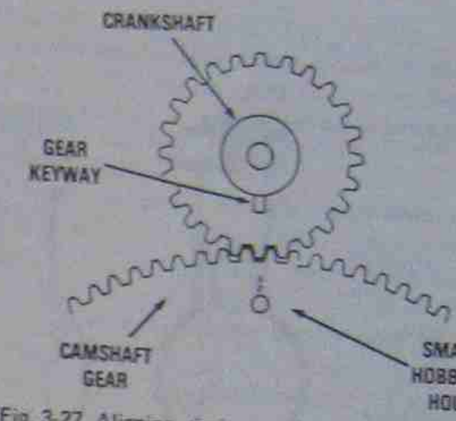


Fig. 3-27 Aligning timing marks on the crankshaft gear and camshaft gear. The larger camshaft gear revolves at one-half crankshaft speed.

FOUR-STROKE CYCLE OPERATION

All of these parts and many others must be assembled correctly if the gasoline engine is to operate properly. The most common method of engine operation is the four-stroke cycle. Most small gasoline engines as well as automobile engines operate on this principle. The four-stroke cycle engine is a very successful producer of power.

Four-stroke cycle means that it takes four strokes of the piston to complete the operating cycle of the engine, figure 3-28. The piston goes down the cylinder, up, down, and back up again to complete the cycle. This takes two revolutions of the crankshaft; each stroke is one-half revolution.

Intake is when the piston travels down the cylinder and fuel mixture enters the combustion chamber. Reaching the bottom of its stroke, the piston comes up on compression and the fuel mixture is compressed into the combustion chamber. Power comes when the fuel mixture is ignited, pushing the piston back down. The piston moves up once more

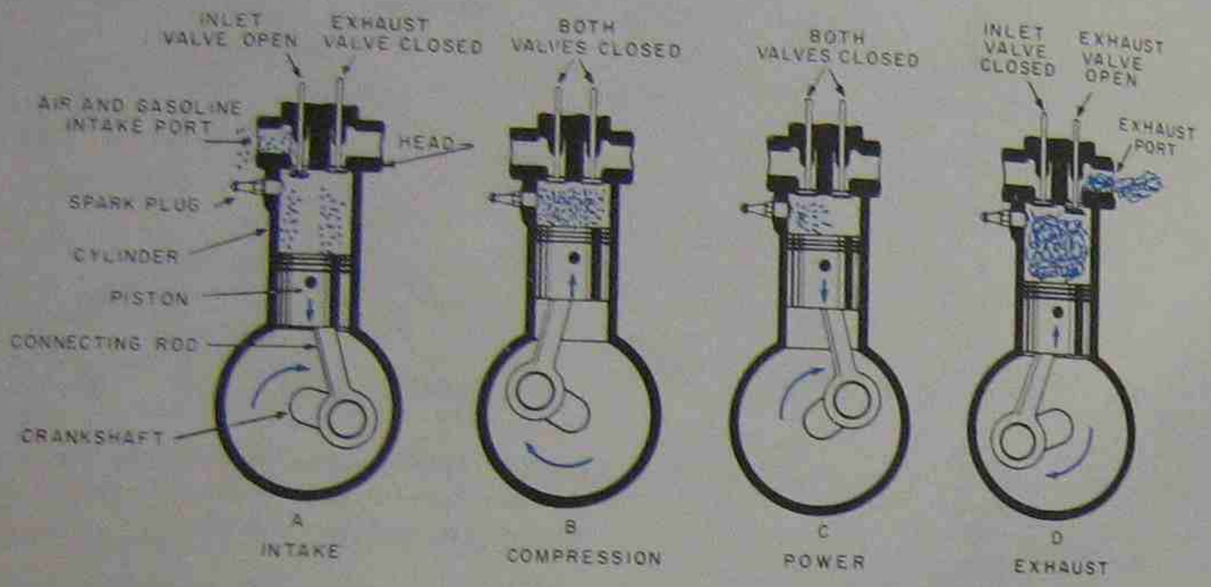


Fig. 3-28 The four-stroke cycle

pushing the exhaust gases out of the combustion chamber. This is exhaust. These four strokes complete the engine's cycle and require two revolutions of the crankshaft. As soon as one cycle is complete, another begins. If an engine is operating at a speed of 3600 rpm there are 1800 cycles each minute.

Intake Stroke

If the fuel mixture is to enter the combustion chamber, the intake valve must be open and the exhaust valve must be closed. With the intake valve open and the piston traveling down the cylinder, the fuel mixture rushes in easily. This is the *intake stroke.*

Pushing down on everything is an atmospheric pressure of 14.7 pounds per square inch (psi) at sea level. When the piston is at the top of its stroke there is normal atmospheric pressure in the combustion chamber. When the piston travels down the cylinder there is more space for the same amount of air and the air pressure is reduced; a partial vacuum is created. The intake valve opens and the normal atmospheric pressure rushes in to equalize this lower air pressure in the combustion chamber. The air/fuel mixture is actually pushed into the combustion chamber, even though it seems to be sucked in by the partial vacuum.

Compression Stroke

When the piston reaches the bottom of its stroke and the cylinder is filled with air/fuel mixture, the intake valve closes and the exhaust valve remains closed. The piston now travels up the cylinder compressing the fuel mixture into a smaller and smaller space. When the fuel mixture is compressed into this small space it can be ignited more easily and it expands very rapidly.

The term *compression ratio* applies to this stroke. *Compression ratio* is the ratio of the total cylinder volume when the piston is at the bottom of its stroke to the volume remaining when the piston is at the top of its stroke. If the piston compresses the fuel mixture into one-sixth of the original space, the compression ratio is 6:1, figure 3-29. An engine whose piston compresses the fuel mixture into one-eighth the original space has a compression ratio of 8:1. The higher the compression, the more powerful the force of combustion.

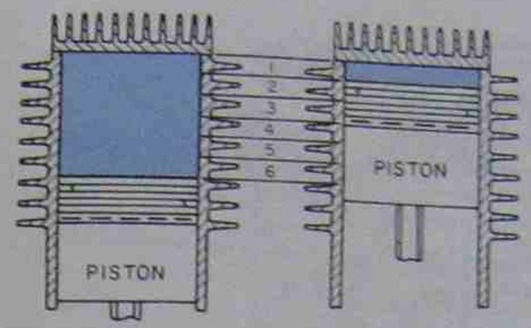


Fig. 3-29 An engine with a six-to-one compression ratio

Power Stroke

When the piston reaches the top of its stroke and the fuel mixture is compressed, a spark jumps across the spark plug igniting the fuel mixture. The fuel mixture burns very rapidly. The burning, expanding gases exert a great pressure in the combustion chamber. The combustion pressure is felt in all directions, but only the piston is free to react. The piston reacts by being pushed rapidly down the cylinder. This is the power stroke. *Power stroke* occurs when the rapidly burning fuel creates a pressure that pushes the piston down thus turning the crankshaft and producing usable rotary motion.

Both intake and exhaust valves must be closed for the power stroke. The force of combustion must not leak out the valves or blow-by the piston rings. Piston rings that fit properly prevent this. The cylinder head gasket and the spark plug gasket should be airtight. The power must be transmitted to the top of the piston and not lost elsewhere.

Exhaust Stroke

When the piston reaches the bottom of its power stroke, the momentum of the flywheel and crankshaft bring the piston back up the cylinder. This is the *exhaust stroke.* The exhaust valve opens, the intake valve remains closed, and the piston pushes the burned exhaust gases out of the cylinder and combustion chamber.

TWO-STROKE CYCLE OPERATION

Another common operating principle for gasoline engines is the two-stroke cycle engine, figure 3-30A. This engine is also very successful and in common use today, especially for outboard motors, chain saws, and lawn mowers, figure 3-30B. The two-stroke cycle engine is constructed somewhat differently from the four-stroke cycle engine. See figure 3-31, or a comparison of moving parts.

Two-stroke cycle means that it takes two strokes of the piston to complete the operating cycle of the engine.

The basic two-stroke cycle consists of a pumping action in the crankcase – high and low pressure caused by the movement of the piston up and down the cylinder. On a four-stroke cycle engine the crankcase plays no part in fuel induction but on a two-stroke cycle engine the crankcase is a vital part.

The two-stroke cycle starts with the piston moving up the cylinder as seen in figure 3-32. As the piston moves up the cylinder, a low pressure or partial vacuum is created in the crankcase; there is a larger space for the

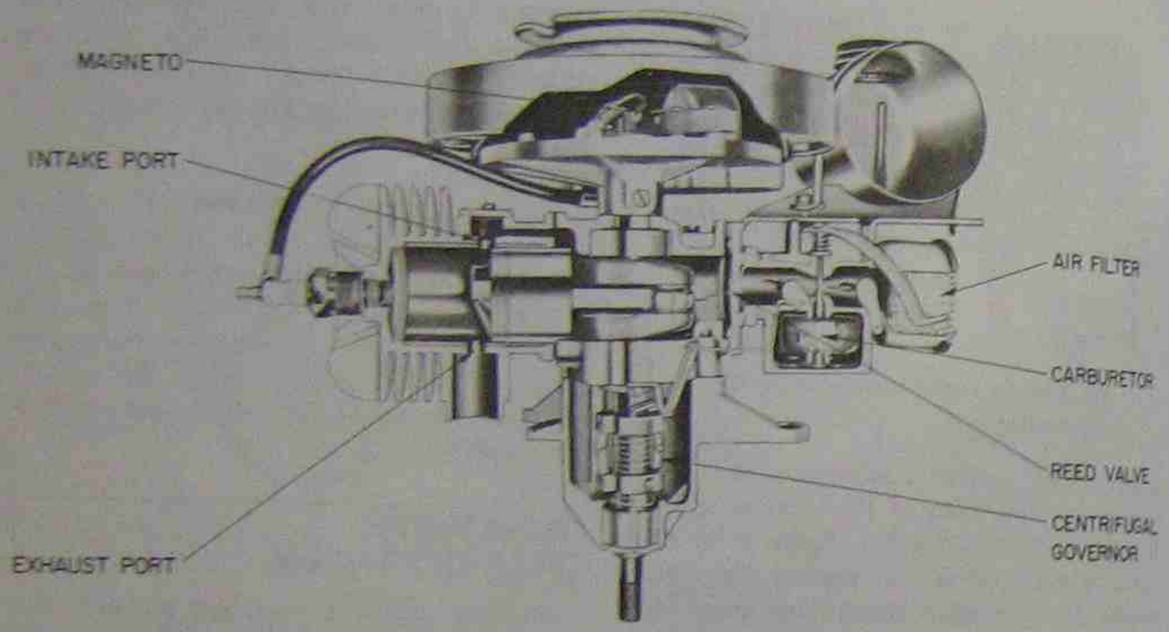


Fig. 3-30A Two-cycle engine



Fig. 3-30B The lightweight and constant lubrication features of a two-cycle engine make it ideal for chain saws. (Photo courtesy of John Deere and Company)

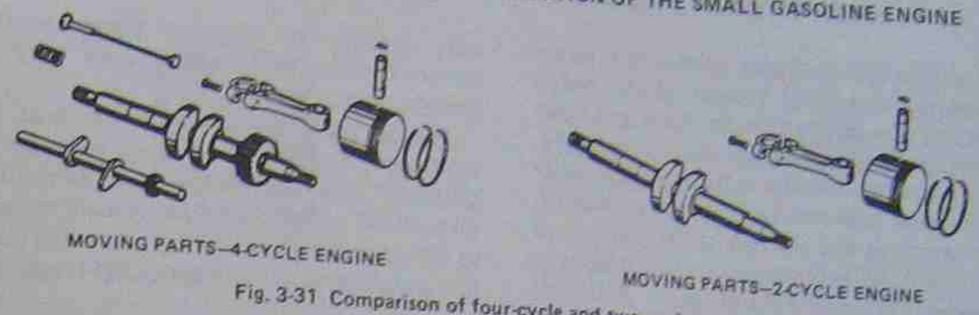


Fig. 3-31 Comparison of four-cycle and two-cycle engines

same amount of air. The greater atmospheric pressure outside rushes through the carburetor pushing open the springy reed valve, filling the crankcase with fuel mixture. When the piston is at the top of its stroke, the pressure in the crankcase and the atmospheric pressure are just about equal and the leaf valve springs shut.

As the piston moves back down the cylinder, the fuel mixture trapped in the crankcase is put under pressure. The reed valve can only open in the opposite direction. Near the bottom of the piston's stroke the intake transfer ports are uncovered by the piston. The pressurized fuel mixture in the crankcase now has a path to escape into the cylinder and it rushes into the cylinder where it can be compressed and burned.

The fuel charge, now in the cylinder, is compressed as the piston moves up the cylinder. A spark ignites the fuel mixture and the great pressure of combustion pushes the piston rapidly down the cylinder. As the piston nears the bottom of its stroke the exhaust ports begin to uncover and the exhaust gases, which are still hot and under pressure, start to rush through the exhaust ports and out of the engine.

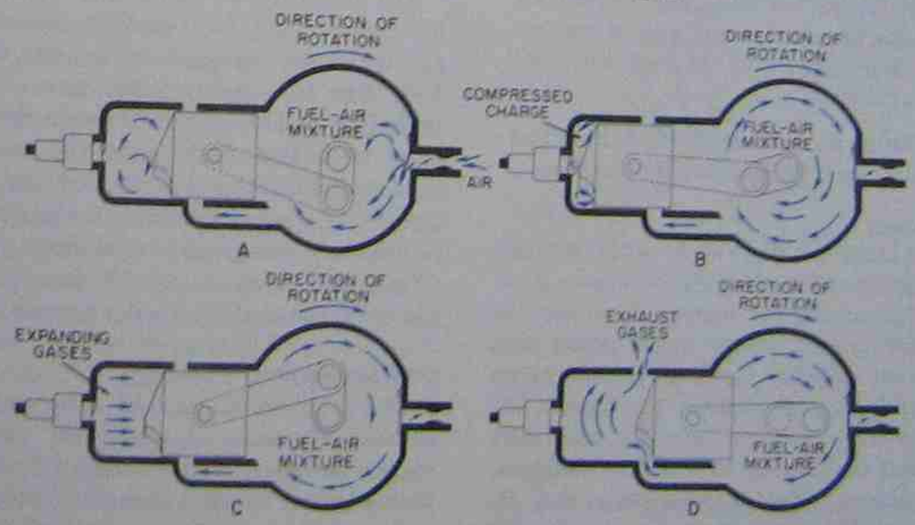


Fig. 3-32 Two-cycle engine operation

Just after the exhaust ports begin to uncover, the downward motion of the piston uncovers the intake transfer ports and compressed fuel mixture from the crankcase begins to rush in. Exhaust is leaving the cylinder at the same time new fuel mixture is entering. The incoming fuel mixture is directed toward the top of the cylinder and its action helps to scavenge out the exhaust gases. With the transfer of fuel complete, the piston moves up covering the intake transfer ports and the exhaust ports thus trapping the fuel mixture for compression.

The cycle is then repeated. If the engine operates at 4000 rpm, the cycle is completed 4000 times each minute. There is a power stroke for each revolution of the crankshaft.

To summarize the two-stroke cycle operation:

- Air/fuel mixture in the crankcase is put under pressure when the piston is going down on the power stroke.
- At the bottom of the power stroke, exhaust gases leave and air/fuel mixture is transferred from the crankcase to the cylinder.
- During the compression stroke, air/fuel mixture is brought into the crankcase.

Crankcase

The crankcase of a two-stroke cycle engine is designed to be as small in volume as possible. The smaller the volume, the greater the pressure created as the piston comes back down the cylinder. Crankcase pressure moves the fuel mixture through the engine. The greater the crankcase pressure, the more efficient the transfer of fuel from the crankcase through the transfer ports into the cylinder. The crankcase must be air tight. The only openings are the reed valves and the intake transfer ports which open only at specific times.

Moving parts in the crankcase must be lubricated; however, there is no reservoir of oil in the crankcase. Instead, the lubricating oil is mixed with the gasoline. A small amount of oil enters the crankcase each time the gasoline and air-fuel mixture enters the crankcase.

Intake Transfer Ports and Exhaust Ports

Intake transfer ports and exhaust ports are holes drilled in the cylinder wall which allow exhaust gases to escape and new fuel mixture to enter from the crankcase. The ports are located near the bottom of the cylinder and are covered and uncovered by the piston. By using ports, many parts seen in the four-cycle engine are eliminated: the valves, tappets, valve springs, cam gears, and camshaft. The remaining major moving parts are the piston, connecting rod, and crankshaft.

Piston (Cross Scavenged)

The piston still serves the same function in the cylinder, but for two-cycle engines the top is usually designed differently, figure 3-33. The two-stroke cycle pistons have a contoured top. On the intake side there is a sharp deflection that sends the incoming air/fuel mixture to the top of the cylinder. On the exhaust side there is a gentle slope so that exhaust gases have a clear path to escape. The loop scavenged two-cycle engine does, however, have a flat top piston.

Loop Scavenging

The loop scavenged two-cycle engine is basically the same as any other two-cycle engine. However, it does not need the contoured piston of the cross scavenged design because it does not have to deflect incoming



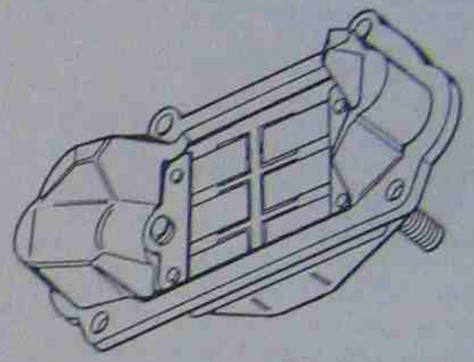
Fig. 3-33 A piston for a two-cycle engine showing the exhaust side and the intake side

gases. The difference is that the intake ports are drilled into the cylinder walls at an angle which aims the incoming fuel mixture toward the top of the cylinder. Usually there are two pairs of intake ports angling in from the sides directing the fuel mixture to the top of the cylinder around and back through the center of the cylinder to scavenge out the last of the exhaust through the exhaust ports. Loop scavenging provides a more complete removal of exhaust gases and produces somewhat more horsepower per unit weight.

Reed or Leaf Valves

Reed, or leaf valves, are located between the carburetor and crankcase. The valve itself is a thin sheet of springy alloy steel. The valve is pushed open by atmospheric pressure which allows fuel mixture to enter the crankcase; it springs closed to seal the crankcase. This occurs when a low pressure is created in the crankcase by the action of the piston moving up the cylinder. There may be only one reed valve or there may be several reed valves working together. The majority of small gasoline engines operating on the two-cycle principle use reed valves even though it is possible to use a poppet valve in the crankcase. Several kinds of reed plates are shown in figure 3-34.

Not all two-cycle engines use reed or leaf valves. Some engines have the compression and power strokes with intake and exhaust taking place between the two but use different valves to achieve the result.



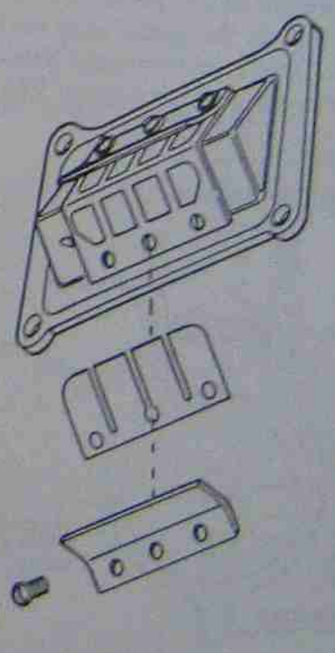


Fig. 3-34 Reed plates (Courtesy Tecumseh Products Company)

Rotary Valve

Some two-cycle engines use a rotary value for admitting fuel mixture, figure 3-35. The rotary valve is a flat disc with a section removed; it is fastened to the crankshaft. The rotary valve normally seals the crankcase. However, as the piston nears the top of its stroke and there is a slight vacuum in the crankcase, the valve is rotated to its open position. This allows fuel mixture to travel from the carburetor through the open valve and into the crankcase.

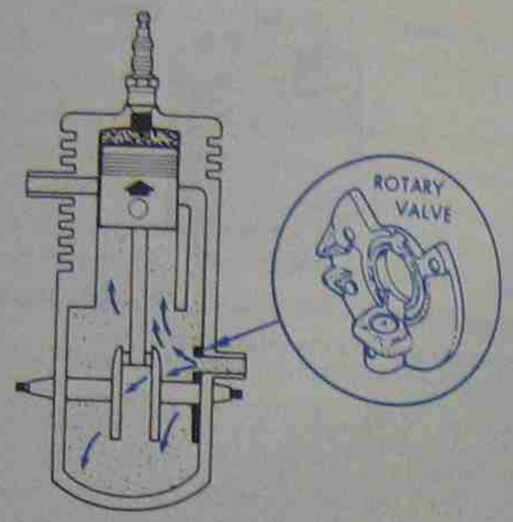


Fig. 3-35 Rotary valve

Third Port Design

Third port design has the regular exhaust ports and intake ports on the cylinder wall but in addition it has a third port in the cylinder wall, figure 3-36. This third port is for admitting fuel mixture to the crankcase. The bottom of the piston skirt uncovers the third port as the piston nears the top of its stroke. The piston's upward travel creates a low pressure in the crankcase. When the port is uncovered, air/fuel mixture rushes into the crankcase. As the piston comes down on the power stroke, the port is sealed off and the trapped mixture is pressurized. It is now ready for transfer through the intake ports into the cylinder.

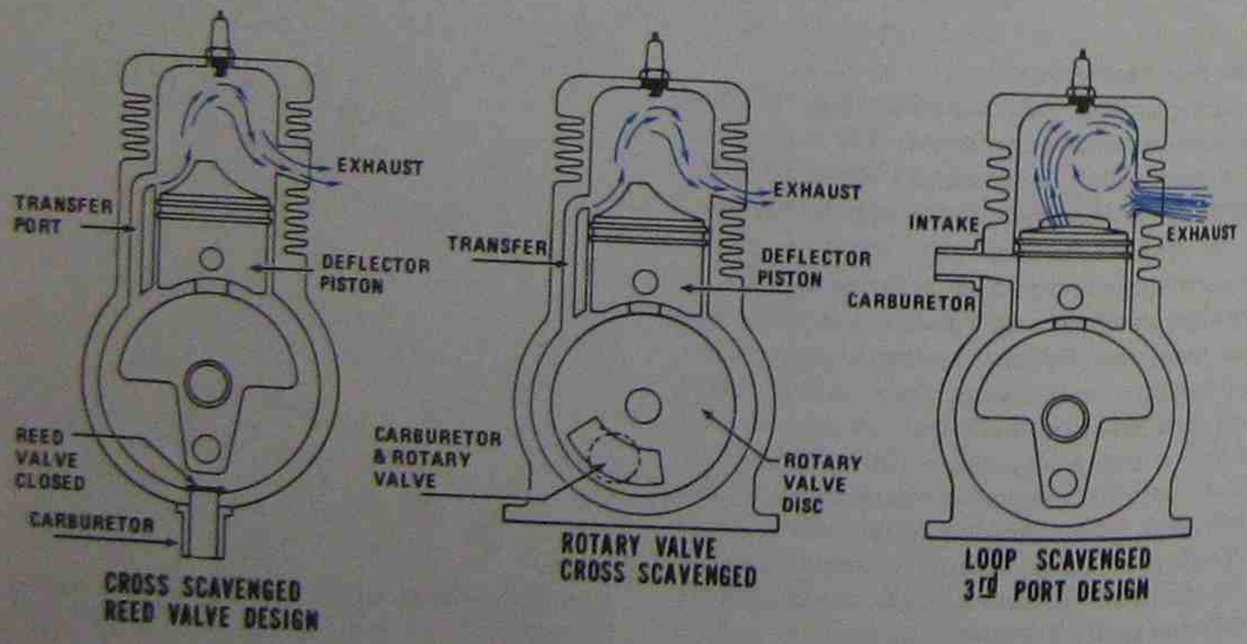


Fig. 3-36 Basic designs of two-cycle spark ignition engines

Poppet Valves

There are some two-cycle engines that use poppet valves to admit new fuel mixture into the crankcase. These poppet valves may be spring loaded and operated by differences in crankcase pressure. They open when the partial vacuum in the crankcase overcomes a slight spring tension. This happens when the piston is on its upward stroke. With the poppet valve open, fuel mixture rushes into the crankcase. The poppet valve may also be operated by cam action. In this case a crankshaft cam opens the valve for the piston's upward stroke.



Fig. 3-37 An all-terrain-vehicle has a powerful small gas engine.

REVIEW QUESTIONS

1. Explain the term *internal combustion.*
2. List the most essential moving parts of the four-stroke gasoline engine.
3. List the most essential stationary parts of the four-stroke gasoline engine.
4. Define the terms: bore, stroke, TDC, and BDC.
5. What purpose does a gasket serve?
6. What is a combustion chamber?
7. What two purposes do piston rings serve?
8. What is the function of the crankshaft?
9. What parts do the connecting rod and wrist pin work with?
10. What three things does the flywheel accomplish?
11. What does a key and keyway do?
12. Explain how the valves operate.
13. Explain what a valve lifter does.
14. Prepare a sketch of a cam.

15. On a four-cycle engine, at what speed does the camshaft revolve relative to the crankshaft?

Four-Stroke Cycle Review Questions

1. Explain what causes the fuel mixture to rush into the cylinder during the intake stroke.
2. What is accomplished on the compression stroke?
3. Explain the power stroke.
4. How many revolutions are required for the complete cycle?

Two-Stroke Cycle Review Questions

1. What parts are replaced by the intake and exhaust ports?
2. What are ports?
3. How are some two-stroke cycle pistons different from four-stroke cycle pistons?
4. Explain the action of the reed or leaf valves.
5. Explain how intake and exhaust take place on a two-cycle engine.
6. What part does the crankcase play in regard to the fuel mixture?
7. How many revolutions are required for the complete cycle?
8. What is the advantage of loop scavenging?

Unit 4 Fuel Systems, Carburetion, and Governors

OBJECTIVES After completing this unit, the student should be able to:

- Identify the basic parts of a fuel system and explain the function of each part.
- Identify the basic parts of the carburetor and explain the function of each.
- Discuss the theory of carburetor operation.
- Discuss several common types of carburetors.
- Discuss how gasoline vaporizes and burns and common problems such as vapor lock, detonation and preignition.
- Identify the basic parts of air vane and mechanical governors and explain how they work.
- Adjust the carburetor for maximum power and efficiency.
- Adjust the governed speed and discuss the action of the governor on the throttle.

The fuel system must maintain a constant supply of gasoline for the engine under all operating speeds and conditions. The carburetor must correctly mix the gasoline and air together to form a combustible mixture which burns rapidly when ignited in the combustion chamber.

A typical fuel system contains a *gasoline tank* (reservoir for gasoline); a *carburetor* (mixing device for gasoline and air); the *fuel line* (tubes made of rubber, copper, or steel through which the gasoline passes from the gas tank to the carburetor); and an *air cleaner* (device for filtering air brought into the carburetor), figure 4–1. In addition, the system may have a *shutoff valve* (valve at the gas tank that can cut off the gasoline supply when the engine is not in use), figure 4–2, a *fuel pump*

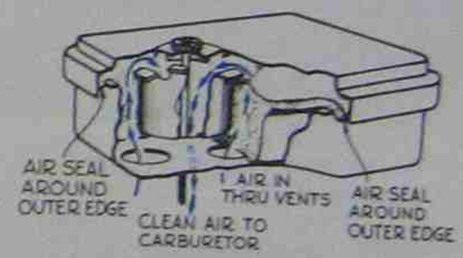


Fig. 4-1 Air cleaner

(pump that supplies the carburetor with a constant supply of gasoline); a *sediment bowl* (small glass bowl attached to the fuel line where dirt and other foreign matter can settle out), figure 4–3, and a *strainer* (fine screen in the gas tank to prevent leaves and dirt from entering the fuel line).

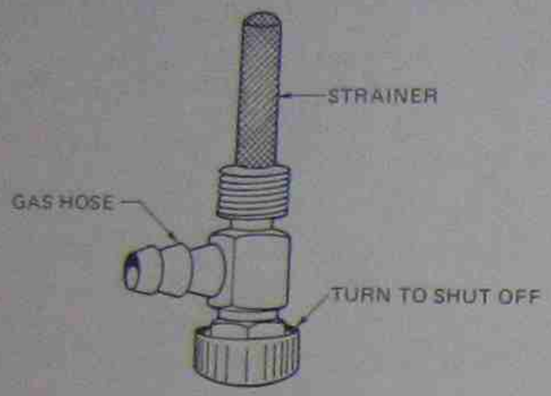


Fig. 4-2 Fuel shutoff valve

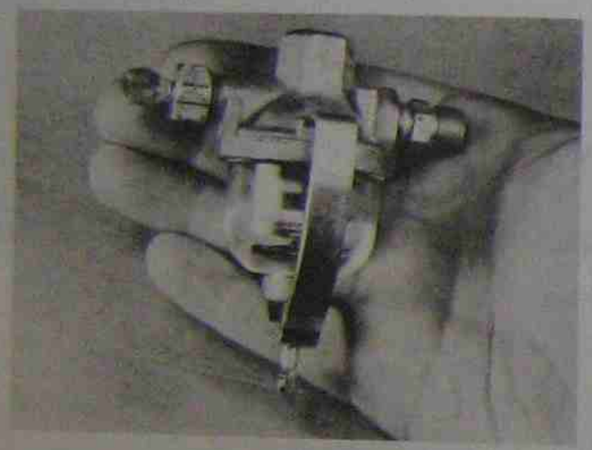


Fig. 4-3 Sediment bowl with built-in fuel shut-off valve

It should be noted that not all fuel systems contain all eight of the basic parts. Shut-off valves, sediment bowls, fuel pumps, and air cleaners are not common to all engines.

A constant supply of gasoline must be available at the carburetor. To provide this supply, four systems are in common use today. These systems are the suction system, gravity system, fuel pump system, and pressurized tank system.

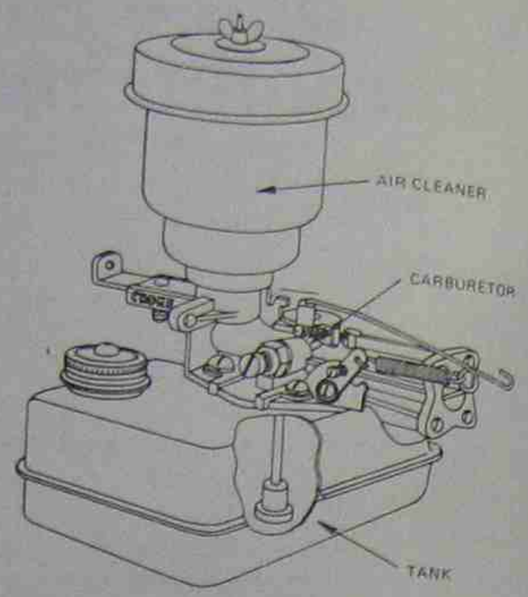


Fig. 4-4 Suction feed fuel system

SUCTION SYSTEM

The suction system is the simplest fuel system, figure 4–4. With this system, the gas tank is located below the carburetor and the gasoline is pushed up into the carburetor. However, the gas tank cannot be very far away from the carburetor or the carburetor action will not be strong enough to allow the gasoline to be pushed from the tank.

GRAVITY SYSTEM

With the gravity system the gas tank is located above the carburetor and the gasoline runs downhill to the carburetor, figure 4–5. To prevent gasoline from continuously pouring through it, the carburetor has incorporated a float and float chamber. The *float bowl* provides a constant level of gasoline without flooding the carburetor. When gasoline is used, the float goes down, opening a valve to admit more gasoline to the float bowl. The float rises



Fig. 4-5 Gravity feed fuel system

and shuts off the gasoline when it reaches its correct level. In actual practice the float and float valve do not rapidly open and close but assume a position allowing the correct amount of fuel to constantly enter the float chamber, figure 4–6. If the engine is speeded up, a new position is assumed by the float and float valve supplying an increased flow of gasoline.

FUEL PUMP SYSTEM

On many engines it is necessary to place the gas tank some distance from the carburetor. Therefore, the fuel must be brought to the carburetor by some means other than gravity or suction. One method is by using a

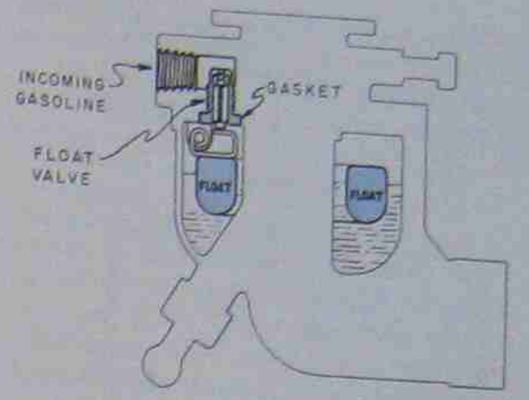


Fig. 4-6 Cutaway of a carburetor showing float and float valve

fuel pump. The automobile engine uses a fuel pump. The outboard motor with a remote fuel tank is a good example of a smaller engine that commonly uses a fuel pump.

The fuel pump used on many two-stroke cycle outboard motors is quite simple. The fuel pump consists of a chamber, inlet and discharge valve, a rubber diaphragm, and a spring. It is operated by the crankcase pressure. As the piston goes up, low pressure in

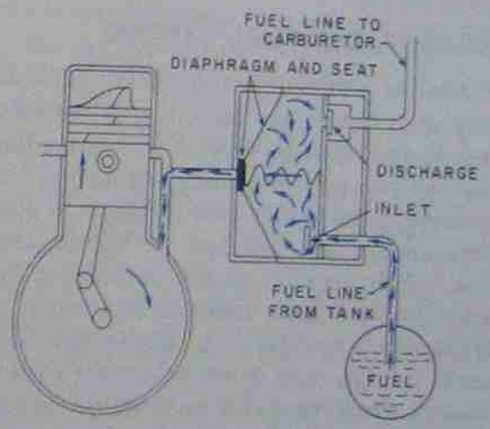


Fig. 4-7 Low pressure in the crankcase allows the fuel chamber to be filled.

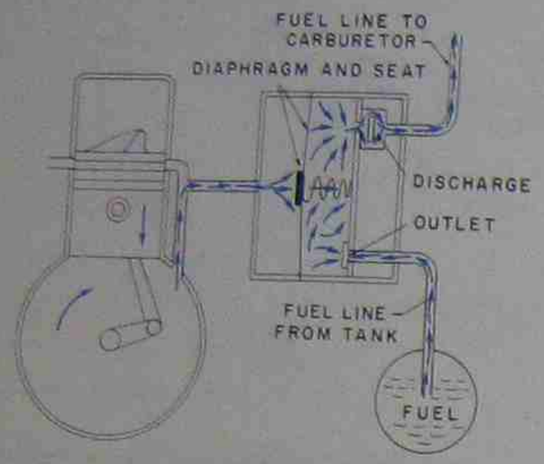


Fig. 4-8 High pressure in the crankcase forces the trapped fuel onto the carburetor.

the crankcase pulls the diaphragm toward the crankcase bringing gasoline through the inlet valve into the fuel chamber, figure 4–7. As the piston comes down, pressure in the crankcase pushes the diaphragm away from the crankcase. When this happens, the intake valve closes and the discharge valve opens allowing the trapped fuel to be forced to the carburetor, figure 4–8.

PRESSURIZED FUEL SYSTEM

Another method for forcing fuel to travel long distances to the carburetor is the pressurized fuel system, figure 4–9. This method is sometimes used with outboard motors. Engines using this system have two hoses or lines between the gas tank and the engine. One line brings gasoline to the carburetor; the other line brings air under pressure from the crankcase to the gas tank. If this method is used, the gas tank must be airtight so that enough air pressure can build up to force the gasoline to flow to the carburetor.

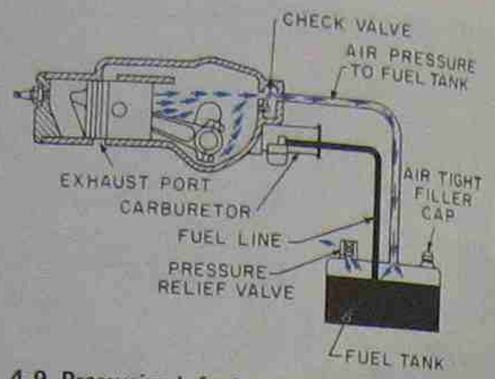


Fig. 4-9 Pressurized fuel systems can be found on some outboard engines.

THE CARBURETOR

The carburetor must prepare a mixture of gasoline and air in the correct proportions for burning in the combustion chamber, figures 4–10 and 4–11. The carburetor must function correctly under all engine speeds, under varying engine loads, in all weather conditions, and at all engine temperatures. To meet all these requirements, carburetors have many built-in parts and systems. Before studying the carburetor's operation in detail, an examination of the basic carburetor parts and their functions is helpful.

Throttle. The throttle controls the speed of the engine by controlling the amount of fuel mixture that enters the combustion chamber by regulating the air flow. The more fuel mixture admitted, the faster the engine speed.

Choke. The choke controls the air flow into the carburetor. It is used only for starting the engine. In starting the engine, the operator closes the choke, cutting off most of the engine's air supply. This produces a *rich mixture* (one containing a higher percentage

of gasoline) which ignites and burns readily in a cold engine. As soon as the engine starts, the choke is opened.

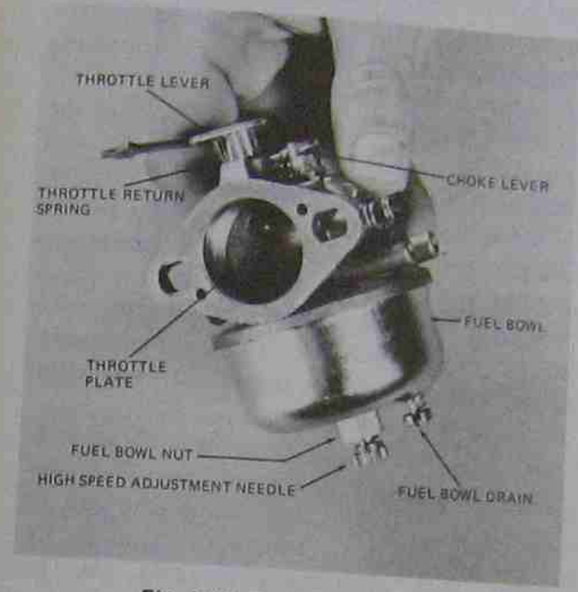


Fig. 4-10 Typical carburetor

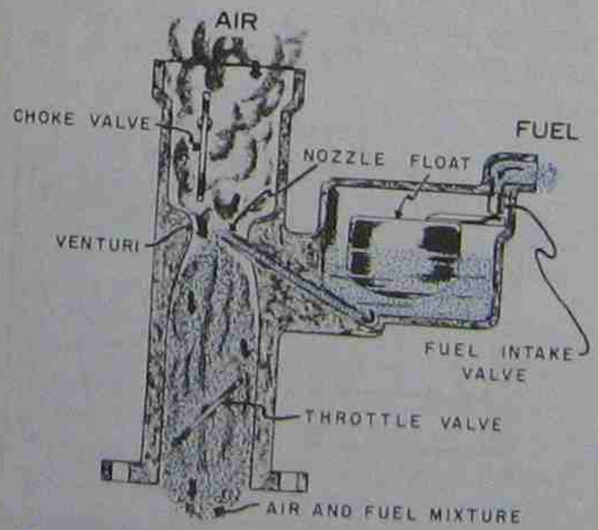


Fig. 4-11 Cross section of a simplified carburetor

Needle Valve. The needle valve controls amount of gasoline that is allowed to pass of the carburetor into the engine, fi 4–12. It controls the richness or leanness the fuel mixture.

Idle Valve. The idle valve also controls amount of gasoline that is available to carburetor but it functions only at low spe or idling. Some carburetors have what called a *slow-speed needle valve* which p forms basically the same job as the idle val

Float and Float Bowl. The float and flo bowl are found on all carburetors except t suction-fed carburetor and diaphragm carbur tors. The float and float bowl maintain constant gasoline level in the carburetor.

Venturi. The venturi is a narrow section o the carburetor that has a smaller cross-section al area for the air to flow through. In the ven turi, the gasoline and air are brought togethe and begin to mix.

Jets. Carburetor jets are small opening through which gasoline passes within the carburetor.

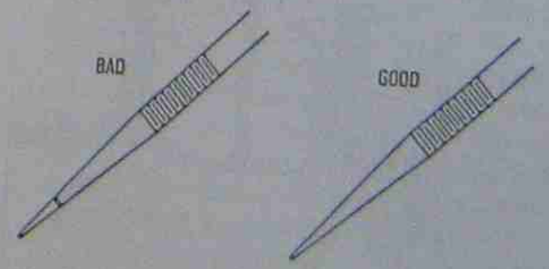


Fig. 4-12 Needle valves (Courtesy Tecumseh Products Company)

CARBURETOR OPERATION

In the beginning, air flows through the carburetor because there is a partial vacuum or low pressure in the combustion chamber as the piston travels down the cylinder. One usually thinks of the air being sucked into the engine by the piston action. Atmospheric pressure outside the engine actually pushes the air through the carburetor to equalize the lower pressure that is in the combustion chamber.

Air flows rapidly through the carburetor as the piston moves down. In the carburetor the air must pass through a constriction called the venturi, figure 4–13. For the same amount of incoming air to pass through this smaller opening, the air must travel faster and this it does. Here a principle of physics comes into use: the greater the velocity of air passing through an opening, the lower the static air pressure exerted on the walls of the opening. The venturi thus creates a low-pressure area within the carburetor, figure 4–14.

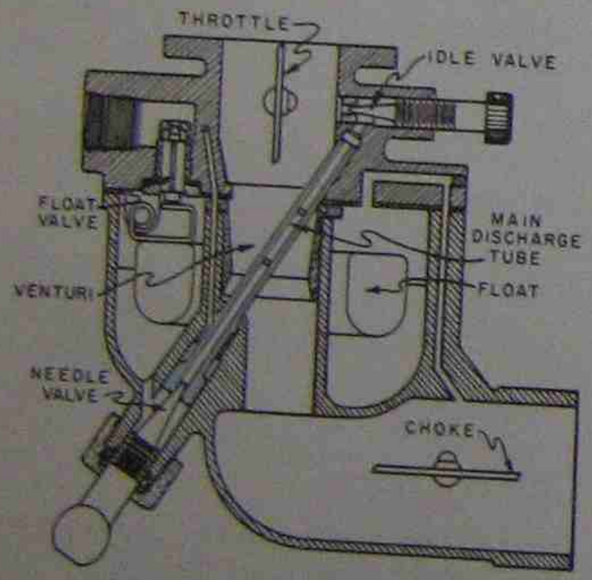


Fig. 4-13 A gravity fed carburetor

The principle of the airfoil is also used to gain lower pressure conditions in the venturi. A fuel supply tube or jet is placed in the venturi section. The action of the incoming air causes a high pressure on the front of the jet but a very low pressure on the back of the jet. Gasoline is available in this jet and streams out of the jet because a low-pressure area has been created by the action of the venturi and the airfoil, and because the gasoline is under atmospheric pressure which is greater. Greater pressure pushes the gasoline out of the discharge jet into the airstream. See figure 4–15 for a simplified illustration of carburetor operation.

As gasoline streams into the airflow, it is mixed thoroughly with the air. The best mixture of gasoline and air is fourteen or fifteen parts of air to one part of gasoline, by weight. This air-to-gasoline ratio can be changed for different operating conditions; heavy load and fast acceleration require more gasoline (richer mixture). The needle valve is used to change this ratio; it controls the

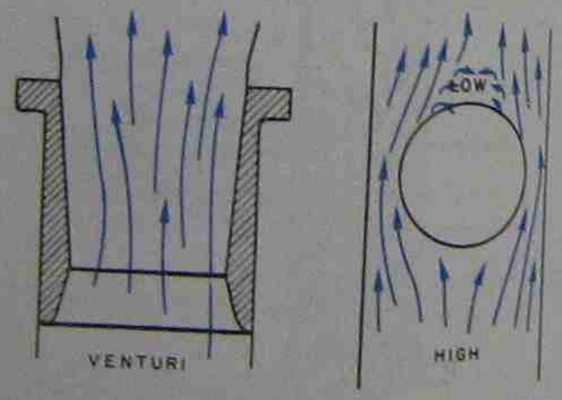


Fig. 4-14 (A) The venturi creates a low pressure in the carburetor. (B) The principle of the air foil also helps create a low pressure.

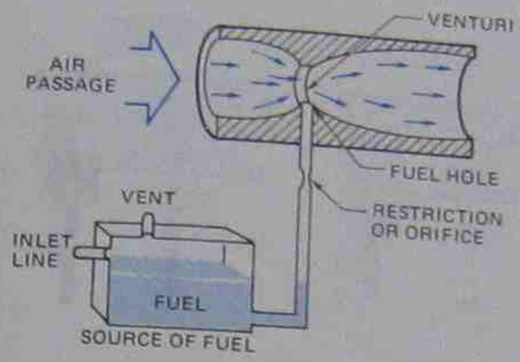


Fig. 4-15 Simplified carburetor operation

amount of gasoline that is available to be drawn from the discharge jet.

The throttle, or "butterfly" valve, is mounted on a shaft beyond the venturi section. The operator of the engine controls its setting to regulate the engine speed. When the throttle valve is wide open it does not restrict the flow of air; air flows easily through the carburetor and the engine is operating at its top speed. As the operator closes the throttle, the flow of air is restricted. A smaller amount of air can rush through the carburetor, therefore, the air pressures at the venturi section are not as low and less gasoline streams from the discharge holes. With less fuel mixture in the combustion chamber, the piston is pushed down with less force during combustion; power and speed are reduced.

The ratio of air to fuel remains about the same through the different throttle settings. However, when the throttle is closed and the engine begins to idle, very little air is drawn through the carburetor and the difference between atmospheric pressure and venturi air is slight. Little gasoline streams from the discharge jet. In fact, the mixture of gasoline is so lean that a special idling device must be built into the carburetor to provide a richer mixture for idling.

In some carburetors, the main discharge jet is continued past the venturi section to the area of the throttle. It discharges fuel into a small well and jet that are behind the throttle when it is closed. The air pressure behind the throttle is very low. Therefore, gasoline streams from the idle jet readily and mixes with the small amount of air that is coming through the carburetor and a rich fuel mixture is provided for idling. A threaded needle valve called the *idle valve* controls the amount of gasoline that can flow from the idle jet. Many carburetors use the air bleed principle to help atomize the gasoline and to make the needle valve easier to adjust. See figure 4–16 for an illustration of these conditions.

When a cold engine is to be started, an extremely rich mixture of gasoline and air must be provided if the engine is to start easily. The choke provides this rich mixture, figure 4–17. The choke is a plate, similar to the throttle, placed in the air horn before the venturi section. For starting, the choke is closed, shutting off most of the carburetor's air supply. When the engine is turned over slowly, usually by hand, little air is drawn through the carburetor. The air pressure within the carburetor is very low and gasoline streams from the main discharge jet, mixing with the air that does get by the choke. As soon as the engine starts, the choke is opened. The fuel mixture provided when the engine is choked is so rich that all the gasoline may not vaporize with the air and raw liquid gasoline may be drawn into the combustion chamber. Continued operation with the choke closed can cause crankcase dilution (the raw gasoline seeps into the crankcase diluting the lubricating oil).

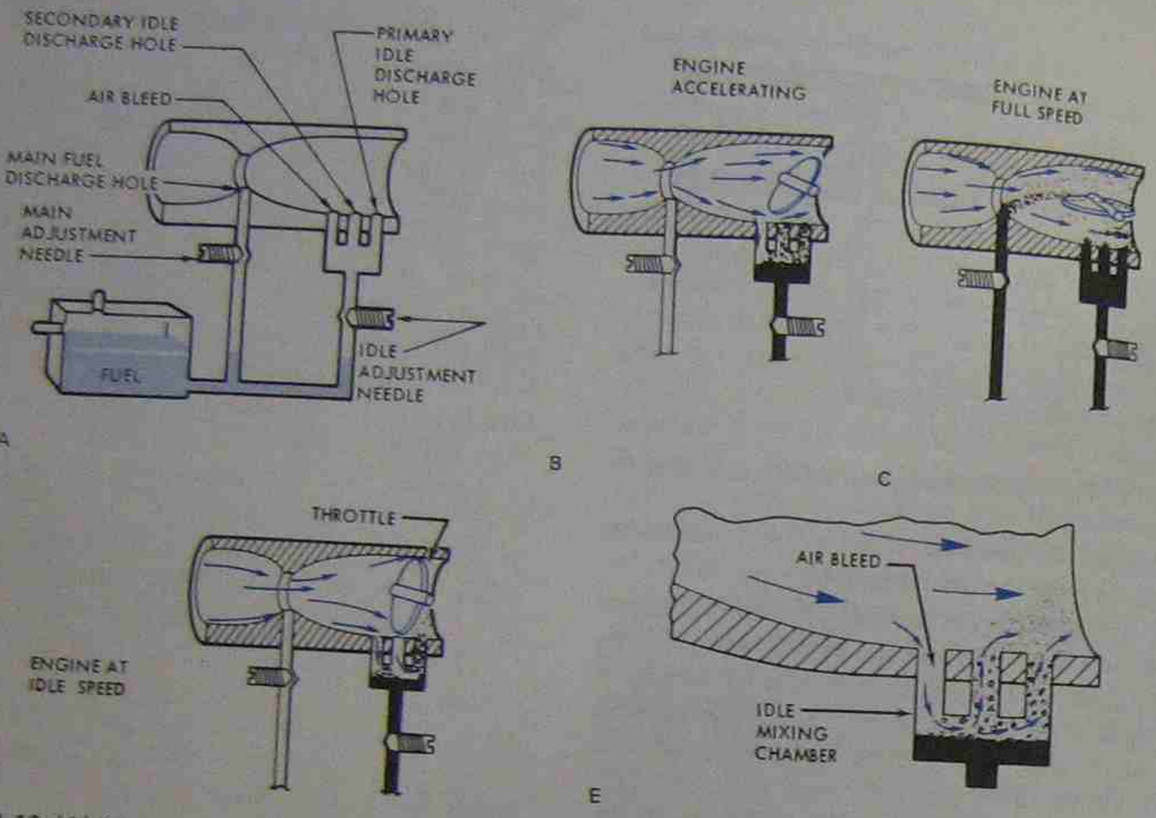


Fig. 4-16 (A) Schematic of basic carburetor parts, (B) engine accelerating, (C) engine at full speed, (D) engine at idle speed, and (E) air bleed principle

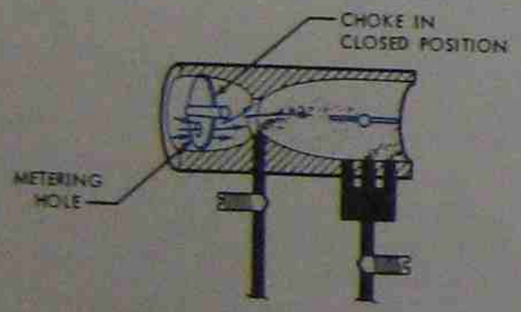


Fig. 4-17 The choke provides a rich mixture for starting.

The complete carburetor operation includes:

- the float and float bowl maintaining a constant reservoir of gasoline in the carburetor
- the venturi section producing a low-pressure area
- the needle valve controlling the richness or leanness of fuel mixture
- the main discharge jet spraying gasoline into the airstream
- the idle valve providing a rich mixture for idling conditions
- the choke producing an extremely rich mixture for easy starting.

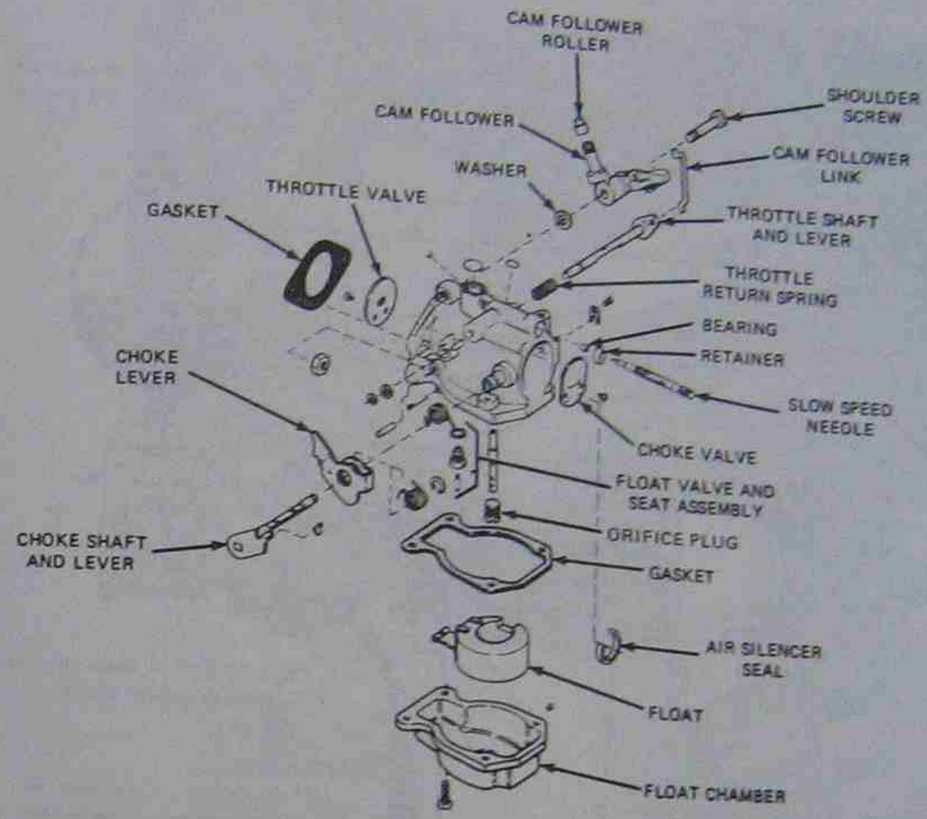


Fig. 4-18 Carburetor components

See figure 4–18 for an exploded view of a carburetor and 4–19 for an illustration of where it fits into the fuel system.

Primer

It should be noted that some carburetors have a *primer* instead of a choke for providing the extra gasoline and rich mixture for starting. Pushing the primer causes liquid or raw gasoline to be squirted into the venturi section of the carburetor. One or two pushes on the primer provides enough gasoline for starting the engine.

DIAPHRAGM CARBURETOR

The diaphragm carburetor has come into wide use, especially on chain saws. It is also found on other applications where the engine may be tipped at extreme angles. The diaphragm supplies the carburetor with a constant supply of gasoline.

The diaphragm carburetor may be gravity fed. Crankcase pressure moves the diaphragm and associated linkages to allow gasoline to enter the fuel chamber. The gasoline is

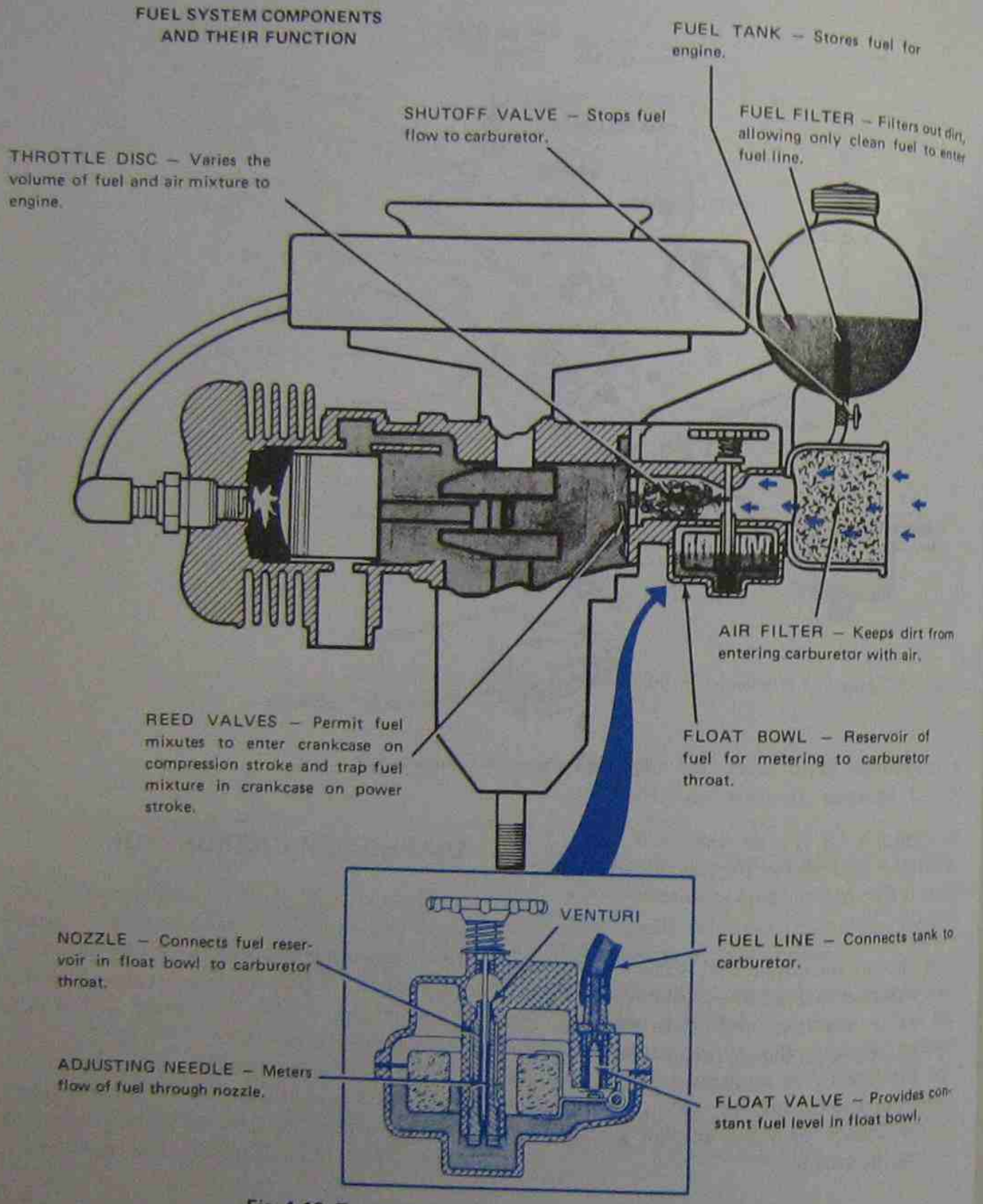


Fig. 4-19 Two-stoke cycle carburetor and fuel system

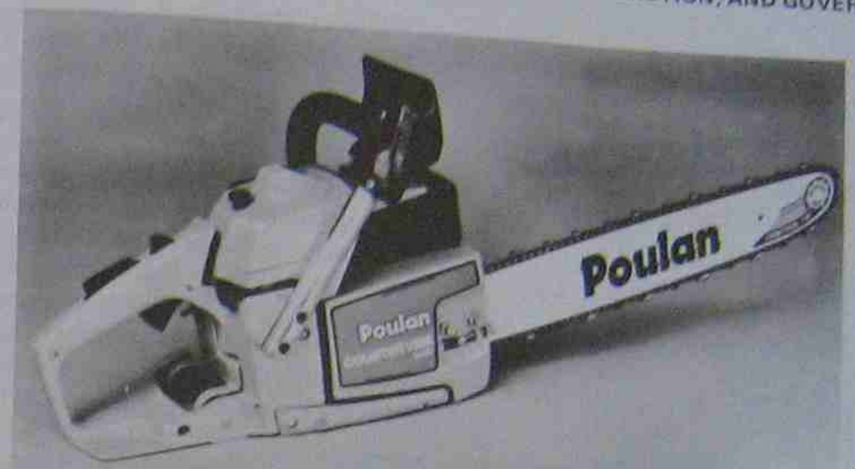


Fig. 4-20 Chain saws commonly use diaphragm carburetors (Courtesy Beaird Poulan Weed Eater, Emerson Electric Company)

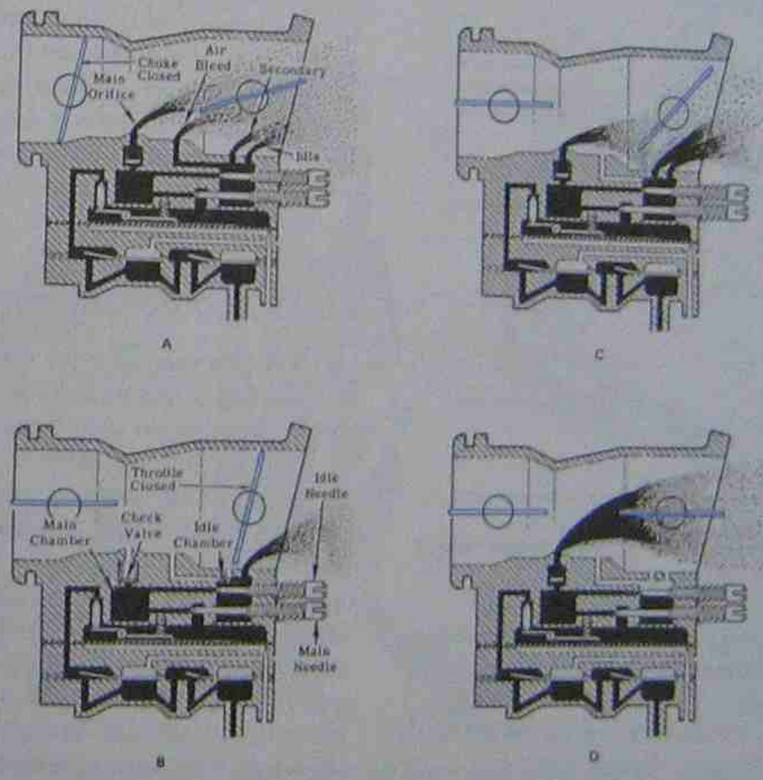


Fig. 4-21 Diaphragm carburetor with built-in fuel pump. (A) choke closed, (B) idle, (C) part throttle, (D) full throttle

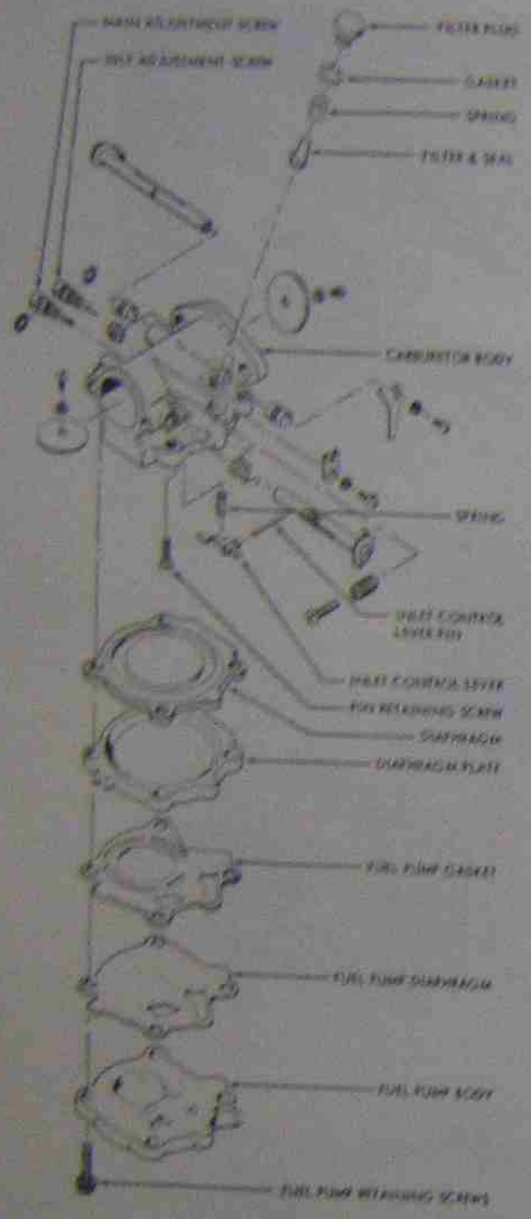


Fig. 4-22 An exploded view of a diaphragm carburetor with a built-in fuel pump

available by gravity and the in-and-out motion of the diaphragm meters out fuel in the correct amount.

Diaphragm carburetors are also made with a built-in fuel pump, figures 4-21 and 4-22. The fuel pump operates on differences in crankcase pressure; its action is much the same as that of the outboard fuel pump previously discussed. Diaphragm carburetors are widely used on small engines.

Other Carburetors

A common carburetor variation uses both the fuel pump and suction feed principles. The Briggs and Stratton Pulsa-Jet® is such a carburetor. At first this carburetor may appear to be an ordinary suction type carburetor but closer examination shows there are two fuel pipes into the carburetor — one long and one short.

The low pressure created by the intake stroke activates the fuel pump drawing gasoline through the long pipe and discharging it into a smaller constant level fuel chamber at the top of the tank. This provides a constant level of gasoline regardless of the amount of gasoline in the tank. It also reduces the amount of lift required to deliver gasoline into the venturi. This carburetor permits a larger venturi and improves the engine's horsepower rating. The Briggs and Stratton Pulsa-Jet® is shown in figures 4-23 and 4-24.

AIR BLEEDING CARBURETORS

There is a tendency for carburetors to supply too rich a fuel mixture at high speeds; the ratio of gasoline to air increases as the velocity of the air passing through the carburetor increases. One method that is commonly used to correct this condition is *air bleeding* (see figure 4-25, view E). Air bleeding involves introducing a small amount of air into the main discharge well vent to restrict the flow of gasoline from the main discharge jet. As engine speeds are increased, greater amounts of air are brought into the main discharge well vent placing a greater restriction on the gasoline flow. The additional air

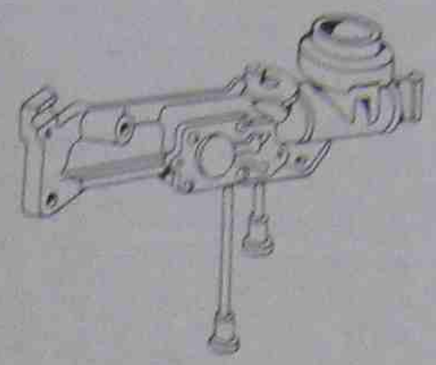


Fig. 4-23 Pulsa-Jet® carburetor

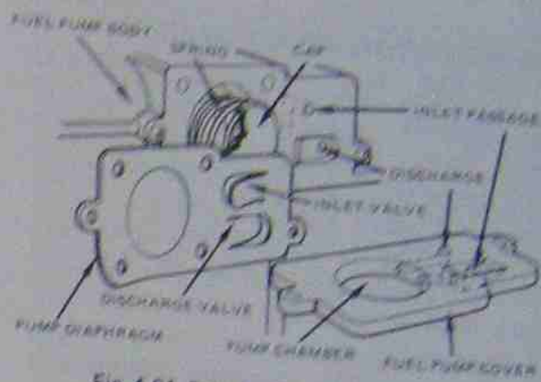


Fig. 4-24 Pulsa-Jet® carburetor pump

overcomes the carburetor's natural tendency to provide too rich a mixture at high speeds. This action maintains the proper ratio of fuel and air between a throttle setting of one-fourth to wide open. The air that enters the discharge well vent mixes with the gasoline and is drawn through the main discharge jet into the main airstream. The Zenith® carburetor shown in figure 4-25, uses the principle of air bleeding.

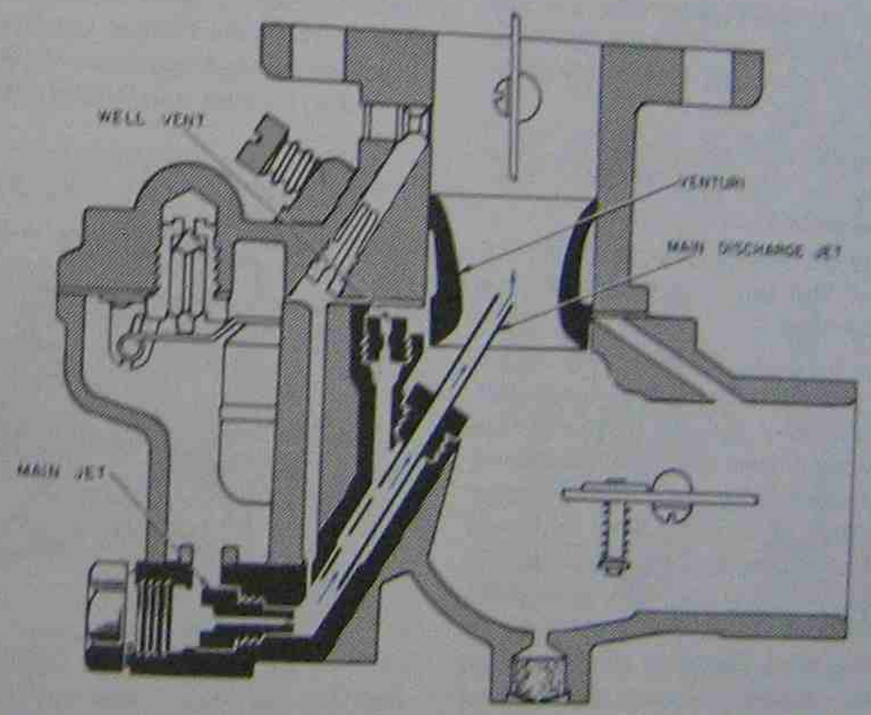


Fig. 4-25 Air brought into the well vent bleeds into the main discharge jet, maintaining the correct air-fuel ratio throughout throttle range.

CARBURETOR ADJUSTMENTS

The engine manufacturer sets the carburetor adjustments at the factory. These settings cover normal operation. However, after a long period of usage, or under special operating conditions, it may be necessary to adjust the carburetor. In adjusting the carburetor, the main needle valve and the idle valve are both reset to give the desired richness or leanness of fuel mixture. Too lean a mixture can be detected by the engine missing and backfiring. Too rich a mixture can be detected by heavy exhaust and sluggish operation.

Procedure

This is a typical procedure for adjusting a carburetor for maximum power and efficiency.

1. Close the main needle valve and idle valve finger tight. Excessive force can damage the needle valve. Turn clockwise to close.
2. Open the main needle valve one turn. Open the idle valve 3/4 turn. Turn counterclockwise to open.
3. Start the engine, open the choke, and allow the engine to reach operating temperature.
4. Run the engine at operating speed (2/3 to 3/4 of full throttle). Turn the main needle valve clockwise slowly, 1/8 turn at a time, until the engine slows down indicating too lean a mixture. Note the position of the valve. Turn the needle valve counterclockwise until the engine speeds up and then slows down indicating too rich a mixture. Note the position of the valve. Reposition the valve halfway between the rich and lean settings.
5. Close the throttle so the engine runs slightly faster than normal idle speed. Turn the idle mixture valve clockwise until the engine slows down, then turn the idle valve counterclockwise slowly, 1/8 turn at a time, until the engine speeds up and idles smoothly. Adjust the idle-speed regulating screw to the desired idle speed, figure 4–26.

   NOTE: Idle speed is not the slowest speed at which the engine can operate; rather, it is a slow speed that maintains good airflow for cooling and a good take-off spot for even acceleration. A tachometer and the manufacturer's specifications regarding proper idle speed are necessary for the best adjustment.
6. Test the acceleration of the engine by opening the throttle rapidly. If acceleration is sluggish, a slightly richer fuel mixture is usually needed.

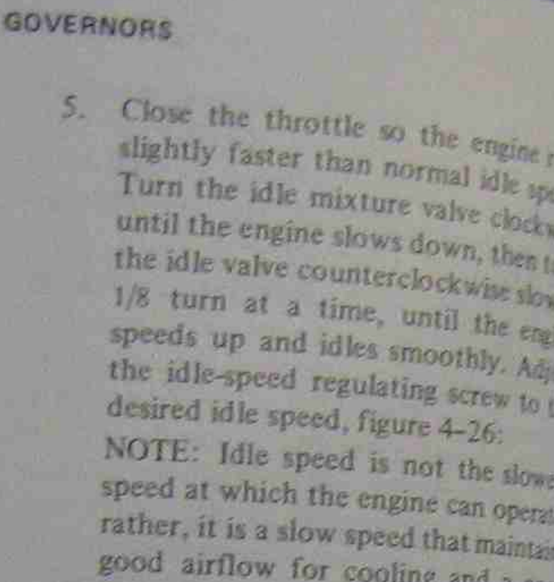


Fig. 4–26 Float-feed type carburetor

CARBURETOR ICING

Carburetor icing can occur when the engine is cold and certain atmospheric conditions are present, figure 4–27. If the temperature is between 28°F and 58°F and the relative humidity is above 70 percent, carburetor icing can take place.

Fuel mixture of gasoline and air rushes through the carburetor and the rapid action of evaporating gasoline chills the throttle plate to about 0°F. Moisture in the air condenses and freezes on the throttle plate when the relative humidity is high, figure 4–28. This formation of ice restricts the airflow through the carburetor; at low or idle settings the ice can completely block off the airflow stalling the engine.

When this condition is present, the engine can be restarted but stalls again at low or idle speeds. As soon as the carburetor is warm enough to prevent ice formation, normal operation can take place.

VAPOR LOCK

Vapor lock can occur anywhere along the fuel line, fuel pump, or in the carburetor when temperatures are high enough to vaporize the gasoline. Gasoline vapor in these places cuts off the liquid fuel supply stalling the engine. If vapor lock occurs, the operator must wait until the carburetor, gas line, and fuel pump cool off and the gasoline vapor returns to liquid before the engine will restart. Vapor lock usually occurs on unseasonably hot days and is more troublesome at high altitudes.

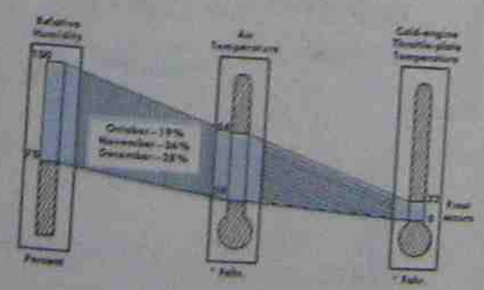


Fig. 4–27 Humidity and temperature conditions which may lead to carburetor icing

GASOLINE

Most internal combustion engines burn gasoline as their fuel. Gasoline comes from petroleum, also called crude oil. Crude oil is actually a mixture of different hydrocarbons such as gasoline, kerosene, heating oil, lubricating oil, and asphalt. These chemicals are all hydrocarbons but they have characteristics that are quite different. Hydrogen is a light, colorless, odorless gas; carbon is black and solid. Different combinations of carbon and hydrogen give the different characteristics of hydrocarbon products.

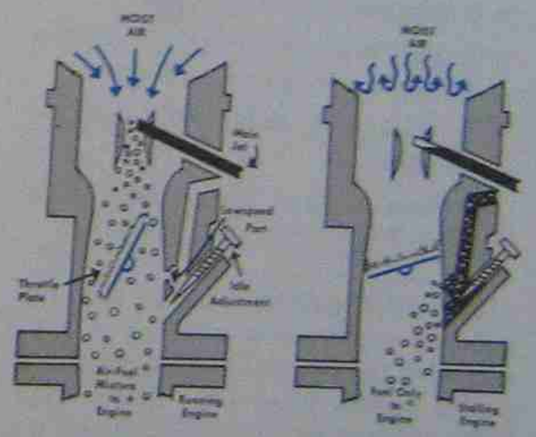


Fig. 4–28 Under carburetor icing conditions, ice forms on the throttle plate cutting off air to the engine when the throttle closes.

The various hydrocarbons are separated by distillation of the crude oil. Crude oil is first heated to a temperature of 700° to 800°F and then released into a fractionating or bubble tower, figure 4–29. The tower contains 20 to 30 trays through which hydrocarbon vapors can rise from below. When the heated crude oil is released into the tower, most of it flashes into vapor. The vapors cool as they rise. Each type of hydrocarbon condenses at a different tray level. Heavier hydrocarbons condense first at relatively high temperatures. The lighter hydrocarbons, such as gasoline, condense high in the tower at relatively low temperatures. Gasoline is then further processed to improve its qualities.

Good gasoline must have several characteristics.

- It must vaporize at low temperatures for good starting.
- It must be low in gum and sulfur content.
- It must not deteriorate during storage.
- It must not knock in the engine.
- It must have proper vaporizing characteristics for the climate and altitude.
- It must burn cleanly to reduce air pollution.
- It must remain a liquid until it mixes with air in the carburetor venturi.

The vaporizing ability of gasoline is the key to its success as a fuel. In order to burn inside the engine, the hydrocarbon molecules of the gasoline must be mixed with air since oxygen is also necessary for combustion. To mix the gasoline and air, there must be rapid motion and turbulence to keep the molecules suspended in the air, figure 4–30. There is rapid motion and turbulence in the carburetor;

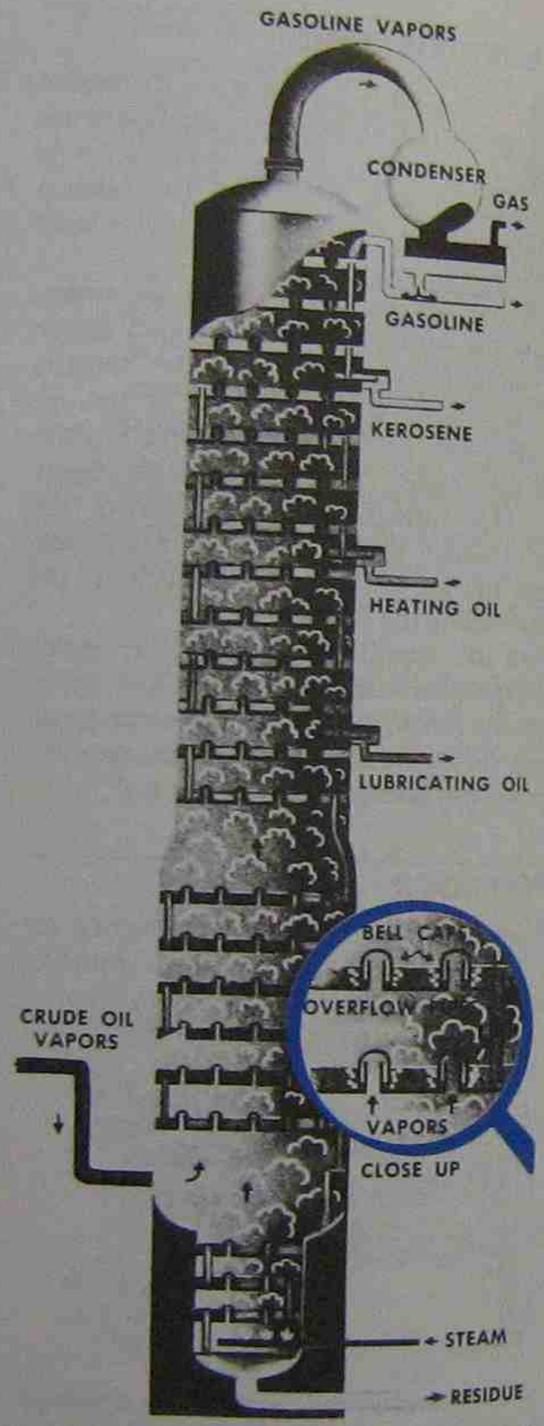


Fig. 4–29 Distillation of petroleum in the bubble tower

this turbulence continues into the combustion chamber. Combustion chambers are designed to create the maximum turbulence so that gasoline molecules will stay suspended in the air until they are ignited. A thorough mixture ensures smooth and complete burning of gasoline which delivers maximum power.

Although the vaporizing ability of gasoline makes it an excellent fuel, it also presents a great fire and explosion hazard. When vaporized, a gallon of gasoline produces 21 cubic feet of vapor. If this vapor were combined with air in a mixture of 1.4 to 7.6 percent gasoline by volume, it would burn rapidly when ignited. Therefore, only one gallon of gasoline properly vaporized would completely fill an average living room with explosive vapor. The safety rules given in unit 2 for the use and storage of gasoline should always be followed.

In engines, the compression of the fuel mixture of gasoline and air results in high combustion pressures and the force necessary to move the piston. This compression may also cause the gasoline to explode (*detonate*) in the engine instead of burning smoothly.

Detonation is also called knocking, fuel knock, spark knock, carbon knock, and ping. To understand it, one has to think in slow motion. Refer to figure 4–31. The spark plug ignites the fuel mixture, and a flame front moves out from this starting point. As the flame front sweeps across the combustion chamber, heat and pressure build. The unburned portion of the fuel mixture ahead of the flame front is exposed to this heat and pressure. If it self-detonates, two flame fronts are created which race toward each other. The last unburned portion of fuel caught between the two fronts explodes with hammerlike force. Detonation causes a knocking sound in the engine and power loss. Re-

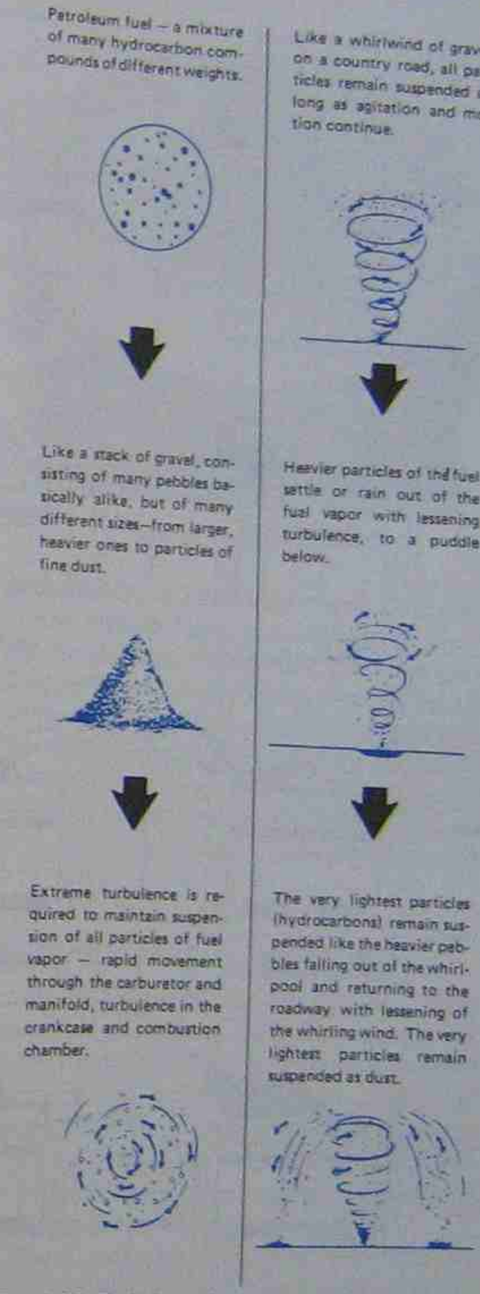


Fig. 4–30 Turbulence is necessary to keep the gasoline molecules suspended in the air.

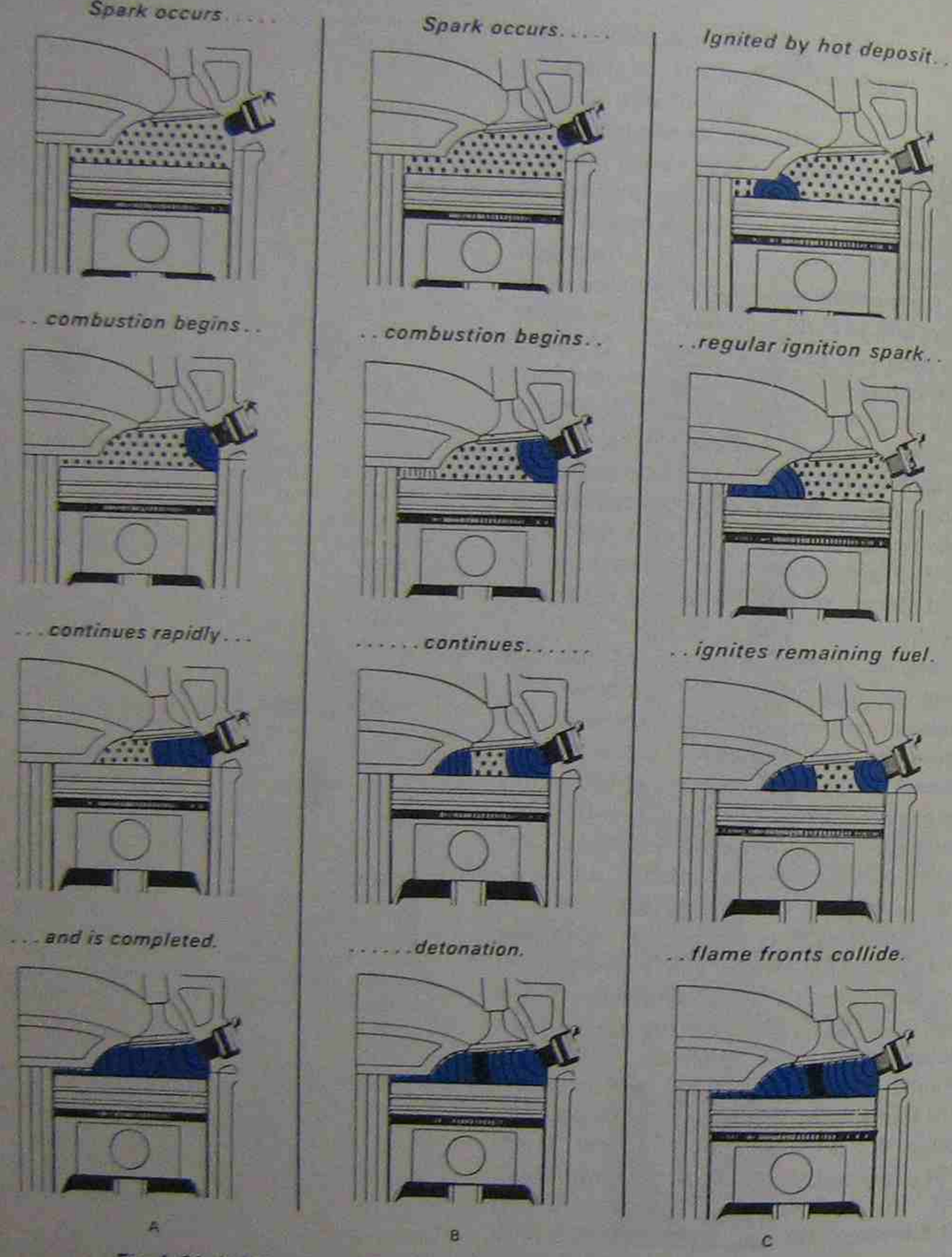


Fig. 4-31 (A) Normal combustion, (B) detonation, and (C) pre-ignition



Fig. 4-32 Detonation damage



Fig. 4-33 Pre-ignition damage

peated detonation can damage the piston, figure 4-32.

Pre-ignition causes the same undesirable effects as detonation, including engine damage, figure 4-33. The cause of pre-ignition, however, is somewhat different. Hot spots, or red-hot carbon deposits, actually ignite the fuel mixture and begin combustion before the spark plug fires.

The antiknock quality of a gasoline, or its ability to burn without knocking, is called its *octane rating*. Gasoline that has no knocking characteristics at all is rated at 100. Usually, tetraethyl lead is added to gasoline to give it the proper antiknock quality. If lead is not used as in unleaded gasoline, special aromatic compounds are used to obtain smooth burning.

The higher the compression ratio of the engine, the higher the octane requirements for the engine's fuel. Low-grade gasoline with an octane rating of 70-85 is suitable for compression ratios of 5-7:1. Regular grade gasoline with an octane rating of 88-94 is suitable for compression ratios of 7-8.5:1. Most small engine manufacturers recommend the use of regular gasoline. High-octane premium gasoline, leaded or unleaded, does not improve the performance of small engines. Premium gasoline with an octane rating of about 100 is suitable for compression ratios of 9-10:1. Super premium has an octane rating of over 100 and is good for engines with compression ratios of 9.5-10.5:1.

ENGINE SPEED GOVERNORS

Speed governors are used to keep engine speed at a constant rate regardless of the load. For instance, a lawn mower is required to cut tall as well as short grass. A governor ensures that the engine operates at the same speed in spite of the varying load conditions. Engines on many other applications also need this constant speed feature.

Speed governors are also used to keep the engine operating speed below a given, preset rate, so that the engine speed will not surpass

te. This maximum rate is established he governor set accordingly by the ers at the factory. This type of speed or protects both the engine and the or from speeds that are dangerously

he case of lawn mowers the governor nits the top speed to conform to safety standards which limit the blade ed to 19,000 feet per minute.

e are two main governor systems used ll gasoline engines: (1) mechanical or igal type and (2) pneumatic or air vane Although there are other types of ors, most of the governors used on small engines are included in one of these categories.

MECHANICAL GOVERNORS

The mechanical governor operates on centrifugal force, figures 4–34 to 4–36. With this method, counterweights mounted on a geared shaft, a governor spring, and the associated governor linkages keep the engine speed at the desired rpm. For constant speed operation the action follows this pattern: when the engine is stopped, the mechanical governor's spring pulls the throttle to an open position. The governor spring tends to keep

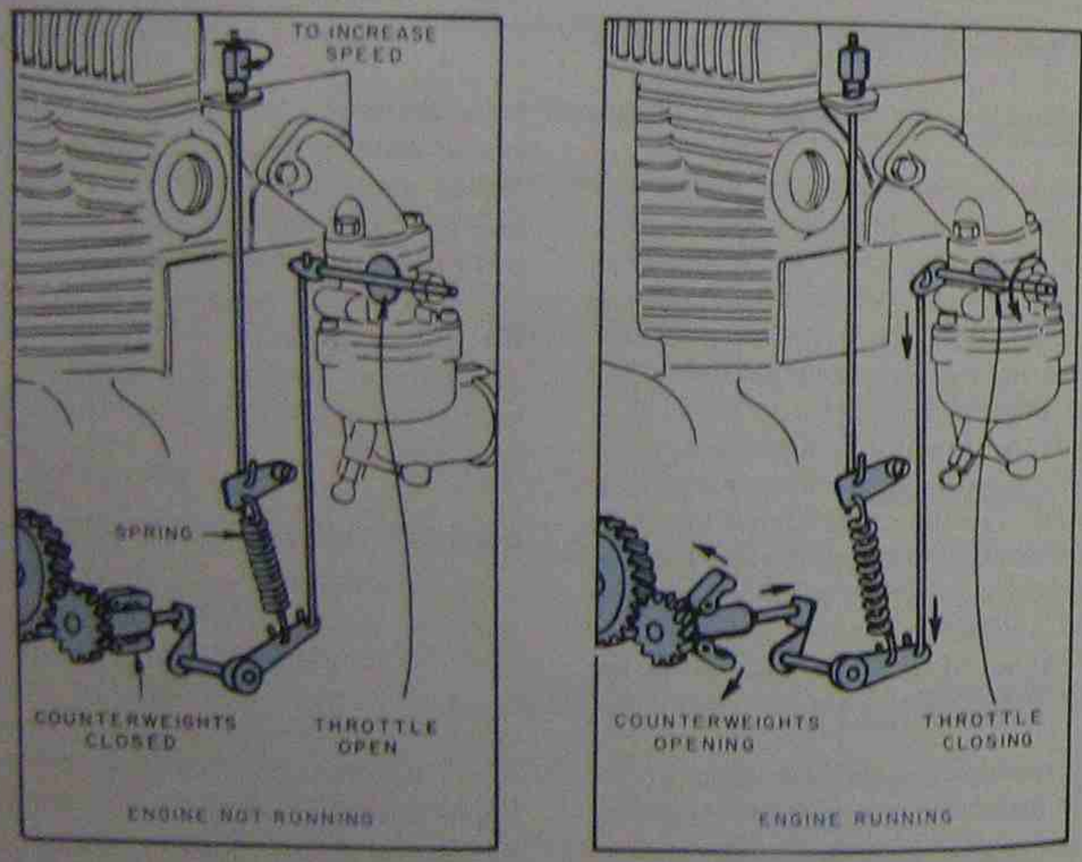


Fig. 4–34 A mechanical governor which operates on centrifugal force

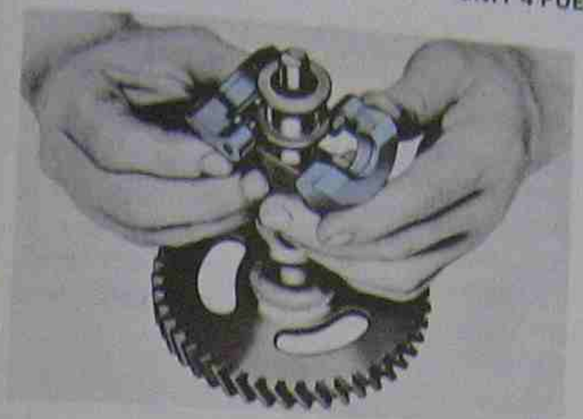


Fig. 4–35 Mechanical governor (centrifugal)

the throttle open but as the engine speed increases centrifugal force throws the hinged counterweights further and further from their shaft. This action puts tension on the spring in the other direction to close the throttle. At governed speed, the spring tension is overcome by the counterweights and the throttle opens no further. A balanced position is maintained and the engine assumes its maximum speed.

If, however, a greater load is placed on the engine, it slows down; the hinged counterweights swing inward due to lessened centrifugal force; the governor spring becomes dominant, opening the throttle wider. With a wider throttle opening, the engine speeds up until governed speed is reached again. The action described is fast and smooth; little time is needed for the governor to meet revised load conditions.

The governed speed can be changed somewhat by varying the tension on the governor spring. The more tension there is on the governor spring, the higher the governed speed.

Another commonly used centrifugal or

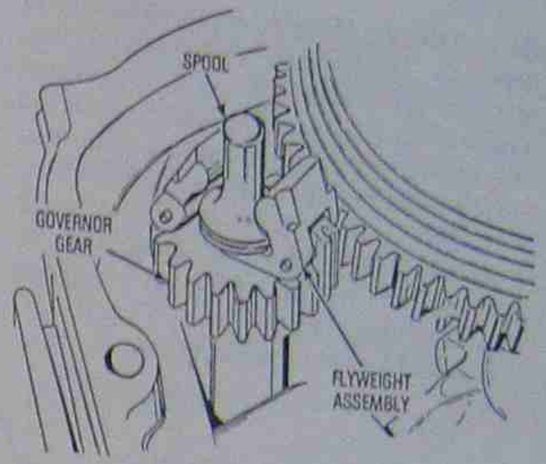


Fig. 4–36 Mechanical governor (Courtesy Tecumseh Products Company)

mechanical governor is the flyball type. With this governor, round steel balls in a spring loaded raceway move outward as the engine speed increases. The centrifugal force applied by these balls increases until it balances the spring tension holding the throttle open. At this point, the governed speed is reached.

PNEUMATIC OR AIR VANE GOVERNORS

Many engines have a pneumatic or air vane governor, figures 4–37 through 4–39. Again, the governor holds the throttle at the governed speed position which prevents it from opening further. An air vane, which is located near the flywheel blower, controls the speed. As engine speed increases, the flywheel blower pushes more air against the air vane causing it to change position. At governed speed the air vane position overcomes the governor spring tension and a balance is assumed.

Engines are often designed so that they can

be accelerated freely from idle speed up to governed speed. With these engines, the governor spring takes on very little tension at low speeds. The operator has full control. As the throttle is opened further and further, there is more tension on the spring, both from the operator and from the strengthening governor action. At governed speed, the force to close the throttle balances the spring tension to open the throttle.

It should be noted that not all engines have engine speed governors. Engines that are always operated under a near constant load do not need the governor. The load of an outboard engine is a good example of a near constant load. Although different loads are placed on the outboard (number of people in boat, position of people in boat, use of trolling mechanism to decrease boat's speed, etc.), the load is constant at full throttle for a given period of use.

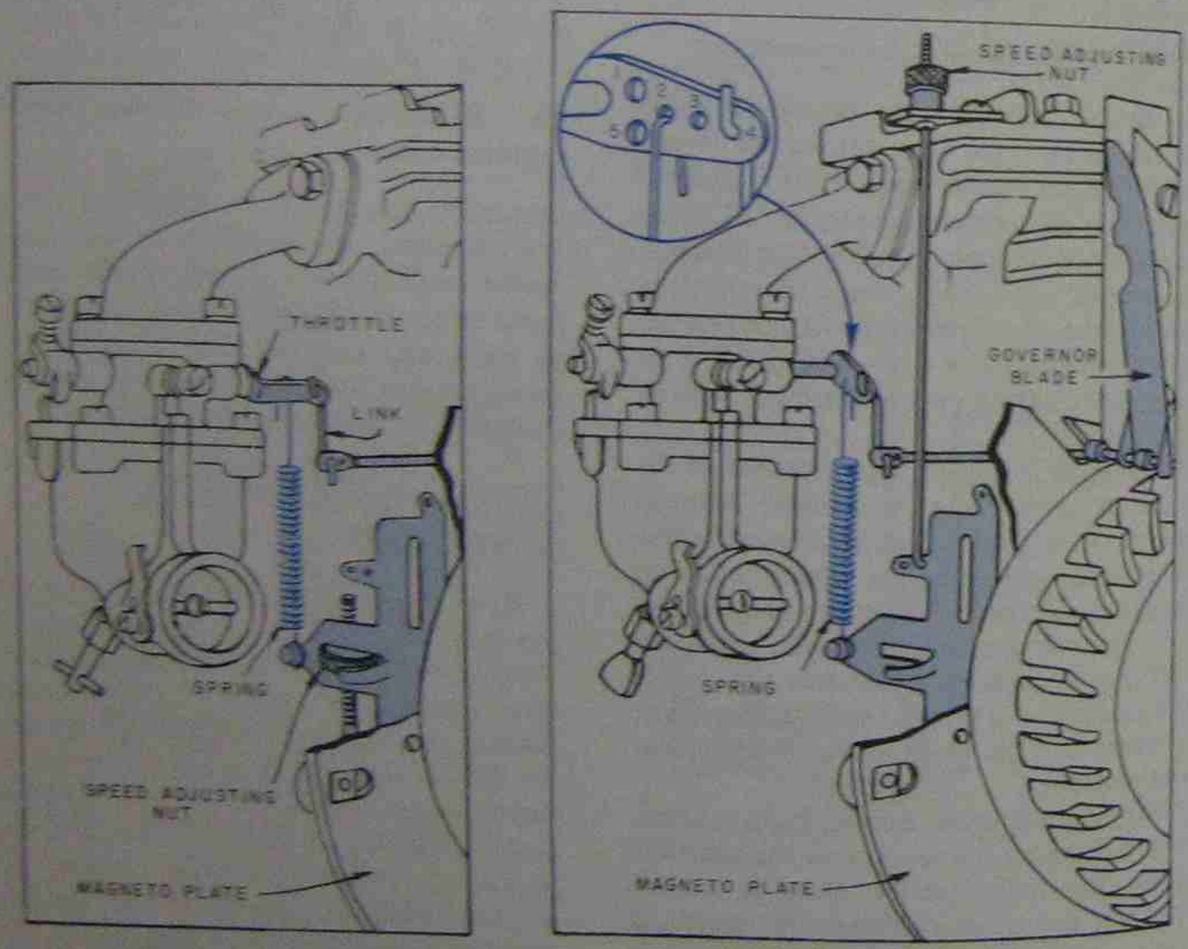


Fig. 4-37 A pneumatic or air vane governor

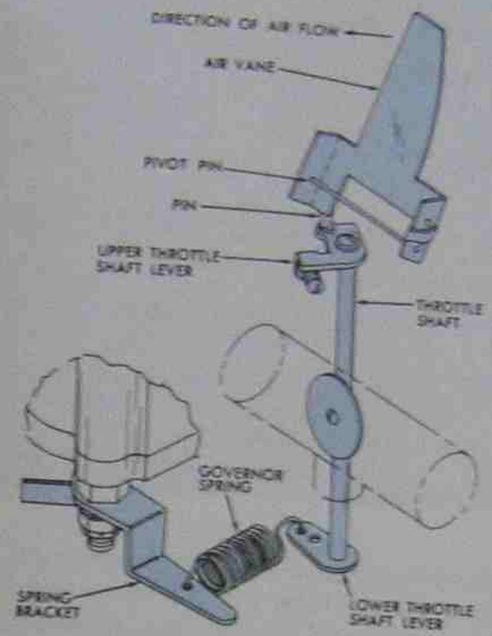


Fig. 4-38 A pneumatic or air vane governor

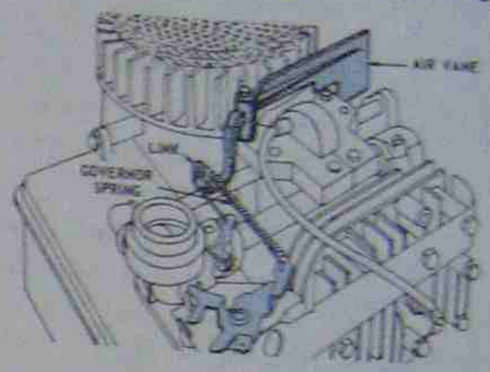


Fig. 4-39 Air vane governor

REVIEW QUESTIONS

1. Name the basic parts of a typical fuel system.
2. What force is used to operate most outboard fuel pumps?
3. How can a pressurized fuel system be recognized?
4. Briefly describe the task of the carburetor.
5. Name the main parts that make up the carburetor.
6. What causes air to flow through the carburetor?
7. What causes low air pressure in the venturi section of the carburetor?
8. What is the function of the throttle?
9. What is the function of the choke?
10. What is the function of the needle valve?

11. Explain the action of the float in a float-type carburetor.
12. What is the advantage of a diaphragm carburetor?
13. Explain the principle of air bleeding.
14. Explain the operation of the accelerating pump.
15. What is a rich mixture?
16. Why is turbulence important inside the combustion chamber?
17. What two main purposes do engine speed governors serve?
18. What are the two main governor systems used on small gasoline engines?
19. Why are some engines made that do not have a speed governor?
20. Can the governed speed be changed? How?

Unit 5 Lubrication

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the several functions of engine lubricating oil.
- Discuss friction bearings and antifriction bearings.
- Discuss lubricating oil quality designations and SAE numbers.
- Discuss how a two-stroke cycle engine is lubricated.
- Correctly drain and refill the crankcase with oil.
- Explain how a two-stroke cycle engine is lubricated.

Whenever surfaces move against one another they cause friction which results in heat and wear. Lubricating oils have one main job to perform in the engine – to reduce friction. The lubricating oil provides a film that separates the moving metal surfaces and keeps the contact of metal against metal to an absolute minimum, figure 5-1.

Without a lubricating oil or with insufficient lubrication, the heat of friction builds up rapidly. Engine parts become so hot that they fail. That is when the metal begins to melt, bearing surfaces *seize* (adhere to other parts), parts warp out of shape, or parts actually break. The common expression is to say the engine burns up.

As an example of friction, lay a book on the table and then push the book slowly. Notice the resistance. Friction makes the book difficult to slide. Now place three round pencils between the book and the table top and push the book. Notice how easily it moves. Friction has been greatly reduced. Oil molecules correspond to the pencils by forming a coating between two moving surfaces. With oil, the metal surfaces roll along on the oil molecules and friction is greatly decreased.

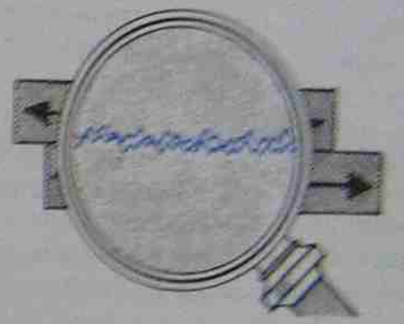


Fig. 5-1 Exaggerated view of metal surfaces in contact

Besides reducing friction and the wear and heat it causes, the lubricating oil serves several other important functions.

Oil Seals Power. The oil film seals power, particularly between the piston, piston rings, and cylinder walls. The great pressures in the combustion chamber cannot pass by the air-tight seal which the oil film provides. If this oil film fails, a condition called blow-by

exists. Combustion gases push by the film and enter the crankcase. Blow-by not only reduces engine power but also has a harmful effect on the oil's lubricating quality.

Oil Helps to Dissipate Heat. Oil helps to dissipate heat by providing a good path for heat transfer. Heat conducts readily from inside metal parts through an oil film to outside metal parts that are cooled by air or water. Also, heat is carried away as new oil arrives from the crankcase and the hot oil is washed back to the crankcase.

Oil Keeps the Engine Clean. Oil keeps the engine clean by washing away microscopic pieces of metal that have been worn off moving parts. These tiny pieces settle out in the crankcase or they are trapped in the oil filter, if one is used.

Oil Cushions Bearing Loads. The oil film has a cushioning effect since it is squeezed from between the bearing surfaces relatively slowly. It has a shock absorber action. For example, when the power stroke starts, the hard shock of combustion is transferred to the bearing surfaces; the oil film helps to cushion this shock. Figure 5-2 illustrates the oil clearance between the journal and the bearing.

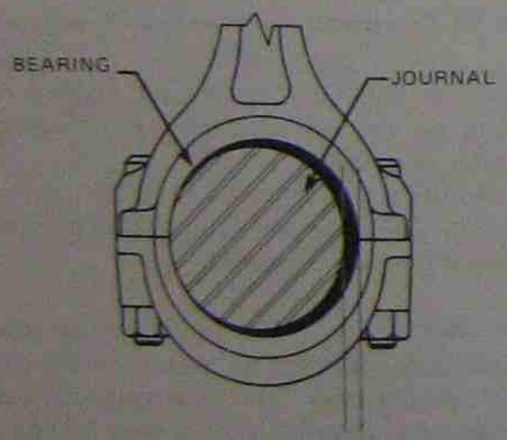


Fig. 5-2 Oil clearance between journal and bearing (exaggerated)

Oil Protects Against Rusting. The oil film protects steel parts from rusting. Air, moisture, and corrosive substances cannot reach the metal to oxidize or corrode the surface.

FRICTION BEARINGS

There are three types of friction bearings used in a small gasoline engine: journal, guide, and thrust, figure 5-3. The *journal bearing* is the most familiar. This bearing supports a revolving or oscillating shaft. The connecting rod around the crankshaft and the main bearings are examples. The *guide bearing* reduces the friction of surfaces sliding longitudinally against each other, such as the piston in the cylinder. The *thrust bearing* supports or limits the longitudinal motion of a rotating shaft.

Bearing inserts are commonly used in larger engines or heavy-duty small engines, particularly on the connecting rod and cap and the main bearings. The inserts are precision-made of layers of various metals and alloys. Alloys such as babbit, copper-lead, bronze, aluminum, cadmium, and silver are commonly used. Crankshaft surfaces are made of steel. Most small engines, however, do not have bearing inserts. They use only the aluminum connecting rod around the steel journal of the crankshaft.

ANTIFRICTION BEARINGS

Antifriction bearings are also commonly used in engines, figure 5-4. They substitute rolling friction for sliding friction. Ball bearings, roller bearings and needle bearings

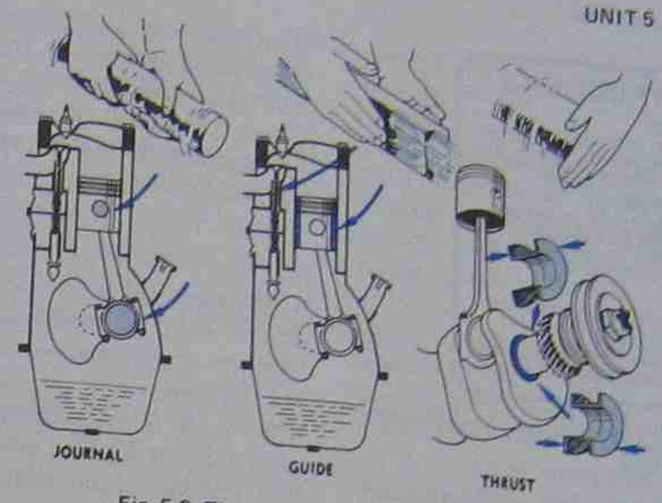


Fig. 5-3 Three major types of friction bearings

are of this type, figure 5-5. On many small engines, the main bearings are of the antifriction type.

QUALITY DESIGNATION OF OIL AND SAE NUMBER

Selecting engine lubricating oils can be confusing. One must be aware of different viscosities, different qualities, different refining companies, different additives, and the meaning of many advertising phrases. Generally, lubricating oils used for various small gasoline engines are the same ones that are used for automobile engines. However, two-stroke cycle engines almost always use special two-cycle oil.

Quality Designation by the American Petroleum Institute (API)

Figure 5-6 is an example of lubricating

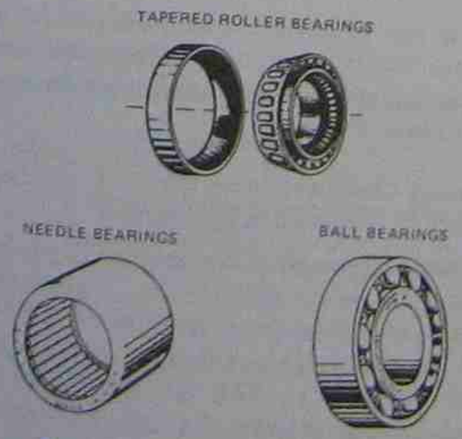


Fig. 5-4 Types of antifriction bearings

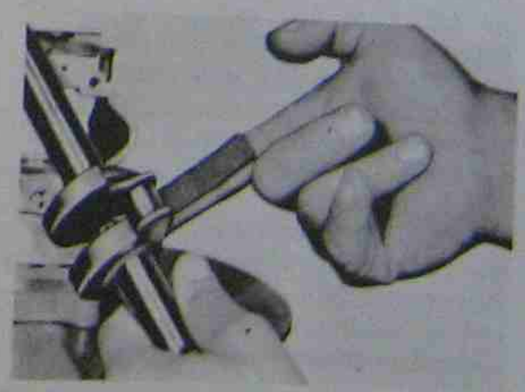


Fig. 5-5 Needle bearings

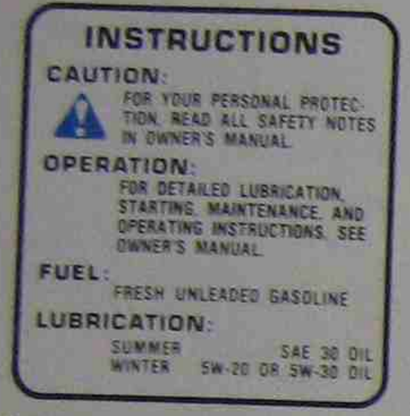


Fig. 5-6 Lubricating instructions on decal (Courtesy Tecumseh Products Co.)

instructions given on the decal. The API classifications are usually found on the top of the oil can and refer to the quality of the oil.

Oils for Service SF. This oil was developed for automotive engines manufactured in 1980 or later. It is the highest-quality oil and meets the manfacturers' maintenance requirements.

Oils for SE (Service Extreme). SE oils are suitable for the most severe type of operation beginning with 1972 models and some 1971 automobiles. Extreme conditions of start-stop driving; short trip, cold weather driving; and high speed, long distance, hot weather driving can be handled by this oil. The oil meets the requirements of automobiles that are equipped with emission control devices and engines operating under manufacturers' warranties.

Oils for SD (Service Deluxe). Most small engine manufacturers approve of the use of SD (formerly MS) oil in their engines. These oils provide protection against high and low temperature engine deposits, rust, corrosion, and wear.

Oils for Service SC. This oil was also formerly classified as suitable for MS. It has much the same characteristics as SD but is not quite as effective as SD oil. SC oil was developed for auto engines of 1964-67, while SD oil was developed for engines of 1968-70 manufacture.

Oils for Service SB (Formerly MM). This oil is recommended for moderate operating conditions such as moderate speeds in warm weather; short-distance, high-speed driving; and alternate long and short trips in cool weather. It is satisfactory for certain older autos but not for new autos under warranty. It is seldom recommended for small engine use.

Oils for Service SA (Formerly ML). No performance requirements are set for this oil. It is straight mineral oil and may be suitable for some light service requirements. SA oil is not recommended by small engine manufacturers.

The new classifications for oils suitable for diesel service are CA, CB, CC, and CD. These replace the old classifications of DG, AM (Supp-1), DM (MIL-L2104B), and DS respectively.

It is wise to buy the best quality oil for an engine. Sacrificing on quality for a few cents savings may be more expensive in the long run due to engine wear.

Viscosity Classification by the Society of Automotive Engineers

The SAE (Society of Automotive Engineers) number of an oil indicates its *viscosity*, or thickness. Oils may be very thin (light), or they may be quite thick (heavy). The range is from SAE 5W to SAE 50; the higher the number, the thicker the oil. The owner should consult the engine manufacturer's instruction book for the correct oil. SAE 10W, SAE 20W, SAE 20, and SAE 30 are the most commonly used oil weights. Usually, manufacturers recommend SAE 30 for summer use and either SAE 10W or SAE 20W for cold, subfreezing weather. In winter, thinner oil should be added since oil thickens in cold weather. The *W*, as in 5W, 10W, and 20W, indicates that the oil is designed for service in subfreezing weather.

Multigrade Oils. Multigrade oils may also be used in small gasoline engines, figure 5-7. These oils span several SAE classifications because they have a very high viscosity index. Typical classifications are SAE 5W-20, or 5W-10W-20; 5W-30 or 5W-10W-20W-30; SAE 10W-30 or 10W-20W-30; 10W-40, and 20W-40. The first number represents the low temperature viscosity of the oil; the last number represents its high temperature viscosity. For example, 10W-30 passes the viscosity test of SAE 10W at low temperatures and the viscosity test of SAE 30 at high temperatures. These oils are also referred to as all-season, all-weather oils, multiviscosity, or multiviscosity grade oils.

Motor Oil Additives

The best oil cannot do its job properly in a modern engine if additives are not blended into the base oil.

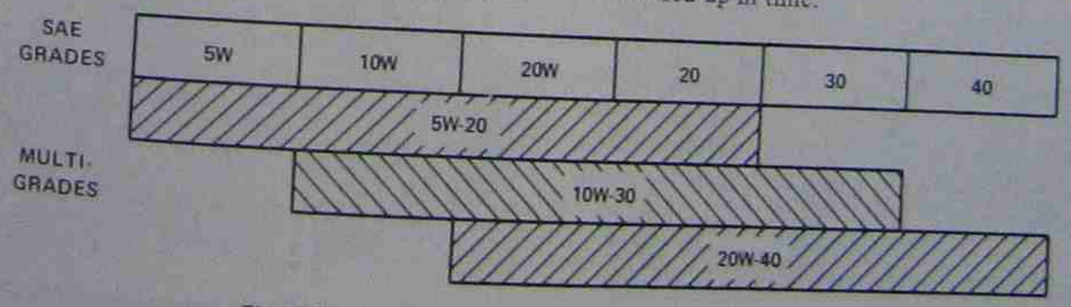


Fig. 5-7 Multigrade motor oils span several SAE (single) grades

Pour-Point Depressants. Pour-Point depressants keep the oil liquid even at very low temperatures when the wax in oil would otherwise thicken into a buttery consistency making the oil ineffective.

Oxidation and Bearing Corrosion Inhibitors. These additives prevent the rapid oxidation of the oil by excessive heat. Viscous, gummy materials are formed without these inhibitors. Some of these oxidation products attack metals such as lead, cadmium, and silver which are often used in bearings. The inhibiting compounds are gradually used up and, thus, regular oil changes are needed.

Rust and Corrosion Inhibitors. These inhibitors protect against the damage that might be caused by acids and water which are by-products of combustion. Basically, acids are neutralized by alkaline materials much the same as vinegar can be neutralized with baking soda. Special chemicals surround or capture molecules of water preventing their contact with the metal. Other chemicals which have a great attraction for metal form an unbroken film on the metal parts. These inhibitors are also used up in time.

Detergent/Dispersant Additives. This type of additive prevents the formation of sludge and varnish. Detergents work much the same as household detergents in that they have the ability to disperse and suspend combustion contaminants in the oil but do not affect the lubricating quality of the oil. When the oil is changed, all the contaminants are discarded with the oil so that the engine is kept clean. Larger particles of foreign matter in the oil either settle out in the engine base or are trapped in the oil filter if one is used.

Foam Inhibitors. Foam inhibitors are present in all high-quality motor oils to prevent the oil from being whipped into a froth or foam. The action in the crankcase tends to bring air into the oil; foaming oil is not an effective lubricant. Foam inhibitors called silicones have the ability to break down the tiny air bubbles and cause the foam to collapse.

LUBRICATION OF FOUR-CYCLE ENGINES

Since all moving parts of the engine must be lubricated to avoid engine failure, a constant supply of oil must be provided. Each engine, therefore, carries its own reservoir of oil in its crankcase where the main engine parts are located.

Basically, the oil is either pumped to or splashed on the parts and bearing surfaces that need lubrication. There are several lubrication systems used on small engines. The following systems are among the most common.

- Simple Splash
- Constant-level Splash
- Ejection Pump
- Barrel-type Pump
- Full-pressure Lubrication

Simple Splash System

The *simple splash system* is perhaps the simplest system for lubrication. It consists of a splasher or dipper that is fastened to the connecting rod cap. There are several different sizes and shapes of dippers, figure 5-8. The dipper may be bolted on with the connecting rod cap or may be cast as a part of the connecting rod cap. Each time the piston nears the bottom of its stroke the dipper splashes into the oil reservoir in the crankcase, splashing oil onto all parts inside the crankcase. Since the engine is operating at 2000 to 3000 rpm, the parts are literally drenched by millions of oil droplets. Vertical crankshaft engines use an oil slinger that is driven by the camshaft, figure 5-9. The slinger performs a similar function to the dipper.

Constant-level Splash System

The *constant-level splash system* has three refinements over the simple splash system: a

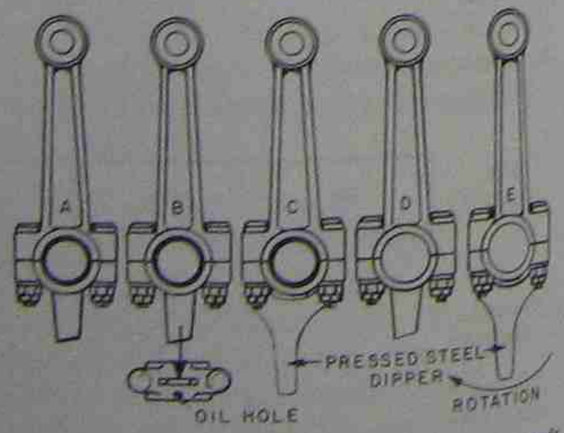


Fig. 5-8 Dippers used on different connecting rods

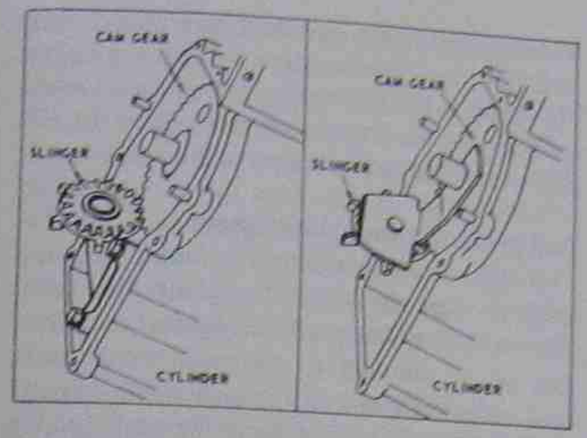


Fig. 5-9 Oil slinger

pump, a splash trough, and a strainer, figure 5-10. With this system a cam-operated pump brings oil from the bottom of the crankcase into a splash trough. Again the splasher on the connecting rod dips into the oil splashing it on all parts inside the crankcase. The strainer prevents any large pieces of foreign matter from recirculating through the system. The pump maintains a constant oil supply in the trough regardless of the oil level in the crankcase.

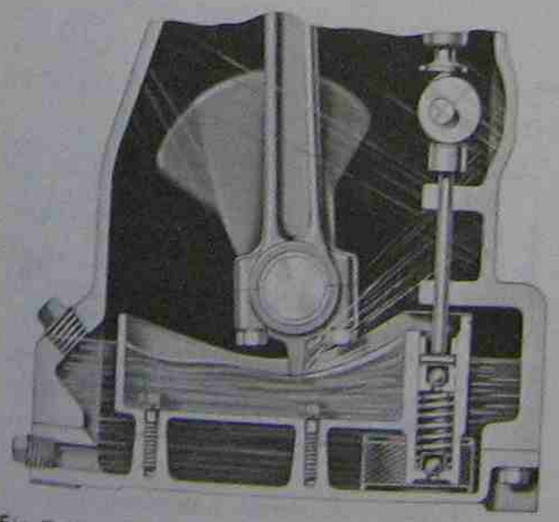


Fig. 5-10 Constant-level splash system used on some engines

Ejection Pump System

Ejection pumps of various types are found on many small engines, figure 5-11. With this method, a cam-operated or electric-operated pump draws oil from the bottom of the crankcase and sprays or squirts it onto the connecting rod. Some of the oil enters the connecting rod bearing through small holes; the remainder of the oil is deflected onto the other parts within the crankcase.

The parts of the ejection pump are the base, screen, check valve, spring, and plunger. The spring tends to push the plunger up but the plunger is driven down every revolution by the cam. A check valve allows the chamber to be filled with oil when the plunger goes up but when the cam pushes the plunger down, the check valve closes, and the trapped oil is squirted or sprayed from the pump.

Barrel-type Pump System

The *barrel-type pump* is also driven by an eccentric on the camshaft, figures 5-12 and

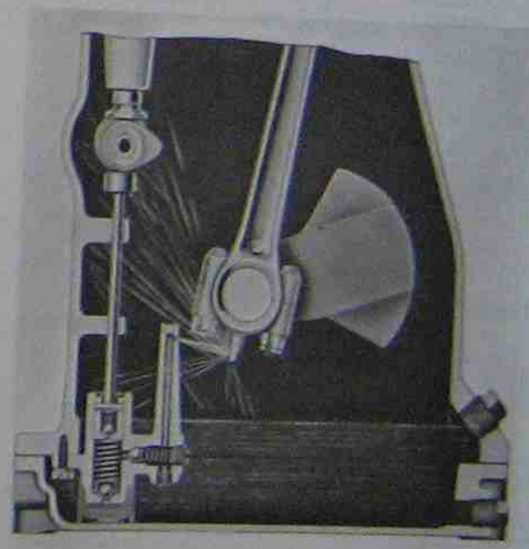


Fig. 5-11 Ejection pump as it is used on some engines

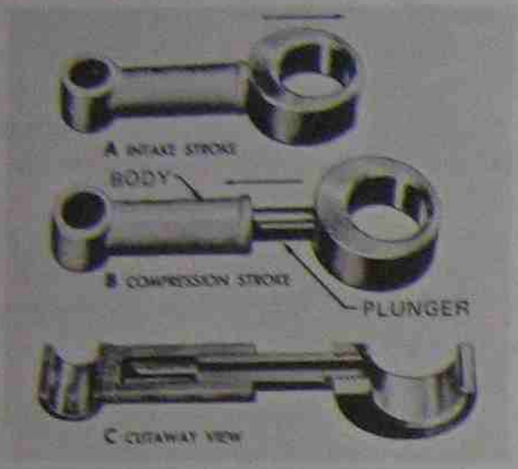


Fig. 5-12 Barrel-type pump

-13. The camshaft is hollow and extends to
e pump of the vertical crankshaft. As the
ump plunger is pulled out on intake, an in-
ke port in the camshaft lines up allowing the
ump body to fill. When the plunger is forced
to the pump body on discharge, the dis-

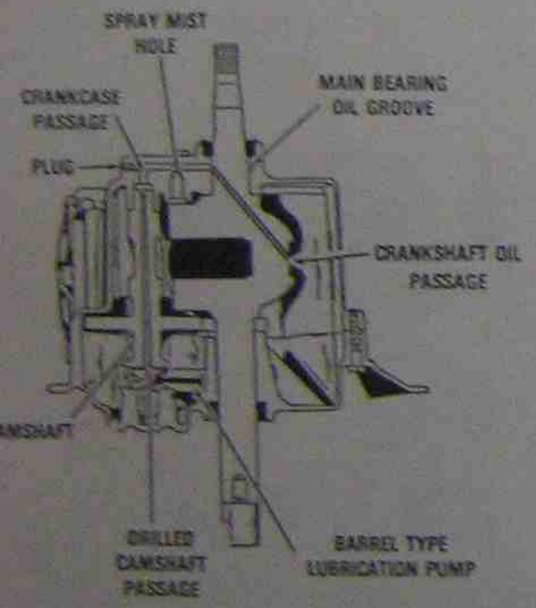


Fig. 5-13 Lubrication oil flow of barrel-type lubrication system (Courtesy Tecumseh Products Company)

charge ports in the camshaft line up allowing the oil to be forced to the main bearing and to the crankshaft connecting rod journal. Small drilled passages are used to channel the oil. Oil is also splashed onto other crankcase parts.

Full-pressure Lubrication System

Full-pressure lubrication is found on many engines especially the larger of the small engines and on automobile engines. Lubricating oil is pumped to all main, connecting, and camshaft bearings through small passages drilled in these engine parts, figure 5-14. Oil is also delivered to tappets, timing gears, etcetera under pressure. The pump used is usually a positive displacement gear type. It is also common to use a splash system in conjunction with full-pressure systems.

LUBRICATING CYLINDER WALLS

Oil is splashed or sprayed onto cylinder walls and the piston rings spread the oil evenly for proper lubrication. Piston rings

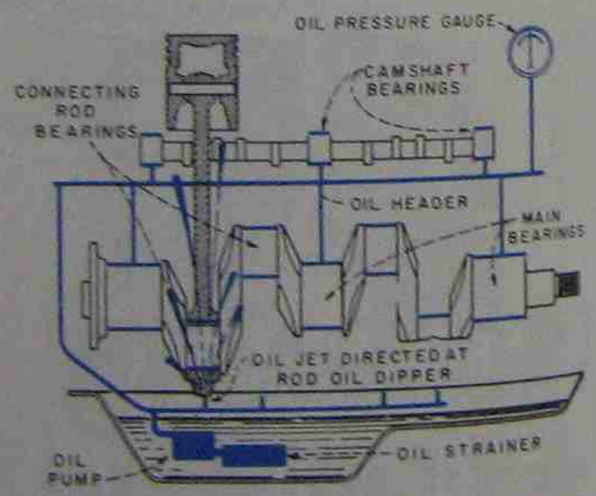


Fig. 5-14 Full-pressure lubrication

must function properly to avoid excessive oil consumption. The rings must put an even pressure on the cylinder walls and give a good seal. If piston ring grooves are too large, the piston rings begin a pumping action as the piston moves up and down. As a result, excess oil is brought into the combustion chamber. Worn cylinder walls, worn pistons, and worn rings can all add to high oil consumption as well as loss of compression and eventual loss of power.

BLOW-BY

Blow-by, the escape of combustion gases from the combustion chamber to the crankcase, occurs when piston rings are worn or are too loose in their grooves. Carbon and soot from burned fuel are forced into the crankcase by the rings. Much of the carbon is deposited around the rings which hinders their operation further.

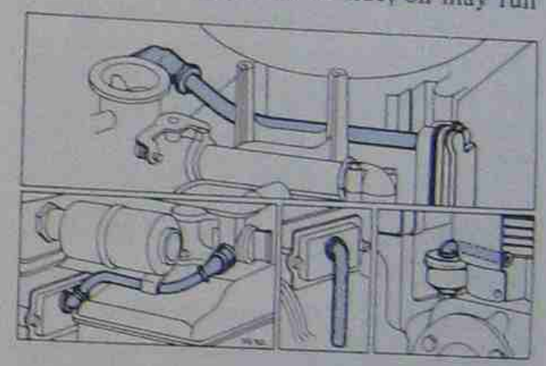
Another damaging result of worn rings can be crankcase dilution. If raw, unburned gasoline collects in the combustion chamber, it can leak by the piston rings and into the crankcase. This dilutes the crankcase oil and reduces the oil's lubricating properties.

CRANKCASE BREATHERS

Four-stroke cycle engines do not have completely airtight, oiltight crankcases. Engine crankcases must breathe. Without the ability to breathe, pressures build up in the crankcase and cause oil seals to rupture or allow contaminants to remain in the crankcase. Pressure buildup may be caused by the expansion of the air as the engine heats up, by the action of the piston coming down the cylinder, and by the blow-by of combustion gases along cylinder walls.

Most single-cylinder engines use breathers, figure 5-15. These breathers allow air to leave but not reenter a reed-type check valve or a ball-type check valve. The breathers place the crankcase under a slight vacuum and are called closed breathers.

Open breathers allow the engine to breathe in and out freely and are usually equipped with air filters. They are located where the splashing of oil is not a problem. Open breathers are often incorporated with the valve access cover. If an engine with this type of breather is tipped on its side, oil may run



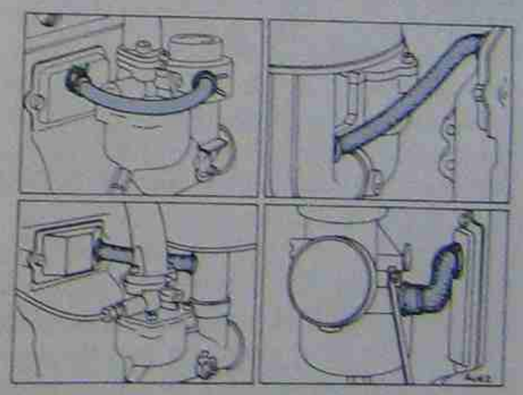


Fig. 5-15 Breather assemblies

out through it. Some breathers are vented to the atmosphere while others are vented back through the carburetor.

OIL CHANGES

The crankcase oil should be changed periodically. The exact number of engine operating hours between oil changes varies depending on the manufacturer. It may be as short a time as every 20 hours or as long a time as every 100 hours. (Every 25 hours is most common.) To ensure minimum engine wear and maximum engine life, follow the manufacturer's lubrication suggestions.

It is best to drain the oil when the engine is hot since more dirt and slightly more oil can be removed. Dirty oil should be replaced because it cannot give proper, high-quality lubrication.

LUBRICATION OF TWO-CYCLE ENGINES

Lubrication of the two-cycle engine is quite different from the four-cycle engine. Since the fuel mixture must travel through the crankcase, a reservoir of oil cannot be stored there. The lubricating oil is mixed with gasoline and then put into the gas tank. The lubricating oil for all crankcase parts enters the crankcase as a part of the fuel mixture. Millions of tiny oil droplets suspended in the mixture of gasoline and air settle onto the moving parts in the crankcase providing lubrication. Oil droplets are relatively large and heavy and quickly drop out of suspension. Much of the oil is carried on into the combustion chamber where it is burned along with the gasoline and air.

On a two-cycle engine, oil must be mixed with the gasoline, figure 5-16. The engine is not operated on gasoline alone. If it were, the heat of friction would burn up the engine in a short time. Some two-cycle engine manufacturers are developing and marketing engines with oil metering devices that eliminate the need to premix the oil and gasoline. Mixing is done automatically in the correct proportions.

Too much oil mixed with the gasoline results in incomplete combustion and a very heavy exhaust. Deposits build up rapidly in the engine, possibly fouling the tip of the spark plug and collecting around the exhaust ports. Clogged exhaust ports reduce the engine's power output considerably and can cause overheating.

Too little oil mixed with the gasoline can cause the engine to overheat. It may even cause scuffing and scoring of the cylinder

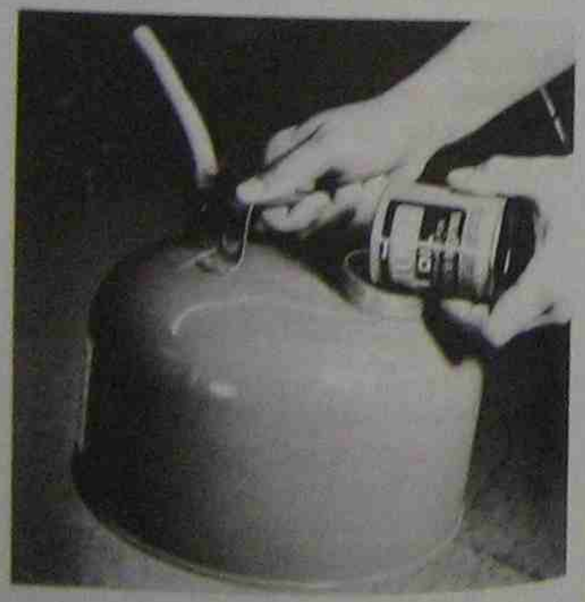


Fig. 5-16 Thorough mixing of oil and gasoline is necessary for two-cycle engines.

walls, bearing damage, or the piston to seize in the cylinder.

In preparing the mixture of gasoline and oil for most two-cycle engines, observe the following rules:

- Mix a good grade of regular gasoline (leaded or unleaded) and oil in a separate container. Do not mix in the gas tank unless it is a remote tank such as is found on many outboard motors.
- Pour the oil into the gasoline to ensure good mixing, and shake the container well. If poorly mixed, the oil settles to the bottom of the tank causing difficult starting.
- Strain the fuel with a fine mesh strainer when pouring it into the tank.
- Use the oil that is specified for the particular two-cycle engine, figures 5-17 and 5-18. Most manufacturers specify their own brand of two-cycle oil. In an emergency other oils may be used, usually SAE 30SB (formerly MM) or SAE 30SD (formerly MS) nondetergent oil. The manufacturer's brand, however, provides the best lubrication with a minimum of deposit formation.
- Mix gasoline and oil in the proportions recommended by the engine manufacturer. One common proportion is three-fourths pint of oil to one gallon of gasoline when breaking in a new engine, and one-half pint of oil to one gallon of gasoline for normal use.



Fig. 5-17 Proper mixing of oil and gasoline for this two-cycle portable generator is essential. (Courtesy of Johnson Motor Co.)

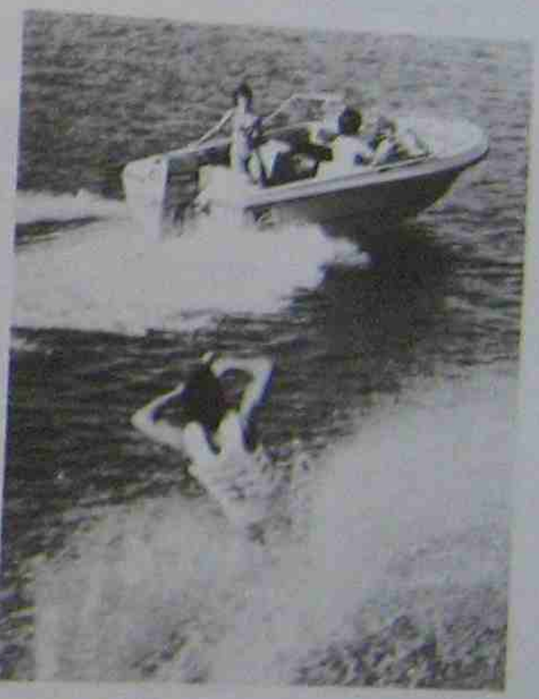


Fig. 5-18 Most outboard motors use two-cycle engines which require mixing of gasoline and oil. (Courtesy Johnson Motor Co.)

NOTE: Mixing proportions vary widely; check the engine's instruction book.

MIXING RATIOS

OUNCES TO BE MIXED WITH GASOLINE

For a Dilution Ratio of	Gallons of gasoline					
	1	2	3	4	5	6
	Ounces of Two-Cycle Oil					
24:1	5	11	16	21	27	32
20:1	6	13	19	26	32	38
16:1	8	16	24	32	40	48

Add oil to gasoline in proportions recommended by manufacturer.

ADDITIONAL LUBRICATION POINTS

Whether the engine has two-cycle or four-cycle lubrication, there may be other lubrication to consider besides the crankcase area. On an outboard engine do not neglect the lower unit which needs a special gear lubricant at several points, figure 5-19. If an engine is powering an implement or other machinery, there may be transmissions, gear boxes, chains, axles, wheels, shafts, and linkages that need periodic lubrication. Lubricate these additional parts with the oil or lubricant recommended by the manufacturer.

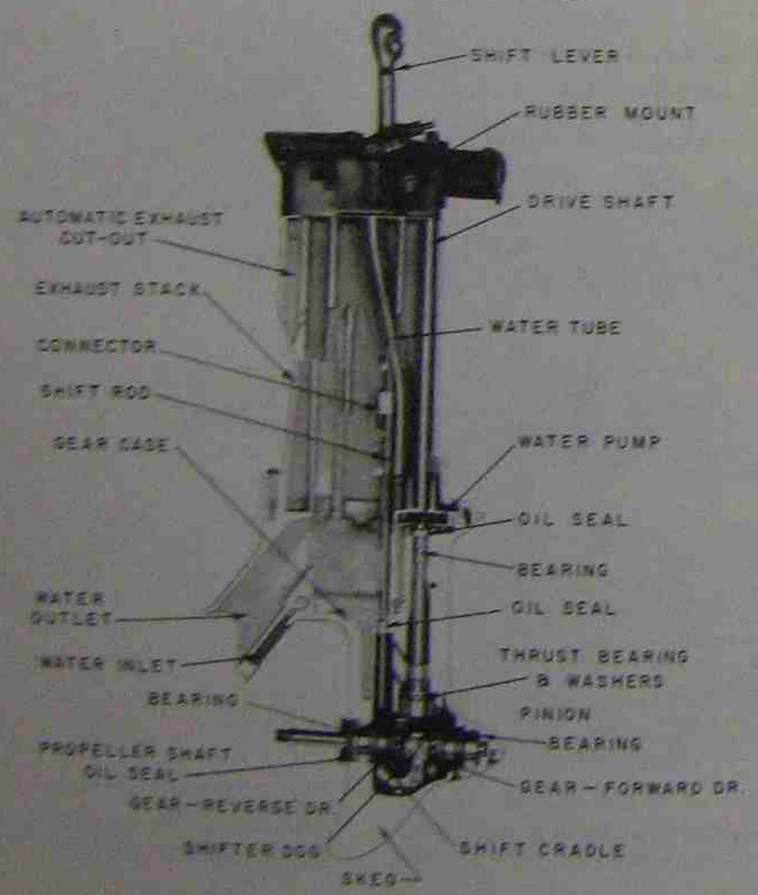


Fig. 5-19 Gear case – lower unit assembly

REVIEW QUESTIONS

1. What is the main job of a lubricant?
2. Explain how the lubricating oil also:
   a. Seals power
   b. Helps to dissipate heat
   c. Keeps the engine clean
   d. Cushions bearing loads
   e. Protects against rusting
3. What are the three types of friction bearings?
4. What is an antifriction bearing?
5. What does an oil's SAE number refer to?
6. What is a multigrade oil?
7. Explain how a detergent oil works.
8. What are the quality designations of oil?
9. List five common four-cycle engine lubrication systems.
10. How are cylinder walls lubricated?
11. Explain blow-by.
12. Briefly explain how two-cycle lubrication is accomplished.
13. What is one common proportion of gasoline to oil for two-cycle engines?
14. What kind of oil should be used for two-cycle engines?

Unit 6 Cooling Systems

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the construction of the water jacket and trace the path of cooling water through the engine.
- Explain the construction and operation of the water pump and trace the path of water through the pump.
- List the basic parts of the air-cooling system and trace the path of cooling air through the engine.

In internal combustion engines, the temperature of combustion often reaches over 4000° Fahrenheit, a temperature well beyond the melting point of the engine parts. This intense heat cannot be allowed to build up. A carefully engineered cooling system is, therefore, a vital part of every engine. A cooling system must maintain a good engine operating temperature without allowing destructive heat to build up and cause engine part failure, figure 6-1.

The cooling system does not have to dispose of all the heat produced by combustion. A good portion of the heat energy is converted into mechanical energy by the engine, benefiting engine efficiency. Some heat is lost in the form of hot exhaust gases. The cooling system must dissipate about one-third of the heat energy caused by combustion.

Engines are either air-cooled or water-cooled; both systems are in common use. Generally, air-cooled engines are used to power machinery, lawn mowers, garden tractors, chain saws, etc. The air-cooled system is usually lighter in weight and simpler; hence, its popularity for portable equipment, figure 6-2.

The water-cooled engine is often used for permanent installation or stationary power plants. Most automobile engines and outboard motors are water-cooled.

AIR-COOLING SYSTEM

The air-cooling system consists of heat radiating fins, flywheel blower, and shrouds for channeling the air. The path of airflow can be seen in figure 6-3.

Heat radiating fins are located on the cylinder head and cylinder because the greatest concentration of heat is in this area. The fins increase the heat radiating surface of these parts allowing the heat to be carried away to the atmosphere more quickly, figure 6-4.

The flywheel blower consists of air vanes cast as a part of the flywheel. As the flywheel revolves, these vanes blow cool air across the fins carrying away the heated air and replacing it with cool air.

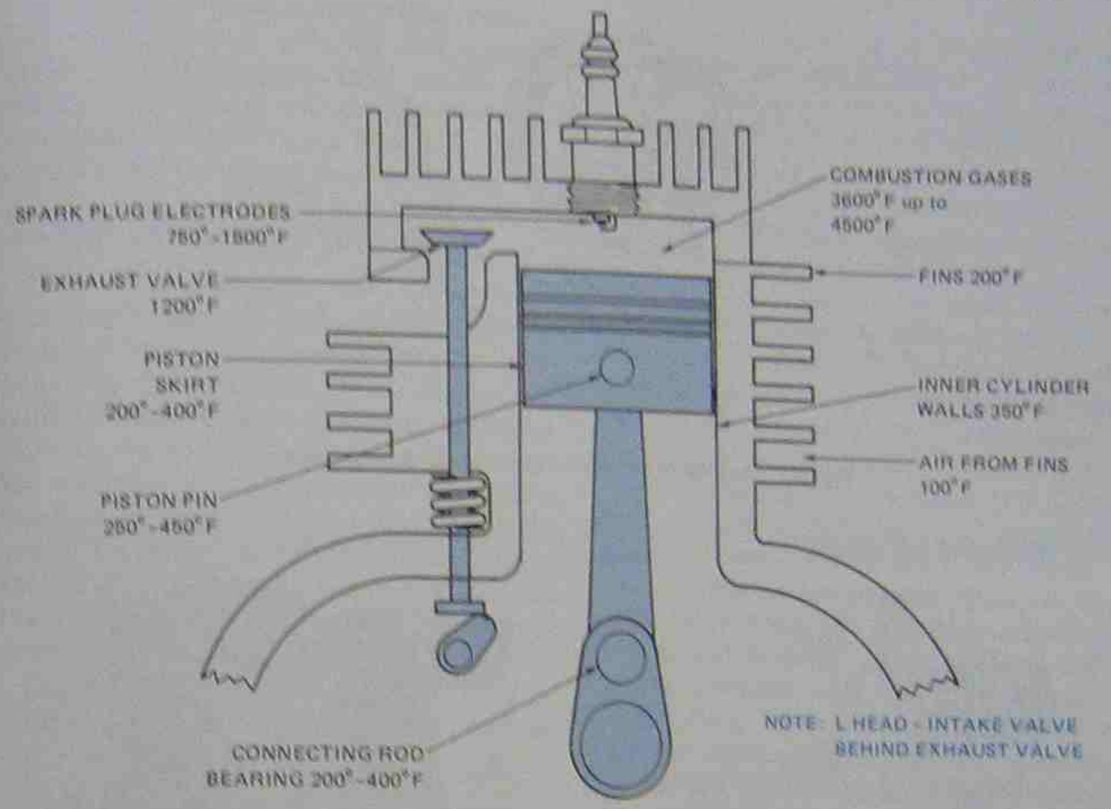


Fig. 6-1 Approximate engine operating temperatures

The shrouds direct the path of the cool air to the areas that demand cooling, figure 6-5. Shrouds must be in place if the cooling system is to operate at its maximum efficiency.

Care of the Air-cooling System

The air-cooling system is almost trouble free. Several points, however, should be considered. Heat radiating fins are thin and often fragile, especially on aluminum engines. If through carelessness they are broken off, a part of the cooling system is gone. Besides losing some cooling capacity, hot spots can develop which may warp the damaged area. Also, it is easy for dust, dirt, grass, and oil



Fig. 6-2 Dirt bikes use air-cooled engines as they are lighter in weight than water-cooled engines. (Courtesy Kawasaki Motor Corp USA)

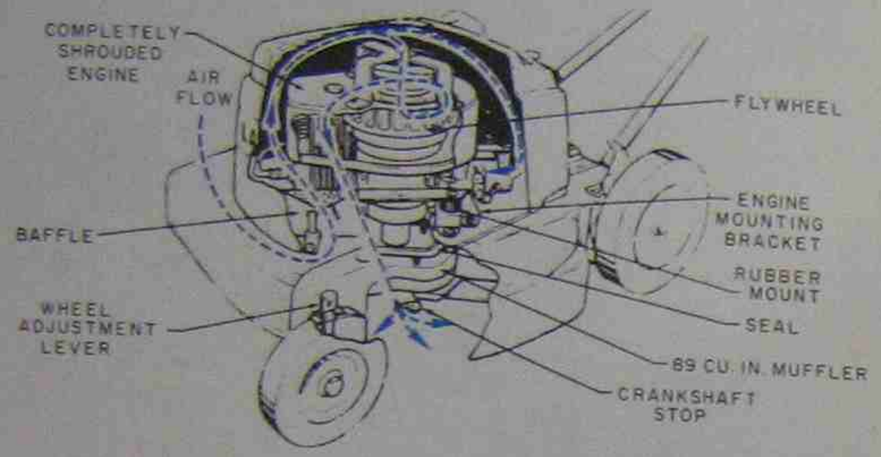
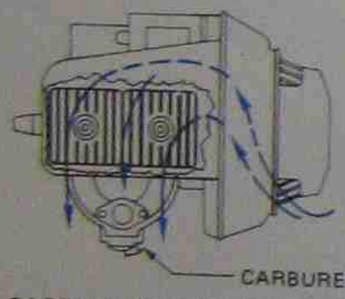


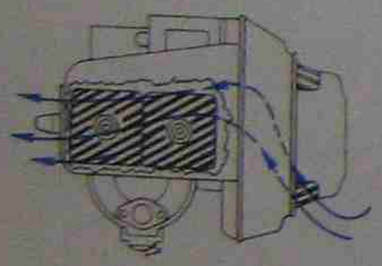
Fig. 6-3 The path of airflow on certain lawn mower engines

STRAIGHT FIN HEADS



CARBURETOR SIDE OUTLET

OBLIQUE FIN HEADS



TOP OR END OUTLET

Fig. 6-4 Airflow across the cylinder head fins

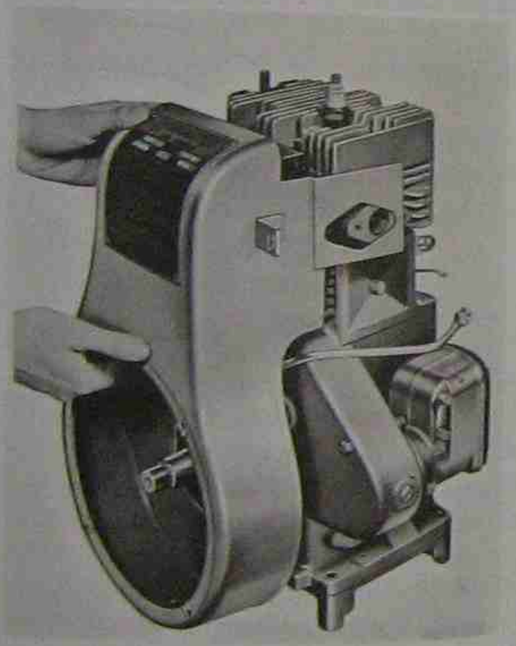


Fig. 6-5 The air shroud is an important part of the air-cooled engine. (Courtesy Wisconsin Motor Corp.)

to accumulate between the fins. Any buildup of foreign matter reduces the cooling system's efficiency. All parts of the system should be kept clean, especially the radiating fins.

The flywheel vanes should not be chipped or broken. Besides reducing the cooling capacity of the engine, such damage can destroy the balance of the flywheel. An unbalanced flywheel causes vibration and an excessive amount of wear on engine parts.

WATER-COOLING SYSTEM

Some small engines are water-cooled as are most larger engines. Such engines have an enclosed water jacket around the cylinder walls and cylinder head. Water jackets are relatively trouble free. However, damaging deposits can build up over a period of time. Salt corrosion, scale, lime, and silt can restrict the flow of water and heat transfer. Water jackets are found on most outboard motors and on the majority of automobile engines. Cool water is circulated through this jacket picking up the heat and carrying it away.

Figure 6-6 shows a cross section of water passage in the head and block. Water cooling systems often found on stationary small gas engines or automobile engines include the following basic parts: radiator, fan, thermostat, water pump, hoses, and water jacket.

The water pump circulates the water throughout the entire cooling system. The hot water from the combustion area is carried from the engine block and head to the radiator. In the radiator, many small tubes and radiating fins dissipate the heat into the atmosphere. A fan blows cooling air over the radiating fins. From the bottom of the radiator the cool water is returned to the engine.

Engines are designed to operate with a water temperature of between 160 degrees and 180 degrees Fahrenheit. To maintain the correct water temperature a thermostat is used in the cooling system. When the temperature is below the thermostat setting, the thermostat remains closed and the cooling water circulates only through the engine, figure 6-7A. However, as the heat builds up to the thermostat setting, the thermostat opens and the cooling water moves throughout the entire system, figure 6-7B.

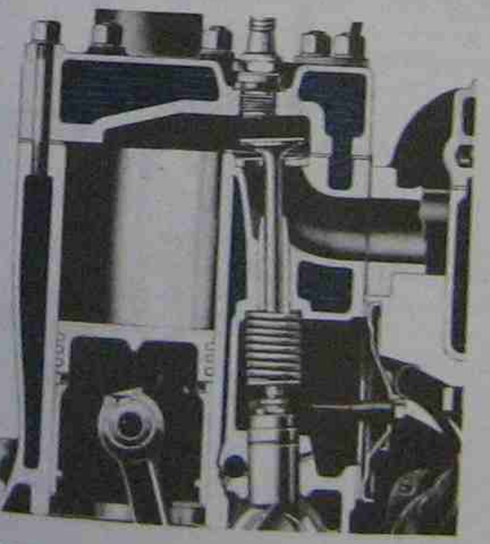


Fig. 6-6 Cross section showing water passages in head and block

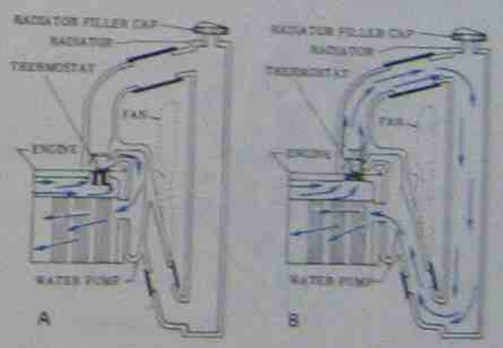


Fig. 6-7 (A) Thermostat closed: water recirculated through engine only. (B) Thermostat open: water circulated through both engine and radiator.

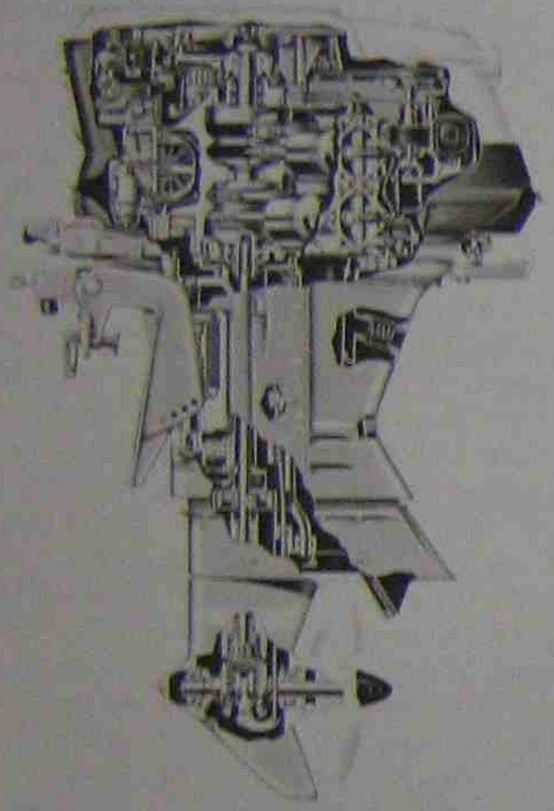


Fig. 6-8 Cutaway of an outboard motor (Courtesy Johnson Motors)

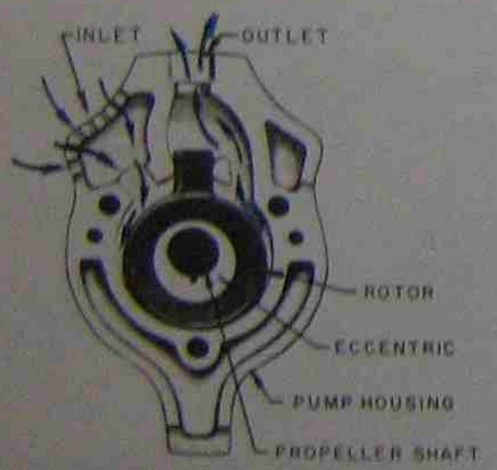


Fig. 6-9 An eccentric rotor water pump with the cover removed to show the eccentric and rotor

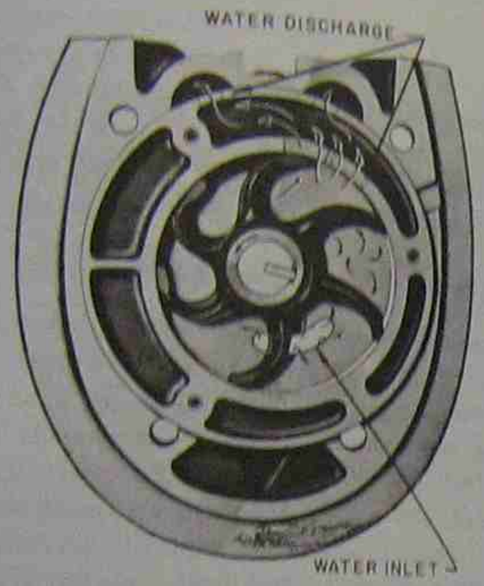


Fig. 6-10 An impeller water pump with the cover removed to show the impeller

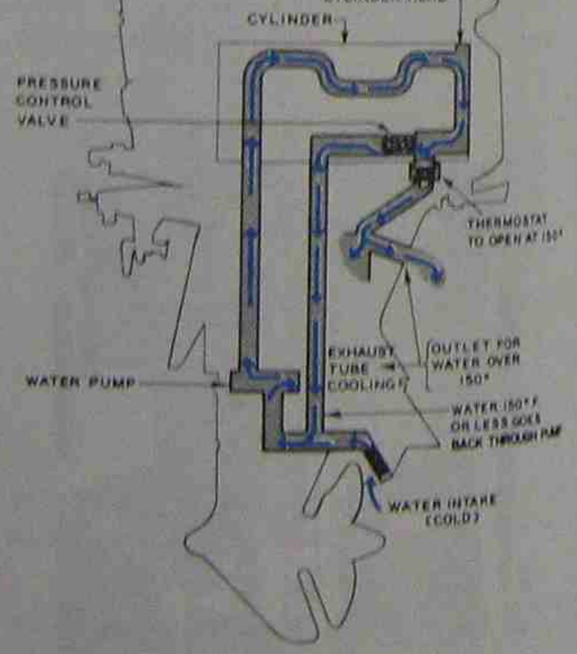


Fig. 6-11 A thermostatically controlled cooling system used on outboard engines

WATER COOLING THE OUTBOARD ENGINE

Cooling the outboard engine with water is a simpler process because there is an inexhaustible supply of cool water present where the engine operates. Outboards pump water from the source through the engine's water jacket and then discharge the water back into the source. A cutaway of an outboard motor is shown in figure 6-8.

The water pump on outboards is located in the lower unit. It is driven by the main driveshaft or the propeller shaft. The cool water is pumped up copper-tube passages to the water jacket. After the cooling water picks up heat, it is discharged into the exhaust area of the lower unit and out of the engine. Several types of water pumps are used on outboard motors. Plunger type pumps; eccentric rotor pumps, figure 6-9; and impeller pumps, figure 6-10, are some examples.

Many outboard motors, especially large horsepower models, are equipped with a thermostatically controlled cooling system, figure 6-11. The temperature of the water circulating through the water jacket is maintained at about 150° Fahrenheit.

REVIEW QUESTIONS

1. How high can the temperature of combustion reach?
2. Does the cooling system remove all the heat of combustion? Explain.
3. Why are air-cooling systems often used for portable equipment?
4. What are the main parts of the air-cooling system?
5. Why are cylinders and cylinder heads equipped with fins instead of being cast with a smooth surface?
6. What are the basic parts of the water-cooling system found on stationary small gas engines?
7. What is the function of the thermostat?
8. What are several types of water pumps used on outboard motors?

Unit 7 Ignition Systems

OBJECTIVES After completing this unit, the student should be able to:

- Discuss electron theory and magnetism.
- Discuss how the basic parts of the magneto are constructed and how they are mounted on the engine.
- Explain the complete magneto cycle.
- Discuss spark advance.
- Discuss solid state ignition.
- Discuss battery ignition systems.

Small gasoline engines normally use a magneto for supplying the ignition spark. A *magneto* is a self-contained unit that produces the spark for ignition, figure 7-1. No outside source of electricity is needed to produce the spark for ignition. The magneto is a simple and very reliable ignition system. On small gas engines that do not have electric starters, lighting systems, radios, and other electrical accessories, a storage battery is not necessary. The magneto is, therefore, ideally suited for these small gasoline engines.

The basic parts of the magneto ignition system are the: permanent magnets, high-voltage coil (primary and secondary windings), laminated iron core, breaker points, breaker cam, condenser, spark plug cable, and spark plug. Before discussing how these parts work together, a review is given of some essentials of electricity and magnetism which explains the construction and function of each individual part.

ELECTRON THEORY

All matter is composed of tiny particles called atoms. The atom is composed of electrons, protons, and neutrons, figure 7-2. The number and arrangement of these particles determines the type of atom: hydrogen, oxygen, carbon, iron, lead, copper, or any other element. Weight, color, density, and all other characteristics of an element are determined by the structure of the atom. Electrons from an atom of copper are the same as electrons from any other element.

The electron is a very light particle that spins around the center of the atom. Electrons move in an orbit. The number of electrons orbiting around the center or nucleus of the atom varies from element to element. The electron has a negative (–) electrical charge.

The proton is a very large and heavy particle in relation to the electron. One or more protons form the center or nucleus of the atom. The proton has a positive (+) electrical charge.

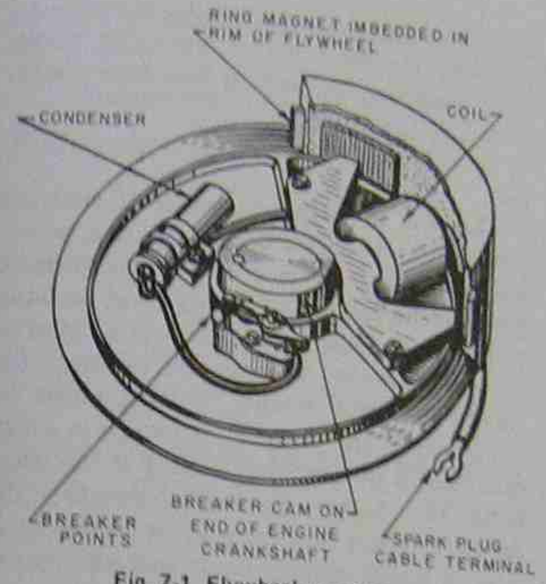


Fig. 7-1 Flywheel magneto

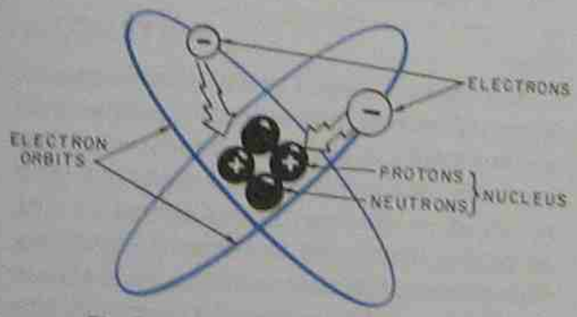


Fig. 7-2 Atomic structures: electron, proton, and neutron

The neutron consists of an electron and proton bound tightly together. Neutrons are located near the center of the atom. The neutron is electrically neutral; it has no electrical charge.

Atoms are normally electrically neutral; that is, the number of electrons and protons

are the same, cancelling out each other's electrical force. Atoms stay together because, unlike electrical charges, they attract each other. The electrical force of the protons holds the electrons in their orbits. Like electrical charges repel each other, so negatively charged electrons do not collide with each other.

In most materials, it is very difficult, if not impossible, for electrons to leave their orbit around the atom. Materials of this type are called nonconductors of electricity or *insulators*. Some typical insulating materials are glass, mica, rubber and paper. Electricity cannot flow through these materials easily.

In order to have electric current, electrons must move from atom to atom. Insulators do not allow this electron movement. However, in many substances, an electron can jump out of its orbit and begin to orbit in an adjoining or nearby atom. Substances which permit this movement of electrons are called *conductors* of electricity. Some typical examples are copper, aluminum, and silver.

Electron flow in a conductor takes place when there is a difference in electrical potential and there is a complete circuit or path for electron flow, figure 7-3. In other words, when the source of electricity is short of electrons, it is positively charged. Since unlike charges attract each other, electrons (being negatively charged) move toward the positive source.

A source of electricity can be produced or seen in several basic forms: mechanical, chemical, static, and thermal. Electricity is produced mechanically in the electrical generator which is commonly connected to water power or steam turbines. The electricity used in homes and factories is produced mechanically. In the magneto, mechanical energy is

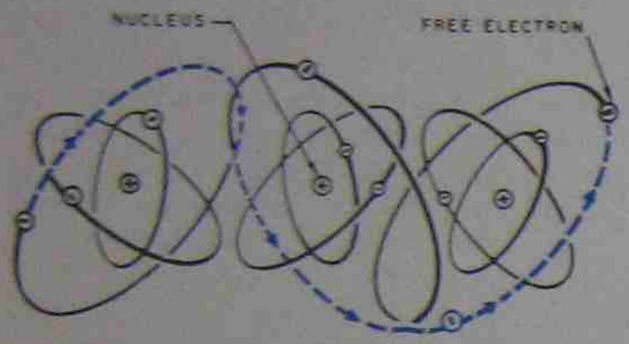


Fig. 7-3 Current: flow of electrons within a conductor

used to rotate the permanent magnet. Electricity produced by chemical action is seen in the storage battery and dry cell. Static electricity can be seen in nature when lightning strikes. The lightning occurs when the air insulation breaks down and electrons are in a positive area. The lightning may be between clouds, from cloud to earth, or from earth to cloud.

UNITS OF ELECTRICAL MEASUREMENT

There are three basic units of electrical measurement: *ampere* (rate of electron flow), *volt* (force or pressure causing electron flow), and *ohm* (resistance to electron flow).

Ampere

The *ampere* is the measurement of electrical current – the number of electrons flowing past a given point in a given length of time. If a person stands at a point on a wire and could count the electrons passing by in one second, 6,280,000,000,000,000,000 (6.28×10^{18}) electrons would be counted, which equals one ampere of current. To help visualize amperage, think of water flowing in a pipe. A small pipe might deliver two gallons of water a minute. A larger pipe might deliver five gallons of water a minute. Electric wires are generally the same; larger wires can handle more amperage or electron flow than smaller wires.

Volt

The *volt* is the measurement of electrical pressure or the difference in electrical potential that causes electron flow in an electrical circuit. The energy source is short of electrons and the electrons in the circuit want to go to the source. The pressure to satisfy the source is called *voltage*. Voltage might be compared to the pressure that water in a high tank places on the pipe located at the street level. The higher the water pressure, the faster the water flow from a pipe below. Likewise, a higher voltage tends to cause greater flow of electrons.

Ohm

The *ohm* is the unit of electrical resistance. Every substance puts up some resistance to the movement of electrons. Insulators such as porcelain, oils, mica, and glass put up a great resistance to electron flow. Conductors such as copper, aluminum and silver put up very little resistance to electron flow. Even though conductors readily permit the flow of electric current they do tend to put up some resistance. In the water pipe example, this resistance can be seen as the surface drag by the sides of the pipe, or scale and rust in the pipe. Using a larger pipe or, electrically, a larger wire is one way of reducing resistance.

OHM'S LAW

In every example of electricity flowing in an electrical circuit, amperes, volts, and ohms each play their part; they are related to each other. This relationship is stated in *Ohm's Law*.

$$\text{Amperes (rate)} = \frac{\text{volts (potential)}}{\text{ohms (resistance)}}$$

The formula is usually abbreviated to:

$$I = \frac{E}{R}$$

For example, if the voltage is 6 and the resistance is 12 ohms, the current is calculated as follows.

$$I = \frac{E}{R} \quad I = \frac{6}{12} \quad I = 0.5 \text{ amperes}$$

The formula can be written to find the resistance, or the voltage.

$$R = \frac{E}{I} \qquad E = I\,R$$

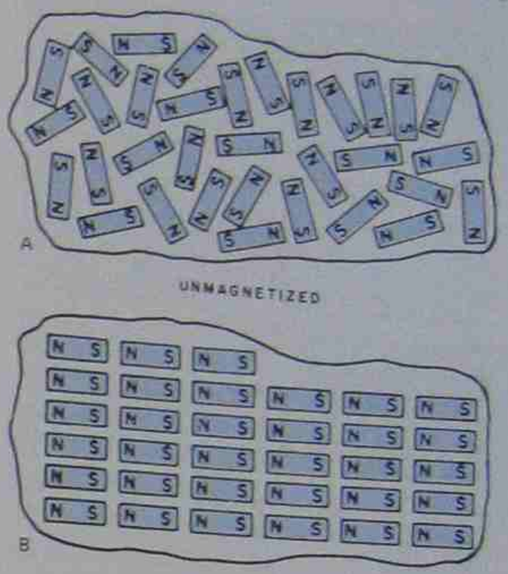


Fig. 7-4 In an unmagnetized bar the molecules are in a random pattern. In a magnetized bar the molecules align their atomic poles.

MAGNETISM

Most people have experimented with a magnet at one time, watching it pick up steel objects and attracting or repelling another magnet. These effects are not entirely explained but scientists generally agree on the molecular theory of magnetism. Molecules are the smallest divisions of substance that are still recognizable as that substance. Several different atoms may make up one molecule. For example, a molecule of iron oxide contains atoms of iron and oxygen. In many substances the atoms in the molecules are more positive at one spot and more negative at another spot. This is termed a *north pole* and a *south pole*. Usually the poles of adjoining molecules are arranged in a random pattern and there is no magnetic force since their effects cancel one another, figure 7-4A. However, in some substances such as iron, nickle, and cobalt the molecules are able to align themselves so that all north poles point in one direction and all south poles point in the opposite direction, figure 7-4B. The small magnetic forces of many tiny molecules combine to make a noticeable magnetic force. In magnets, like poles repel each other and unlike poles attract each other just as like and unlike electrical charges react, figure 7-5. Electricity and magnetism are very closely tied together.

Some substances keep their molecular alignment permanently and are classed as *permanent magnets*. Hard steel has this ability. Other materials such as a piece of soft iron (a nail), can attain the molecular alignment of a magnet only when it is in a magnetic field. As soon as soft iron is removed from the magnetic field, its molecules dis-

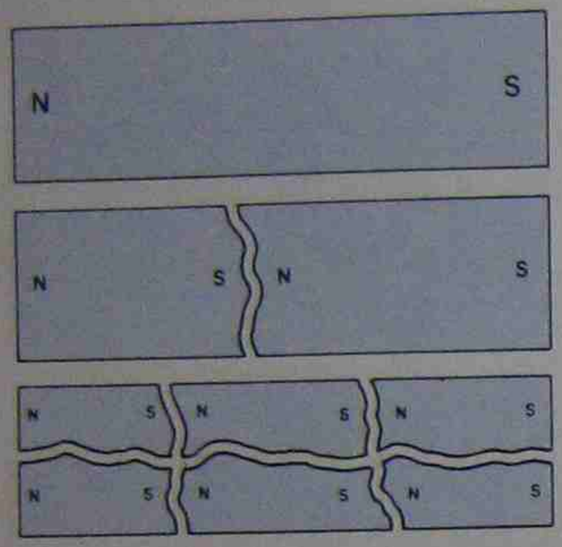


Fig. 7-5 A magnetic field surrounds every magnet. Like poles repel each other; unlike poles attract each other.

arrange themselves and the magnetism is lost. Such substances are termed *temporary magnets*.

More than 100 years ago Michael Faraday discovered that magnetism could produce electricity. Magnetos used on gasoline engines apply this discovery. Faraday found that if a magnet is moved past a wire, electrical current starts through the wire. If the magnet is stopped near the wire, the current stops. Electricity flows only when the magnetic

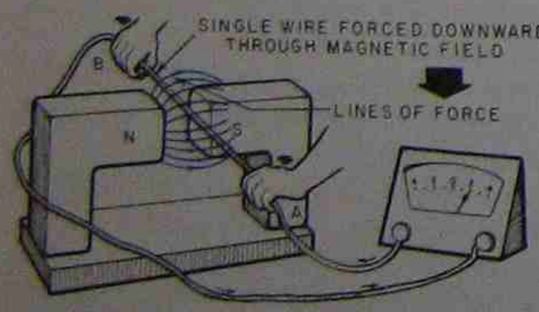


Fig. 7-6 Current flows in the wire as it moves down through the magnetic field.

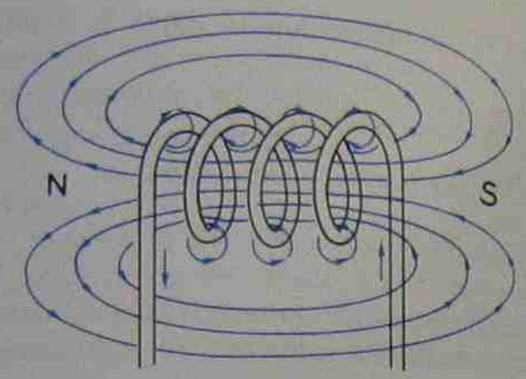


Fig. 7-7 When electricity flows through a coil of wire, a magnetic field is set up around the coil.

field or magnetic lines of force are being cut by the wire, figure 7-6.

Another principle that the magneto uses is that when electrons flow through a coil of wire, a magnetic field is set up around the coil, figure 7-7. The coil itself becomes a magnet. Therefore, when electrons flow through the coils in a magneto, a magnetic field is set up.

TRANSFORMERS

The principle of the transformer and induced voltage is also used in the magneto. In a transformer there is a primary coil and a secondary coil wound on top of the primary; the two are insulated from each other, figure 7-8. These coils are wound on a soft iron core. When alternating current passes through the primary coil there is an alternating magnetic field set up in the iron core. The magnetic lines of force cut the secondary coil and induce an alternating voltage within the coil. The voltage produced depends on the ratio of windings in the primary coil and secondary coil. If there are more windings in the secondary than in the primary, the secondary voltage is higher; a *step-up transformer*. If there are more windings in the primary than in the secondary, the secondary voltage is smaller; a *step-down transformer*. Although the magneto does not operate on alternating current, it does use the principle of the step-up transformer.

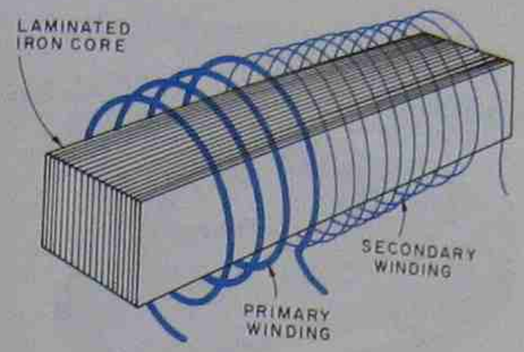


Fig. 7-8 A simple transformer

In a small gasoline engine magneto, there is a magnetic field which induces current in the primary coil, thus setting up a magnetic field around both the primary and secondary coils. At the point of maximum current, the circuit is broken in the primary. Electrons can no longer flow; therefore, the magnetic field collapses. This rapidly collapsing magnetic field induces a very high voltage in the secondary coil igniting the fuel mixture.

Before studying in detail how the magneto operates, it is useful to understand the function of each part. The seven basic parts which work together to produce the ignition spark are the permanent magnets, high-voltage coil, laminated iron core, breaker points, condenser, spark plug lead, and spark plug. An example of a magneto ignition system is shown in figure 7-9.

PERMANENT MAGNETS

Permanent magnets are usually made of an alloy called *alnico*, a combination of aluminum, nickle, and cobalt. This magnet is quite strong and keeps its magnetism for a very long time. On a flywheel magneto the magnet is cast into the flywheel and cannot be removed. The other magneto parts are often mounted on a fixed plate underneath the flywheel. The magnet revolves around the other parts of the magneto. Sometimes the other magneto parts are mounted near the outside rim of the flywheel and the permanent magnets pass by each revolution.

Rotor-type permanent magnets are also in use, figure 7-10. With this type of construction the permanent magnet rotor may be mounted on the end of the crankshaft or the rotor may be geared to the crankshaft. The rotor lies within the other magneto parts.

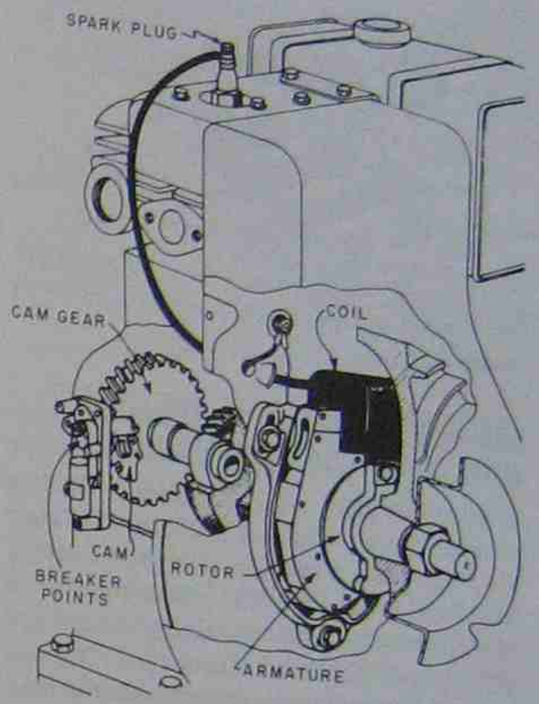


Fig. 7-9 The basic parts of a magneto ignition system

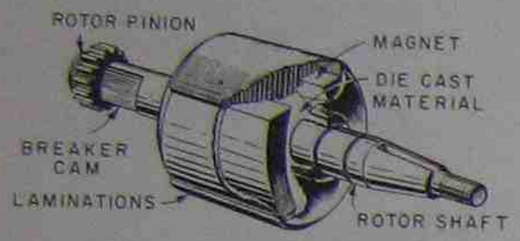


Fig. 7-10 Rotor-type permanent magneto

Care should be taken not to drop or pound the magnet as this causes it to lose some of its magnetism.

HIGH-VOLTAGE COIL (PRIMARY AND SECONDARY WINDINGS)

Refer to figure 7-11. The primary winding of wire consists of about 200 turns of a heavy wire (about 18 gauge) wrapped around a laminated iron core. The primary coil is in the electrical circuit containing the breaker points and condenser, figure 7-12. When a magnet is brought near this coil and iron core, magnetic lines of force cut the coil and electrical current is produced. Usually this current flows from the coil through the closed breaker points and is grounded. This makes a complete circuit.

The secondary winding of wire consists of about 20,000 turns of a very fine wire wrapped around the primary coil. The secondary coil is in the electrical circuit containing the spark plug. When current flows in the primary, a magnetic field gradually expands around both coils. However, voltages produced in the secondary are quite small because of the high resistance of the small diameter secondary windings. When the breaker points open, the circuit is broken, electricity stops flowing and the magnetic field suddenly collapses. The suddenly collapsing magnetic field induces

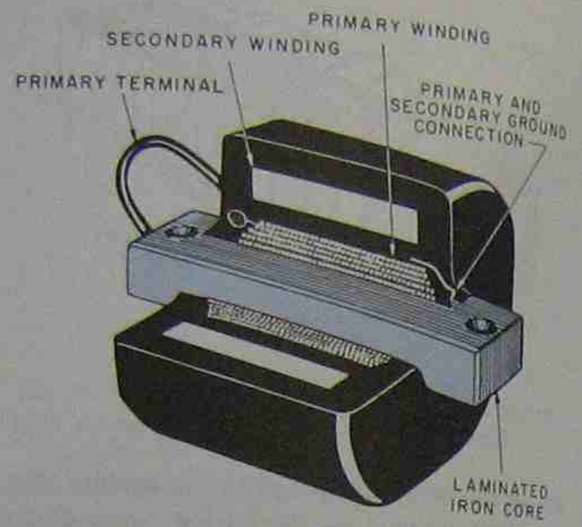


Fig. 7-11 Construction of a high-tension magneto ignition system

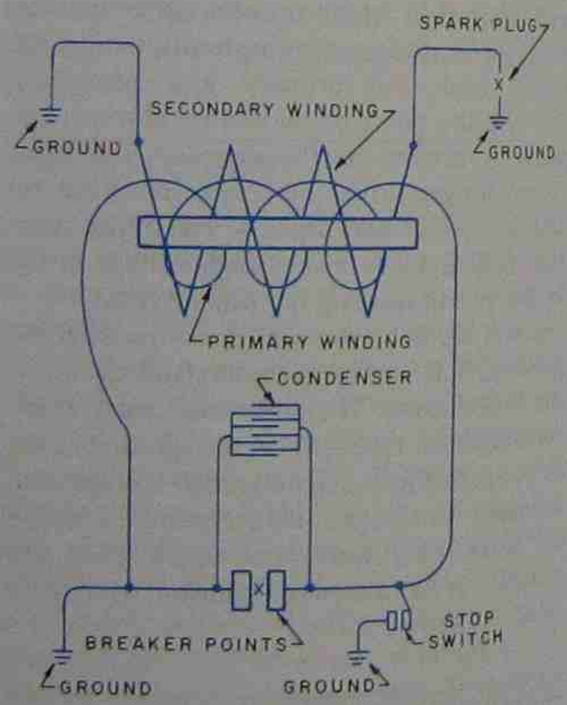


Fig. 7-12 Schematic wiring diagram of a magneto

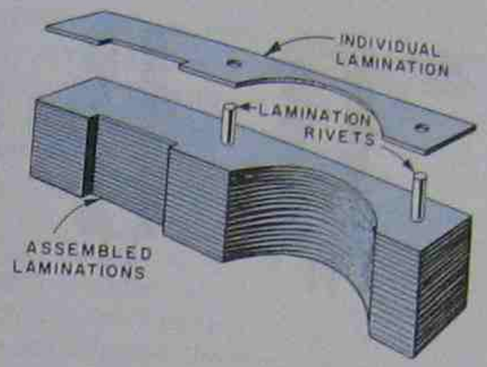


Fig. 7-13 Laminated iron core

very high voltage in the secondary coil which is enough to jump the spark gap in the spark plug.

LAMINATED IRON CORE

The laminated iron core is made of many strips of soft iron fastened tightly together, figure 7-13. The soft iron core helps to strengthen the magnetic field around the primary and secondary coils, but the core cannot retain the magnetism and become permanently magnetized. The purpose of using many strips instead of a solid core is to reduce eddy currents (stray currents that try to flow in the opposite direction) which create heat in the core. The general shape of the laminated core may vary from magneto to magneto but its function remains the same.

BREAKER POINTS

The breaker points are made of tungsten and mounted on brackets, figure 7-14. The two points are usually closed or touching each other providing a path for electron flow. However, just before the spark is desired, the breaker points are opened by cam action

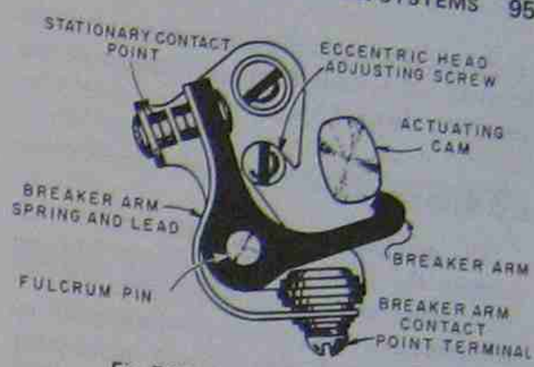


Fig. 7-14 Breaker point assembly

breaking the electrical circuit. Breaker points open and close anywhere from 800 times per minute to 4500 or more times per minute depending on the engine speed.

When the breaker points are open they are usually separated by 0.020 of an inch; the exact opening varies from magneto to magneto. This separation is critical to the function of the magneto. Therefore, the breaker point gap must be adjusted correctly.

BREAKER CAM

The breaker cam actuates the breaker points. One bracket of the breaker assembly rides on this cam. As the cam rotates, it opens and closes the breaker points.

On most two-cycle engines, this cam is mounted on the crankshaft and opens the normally closed breaker points once each revolution. On most four-cycle engines, the breaker cam is mounted to operate from the camshaft which is turning at one-half crankshaft speed. By mounting the breaker points here, they open once every two revolutions of the crankshaft. This provides a spark for the power stroke but none for the exhaust

stroke. The shape of the cam depends on the number of cylinders and the design of the magneto, figure 7-15.

CONDENSER

The condenser acts as an electrical storage tank in the primary circuit, figures 7-16 and 7-17. When the breaker points open quickly, the electrons tend to keep flowing. If no condenser was present, a spark could jump across the breaker points. If this happened, the breaker points would soon burn up resulting in a weakening effect on the voltage produced by the magneto secondary coil. The condenser provides an electrical storage



Fig. 7-15 Common breaker cam shapes

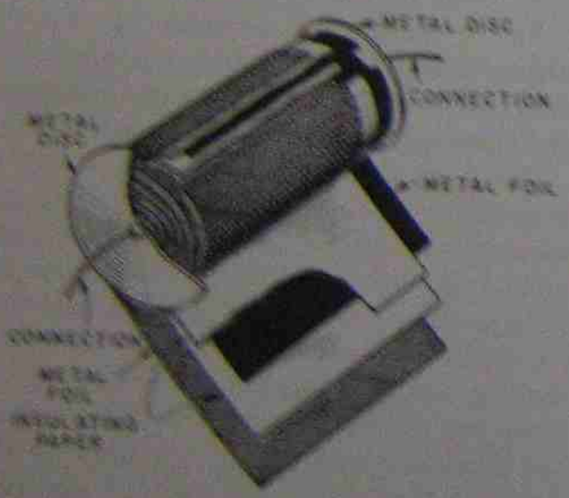


Fig. 7-16 Cutaway showing the construction of a condenser

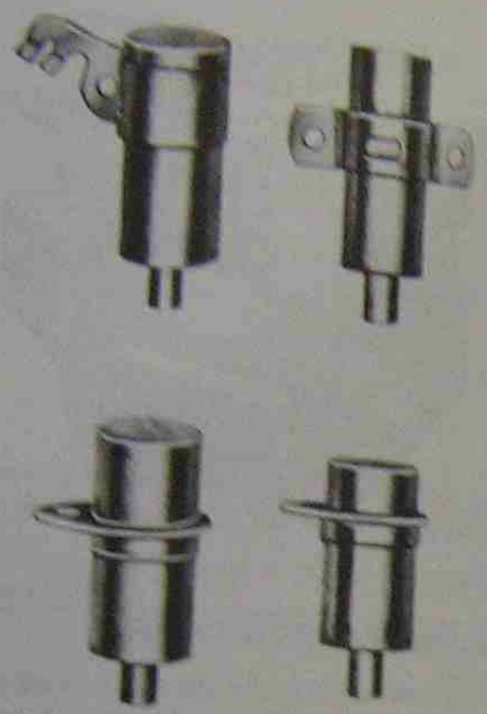


Fig. 7-17 Typical condensers

tank for this last surge of electron flow. The action of the condenser provides for a very abrupt interruption of the primary circuit. The condenser's discharge helps to induce high voltages in the secondary coil as the magnetic fields reverse. The condenser can be easily located because it usually looks like a miniature tin can.

SPARK PLUG CABLE

The spark plug cable connects the secondary coil and the spark plug providing a path for the high-tension voltage. This part is often referred to as the high-tension lead.

SPARK PLUG

The spark plug is a vital part of the ignition system. In this part the resulting work of the magneto parts is seen. Basically, the spark plug consists of a shell, ceramic insulator, center electrode, and ground electrode. The two electrodes are separated by a gap of about 0.035 of an inch. The path of electricity is down the center electrode and across the air gap to the ground electrode. The voltage must jump the air gap. When a high-tension voltage of about 20,000 volts is reached, a spark jumps between the electrodes. This spark ignites the fuel mixture within the combustion chamber.

THE COMPLETE MAGNETO CYCLE

Refer to figure 7-18 for illustrations of the steps in the magneto cycle. When the permanent magnet is far away from the high-tension coil, it has no effect on the coil. As the permanent magnet comes closer and closer, the primary coil feels the increasing magnetic field; the coil is being cut by magnetic lines of force. Therefore, electrons flow in the primary coil. This current passes through the breaker points and into the ground. When the permanent magnet is nearly opposite the high-voltage coil the magnetic field around both coils is reaching its peak. Also, the piston is reaching the top of its stroke compressing the fuel mixture.

At this time, the position of the permanent magnet causes the polarity of the laminated iron core and the coils to reverse direction. This change of direction is momentarily choked or held back by the coil. The breaker points then open interrupting the current flow and allowing the reversal and rapid collapse of the intense magnetic field that had been built up around the primary and secondary coils. Magnetic lines of force are cutting coils very rapidly and high voltages are

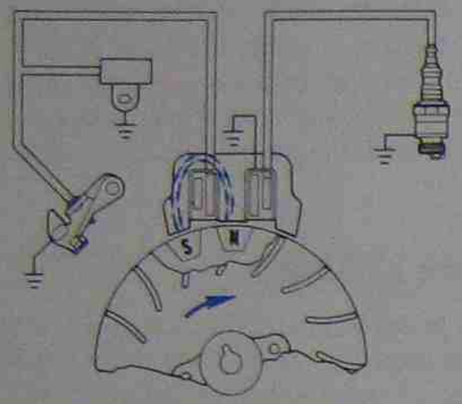
induced in the coils. In the secondary coil, the voltage may reach 18,000 to 20,000 volts which is enough to jump across the spark gap in the spark plug. This spark ignites the fuel mixture and the piston is forced down the cylinder.

SPARK ADVANCE

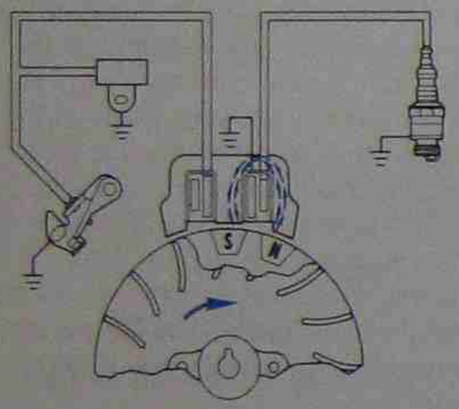
When fuel burns in the combustion chamber, it does not exert all of its power immediately. A very short period of time is required for the fuel to ignite and reach its full power. Even though this time lag is very short, it is very important in an engine operating at high speeds. For example, if the mixture was not ignited until the piston reached top dead center, the piston would already be starting back down the cylinder before the full force of the burning fuel is reached. This results in loss of power. Therefore, it is necessary to ignite the fuel slightly before the piston reaches the top of its stroke to realize the full force of combustion. Causing the spark to occur earlier in the engine cycle is called *spark advance*.

The spark is advanced more and more as the engine speed increases because there is less time for combustion to take place. For example, in a four-cycle engine operating at 2000 rpm, each power stroke takes about 1/64 of a second. If the speed is increased to 4000 rpm, each power stroke takes only 1/128 of a second. If the speed is doubled, there is only one-half as much time for combustion to take place. Also, high speeds give the engine higher compression and a more forceful mixture. At high speeds the spark jumps the spark gap before the piston reaches the top of its stroke.

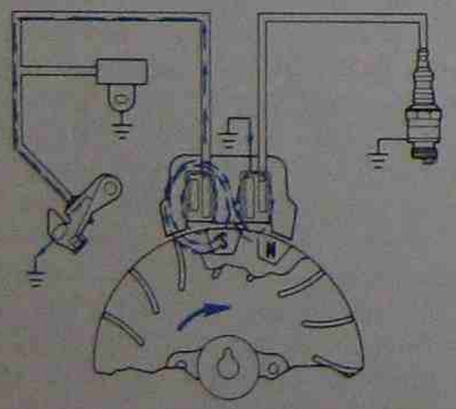
At slow speeds the spark is delayed and occurs later in the cycle, slightly before the



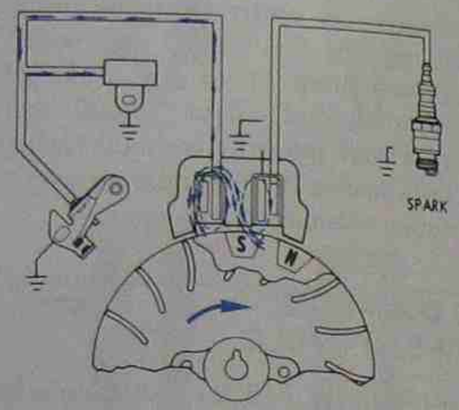
(A) Magnetic field as magnets approach the coil and laminated core



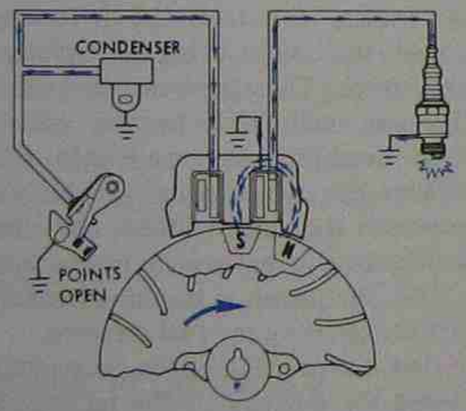
(B) Polarity of magnetic fields reverses rapidly



(C) Current flows in the primary circuit as magnetic fields reverse



(D) Current stops as breaker points open



(E) Collapsing magnetic fields and condenser surge induces high voltage to jump the gap at the spark plug

Fig. 7-18 The magneto cycle

piston reaches top dead center. At slow speeds there is more time for combustion to take place. Also, compression is lower and not as much air/fuel mixture is drawn into the combustion chamber.

Regulating spark advance is done by controlling the time that the breaker points open. Advancing the spark can be done automatically or manually. Both methods are used on some small gasoline engines.

MANUAL SPARK ADVANCE

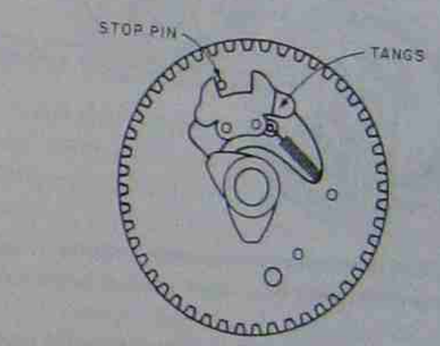
Manual spark advance is usually accomplished by loosening the breaker point assembly and rotating it slightly to an advanced position. It is then locked in its new position.

Many outboard motors have a type of manual spark advance although it is generally referred to by manufacturers as a spark-gas synchronization system. The magneto plate on which the breaker points are mounted is located underneath the flywheel. This plate can be rotated through about 25 degrees. The breaker cam is securely mounted on the crankshaft; its relative position cannot be changed. Spark advance is obtained by moving the magneto plate so the breaker points are opened earlier in the cycle. The throttle and magneto plates are linked together so that opening the throttle also advances the spark. At full throttle the spark is fully advanced. At idling speeds the throttle is closed and the magneto plate is positioned for minimum spark advance.

AUTOMATIC SPARK ADVANCE

Automatic spark advance is usually accomplished by a centrifugal mechanism which is capable of changing the relative position of the breaker cam and the breaker points, figures 7-19 and 7-20. Here the breaker cam can be rotated through a small distance on its shaft, about 25 degrees. A spring holds the cam in the retarded position at idling and slow speeds. As the engine speed increases, centrifugal force throws the mechanism's hinged weights outward. This outward motion overcomes the spring's tension and this motion is used to rotate the cam to a more advanced position. At full speed the cam has been rotated its full limit for maximum spark advance.

Some engines, especially automotive types, also have a vacuum advance mechanism working with a centrifugal mechanism to provide more accurate spark advance, especially at slow speeds. Automatic spark advance can



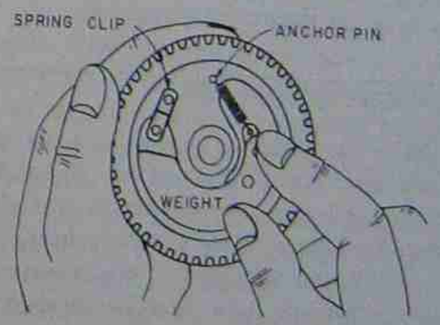


Fig. 7-19 Spark advance mechanism with breaker cam and weight mounted on the camshaft gear

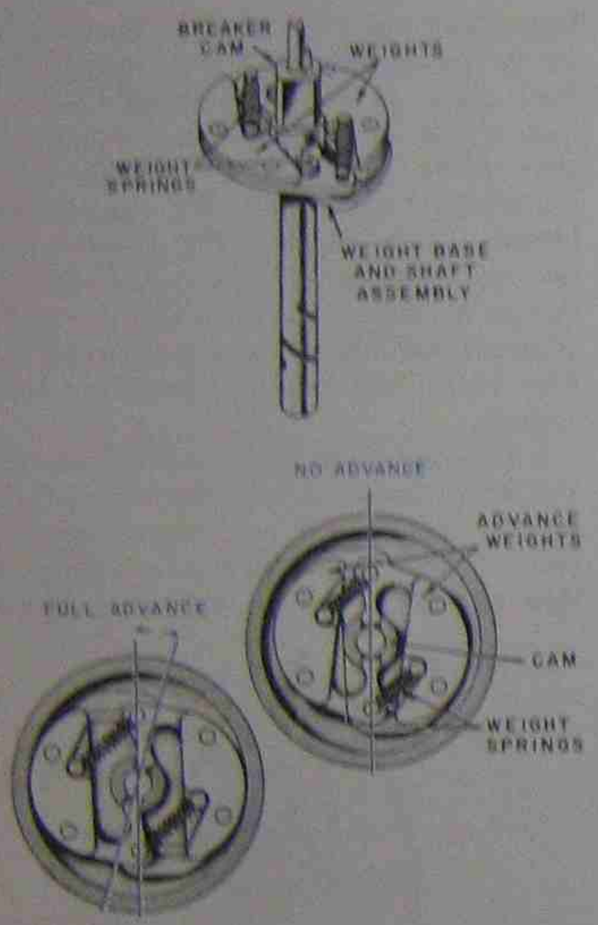


Fig. 7-20 Automatic spark advance mechanism changes the breaker cam's position in relation to the points

also be used to move the breaker point assembly to secure the proper advance.

IMPULSE COUPLING

When an engine is started by hand, it is turned over slowly. The voltages produced by the magneto depend upon the speed at which magnetic lines of force cut the primary coil. Therefore, the voltages produced for starting can be quite low, resulting in a weak spark.

Some engines are equipped with an impulse coupling device to supply higher voltages and a hotter spark for slow starting speeds. Using a tight spring and retractable pawls the rotation of the magneto's magnetic rotor can be stopped for all but the last few degrees of its revolution, figure 7-21. During the last few degrees of the revolution, the pawl retracts allowing the spring to snap the magnetic rotor past the firing position at a very high speed. A high voltage can be produced because magnetic lines of force are cutting the primary coil rapidly.

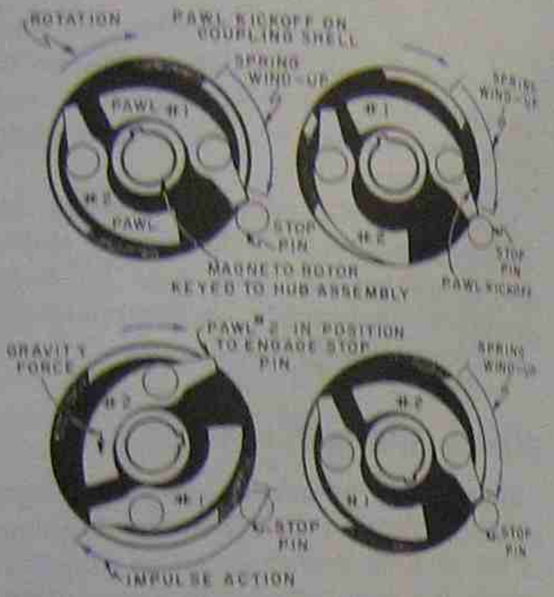


Fig. 7-21 Sequence of operation for impulse coupling for 180 degrees spark magneto

MAGNETO IGNITION FOR MULTICYLINDER ENGINES

Magnetos are often used for multicylinder engines. However, having more than one cylinder to supply with a spark does present a problem. Two solutions to this problem are in common use today.

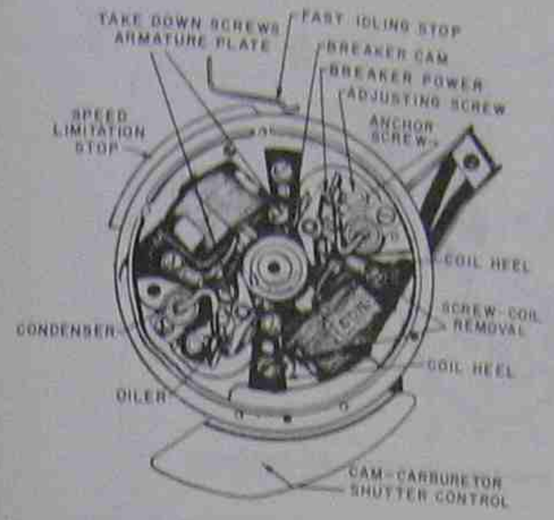


Fig. 7-22 Two complete magnetos are installed on this armature plate.

Two-, three- and four-cylinder engines can have magneto ignition by simply installing a separate magneto for each cylinder. This method is commonly used with outboard engines using a flywheel magneto. Instead of mounting just one magneto on the armature plate under the flywheel, a magneto is installed for each cylinder, figure 7-22. The breaker points of each magneto ride on the common cam. In two-cylinder engines the magnetos are 180 degrees apart; three-cylinder engines 120 degrees apart; and four-cylinder engines 90 degrees apart. Each magneto functions separately to supply its cylinder with a spark.

Another solution is to use a distributor and a two-pole or four-pole magnetic rotor, figure 7-23. Only one complete magneto is used even though the engine may have two or four cylinders. In the case of a two-pole rotor used on a two-cylinder engine, the magneto can produce two sparks every revolution of the magnetic rotor, one every 180 degrees rotation. A two-lobed cam is used to open the breaker points twice each rotor revolution. The distributor rotor channels the high-tension voltage to the correct spark plug.

ENGINE TIMING

The spark must jump the spark gap at exactly the right time. This is just before the piston reaches top dead center. In many engines, the breaker cam is driven by the camshaft, therefore, the gear on the crankshaft and the camshaft gear must be assembled correctly. These two gears are usually marked with punch marks so the repairer can easily make the correct assembly, figure 7-24. Incorrect alignment of the gears can cause poor operation or no operation at all.

SOLID STATE IGNITION

Solid state ignition refers to the fact that solid state electronic parts (namely transistors), replace the breaker points. The breaker points in a conventional ignition system can be a source of trouble. The breaker cam is also eliminated so there are no moving parts in the system. Sometimes the systems are called *capacitor discharge systems, breakerless ignition, transistorized ignition* or *electronic ignition.* These systems can be used with just a conventional flywheel magnet as the source of the magnetic force, or they may be used with a generator or an alternator battery system.

The main components of the solid state ignition system are a generator or alternator coil, trigger module, ignition coil assembly, and flywheel magnets. The system has a conventional spark plug and spark plug lead. A

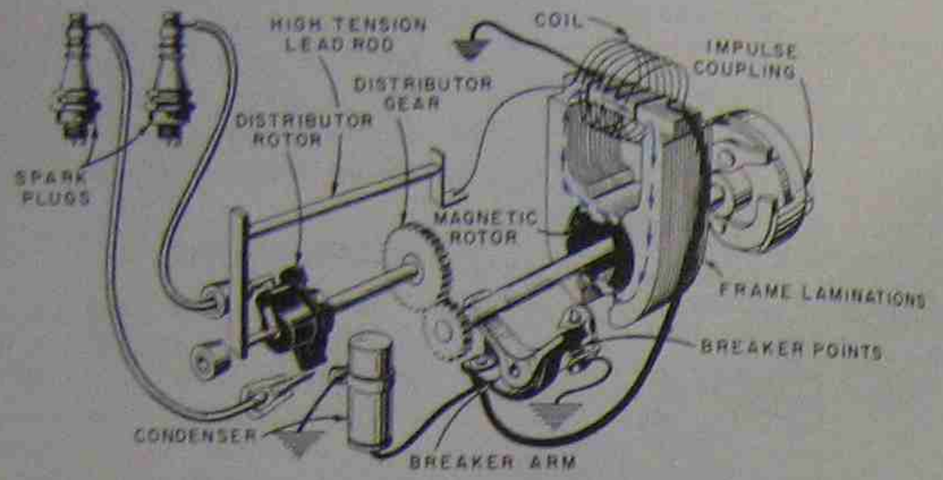


Fig. 7-23 Diagram of rotating-magnet magneto with jump-spark distributor

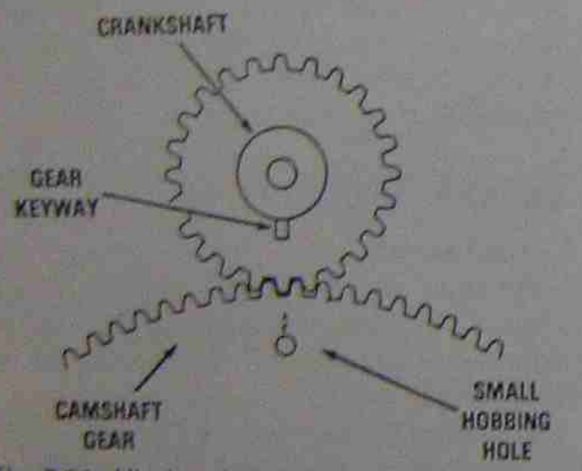


Fig. 7-24 Aligning timing marks on the crankshaft gear and camshaft gear. Notice the larger camshaft gear revolves at one-half crankshaft speed.

schematic drawing of a solid state ignition system is shown in figure 7-25.

The trigger module contains transistor diodes which rectify the alternating current, changing it into direct current. Transistors control the flow of electric current by acting somewhat like a valve. Their resistance to flow can be changed by a small current to the transistors. In addition to the diode rectifiers, the trigger module contains a resistor, a sensing coil and magnet, and a silicon controlled rectifier (SCR). The silicon controlled rectifier acts as a switch.

The ignition coil contains primary and secondary windings similar to those of a conventional magneto coil plus a condenser or capacitor. Capacitors and condensers are basically the same electrically. The operation of the solid state ignition system follows this cycle:

1. The rotating magnet on the flywheel sets up an alternating current in the charging coil. This alternating current is rectified into direct current and stored in the capacitor. The diode rectifiers permit flow in one direction only so the capacitor cannot discharge back through the diodes.
2. The magnet group passes the trigger coil, setting up a small current which triggers or gates the SCR. This gating makes the SCR conductive so that the stored voltage of the capacitor surges from the capacitor through the SCR

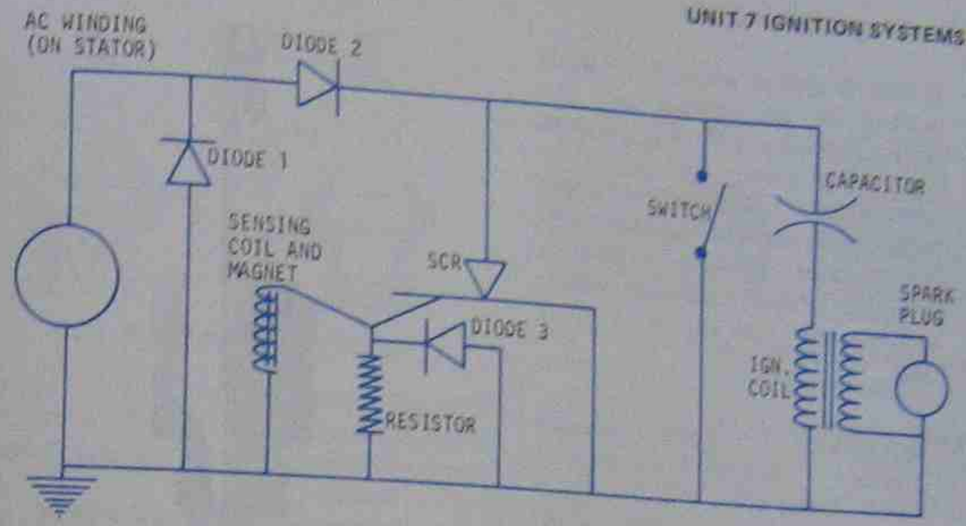


Fig. 7-25 Schematic of a solid-state ignition system

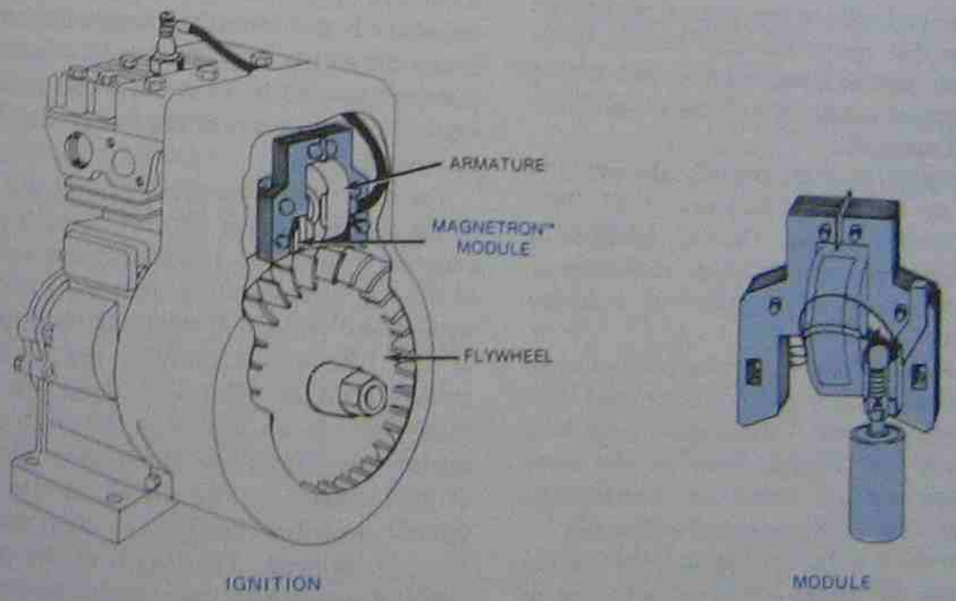


Fig. 7-26 Solid-state ignition "Magnetron™" used by Briggs and Stratton

It then is applied across the primary winding of the ignition coil. This surge of energy sets up a magnetic field in the primary winding of the ignition coil. A magnetic field is also induced around the secondary coil, and voltages of about 30,000 are produced which is sufficient voltage to jump the spark gap at the spark plug.

Solid state ignition offers several advantages such as automatic retarding of the spark at starting speeds, longer spark plug life, faster voltage rise, and high-energy spark which makes the condition of the plug and its gap less critical.

SPARK PLUG

The spark plug is the part of the ignition system that ignites the fuel mixture, figure 7-27. It operates under severe and varying temperature conditions and is a critical part in engine operation.

All spark plugs are basically the same but they do differ in thread size, reach, heat range, and spark gap. There are hundreds of different types of spark plugs, each designed for the special requirements of a certain engine.

The *shell* of the spark plug is threaded so that it can easily be installed or removed from the cylinder head. Various spark plugs have different thread sizes. Some of the more common standard thread sizes are 10 millimeters, 14 millimeters, and 18 millimeters.

The *reach* of the spark plug is the distance between the gasket seat and the bottom of the spark plug shell, or about the length of the cut threads. The reach ranges from about 1/4 inch to 3/4 inch. Each engine must be

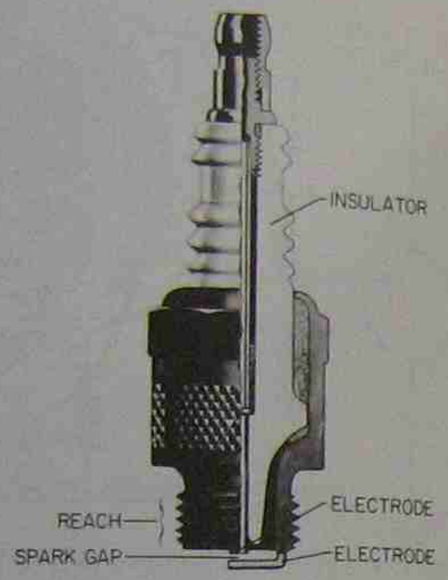


Fig. 7-27 Cutaway of a spark plug

equipped with a spark plug of the correct reach since reach determines how far the electrodes protrude into the combustion chamber. If the reach is too small, the electrodes have difficulty igniting the fuel when the spark jumps. If the reach is too great, the top of the piston may strike the electrodes on its upward stroke.

The *heat range* of a spark plug is the range of temperature within which the spark plug is designed to operate. If a spark plug operates at too low a temperature, it is quickly fouled with oil and carbon. If the spark plug operates at too high a temperature, the electrodes quickly burn up. The heat range for spark plugs depends on how fast the heat can be carried away from the electrodes. The path of heat transfer is from the electrodes to the ceramic insulator through the shell and into the cylinder head. The length of the ceramic insulator exposed to the combustion chamber determines the heat range of a spark plug. The longer this insulator, the longer the heat path and the hotter the spark plug's operating

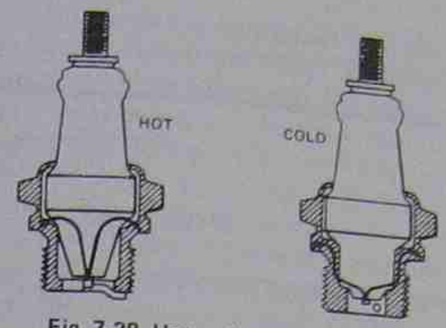


Fig. 7-28 Hot and cold spark plugs

temperature. Likewise, the shorter this insulator, the shorter the heat path and the colder the spark plug's operating temperature, figure 7-28.

In general, cold spark plugs are used for high-speed engine operation where excessive heat could burn the plug. Hot spark plugs would be suitable for slow speed operations where excessive carbon buildup may otherwise occur.

The *spark gap* (distance between the electrodes) must be correctly set. It is within this small space that the spark jumps and combustion begins. The gap must be large enough for sufficient fuel mixture to get between the

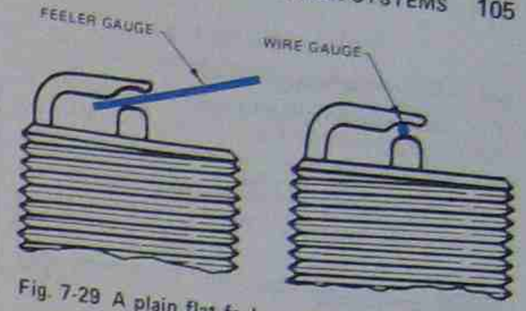


Fig. 7-29 A plain flat feeler gauge cannot accurately measure the true width of a spark gap.

electrodes but not so large as to prevent the spark from jumping across. The spark gap for various plugs ranges from about 0.020 inch to 0.040 inch.

If the spark plug is removed for cleaning, the gap should be checked and reset according to the manufacturer's specifications. A wire gauge should be used, figure 7-29.

BATTERY IGNITION

Battery ignition systems are often used on the larger types of small gasoline engines (4 to 15 horsepower), figure 7-30. With the battery a starter motor can be used to crank the en-

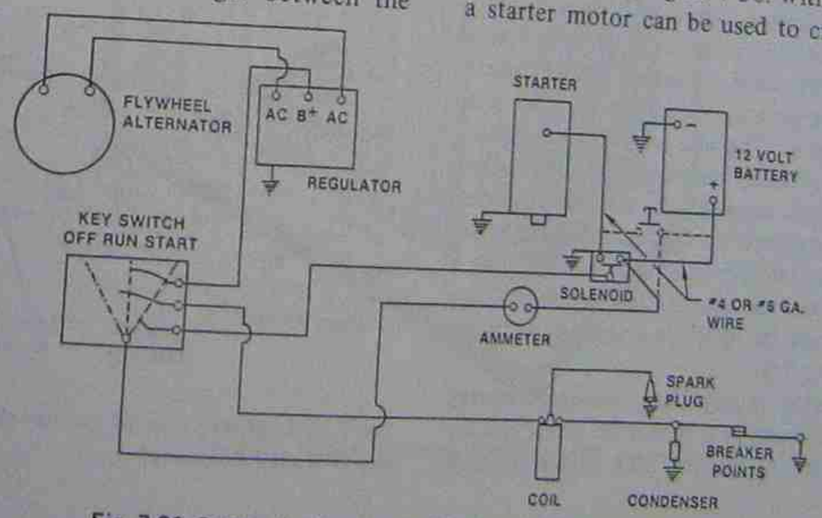


Fig. 7-30 Battery ignition system (Courtesy of Kohler Company)

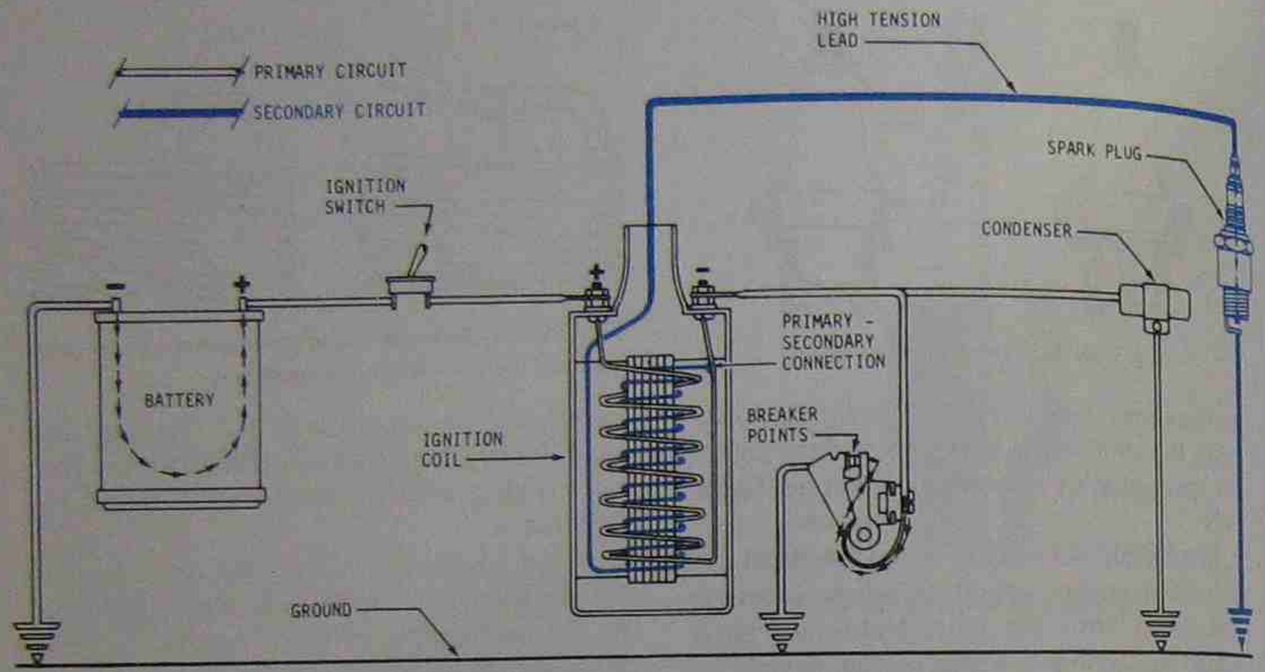


Fig. 7-31 Battery ignition system, primary (low voltage) and secondary (high voltage) circuits

gine. This eliminates the need for various types of hand-pulled or windup starters. The battery can also be used for lights or other accessories.

A typical battery ignition system includes virtually all of the magneto system parts that have been discussed earlier: the high-tension coil, breaker points, condenser, breaker cam, and spark plug. The one part that is replaced is the permanent magnet. The permanent magnet which supplies the energy to excite the coil is replaced by the battery. The most common systems for a small engine include a starter motor, battery, starter switch, voltage regulator, and the ignition system parts themselves, figure 7-31.

The starter motor uses electrical energy from the battery as a motor to crank the engine for starting, figure 7-32. After starting,

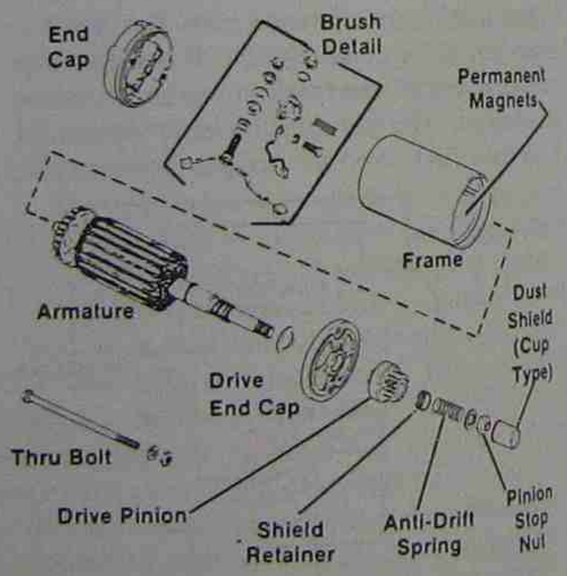


Fig. 7-32 Exploded view of a motor generator (Courtesy of Kohler Company)

the unit acts as a generator to keep the battery charged. Electrical energy is changed to mechanical energy for starting and mechanical energy is changed to electrical energy for charging the battery. With the starter switch closed, the motor turns the crankshaft through a V-belt drive. Upon starting, the starter switch is released but the motor does not disengage. The V-belt drive continues but now the motor acts as a generator for recharging the storage battery. It should be noted that a typical auto system has a separate starter which disengages upon starting and a separate generator for charging the battery.

The storage battery may be either the 6-volt or 12-volt type, figure 7-33. The battery case contains alternate plates of lead peroxide and spongy lead, both active but chemically quite different. Separators prevent the plates from touching each other, figure 7-34. The battery is filled with a solution of sulfuric acid and water. Electrically speaking, the spongy lead plates are cathodes or the negative section, lead peroxide plates are the anodes or the positive section, and the sulfuric acid and water are the electrolyte.

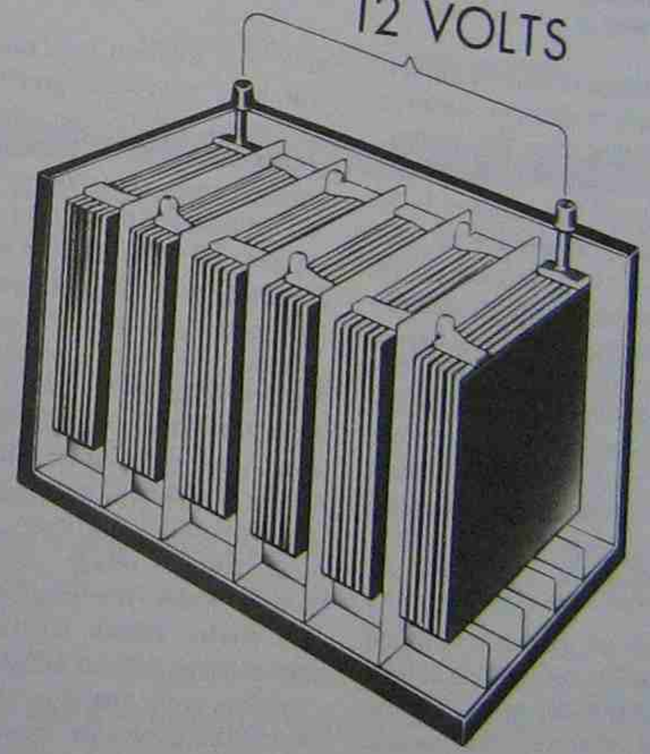


Fig 7-33 Twelve-volt battery with six cells

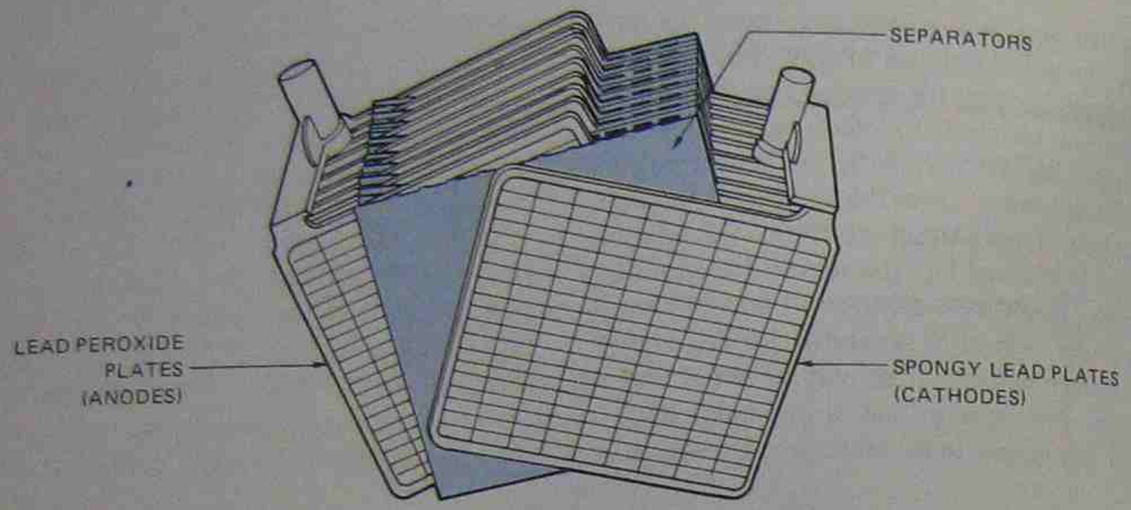


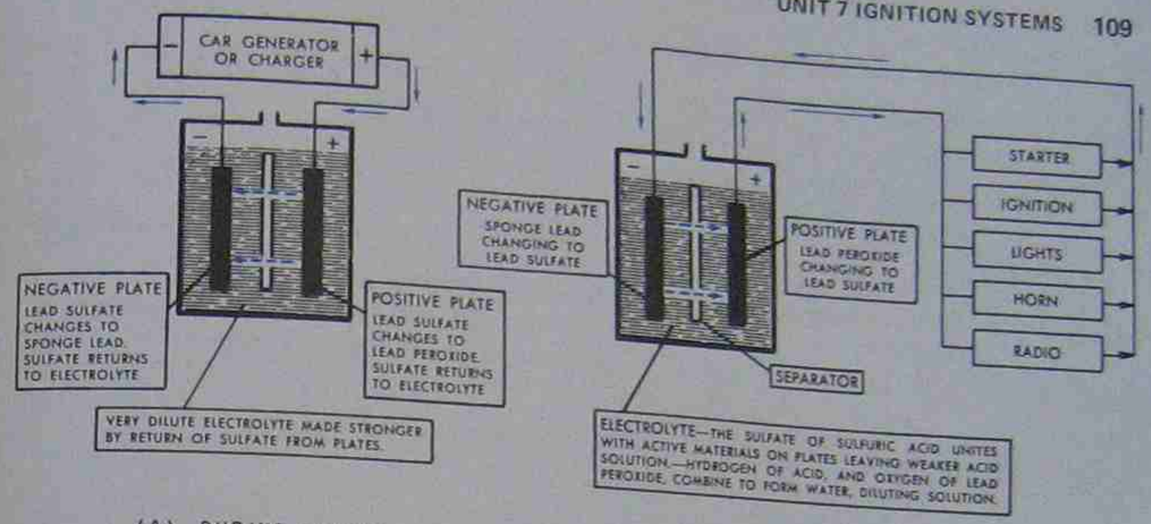
Fig 7-34 Separators prevent the lead peroxide plates and spongy plates from touching each other.

There is a voltage difference between the two groups of plates. When a complete circuit is made, current discharges from the battery. The circuit is closed and the electrolyte attacks the lead plates. The current is in motion and the battery is discharging. The lead peroxide plates start to become coated with lead sulfide and begin to look like the negative plates. The sulfuric acid breaks down forming the lead sulfide and water. The water further dilutes the electrolyte. When the battery is discharged, the negative and positive plates are very similar in chemical structure. Voltage depends on the chemical difference between the two active materials. Figure 7-35 illustrates the electrochemical action in a battery.

Since the solution of sulphuric acid and water gets weaker or less dense as the battery discharges, the condition of the battery can be determined by checking the specific gravity of the solution with a battery hydrometer. The solution in a fully charged battery will have a specific gravity of 1.300. In a discharged battery, the solution has a specific gravity of 1.120. Remember, the specific gravity of water is 1.000.

Fortunately, the action of the battery can be reversed. The starter generator recharges the battery without damage to the battery. The battery is recharged when the voltage produced by the generator is greater than battery voltage and the current being drawn from the battery is not greater than the input from the generator. Thus, the chemical action is reversed, and the battery is returned to its charged condition.

A current-voltage regulator comes into action when the engine has started and the starter switch is off and the engine is operating at 800 to 1000 rpm. The regulator prevents over charging the battery and also keeps the generator from producing voltages and current flow that could be damaging to the system.



(A) DURING CHARGE (B) DURING DISCHARGE

Fig. 7-35 Electrochemical action in a battery

REVIEW QUESTIONS

1. What three particles make up the atom?
2. Explain how electrons can move in a conductor.
3. What are the three ways that electricity can be produced or seen?
4. Explain the following electrical measurements: amperes, volts, and ohms.
5. State Ohm's Law.
6. Explain how permanent and temporary magnets differ.
7. What happens when a wire is cut by magnetic lines of force?
8. What happens to a coil of wire when electric current flows through it?
9. Explain how a transformer works.
10. In a magneto, what is the source of the magnetic field?
11. What are the two parts of the high-voltage coil?
12. What purpose does the laminated iron core serve?

13. What is the function of the breaker points? How are they opened?
14. What is the function of the condenser? The spark plug?
15. What are the two electrical circuits in the magneto?
16. Why must the spark be advanced at high speeds?
17. What is the advantage of impulse coupling?
18. Can magneto ignition be used for multicylinder engines?
19. What parts of a conventional magneto are replaced on a solid state ignition system?
20. Explain the function of the transistor diodes in a solid state ignition system.
21. Explain how a silicon controlled rectifier acts as a switch or gate.
22. In what four ways do spark plugs differ?
23. What is the main advantage of having a battery in the ignition system?
24. a. When does the motor generator work as a motor?
    b. When does it work as a generator?
25. Storage battery plates are made of what material?
26. What is an electrolyte?

Unit 8 Routine Care, Maintenance, and Winter Storage

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the important areas of routine care and maintenance.
- Identify types of spark plug fouling.
- Clean and regap spark plugs.
- Discuss the various types of air cleaners and their care.
- Correctly prepare an engine for winter storage.
- Locate routine care and maintenance information in an owner's instruction book.

A gasoline engine represents an investment. To safeguard this investment the engine operator must perform certain routine steps in care and maintenance. Routine care and maintenance help to ensure the longest life possible for engine parts and can save on repair bills.

The best source of information on engine care is the owner's manual or operator's instruction book that comes with every new engine. The book contains the information that the manufacturer considers necessary for the owner to know. The information included allows the owner to obtain top performance and long engine life. Some typical topics discussed are lubrication procedures, carburetor adjustment, ignition system data, air cleaner cleaning instructions, winter storage, and care of the machine that the engine is used on. The information in the book is important. A person with a new engine should read and thoroughly understand the instruction book before touching the engine. A plastic cover helps to keep the book in good condition.

ROUTINE CARE AND MAINTENANCE

Routine care and maintenance is given to an engine during its normal use. It is provided to keep the engine operating at its peak efficiency and to prevent undue wear of engine parts. There are four basic points to consider: oil supply, cooling system, spark plugs, and air cleaner, figure 8-1.

Oil Supply

On a four-cycle engine, the oil supply in the crankcase should be checked daily or each time the engine is used. If the oil level has dropped below the *add* mark on the dipstick, fill the crankcase to the proper level. If the engine does not have a dipstick, fill the crank-

WARNING: Before servicing engine or equipment, always remove the spark plug leads to prevent engine from starting accidentally. Ground the plug leads to prevent sparks that could cause fire.

MAINTENANCE PROCEDURES	FREQUENCY
Clean Air Intake Screen *	DAILY
Check Oil Level	DAILY
Replenish Fuel Supply	DAILY
Service Precleaner *	DAILY
Change Oil	25 HRS.
Clean Cooling Fins and External Surfaces *	50 HRS.
Check Air Filter *	50 HRS.
Change Oil Filter	50 HRS.
Check Spark Plugs	100 HRS.
Have Breaker Points Checked*	100 HRS.
Have Ignition Timing Checked*	500 HRS.
Have Valve & Tappet Clearance Checked*	500 HRS.
Have Cylinder Heads Serviced	500 HRS.*

*If engine is operated under dirty, dusty conditions, maintenance procedures should be performed more frequently than stated.

*Have these services done only by a Kohler engine specialist.
•250 hours when leaded gasoline is used.

Fig. 8-1 All engines should have a service schedule similar to this one for a Kohler Model K582 engine. (Courtesy of Kohler Company)

case until the oil can be seen in the filler hole. A new engine or one that is being used for the first time must be carefully checked to be sure that oil is in the crankcase.

Most manufacturers recommend that the oil be changed after a short period of time when breaking in a new engine. Depending on the manufacturer, this first oil change should be after two to twenty hours of operation.

After the oil has been changed once, the engine can go for longer periods of time between oil changes. Lauson specifies changing engine oil after every 10 hours of operation; Briggs and Stratton after every 20 hours; Kohler after every 25 hours; Gravely and Wisconsin after every 50 hours; Onan after every 100 hours. Each manufacturer's instruction book gives the length of time between oil changes and the exact SAE number and quality of oil to be used.

Two-cycle engines have their lubricating oil mixed with the gasoline. The owner's manual specifies the proportions of oil to gasoline and the type of oil to be used.

Cooling System

The most important consideration regarding the cooling system is to keep it clean. On air-cooled engines, clean the radiating fins, flywheel vanes, and shrouds whenever they begin to accumulate grass, dirt, etc., figure 8-2. Do not allow deposits to build up which reduce the engine's cooling capacity. How often the cooling system is cleaned depends on the dust conditions under which the engine operates.

On a water-cooled engine, check the water level in the radiator before operating the engine. If the water level is low, fill it to the correct level.

Outboard motors need little routine care for the cooling system. However, each time the engine is started the operator should

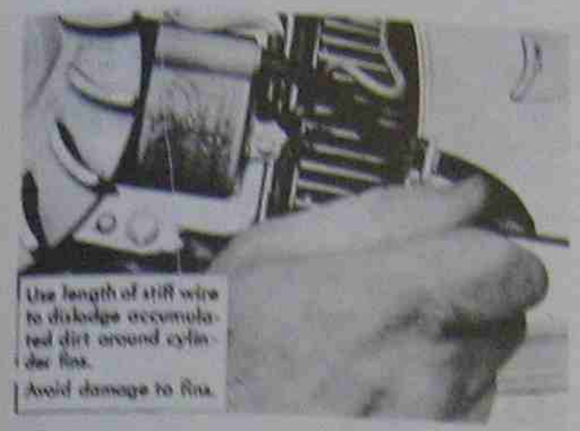


Fig. 8-2 Keep heat radiating fins clean

check to see that the engine is pumping water. This can be detected on most engines by a small amount of water coming from the telltale holes. If the engine is not pumping water, it should be stopped immediately and the source of the trouble corrected. Do not put hands by the underwater discharge to determine if the engine is pumping water as the propeller may be dangerously close. If the engine's cooling system is thermostatically controlled, it may take a few moments for the thermostat to open to allow a flow of water from the engine.

Spark Plugs

Spark plugs need to be cleaned and regapped periodically. Spark plugs are usually cleaned after 100 hours of operation; some manufacturers recommend cleaning after as little as 50 hours, while a few manufacturers do not recommend cleaning at all, but advise regular replacement. Since spark plugs operate under severe conditions, they become fouled easily. Knowing the signs of fouling can often tell about the engine's overall condition. Common problems that develop with spark plugs are carbon fouling, burned electrodes, chipped insulator, and splash fouling, figure 8-3.

Normal spark plugs have light tan or gray deposits but show no more than 0.005 inch increase in the original spark gap. These can be cleaned and reinstalled in the engine.

Worn out plugs have tan or gray colored deposits and show electrode wear of 0.008 inch to 0.010 inch greater than the original gap. Throw away such plugs and install new ones.

Oil fouling is indicated by wet, oily deposits. This condition is caused when oil is pumped (by the piston rings) to the combustion chamber. A hotter spark plug can help but the condition may have to be corrected by engine overhaul.

Gas fouling or fuel fouling is indicated by a sooty, black deposit on the insulator tips, electrodes, and shell surfaces. The cause may be a too rich fuel mixture, light loads, or long periods at idle speed.

Carbon fouling is indicated if the plug has dry, fluffy, black deposits. This condition may be caused by a too rich fuel mixture, improper carburetor adjustment, choke partly closed, or clogged air cleaner. Also, slow speeds, light loads, long periods of idling, and the resulting cool operating temperature can cause deposits not to be burned away. A hotter spark plug may correct carbon fouling.

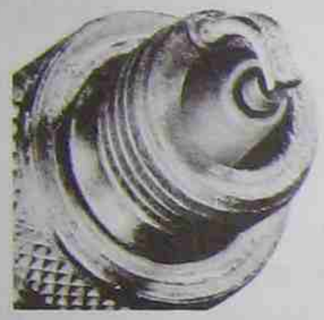
Lead fouling is indicated by a soft, tan, powdery deposit on the plug. These deposits of lead salts build up during low speeds and light loads. They cause no problem at low speed but at high speeds, when the plug heats up, the fouling often causes the plug to misfire, thus limiting the engine's top performance.



NORMAL SPARK PLUG



WORN OUT SPARK PLUG



CARBON-FOULED SPARK PLUG



CHIPPED INSULATOR ON SPARK PLUG



OVERHEATED SPARK PLUG



OIL-FOULED SPARK PLUG



SPLASH-FOULED SPARK PLUG



BENT SIDE ELECTRODE

Fig. 8-3 Normal and damaged spark plugs

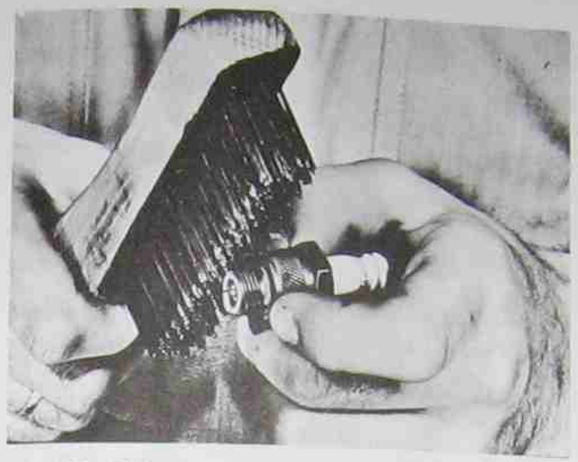


Fig. 8-4 Wire brush the shell and threads

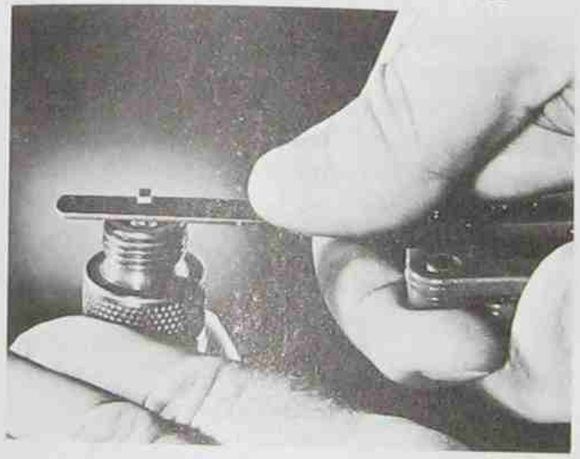


Fig. 8-5 File electrodes

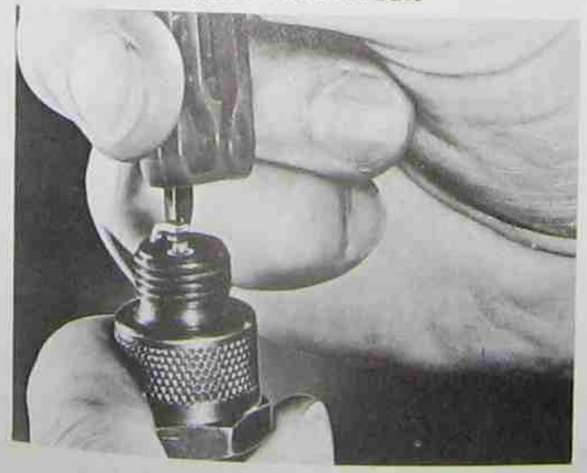


Fig. 8-6 Regap the plug

Burned electrodes are indicated by thin, worn away electrodes. This condition is caused by the spark plug overheating. This overheating can be caused by lean fuel mixture, low octane fuel, cooling system failure, or long periods of high-speed heavy load. A colder plug may correct this trouble.

Splash fouling can occur if accumulated cylinder deposits are thrown against the spark plugs. This material can be cleaned from the plug and the plug reinstalled. If spark gap tools or pliers are not properly used, the electrode can be misshaped into a curve.

Cleaning Spark Plugs. If inspection indicates that the spark plug needs cleaning, it can be cleaned within a few minutes. First, wire brush the shell and threads not the insulator and electrodes, figure 8-4. Then wipe the plug with a rag that has been saturated with solvent. This removes any oil film on the plug. Next, file the sparking surfaces of the electrodes with a point file, figure 8-5. Finally, regap the electrodes setting them according to specifications, figure 8-6. Check the gap with a wire spark gap gauge, figure 8-7. Abrasive blast cleaning machines found



Fig. 8-7 Check the spark gap

in many service stations are not recommended by several engine manufacturers. Do not allow any foreign material to fall into the cylinder while the spark plug is out. Also, do not forget the spark plug gasket when reinstalling the spark plug. This copper ring provides a perfect seal and the proper cooling for the spark plug.

Cleaning cannot repair a broken, cracked, or otherwise severely damaged spark plug. Cleaning is designed to maintain good operation and prolong spark plug life. Many small engine manufacturers recommend the installation of a new spark plug at the beginning of each season. On a single-cylinder engine, the spark plug is more critical than on a six- or eight-cylinder engine.

Air Cleaner

The air cleaner serves the important function of cleaning the air before it is drawn through the carburetor and into the engine. Small abrasive particles of dust and dirt are trapped in the air cleaner, figure 8-8. The air cleaner should be periodically cleaned; how often depends mainly on the atmosphere in which the engine is operating, figure 8-9. In a dusty atmosphere, (a garden tractor used in a dry garden for example), the air cleaner should be cleaned every few hours. Under normal conditions, the air cleaner should be cleaned every 25 hours or sooner.



Fig. 8-8 About this much abrasive material would enter a six-cylinder engine every hour if the air cleaner was not used.

If an engine is always operated in a clean atmosphere it may not be equipped with an air cleaner. Examples are snowmobiles, snow throwers, and outboard motors.

Air cleaners can be classified as either oil type or dry type. Oil type includes oil-bath air cleaners and oil-wetted polyurethane (foam) filter element air cleaners. Dry type includes foil, moss, or hair element, felt or fiber hollow element, and metal cartridge air cleaners.



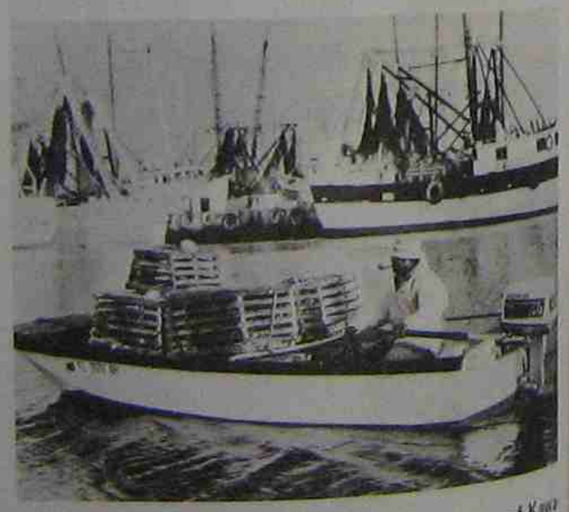


Fig. 8-9 Engines operating in different environments have different air cleaner requirements. (Courtesy of Kawasaki Motor Corporation and Evinrude Motor Division)



Fig. 8-10 Oil-bath air cleaner





Fig. 8-11 Clean, fill, reassemble air cleaner

Oil-type Air Cleaners

Oil-bath Air Cleaner. The oil-bath air cleaner carries a small amount of oil in its bowl, figure 8-10. The level of this oil should be checked before each use of the engine. If the oil level is low, fill it to the mark but not above the mark. Use the same type of oil as is used in the crankcase. As this cleaner works, both the oil and filter element become dirty. To clean an oil-bath air cleaner, disassemble the unit and then pour out the dirty oil. Wash the bowl, cover, and filter element in solvent. Dry all parts. Refill the bowl to the correct level and then reassemble the unit, figure 8-11.

Oil-wetted Polyurethane Filter Element Air Cleaner. Shown in figure 8-12, this type of air cleaner is perhaps the most common. Clean it by washing the element in kerosene, liquid detergent and water, or an approved solvent. Dry the element by squeezing it in a cloth or towel. Apply considerable oil to the foam and work it throughout the element.

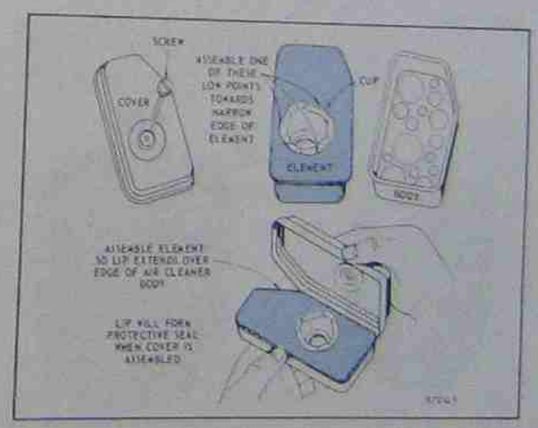


Fig. 8-12 Oil foam air cleaner

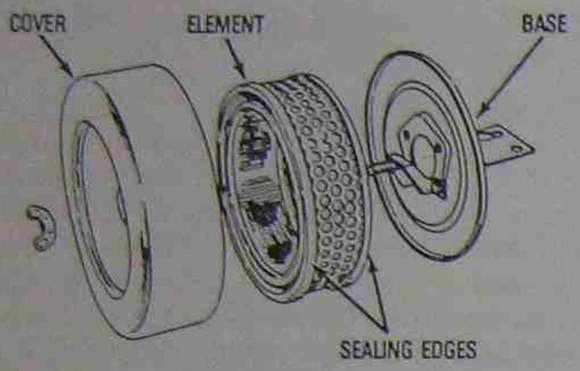


Fig 8-13 Paper element-type air cleaner

Squeeze out any excess oil and then reassemble the air cleaner. Make sure it overhangs the edges. Do *not* neatly tuck it in.

Dry-type Air Cleaners

Foil, Moss, or Hair Element Air Cleaner. This type of element is also washed in solvent. After washing, allow the element to dry, then return it to the air cleaner body.

Paper Element Air Cleaners. These air cleaners should be cleaned by blowing compressed air through them in the opposite direction from normal flow, figure 8-13. Dirt and dust particles will be blown out of the element.



Fig. 8-14 Metal-cartridge type air cleaner

Metal-cartridge Air Cleaners. These air cleaners are cleaned by tapping or shaking to dislodge dirt accumulations, figure 8-14.

Air cleaner elements are replaceable parts. If they wear out or become very clogged, they should be thrown away and replaced with a new filter element. As a simple test to determine if the air cleaner is badly clogged: (1) run the engine with the air cleaner removed; (2) then, with the engine still running, replace the air cleaner; and (3) notice if the engine speed remains constant or drops down. Any noticeable drop in speed probably indicates that the filter element is clogged.

Periodically inspect the engine for loose parts. Do not neglect to lubricate the engine's associated linkages, gear reduction units, chains, shafts, wheels, or the machinery the engine powers. These requirements vary greatly from engine to engine. On an outboard engine remember that the lower unit requires special lubrication.

EXHAUST PORTS (TWO-CYCLE)

Cleaning the exhaust ports of a two-cycle engine can also be considered a part of routine care and maintenance, figure 8-15. Over a period of time these ports can become clogged with carbon deposits which greatly reduce power and performance. After removing the muffler to expose the ports, the carbon can be cleaned out with a soft object such as a dowel rod. Be sure to move the piston so that it covers the ports. This prevents loose deposits from going into the cylinder.

WINTER STORAGE AND CARE

Preparing an engine for winter storage at the end of the season should be done carefully. Several procedures should be done:

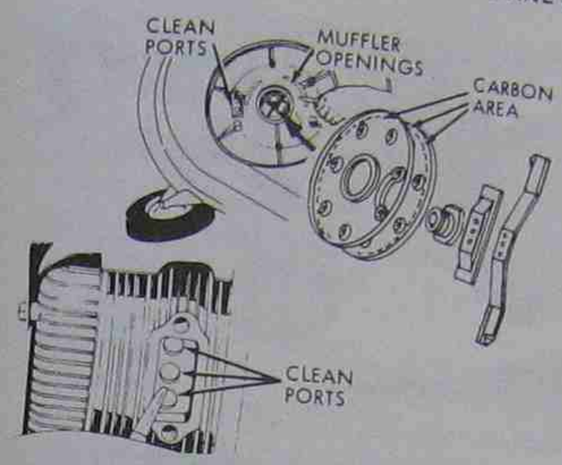


Fig. 8-15 Cleaning the exhaust ports

- Drain the fuel system.
- Inject oil into the cylinder (upper cylinder).
- Drain the crankcase (four-cycle).
- Clean the engine.
- Wrap the engine in a canvas or blanket and store in a dry place.

The entire fuel system should be drained: tank, fuel lines, sediment bowl, and carburetor. Gasoline that is stored over a long period of time has a tendency to form gummy deposits or varnish. These deposits could damage and block the fuel system if gasoline stands in the system for a long time. Do not plan to hold gasoline over from season to season. Purchase a new supply when the engine is returned to use.

Many manufacturers recommend that a small amount of oil be poured into the cylinder prior to storage. Remove the spark plug and pour in the oil (about a tablespoon in most cases). Turn the engine over by hand a few times to spread the oil evenly over the cylinder walls. Replace the spark plug.

Some manufacturers suggest that the oil be introduced into the cylinder while the engine is running at a slow speed and just before the engine is stopped. To do this, the air cleaner is removed and a small amount of oil is poured in. The oil goes through the carburetor and then into the combustion chamber. When dark blue exhaust is produced the engine can be stopped.

The crankcase should be drained while the engine is warm so the oil drains more readily. In some cases the crankcase is then refilled; on most engines it need not be refilled until the engine is returned to service.

Any unpainted surfaces that might rust should be lightly coated with oil before storage. Linkages should be oiled. The radiating fins and the engine in general should be cleaned. Do not put too much oil on the engine as it will collect dirt and be difficult to remove.

Finally, wrap the engine in a canvas or dry blanket and store the engine in a dry place. A garage, dry shed, or dry basement is good. Do not allow the engine to be left outside, exposed to the weather.

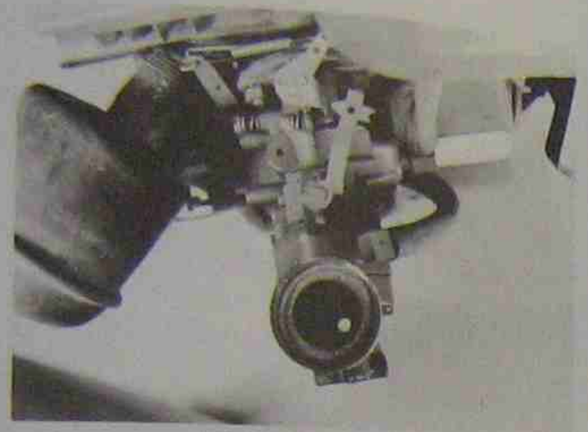
RETURNING THE ENGINE TO SERVICE

Upon returning the engine to service refill the gas tank with new gasoline. Before filling the gas tank check to see if any water has condensed in the tank. If so, drain the water completely.

Check for condensation in the crankcase and refill the crankcase with new oil of the correct type, figure 8-16. Also, clean the air cleaner and refill the bowl with oil if it is an oil-bath type.



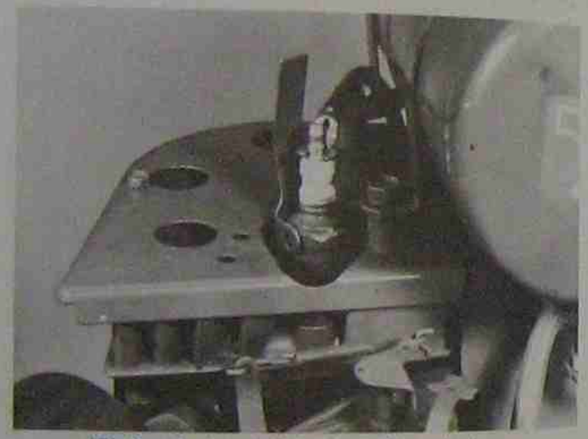
(A) Fill the gas tank



(D) Choke closed



(B) Check the oil in the crankcase



(E) Spark plug shorting bar off spark plug



(C) Fuel shut-off valve open



(F) Air cleaner clean

Fig. 8-16 Things to check before returning the engine to service (Courtesy Clinton Engines Corporation)

Check the spark plug; clean and regap it. Many manufacturers of small engines recommend that a new plug be installed at the beginning of each season to ensure peak performance throughout the season.

SPECIAL CONSIDERATIONS FOR OUTBOARD MOTORS

Winter Storage

Generally, winter storage for outboard motors is similar to that for other engines. One notable difference is the cooling system. Being water cooled, all water must be removed from the cooling system. If a water-filled cooling system on an idle engine is exposed to freezing weather, cracked water jackets and other major damage can result.

To remove the water from the system, remove the engine from the water, set the speed control on stop (to prevent accidental starting), and turn the engine over several times by hand. This allows the water to drain from the water jackets and passages.

Salt Water Operation

Although most engines are treated with anticorrosives, not all engines are free from corrosion. If an engine normally used in salt water is not to be used for a while, its cooling system should be flushed with fresh water to prevent any possible corrosion.

Use in Freezing Temperatures

If the engine is being used during freezing temperatures, care must be taken not to allow the cooling water to freeze in the engine or lower unit during an idle period. While the engine is operating there is no danger of freezing.

REVIEW QUESTIONS

1. Explain what routine care and maintenance is and why it is important.
2. Where can routine care and maintenance information be found?
3. What are the four basic points to be considered in routine care and maintenance?
4. How often should the oil in the crankcase be checked?
5. How often should the oil in the crankcase of a Briggs and Stratton engine be changed?
6. What are the two types of cooling systems?
7. How often should the air-cooling system be cleaned?
8. How is an air-cooling system cleaned?
9. What care should be given a water-cooling system?
10. How often should spark plugs by cleaned? Why do some manufacturers recommend no cleaning of spark plugs?
11. What is the purpose of cleaning a spark plug?

12. List several types of spark plug fouling.
13. What are the steps in cleaning a spark plug?
14. What is the purpose of the air cleaner?
15. How often should air cleaners be cleaned?
16. What are the two basic types of air cleaners?
17. Discuss the cleaning of the several types of air cleaners.
18. List the general steps in winter storage of engines.
19. List the general steps in returning the engine to service.
20. What special considerations must be made for outboard motors?

SECTION 3
OTHER INTERNAL COMBUSTION ENGINES

Unit 9 The Automobile Engine

OBJECTIVES After completing this unit, the student should be able to:

- Recognize the parts of an automobile engine and discuss their function.
- Discuss the operation of the fuel, ignition, lubrication, cooling and exhaust systems.
- Explain pollution reducing designs of the automobile engine.
- Recognize parts of the drive system and discuss their function.
- Recognize and avoid unsafe conditions when working on an automobile.

The automobile engine is a larger version of the small gasoline engine, figures 9–1 and 9–2. The engine has the same basic parts, the same basic systems, and operates on the same four-stroke cycle principle. Every engine is designed and engineered for a specific purpose, but the basic parts and operating principles remain almost unchanged, figures 9–3 and 9–4. A thorough knowledge of any one engine makes it easier to understand other engines.

The foundation of the engine is the block, figure 9–5. This casting contains all of the cylinders, usually four, six, or eight. Four-cylinder engines normally have their cylinders in a straight line and are called an in-line engine, figure 9–6. Six-cylinder engines may be either in-line or "V." The V-6 engine has three cylinders on each side and the block, when viewed from the front, takes on a "Y" shape, figure 9–7. Today's eight-cylinder engines are V-8s, having four cylinders on each side.

The lower part of the block is called the crankcase. It provides mounting for the crankshaft and space for the crankshaft to revolve. Bolted to the bottom of the block is the oil

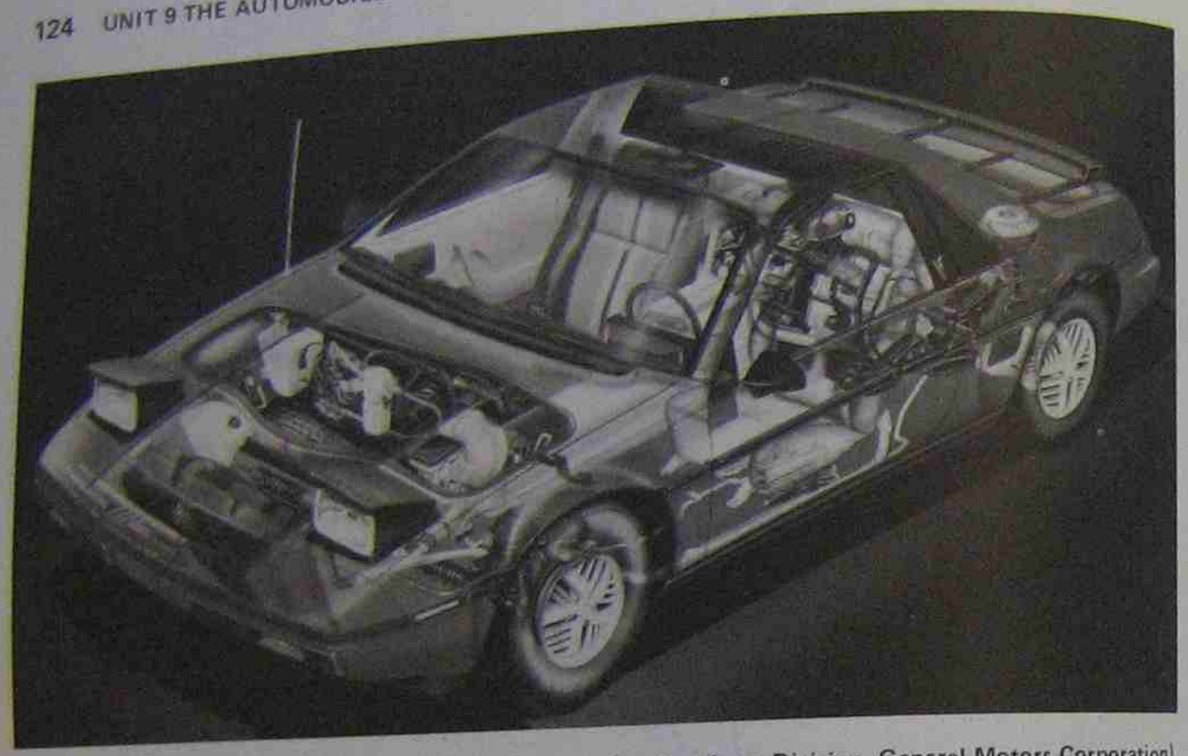


Fig. 9-1 Pontiac Fiero cutaway view (Photo courtesy Pontiac Motor Division, General Motors Corporation)

pan, figure 9–8. This part is usually a stamped-steel pan that acts as a reservoir for the engine's oil supply. It is called the sump, base, or crankcase.

The cylinder head is bolted to the top of the block; one head for six-cylinder engines and two heads for V-8 engines, figure 9–9. Most modern engines have overhead valves or valves mounted in the cylinder head, called valve in-head. The valve system and cylinder head are more complicated on overhead valve engines, figure 9–10. Instead of simply pushing the valves up for opening, like most small engines, the valves must be pushed down for opening. Since more parts are needed, rocker arms are added to make this change in direction, figure 9–11. Some rocker arms mount on a shaft, while others are separately bolted to the head. The cylinder head, therefore, contains the intake and exhaust valves, rocker arm shaft, rocker arms, valve springs, and other valve parts.

The camshaft is usually in the engine block. The cam movement is transferred to the rocker arm through a push rod. The train is: camshaft, tappet, push rod, rocker arm, valve, as seen in figure 9–12. When the nose of the cam pushes up on the tappet, push rod, and rocker arm; the rocker arm pushes the valve down or open, figure 9–13.

Engines are also manufactured with overhead cams, figures 9–14 and 9–15. The camshaft is located in the head, with the cams pushing directly on the rocker arms, figure 9–16.

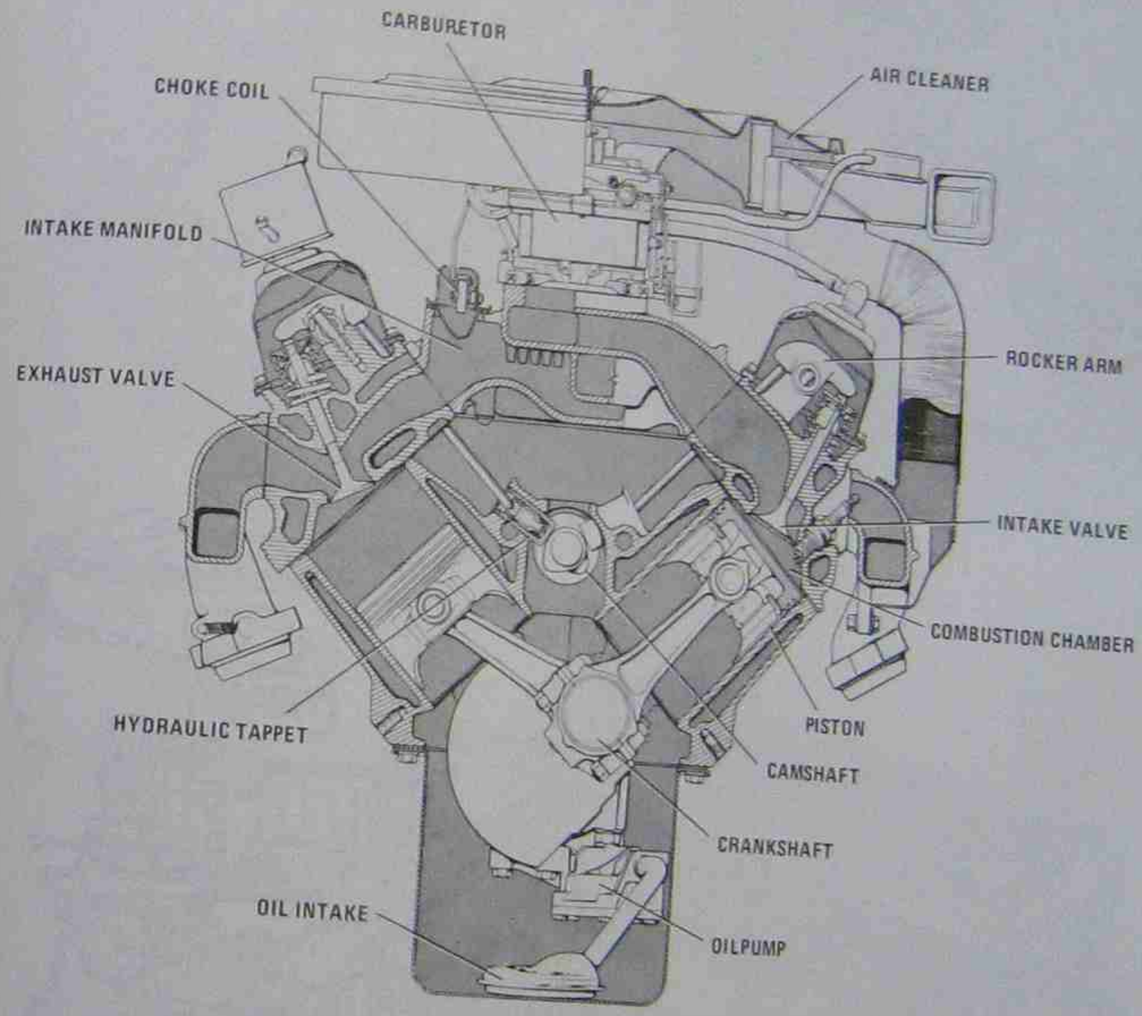


Fig. 9-2 Engine cross section

Unit 10 Diesel Engines

OBJECTIVES After completing this unit, the student should be able to:

- Explain how a diesel engine operates.
- Discuss the advantages of the diesel.
- Explain fuel injection and how it works.
- Discuss supercharging and turbocharging.

For centuries, the natives of the South Pacific have employed an ingenious method for lighting fires. Using a bamboo cylinder in which dry tinder is placed, a close-fitting plug is driven sharply into the open end. The air entrapped in the cylinder is compressed and heated to the point where the tinder ignites. This spontaneous combustion from the heat of compression is the principle of *compression ignition*, the basis on which the diesel engine operates.

The characteristic, then, of the diesel engine which distinguishes it from other internal combustion engines in the **absence of any external ignition device**, figure 10-1. The gasoline engine uses an outside spark source to ignite the fuel mixture. This type of engine is thus known as the *spark-ignition engine*. The diesel, however, uses only the heat generated by the compression of air in the cylinder to ignite the fuel. Thus, the diesel is classified as a *compression-ignition engine*.

The inventor of the diesel engine, Dr. Rudolph Diesel, was born in 1858 of German parents. He became interested in engines during his college years from which he graduated when he was 21 years old with an engineering degree. He then immediately set out to build an engine that would be more efficient than the low-efficiency steam engines of the time. His first engine was patented in 1892, but when built, it exploded as he tried to start it. The tragedy did not cause him to give up. In 1897, Dr. Diesel produced a successful single-cylinder engine capable of developing 25 horsepower (18.6 kilowatts).

The first commercial diesel engine was put into service a year later in St. Louis, Missouri. It was a two-cylinder, 60-horsepower (44.8 kilowatts) engine. The use of diesel engines spread rapidly, in a few years, thousands of engines were in use.

The first engines were heavy, weighing as much as 250 pounds per horsepower (152 kilograms per kilowatt), were used mostly to replace steam engines in large installations such as stationary power plants or on large boats. They could not compete with the gasoline engine used on land vehicles where weight was a more important factor. Today, because diesel engines are much lighter in weight—as little as 7 pounds per horsepower (4.3 kilograms per kilowatt)—they are commonly found on all types of trucks, heavy road machinery, railroad locomotives, and in some automobiles.

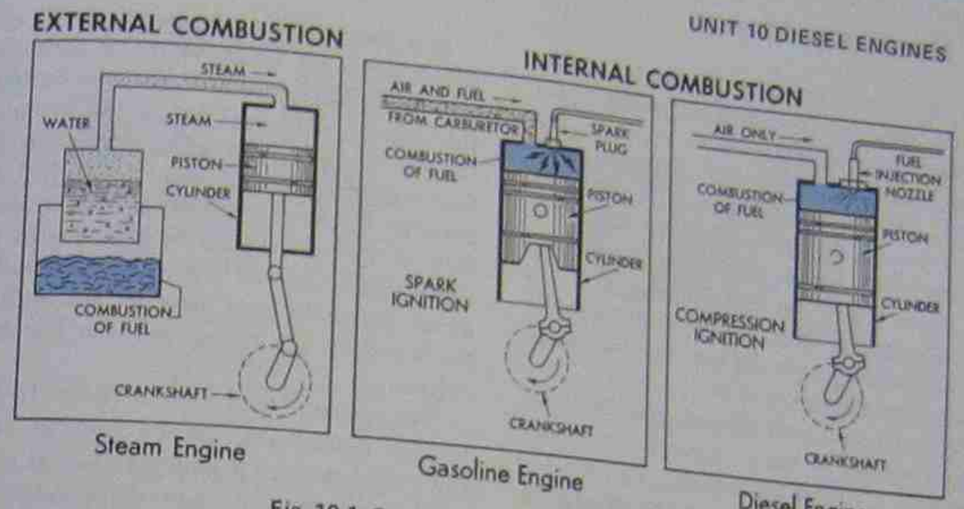


Fig. 10-1 Comparison of combustion systems

A major difference between diesel and gasoline engines is the *compression ratio* for which each engine is designed. Compression ratio is defined as the ratio of the cylinder and clearance volume with the piston on bottom dead center to the clearance volume alone with the piston on top dead center, figure 10-2.

Diesel engines are all high-compression engines, usually in the range of 17:1 versus 8.5:1 for gasoline engines. Compression ratios in the area of 17:1 are not possible in a carburator-fed gasoline engine even using the best anti-knock gasoline since a mixture of air and gasoline would ignite long before the piston reached top dead center because of the intense heat caused by the high compression.

The high compression ratio is what gives the diesel its efficiency advantage, because more of the potential energy in the fuel is put to work. When the stored energy of a fuel is released or burned, in other engines, all of the energy does not do useful work. Much of the heat energy is lost either in waste exhaust

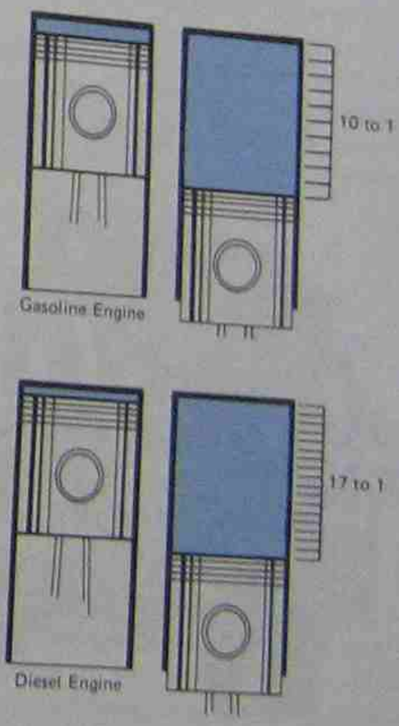


Fig. 10-2 Compression ratios of gasoline and diesel engines

gases, to friction, or in heating up the engine. That is why, of the common engine types, the diesel engine is the most efficient. The simple steam engine has an efficiency of 6 to 8%. The steam turbine and condensing engine has an efficiency of 16 to 33%. The gasoline engine has an efficiency of 25 to 32%. The diesel engine has an efficiency of 32 to 38%. Remember that, the more efficient the engine, the less fuel it will have to consume to do the same amount of work.

The construction of gasoline and diesel engines is similar in many respects: crankcase, crankshaft, cylinder, piston, etc., figure 10-3. The main differences between the engines lie in four points: (1) how the air enters the cylinder, (2) how the fuel enters the cylinder, (3) how the fuel is ignited and, (4) how the exhaust gases leave the cylinder.

The diesel can be either a four-stroke or a two-stroke cycle engine. Therefore, the differences also depend on which engine is discussed.

In a two-stroke cycle diesel the air enters the cylinder by being blown in through intake ports that are located near the bottom of the cylinder. The fuel enters the cylinder at the top of the compression stroke through a fuel injector, and is ignited by the high temperature of the compressed air. Upon completion of the power stroke, the exhaust gases leave when exhaust valves are opened. At about the same time, new air is forced into the cylinder scavenging out the last bit of exhaust.

The system illustrated in figure 10-4 is a uniflow system with intake ports all around the cylinder and an exhaust valve at the top of the cylinder. One side of the cylinder has ports for incoming air while the other side has ports for the exit of the exhaust. The principle used is the same as that for small two-stroke cycle gasoline engines that use loop or cross flow scavenging. Hot exhaust gases leave the combustion chamber on their own, then a new charge of air rushes in behind to scavenge

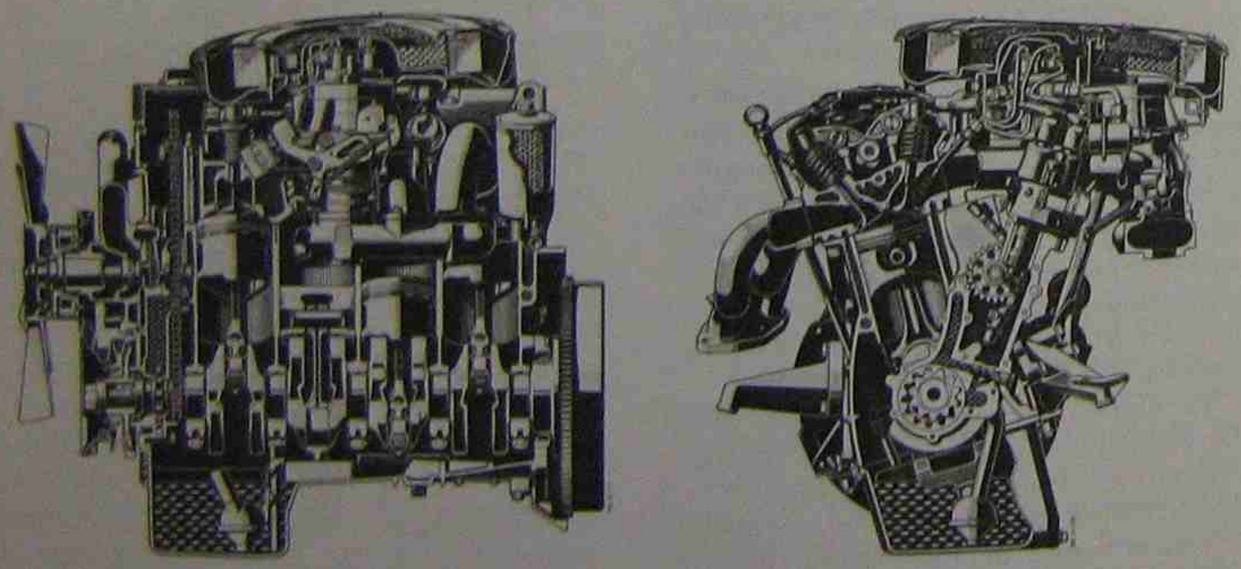
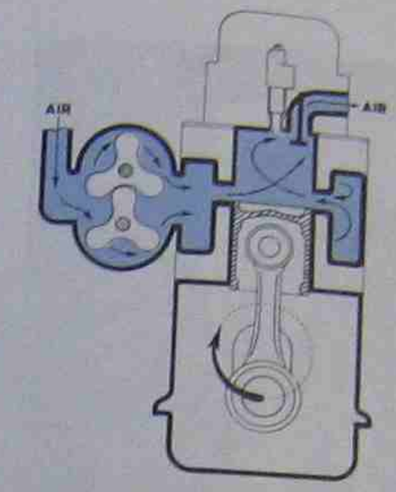
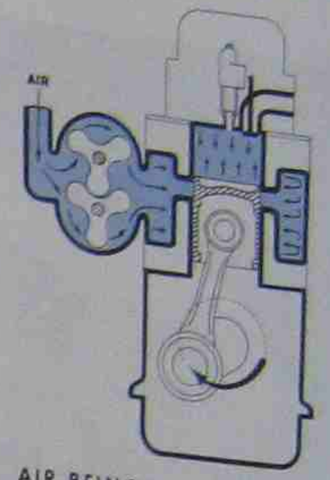


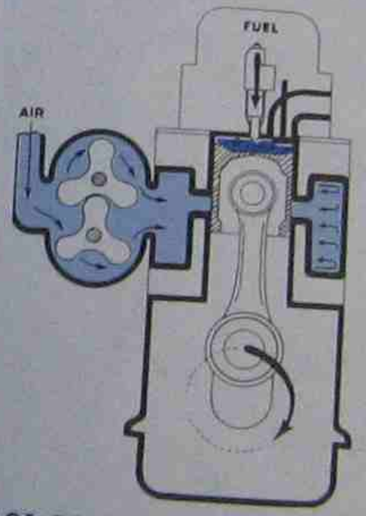
Fig. 10-3 Cross-section view of diesel engine for automative use (Courtesy of Mercedes-Benz of North America, Inc.)



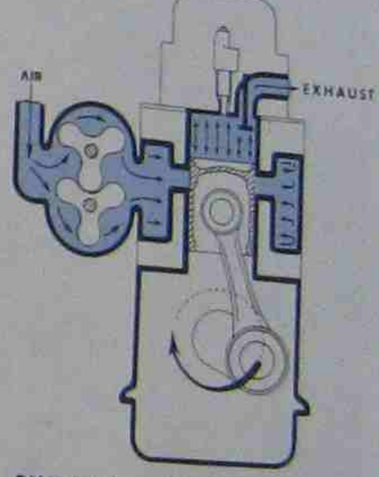
AIR ENTERING THROUGH PORT TO COMBUSTION CHAMBER



AIR BEING COMPRESSED WITH EXHAUST VALVE CLOSED



CHARGE OF FUEL BEING INJECTED INTO COMBUSTION CHAMBER



EXHAUST TAKING PLACE AND CYLINDERS ABOUT TO BE SWEPT CLEAN WITH SCAVENGING AIR

Fig. 10-4 Two-stroke cycle diesel engine

out the last of the exhaust. Many two-stroke cycle diesels are loop or cross flow scavenged.

In a four-stroke cycle diesel, the air enters the cylinder through an intake valve. Sometimes there are two intake valves per cylinder to increase airflow, figure 10-5. On most modern four-stroke cycle engines, a turbocharger brings large quanitiies of air into the cylinder. However, the air does not pass through a carburetor, figure 10-6. Fuel is

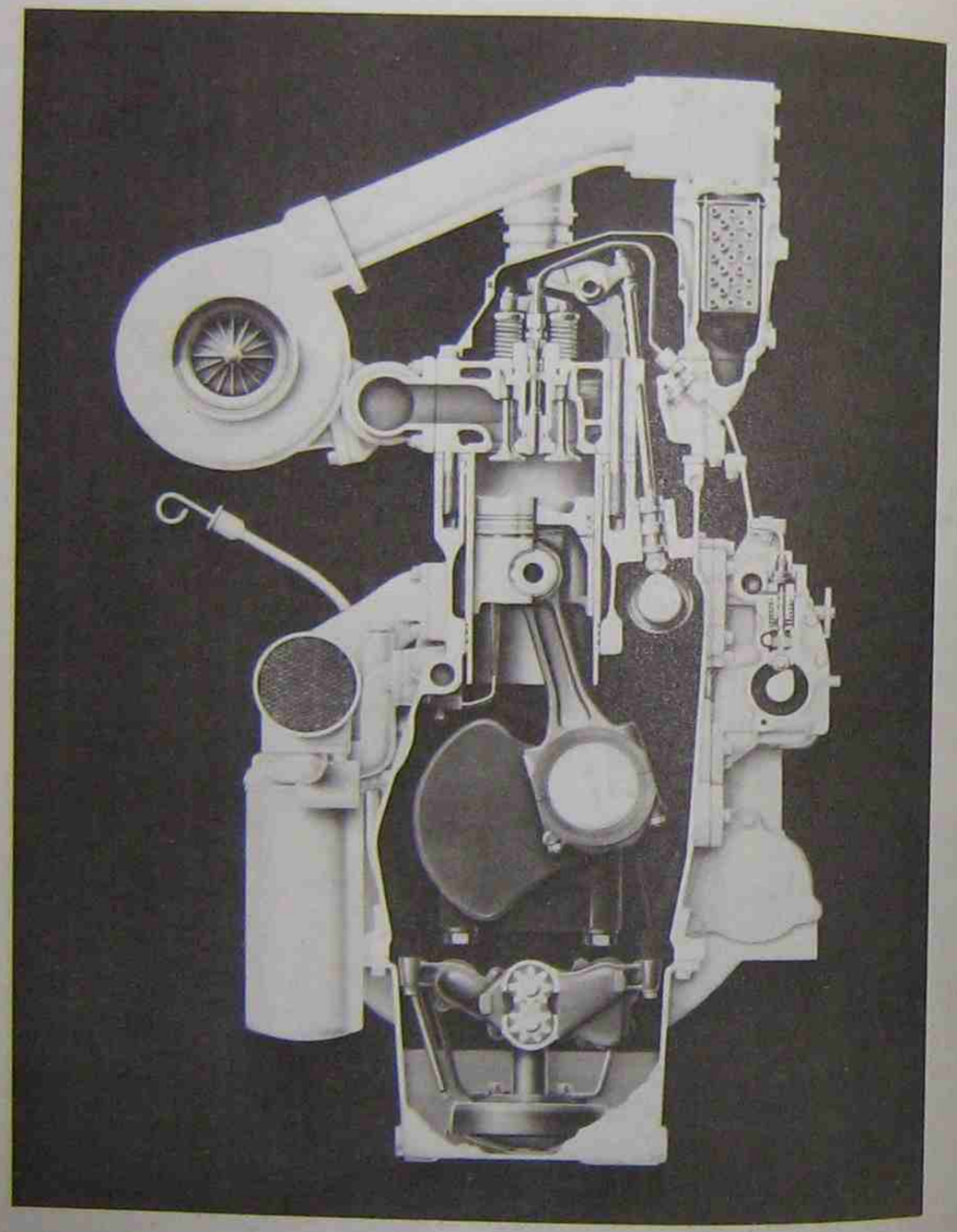


Fig. 10-5 Cross-section view of four-stroke cycle, in-line diesel with turbocharger

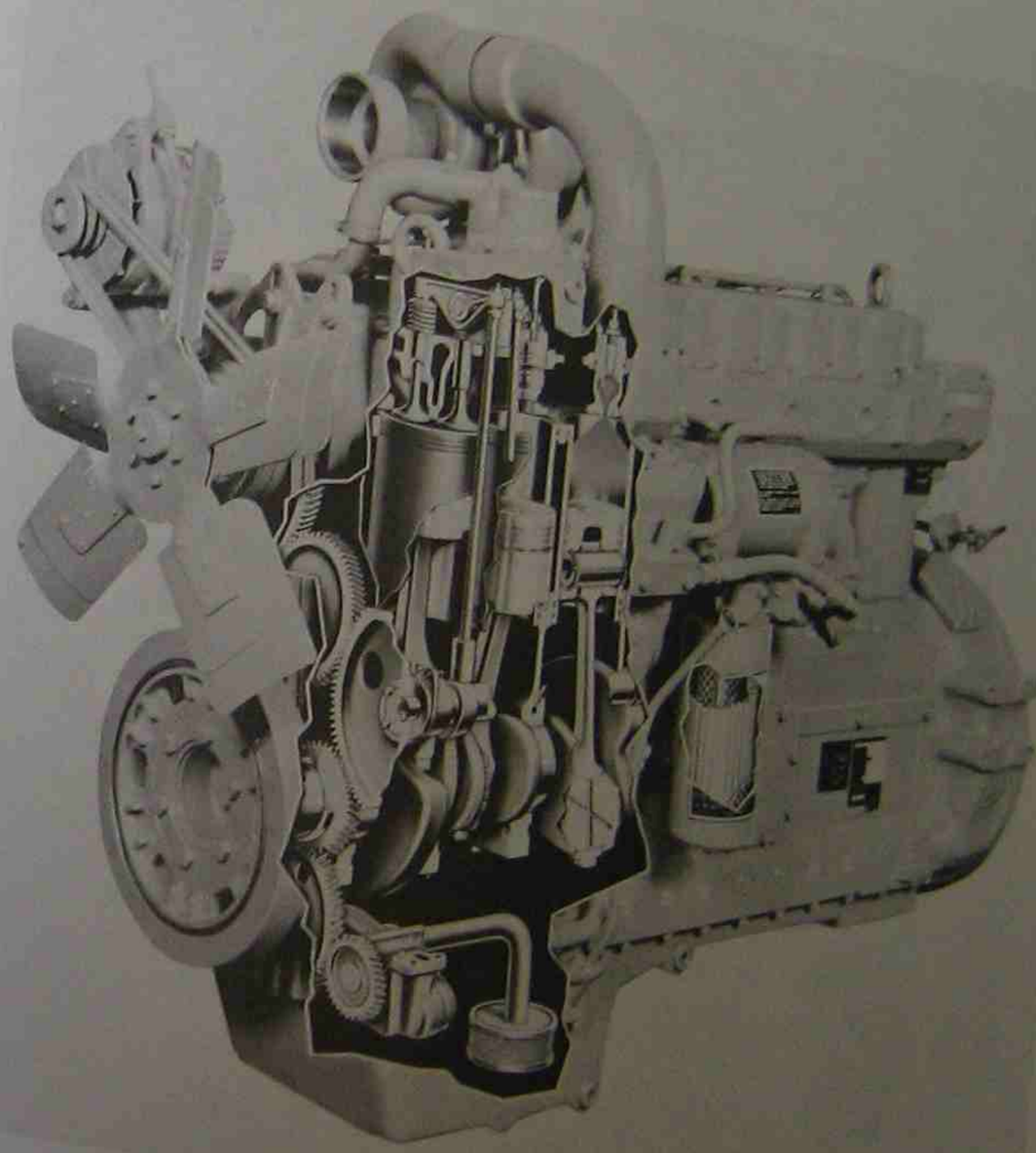


Fig. 10-6 Cutaway view of four-stroke cycle diesel

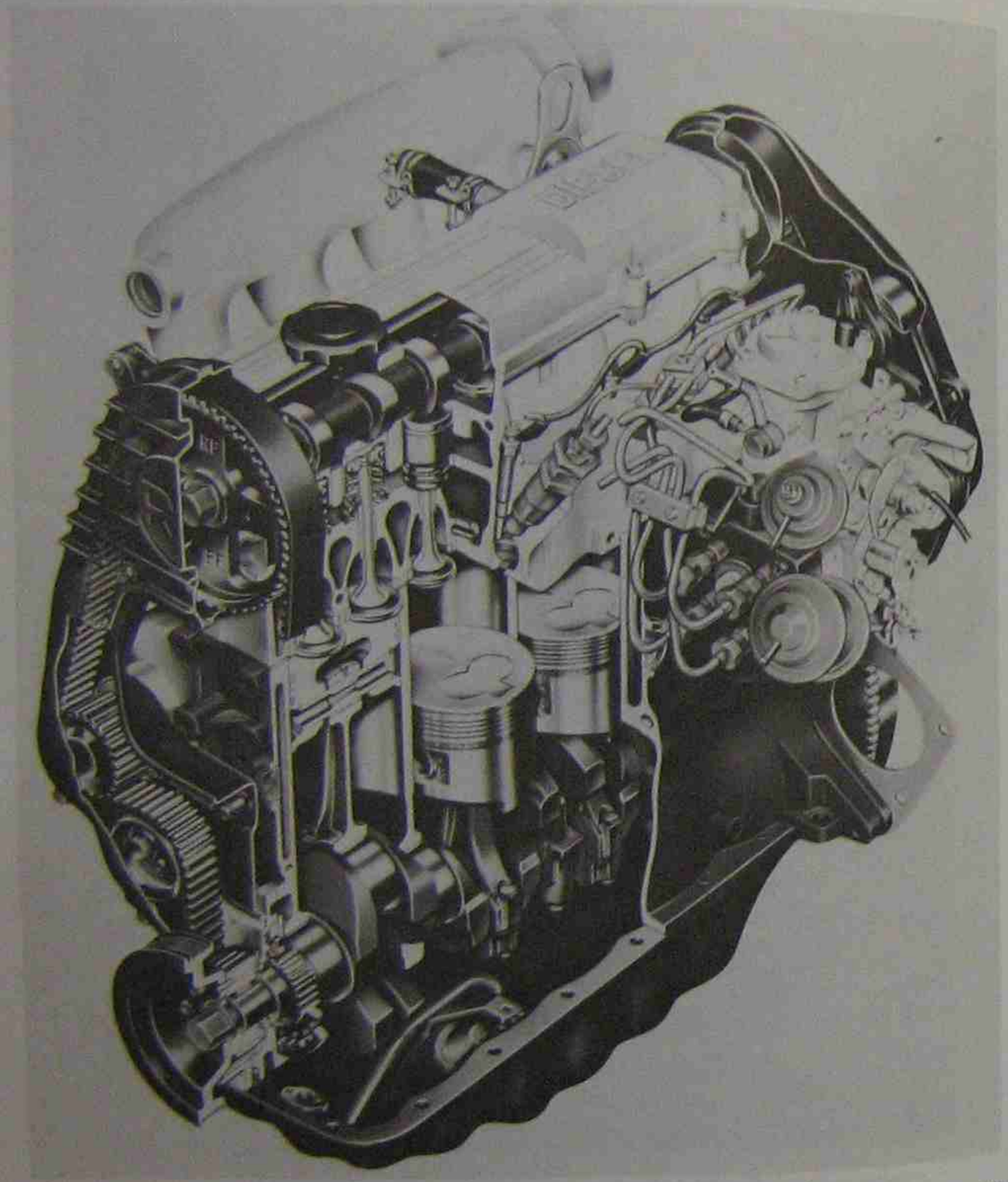


Fig. 10-7 Four-cylinder, 2.0 liter, turbocharged diesel engine. Note the fuel injectors (Courtesy of Ford Motor Company)

introduced in the cylinder when the piston reaches the top of the compression stroke, through the tip of a fuel injector, figure 10-7. The fuel is ignited by the high temperature of the compressed air. The exhaust gases leave as they would in a gasoline engine, being pushed out by the upward motion of the piston on the exhaust stroke and by the scavenging effect of the new incoming air.

FUEL INJECTION

The fuel injector eliminates the need for a carburetor on the diesel. With the air tightly compressed and at a high temperature, the fuel injector sprays diesel oil into the cylinder as a mist or fog, figure 10-8, and begins burning immediately upon contact with the superheated air.

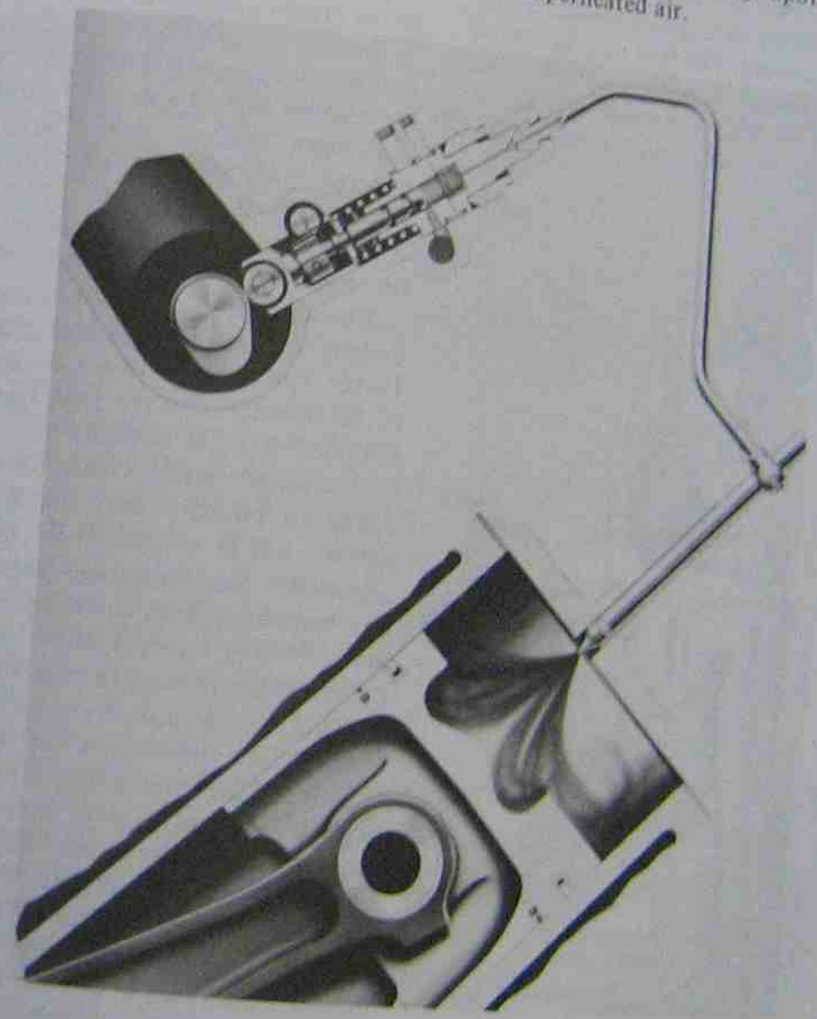


Fig. 10-8 Direct or open charging showing injector and injection pump

The fuel injector parts are machined to extremely exacting tolerances, figure 10-9. The unit is a precision machine in itself. For example, on a unit injector, the injection pump piston is fitted to the pump cylinder to an accuracy of 30 to 60 millionths of an inch (762 to 1524 micrometers). Such accuracy is necessary since the fuel is forced through the injector nozzle in a split second and at a tremendous pressure. The fuel may be forced through the several needlepoint-sized holes at the nozzle tip with a pressure of 3000 to 30,000 pounds per square inch (20.7 to 207 megapascals). There cannot be leakage between the plunger and cylinder. The injector must meter out the exact amount of fuel needed. Usually each cylinder of the engine is fitted with its own fuel injector. Sometimes each cylinder is equipped with its own fuel pump, however, fuel pumps can be made to supply several injectors in much the same way that a car's distributor channels high voltage to the proper cylinder at the correct instant.

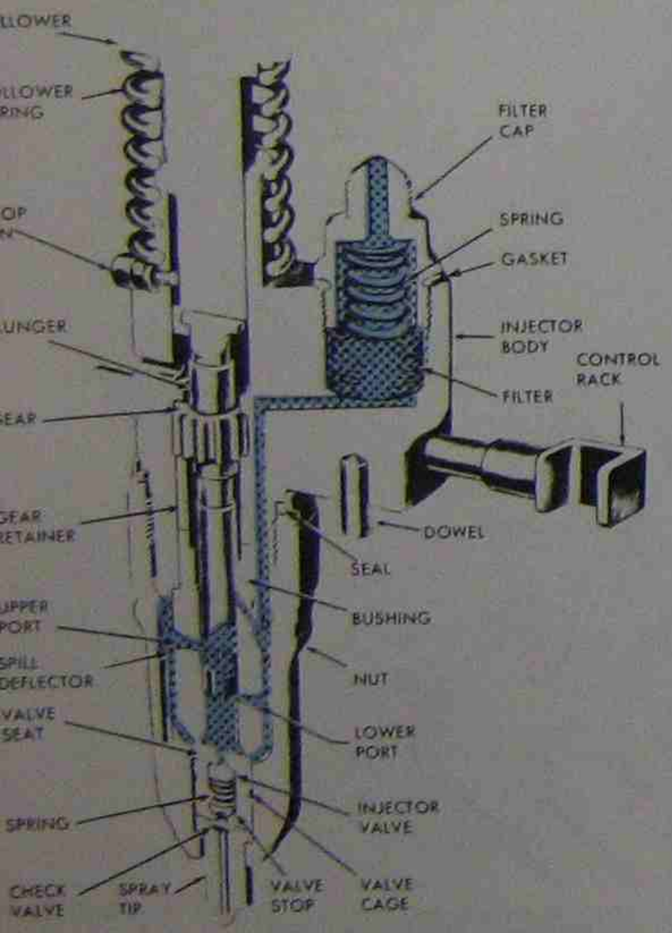


Fig. 10-9 Fuel injector assembly

Another factor in the complexity of the fuel injector is that as the engine speed varies, the amount of fuel sprayed from the injector is changed; just the right amount of fuel is metered out for the desired speed. The amount of air taken into the cylinder and compressed remains the same throughout the speed range, however.

Various types of combustion chamber designs are used in diesel engines, figure 10-10. The *open* or direct design allows fuel to be directly injected into the combustion chamber. This is suitable for all large and slower speed diesels. Other designs are being tested to improve smoothness and prevent knock, which are common problems with high-speed diesel engines. The *auxiliary* design includes a small chamber to the main cylinder. Fuel is injected into the chamber and the restricted passage increases the turbulence of the discharge into the main chamber. Similarly, in the *precombustion* design, burning begins in the precombustion chamber and explodes violently into the main cylinder for complete combustion, figure 10-11. The *air cell* design is a means of increasing the force of the combustion. The energy cell, with its chamber opposite from the fuel injector, produces a smooth buildup of pressure in the main chamber rather than a violent burst.

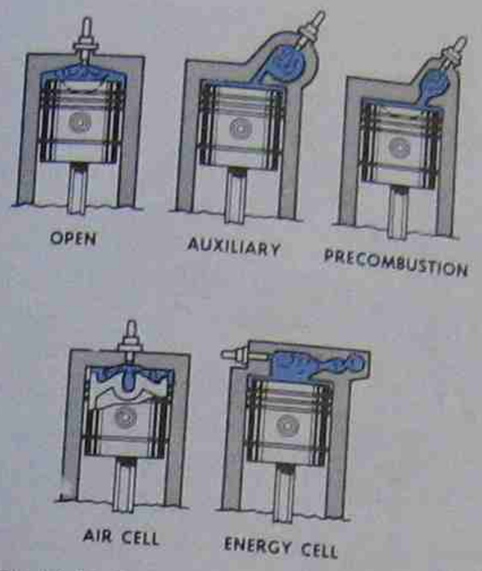


Fig. 10-10 Combustion chamber designs

SUPERCHARGING

The more air that can be packed into the cylinder, the better. Superchargers supplement the pumping action of the pistons in four-stroke cycle engines and provide rapid air movement in two-stroke cycle engines, greatly increasing the efficiency of both.

One common type of supercharger is the Roots blower, figure 10-12. It consists of 2 three-lobe, intermeshing spiral gears which trap air and force it to the opposite side. It turns constantly and pumps air under pressure to the cylinder. Its action might be compared to a revolving door.

Turbocharging is also very common, figure 10-13. The turbocharger is a centrifugal air pump driven by the exhaust gases of the diesel, figure 10-14. This device does not rob power from the engine in order to operate, but uses energy that would otherwise be wasted. Turbocharging can increase the power de-

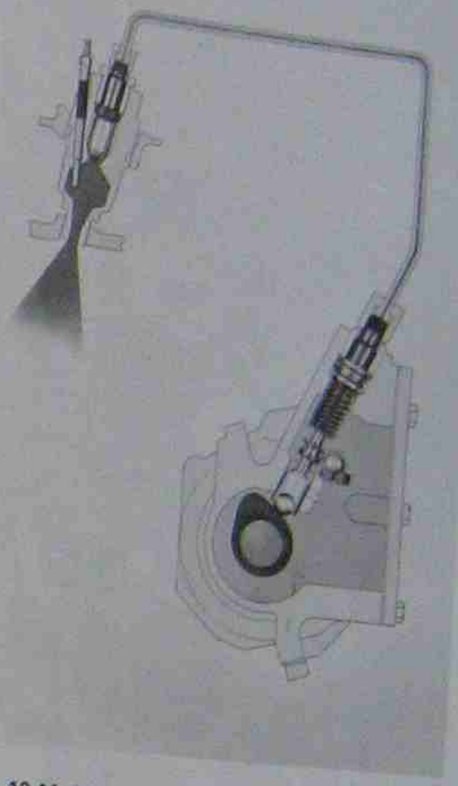


Fig. 10-11 Injector and injector pump using precombustion design

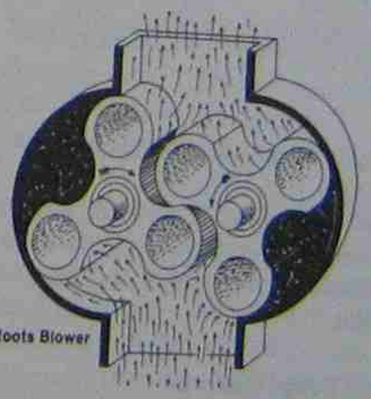


Fig. 10-12 The Roots blower

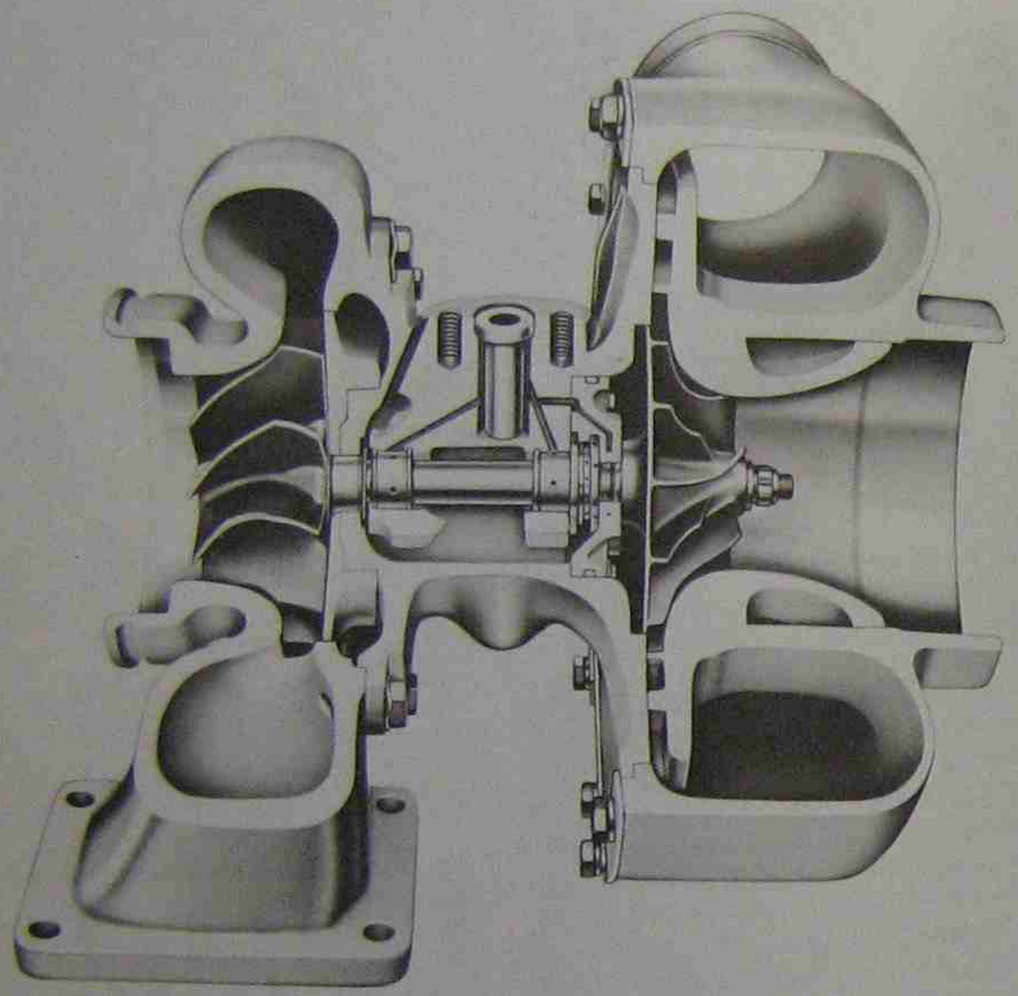


Fig. 10-13 Cutaway of turbocharger shows exhaust-driven turbine on left and centrifugal blower on right

veloped by an engine by 50 to 150%. Supercharging and turbocharging have done much to reduce the size, weight, and cost of diesel engines.

Other Design Features

High speed diesels have a crankshaft speed range of 1200 to 4000 revolutions per minute, and can develop 482 horsepower (360 kilowatts) at 2100 revolutions per minute. To save space and keep them light in weight, most of these engines are designed using the "V" block, figure 10-15. They are used in farm tractors, highway vehicles, and earth moving equipment.

Medium speed diesels have a speed range of

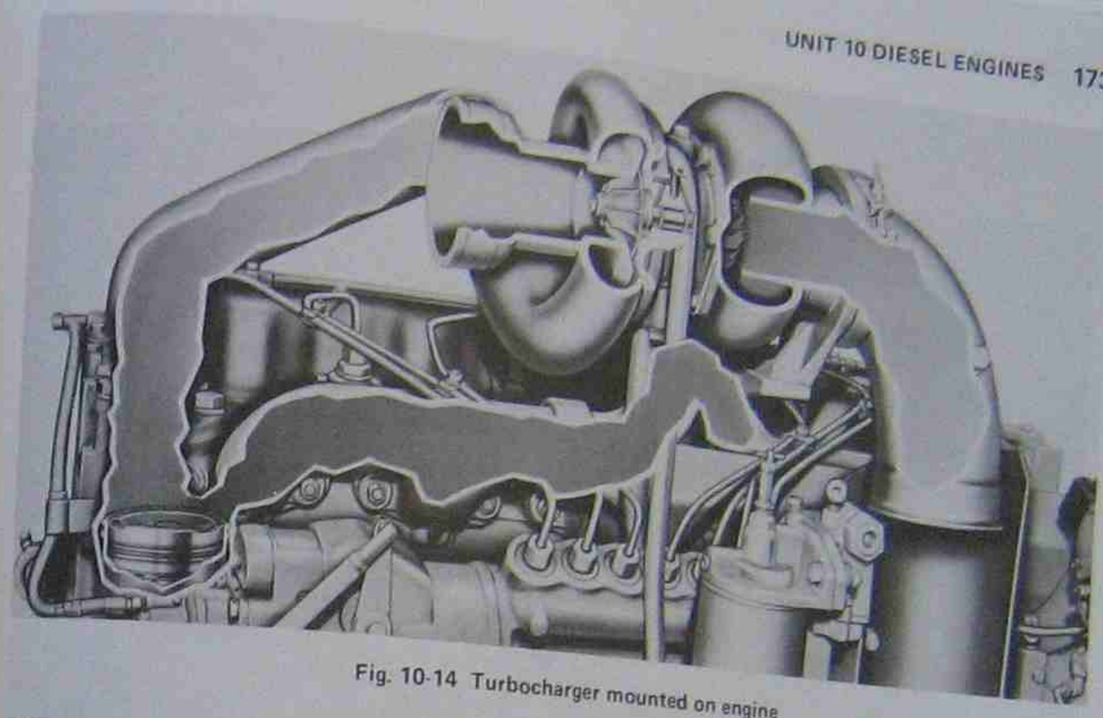


Fig. 10-14 Turbocharger mounted on engine

500 to 1200 revolutions per minute and will be 2000 horsepower (1.5 megawatts). They are used mostly for locomotives, ships, and stationary equipment. Cylinder bores range from 8 to 9 inches (203 to 229 millimeters) in diameter.

Low speed diesels operate as low as 115 revolutions per minute, developing up to 12,500 horsepower (9 megawatts). These huge engines, with cylinder bores measuring up to 29 inches (737 millimeters), are used in power plants to drive electric generators.

It is common for people to think of diesel fuel as being cheap or of low quality. Nothing could be further from the truth. It is distilled petroleum fuel oil produced in much the same manner as gasoline. The quality of the fuel is high and it is produced to exacting standards. It must burn leaving little or no deposit, be very clean, and ignite properly. Surprisingly, the price of diesel fuel and gasoline is almost the same at the refinery. Any cost difference may be due to greater taxation on one or the other. The economy of operating a diesel does not come from burning cheaper fuel, rather it comes from burning the fuel in a very efficient engine.

It will be helpful to follow one cycle of a two-stroke cycle diesel engine in order to understand this fact better, figure 10-17. At the top of the compression stroke, the air is tightly compressed and held at a temperature of 1000°F (538°C). Now the fuel injector sprays an oil fog into the combustion chamber. The oil begins burning immediately and the extreme pressures push the piston rapidly back down the cylinder. When the piston nears the bottom of its stroke, two things happen: (1) intake ports are uncovered and air is blown into the cylinder, (2) the exhaust valves

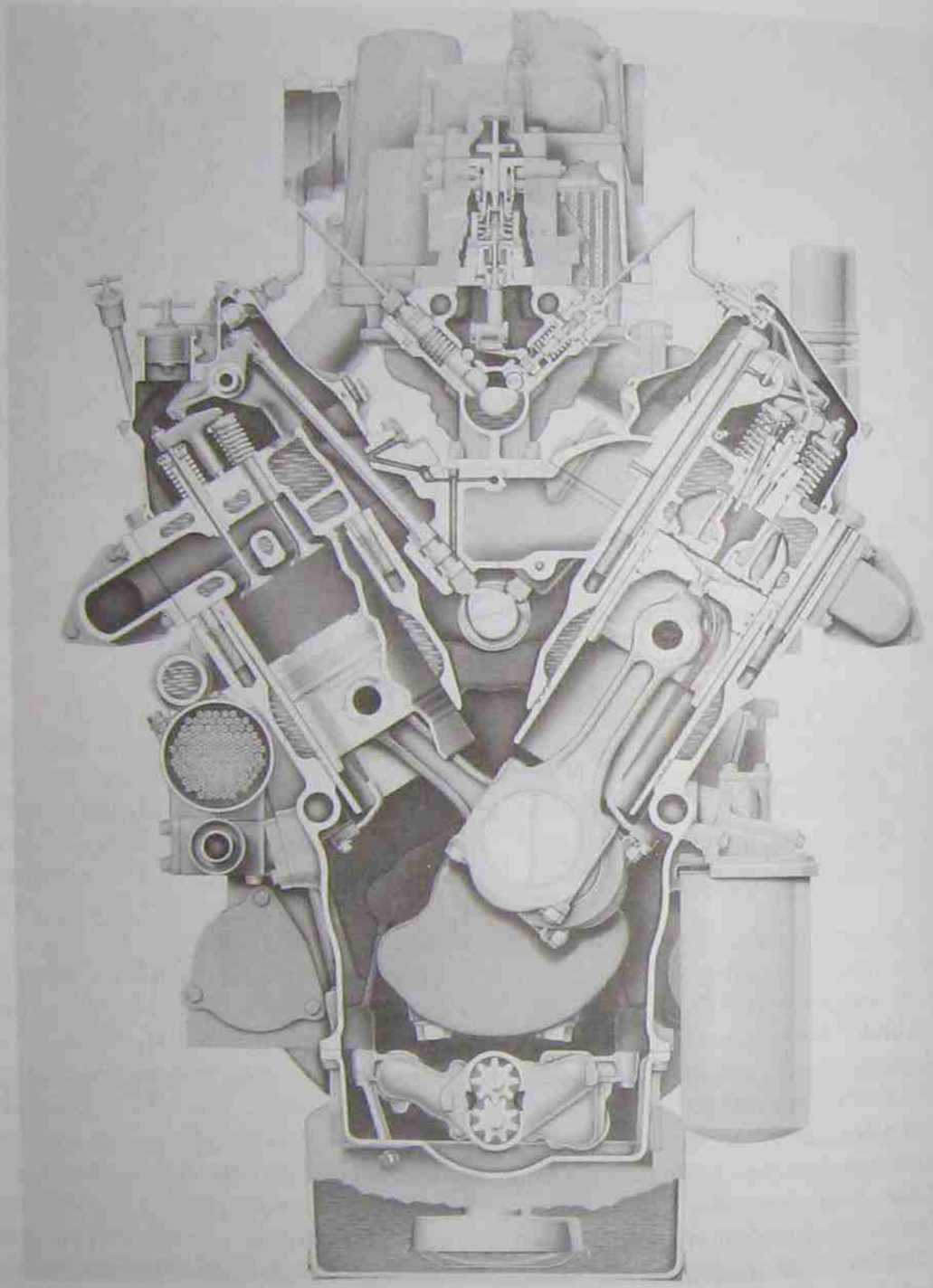


Fig. 10-15 Cross-section view of four-stroke cycle "V" block diesel engine

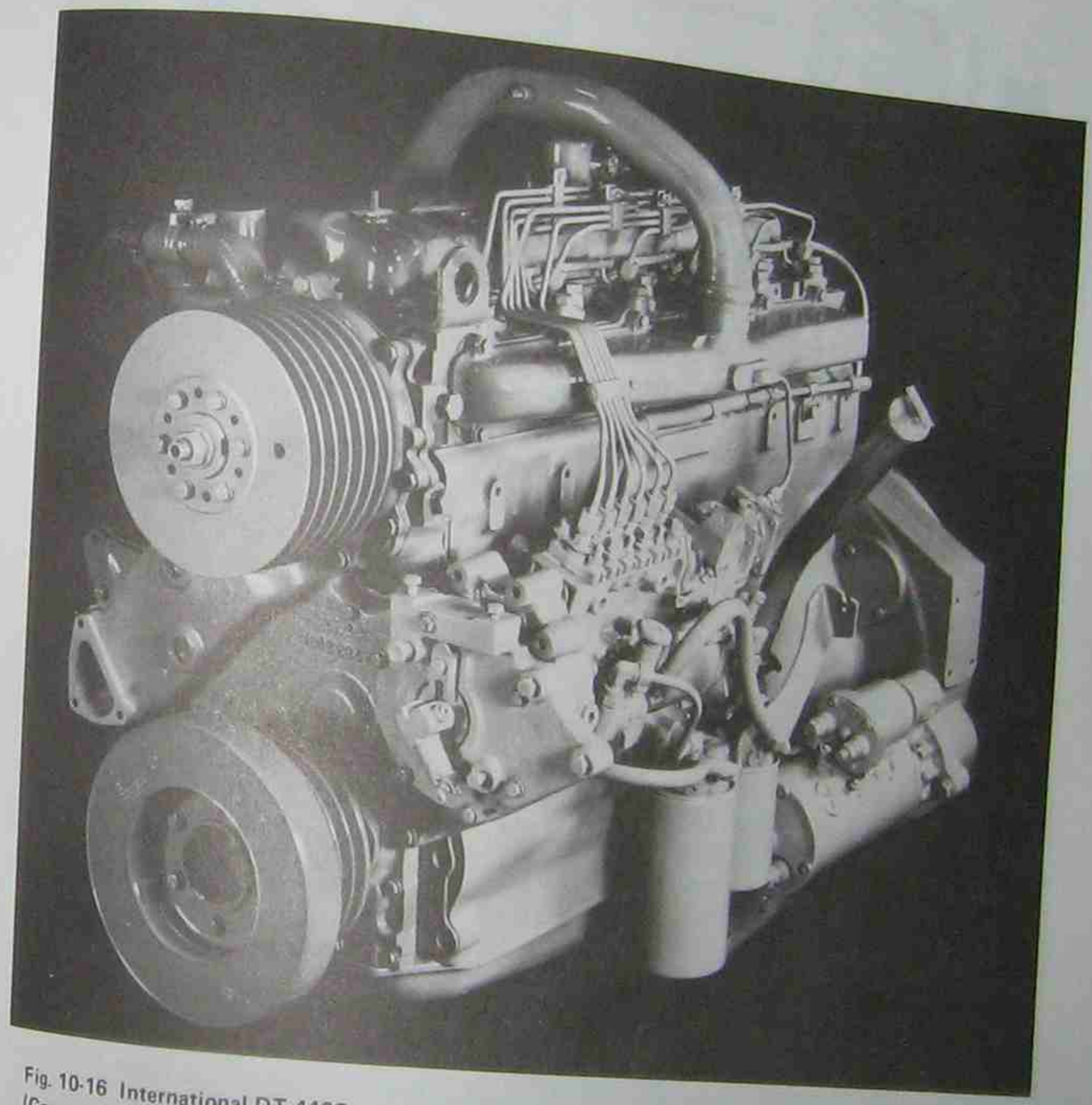


Fig. 10-16 International DT-446C turbocharged, in-line, six-cylinder medium diesel engine for highway use (Courtesy of International Harvester)

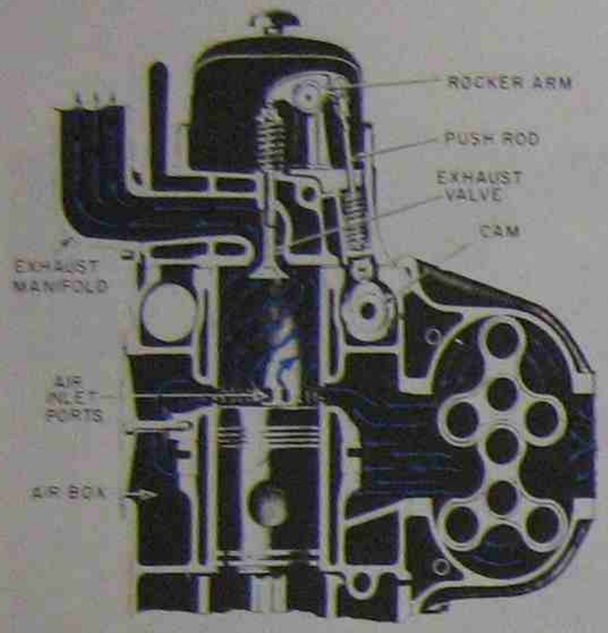


Fig. 10-17 Intake and exhaust system of two-stroke cycle diesel



Fig. 10-18 Diesel cylinder sleeve can be removed from the engine block

located at the top of the cylinder open, allowing exhaust gases to leave. The last amount of exhaust is scavenged from the cylinder by the incoming air. Exhaust valves now close, the piston moves upward sealing off the intake ports, and the air charge is trapped and compressed.

Since the diesel requires heat to ignite the fuel mixture, it is a difficult engine to start in very cold weather. There are several methods used to pre-heat the cylinder or make the fuel easier to ignite:

- Glow plugs are used to heat the combustion chamber.
- Special electric heaters warm the oil or water before starting.
- Ether is even injected into the air intake to improve the burning of the fuel.

Because it is difficult to start when cold, it is not unusual to leave a diesel truck running

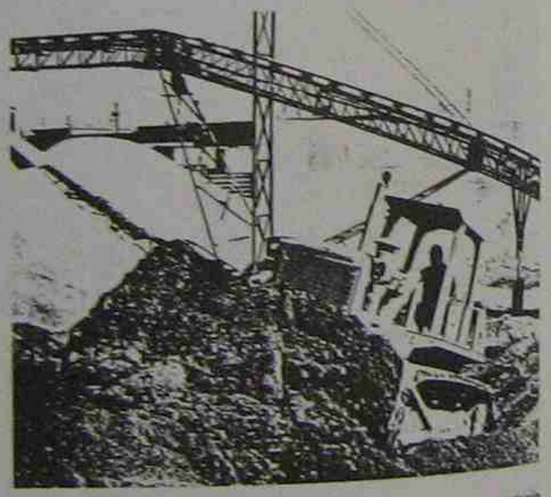


Fig. 10-19 Long hours under heavy load do not strain the diesel (Courtesy International Harvestor Company)

even if it is not to be used again for several hours, or even overnight.

The diesel is also difficult to stop once it is running. A gasoline-powered engine has an ignition system which can be shut off or shorted out to stop it; the diesel does not. Instead, it is stopped by a decompressing device that holds open the intake valves to prevent the pistons from building up enough pressure to ignite the fuel. Although the engine could be stopped by shutting off the fuel supply, this would only drain the system and leave no fuel in the pump or injectors for restarting.

Diesel Uses

The world of the diesel is constantly expanding. One of the most important applications of the diesel is the diesel locomotive; this has made the steam locomotive nearly obsolete. Diesel engines for boats, trucks, road machinery, buses, offshore oil drilling rigs, and transportable electric power units are other applications where the diesel is very effective. It is an engine known for durability and ease of maintenance, figure 10-18. Because of its slower speeds, it can operate continuously for many hours without requiring major repairs, figure 10-19. The diesel is enjoying expanded popularity as an automobile engine because of its fuel efficiency, figure 10-20, and its ability to meet government pollution control standards with little difficulty, figure 10-21.

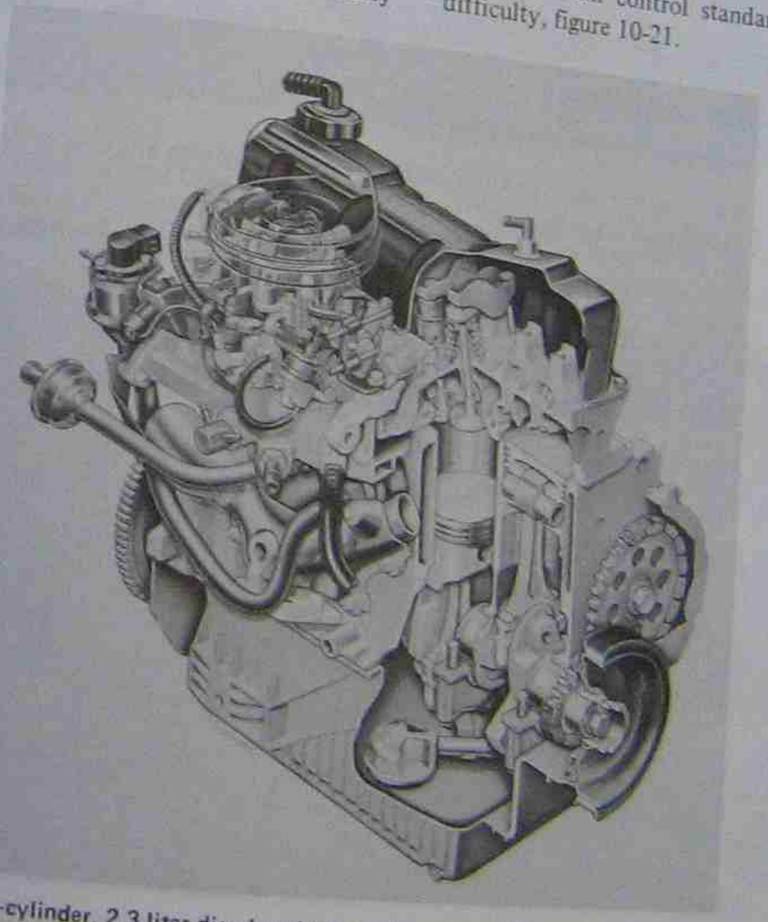


Fig. 10-20 Four-cylinder, 2.3 liter diesel engine for automative use (Courtesy of Ford Motor Company)



Fig. 10-21 Diesel-powered automobile (Courtesy Mercedes-Benz of North America Inc.)

REVIEW QUESTIONS

1. What were early diesel engines used for?
2. Why does the diesel produce more power with a given amount of fuel energy than other engines?
3. What does the diesel's high compression ratio have to do with its success?
4. Why doesn't the diesel use a carburetor?
5. What temperature does the air reach under compression?
6. What causes the fuel to ignite in the combustion chamber?
7. How does the fuel get into the cylinder?
8. What is the purpose of an air blower on a diesel engine?
9. When engine speed is changed, what is varied: fuel, air, or both fuel and air?
10. Explain why diesel fuel is not cheap or low-grade fuel.

Unit 11 Jet Engines

OBJECTIVES After completing this unit, the student should be able to:

- Explain the principle of jet propulsion.
- Compare rocket and jet engines.
- Identify and explain the operation of:
  - A. ramjets
  - B. pulsejets.
  - C. turbojets.
  - D. turboprops.
  - E. turbofans.

Most of us think of jet propulsion as a new idea, one developed during this century. While the most notable application of jet propulsion, the jet aircraft, figure 11-1, has come about during the past few decades, the theory and use of jet propulsion stretches back for



Fig. 11-1 The jet engine powers modern commercial and military aircraft. (Photo courtesy of Electric Power Research Institute)

Unit 13 Gas Turbine Engines

OBJECTIVES After completing this unit, the student should be able to:

- Explain the gas turbine's basic principles of operation.
- List the advantages of gas turbines.
- Discuss the development of the gas turbine in automobiles, trucks, and aircraft.

WHY GAS TURBINE?

The term gas refers to the method that is used to drive the turbine wheel. Various fuels can be used to create the gas: natural gas, naphtha, distillate oil, residual fuels, jet fuels, diesel fuel, and kerosene. Gas, then, is the combustion product of fuel and air that rushes through the turbine, potential chemical energy converted into kinetic thermal energy.

The thermodynamic cycle of the gas turbine is similar to other types of fuel-burning engines. Air and fuel are brought together, or ignited, and the resulting hot gases are directed against a surface that can respond to the pressure–surfaces such as a turbine blade or a reciprocating engine's piston. However, the turbine is a steady-flow process while reciprocating engines are a batch process; a batch of fuel mixture enters on the intake stroke and is processed as a unit.

Gas turbines have a large appetite for air which can be satisfied only by drawing air into the turbine with a compressor. A portion of the output gases are used by the gas turbine to drive the compressor. The compressors themselves may be axial flow, centrifugal flow, or a combination of both.

GAS TURBINES AND JET ENGINES

This introduction may bring to mind the jet engine principles and components that were discussed in Unit 11. It is important to distinguish between the two prime movers, jet engines and gas turbines. The turbojet discussed in the other unit is clearly a turbine type of engine, but the primary purpose of the engine is that of the reaction of the gases producing thrust as they *leave* the engine. And, even though the vast portion of the power produced by a turboprop aircraft is used to power the propeller, still about 10% of the propulsive force is derived from the jet principle as gases leave the engine.

The gas turbines discussed in this unit do not rely on jet thrust principles. Their construction and application is strictly that of a turbine shaft driving a mechanism.

GAS TURBINE APPLICATIONS

Gas turbines have found many uses even though their development, like that of the turbojet, has been underway for a relatively short time. In some applications their use has been rather firmly established, such as in electrical generation and powering helicopters. However, in other applications, such as passenger automobiles, research and development continues.

Applications of turbines can be classified into several areas:

- Gas turbines for trucks, buses, large military vehicles, and off-the-road equipment
- Gas turbines for automobiles
- Gas turbines for helicopters and small propeller aircraft
- Gas turbines for marine use
- Gas turbines for process industries
- Gas turbines for electrical generation
- Gas turbines for multipurpose use

BASIC PRINCIPLES

The basic principle of the gas turbine engine is converting the kinetic energy of hot expanding gases into mechanical rotary energy of a turbine wheel. The typical gas turbine first brings large quantities of air into the engine with the aid of a compressor. Fuel enters the combustion chambers where it is combined with the air and ignited. The hot, expanding gas is directed against the buckets or blades mounted on the turbine wheel. In addition to the gasifier turbine that drives the compressor, there is a power turbine that provides shaft power to the driven machine. It is at the turbine wheel that most of the kinetic energy of the expanding gases is converted to mechanical rotary energy. An operating cycle of this type is referred to as a simple *open cycle* because the gases are exhausted directly to the atmosphere, figure 13-1.

It is in the area of exhausting gases that heat and efficiency can be lost in any engine. The waste involved in the reciprocating piston engine is obvious. Hot gases are removed from

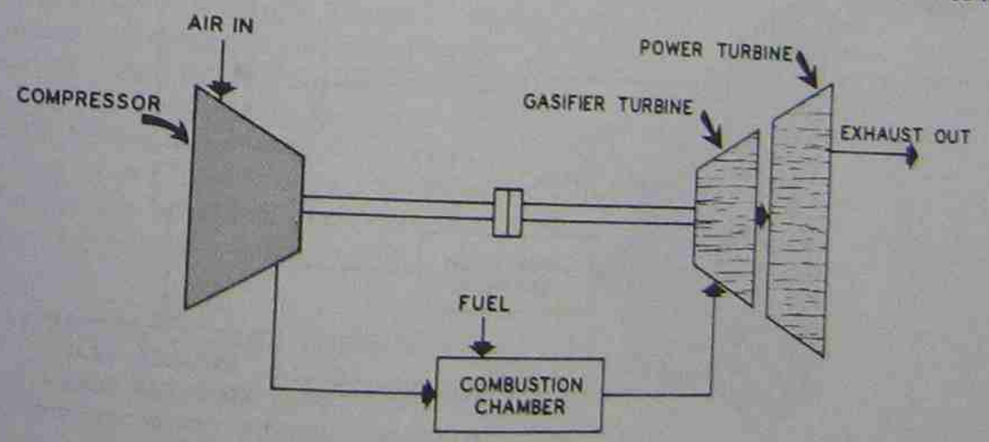


Fig. 13-1 Simple open cycle gas turbine

the engine even though much heat energy remains. Gas turbines are frequently designed to minimize this type of waste. Passing the gases through several stages of turbine wheels uses the energy to a greater degree than a single turbine wheel. Also, a *regenerator* that uses exhaust heat to preheat the incoming air increases efficiency, figure 13-2.

Another technique that can be used to increase thermal efficiency is to exhaust the gases from the gas turbine to a steam turbine system forming a combined cycle, figure 13-3.

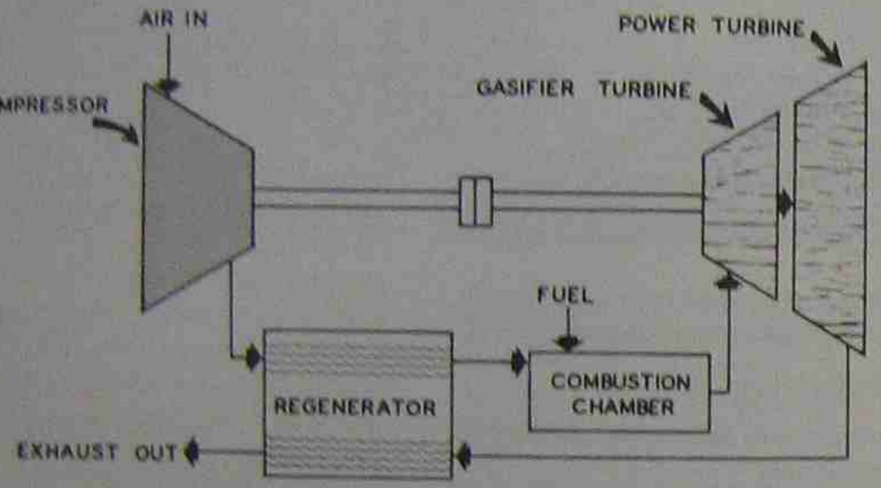


Fig. 13-2 Regenerative open cycle gas turbine

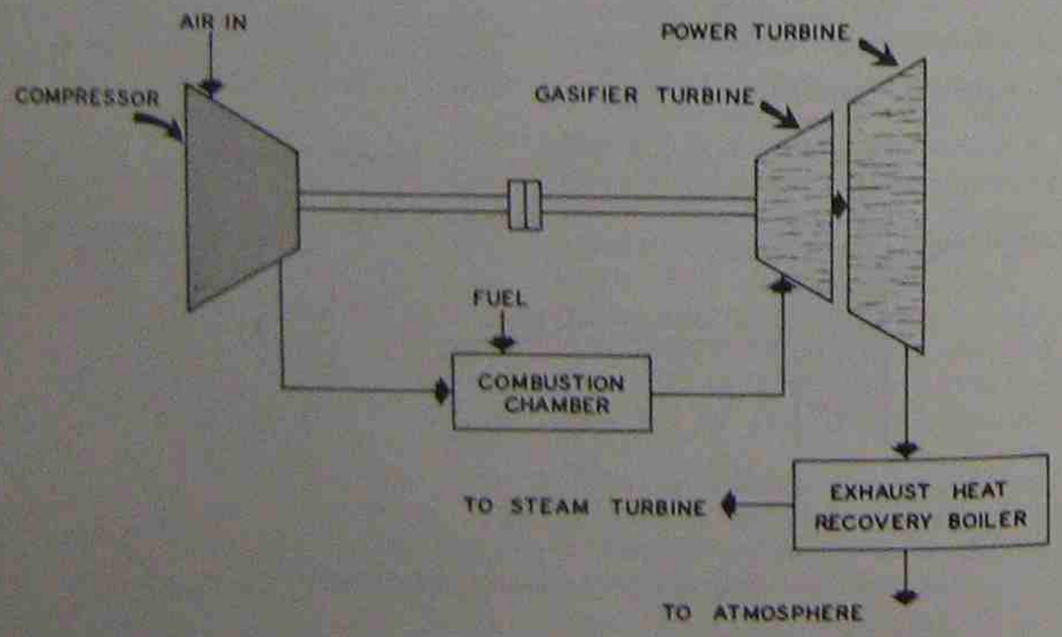


Fig. 13-3 Combined cycle gas turbine with steam turbine

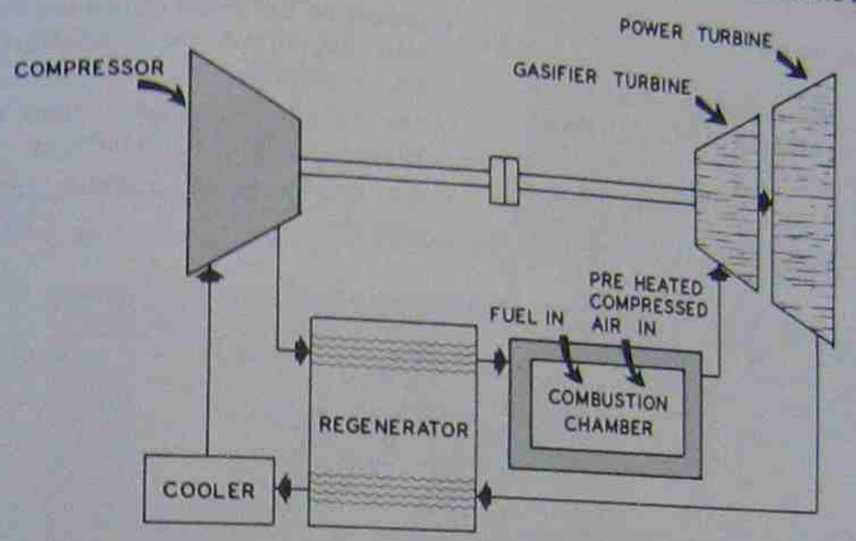


Fig. 13-4 Closed cycle gas turbine

Gas turbines can also operate on the *closed cycle* principle, figure 13-4. In this case, hot combustion gases superheat, but do not contact, the working gas which is expanded through the gasifier and power turbines, channeled to the regenerator where it gives up heat, and then to the cooler for further temperature reduction. The gas is then compressed and ready for expansion through the system. Since the working gas does not come in direct contact with the combustion products, friction losses are reduced as well as turbine wear. The incoming combustion air also has the benefit of the regenerator. Any fuel may be used: oil, gas, or solid.

ADVANTAGES OF GAS TURBINES

Gas turbines have many advantages. High on the list is the smooth, vibration-free power that is produced. There are no reciprocating parts, just continuous rotary motion. Gas turbines require little warmup time, so they can be brought up to full operating power in a short time. Of course, advantages vary with the application but it could be further said

ENGINE SIZE COMPARISON
GAS TURBINE vs. CONVENTIONAL

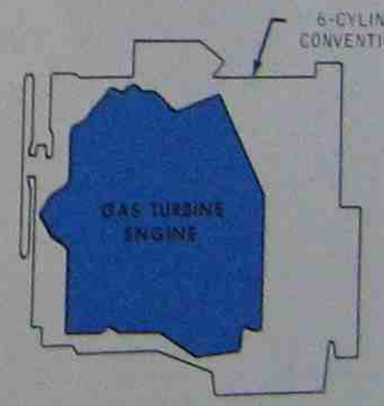


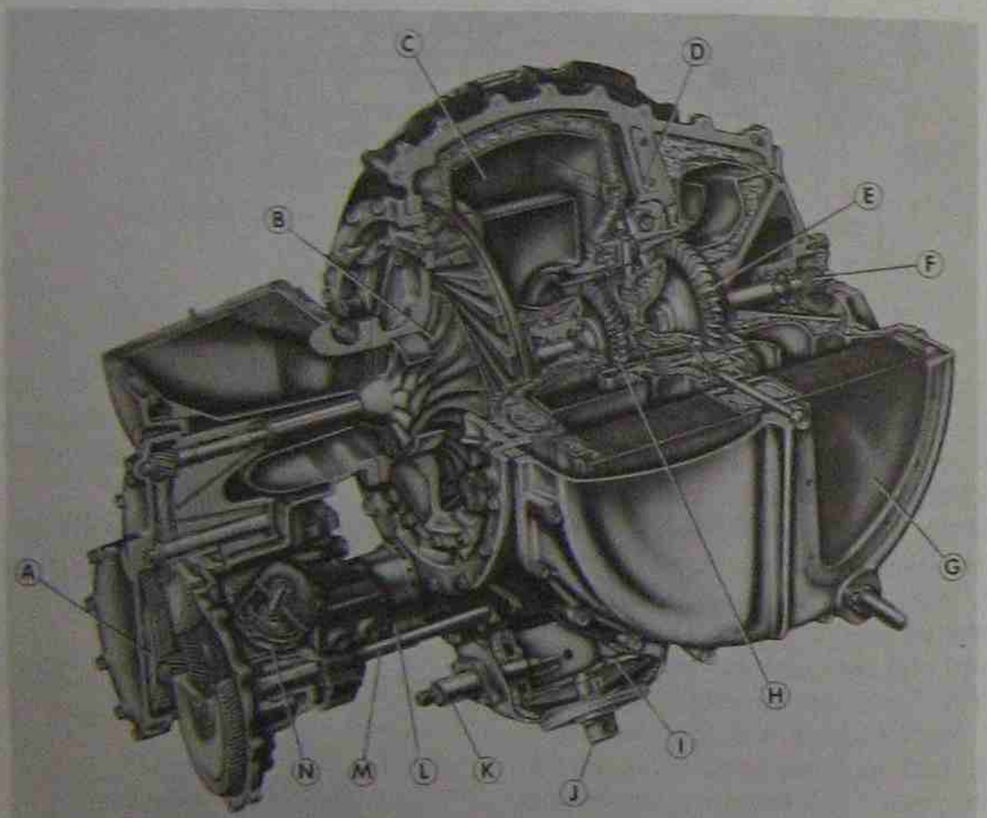
Fig. 13-5 Showing comparison of sizes between gas turbine and standard 6-cylinder engines

that gas turbines:

- compete very well with other prime movers on size and weight per horsepower, figure 13-5.
- operate well on a wide variety of relatively inexpensive fuels.
- present no significant maintenance problems and, in fact, are considered to be easy to maintain.

In the case of vehicular applications, there are additional advantages. Gas turbines:

- are air-cooled; no radiator freezing problems.



MAIN COMPONENTS OF THE TWIN-REGENERATOR GAS TURBINE: (A) accessory drive; (B) compressor; (C) right regenerator rotor; (D) variable nozzle unit; (E) power turbine; (F) reduction gear; (G) left regenerator rotor; (H) gas generator turbine; (I) burner; (J) fuel nozzle; (K) igniter; (L) starter-generator; (M) regenerator drive shaft; (N) ignition unit.

Fig. 13-6 Cutaway view of Chrysler regenerative gas turbine A-831 (Courtesy Chrysler Corporation)

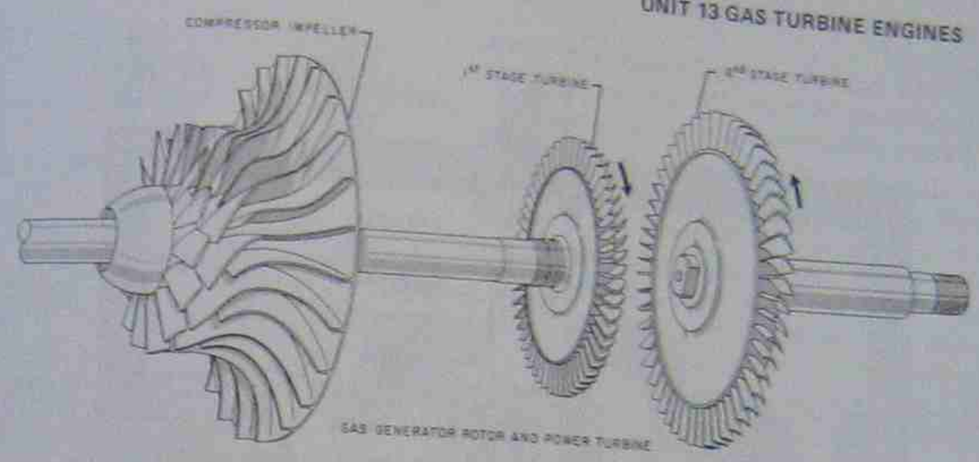


Fig. 13-7 Basic parts of the two-shaft turbine

- have fewer moving parts than reciprocating engines.
- start easily in cold weather.
- combustion is very complete. Exhaust is cleaner than that of other engines and, therefore, the gas turbine represents less of an air pollution problem.
- do not stall under overload.
- supply heat for passengers instantly.

SPECIAL CONSIDERATIONS

Gas turbines do require some special considerations in certain areas. One is their appetite for clean air. The air must be well cleaned or it will damage the precision parts within the turbine. Turbines also operate best at top speed. To slow a turbine down by reducing the fuel available lessens the efficiency of the turbine. These problems have been difficult for engineers and researchers to solve, especially in vehicular applications.

VEHICULAR DEVELOPMENT

Vehicular turbine applications must solve the problems of fuel consumption, wide variety of speed requirements, exhaust temperature, and engine braking. The regenerative gas turbine is able to do this, figure 13-6.

The turbine developed by Chrysler engineers is a two-shaft regenerative type. Figure 13-7 illustrates the first stage gas generator rotor which drives the compressor, and the second stage power turbine which provides power for propelling the auto. The regenerators are rotating heat exchangers that extract heat from the exhaust gases and then use this heat to preheat air as it comes from the compressor to the burner or combustion chamber, figure 13-8. The regenerators serve to increase fuel economy and reduce temperature.

Air is drawn into the turbine and compressed by a centrifugal compressor. The compressed air picks up heat as it passes through the regenerator. Arriving at the burner, the air is burned with the fuel. Through the combustion process, the energy level of the fuel is

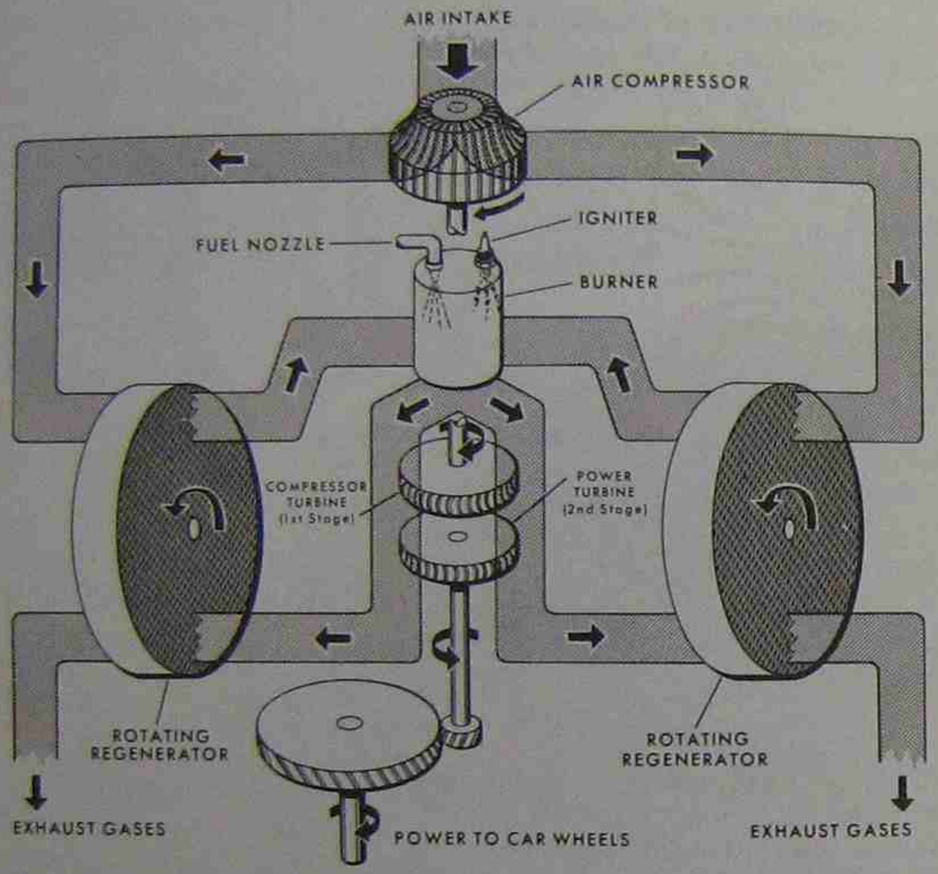


Fig. 13-8 Diagram of gas turbine operation

increased and this gas is applied to the first stage turbine which drives the compressor. The hot gases are then applied to the second stage turbine or power turbine which drives the auto through transmission. Before entering the exhaust ducts, the hot gases pass through the honeycomb regenerator drums.

The first stage turbine always rotates whenever the turbine is operating. This can be anywhere from 18,000 revolutions per minute to idle to 44,600 revolutions per minute at full power. The power turbine speed may range from zero when the auto is standing still to a maximum of about 45,700 revolutions per minute.

Fixed nozzles direct the hot gases against the first stage turbine wheel. However, at the second stage or power turbine wheel, the variable nozzle is used, figure 13-9. This is a feature of the Chrysler turbine. The variable nozzles permit engine braking or acceleration at all speed ranges. The nozzles are linked to the accelerator, which changes nozzle direction. At starting or idle, the nozzles are in an axial position, but as the accelerator pedal is depressed, the variable nozzles are turned toward the direction of turbine wheel rotation. The variable nozzles are also used to provide engine braking. If the auto is traveling at more than 15 miles per hour (24 kilometers per

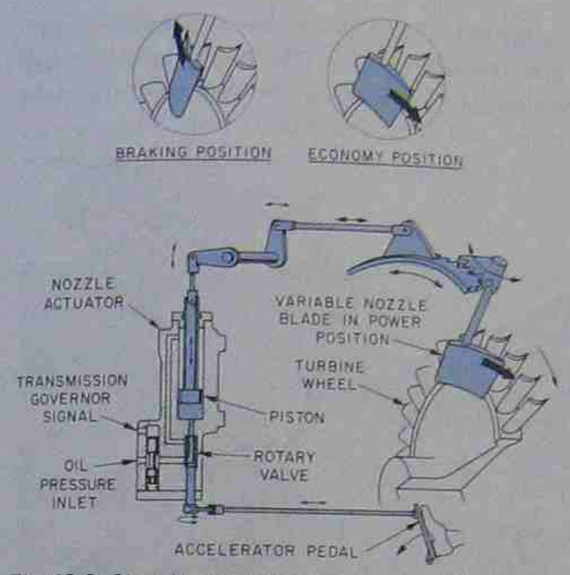


Fig. 13-9 Chrysler variable nozzle system (Courtesy Chrysler Corporation)

hour) and the accelerator is released, the nozzles are moved to such a position that the gases will be directed against the turbine wheel's direction of rotation. At speeds of less than 15 miles per hour, release of the accelerator will cause the nozzles to assume an axial position or open idling position.

Fuel control must be variable to insure a high degree of operating economy. Operating at full power for all auto speed requirements would be quite wasteful. This fuel control system consists of a fuel pump, governor, pressure regulator, and metering orifice. At constant speeds, the governor will provide fuel to the burner in response to the position of the accelerator. Fuel flow will shut off when the accelerator pedal is released, but fuel will resume flowing when idle speed is reached.

This engine has excellent acceleration and flexibility as shown by its horsepower and torque curves, figure 13-10. It is difficult to stall this turbine because even if torque requirements become very great, the power turbine will merely slow down. The compressor will continue to function normally.

General Motors has been researching the

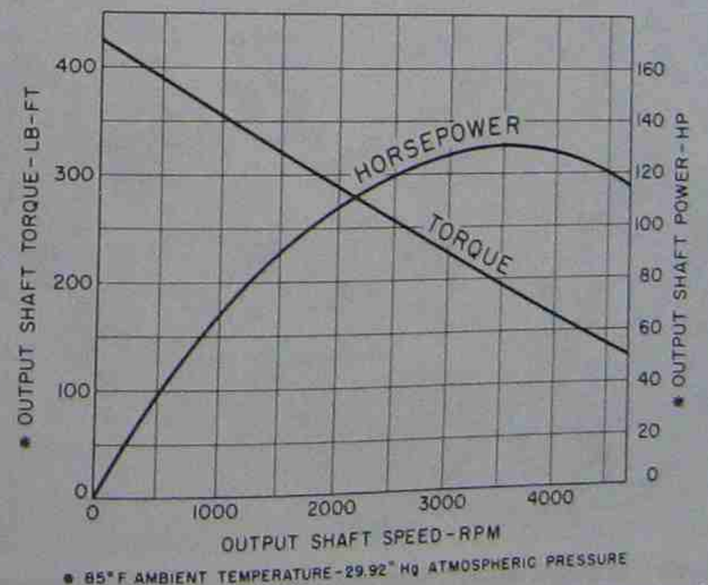


Fig. 13-10 Horsepower and torque curves for Chrysler turbine (Courtesy Chrysler Corporation)

use of the gas turbine for automobiles since the early 1950s. Their GT series is used on the Firebird experimental automobiles, figure 13-11. The GM engineering staff's latest work on gas turbines designed for passenger cars is the GT-225, a small size regenerative turbine, figure 13-12. It is being used to test compressors, combustors, regenerators, controls, and new materials. This turbine can burn kerosene or diesel fuel. Hydrocarbon and carbon monoxide emissions are low, but the high emission of oxides of nitrogen is a problem with turbines. However, the GT-225 engine equipped with a pre-chamber combustor was able to meet the 1978 Federal emission standards. Research continues on fue

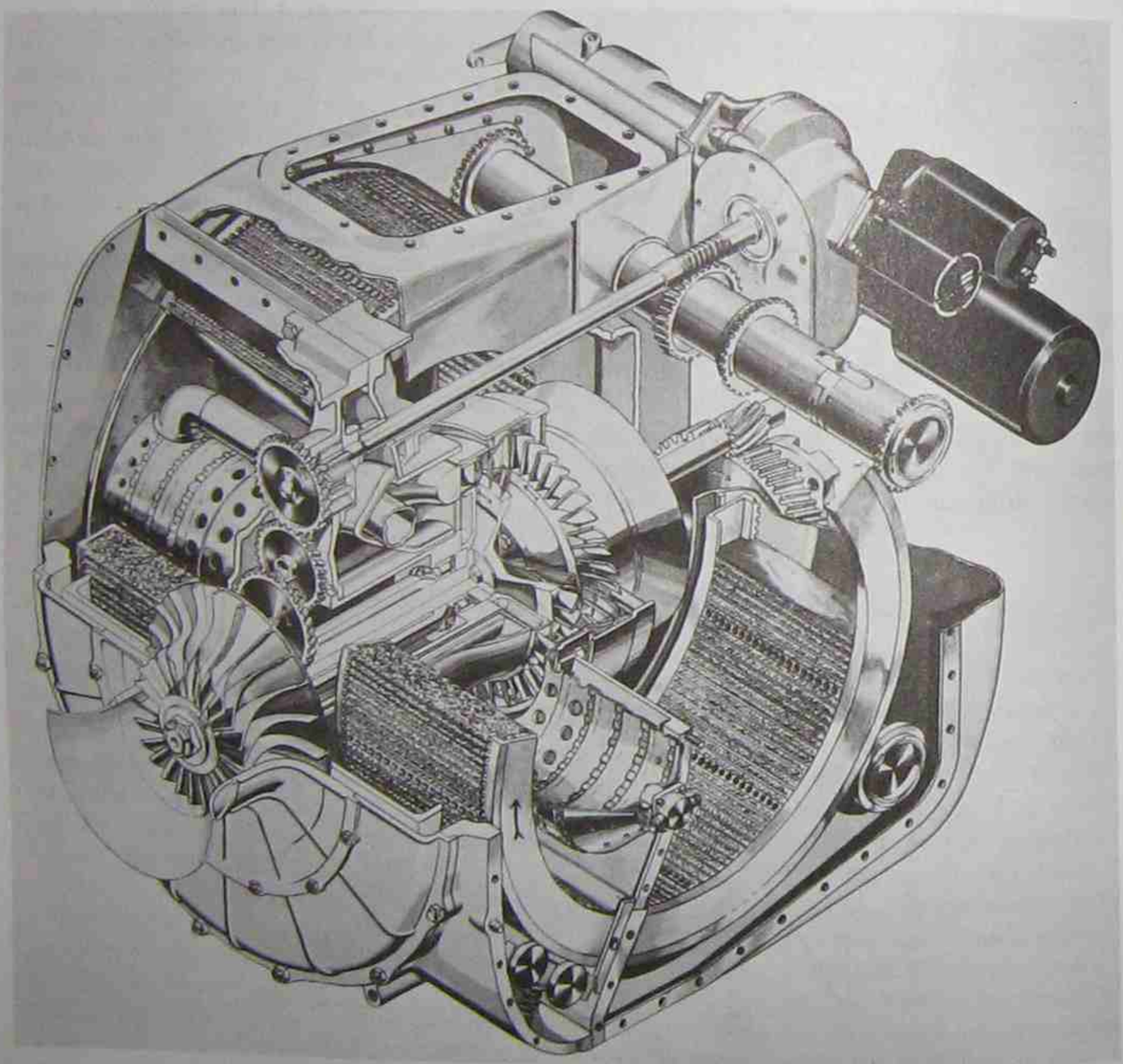


Fig. 13-11 Cutaway of General Motors GT-305 engine (Courtesy General Motors Corporation)



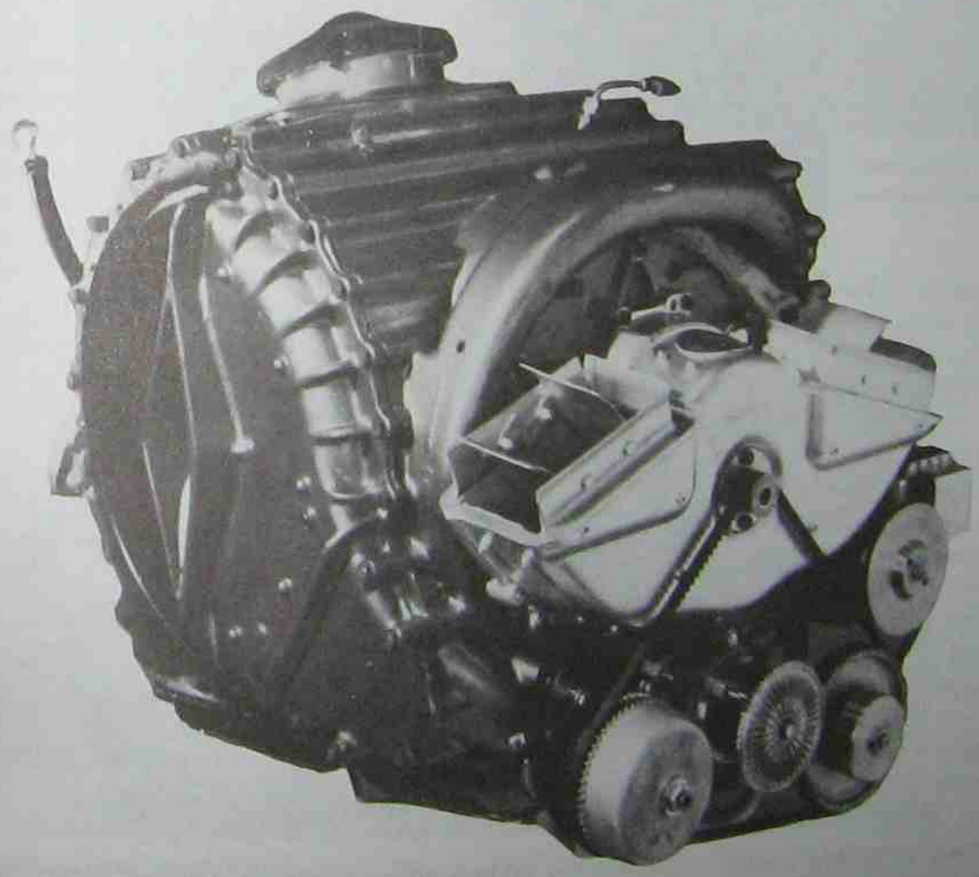


Fig. 13-12 General Motors AGT-1 gas turbine and the latest, smaller AGT-5 (Courtesy General Motors Corporation)



Fig. 13-13 General Motors GT-225 experimental gas turbine (Courtesy General Motors Corporation)



Fig. 13-14 Note that the air scoops on this GM truck turbine installation. (Courtesy General Motors Corporation)

economy and engine durability, figure 13-13.

High noise level and high exhaust temperatures have led research away from the automobile toward development of engines capable of competing directly with the diesel in the heavy-duty vehicle market, figure 13-14. The GT-309 turbine by GM has developed into the 404 and 505 industrial gas turbine engines, figure 13-15.

General operating principles for this regenerative gas turbine are similar to smaller automobile units. A centrifugal compressor compresses air to 3.8 times atmospheric pressure and directs it through the regenerative drum to the combustors. High energy gases from the combustion process are directed against the gasifier turbine and then against the power turbine.

The General Motors turbine employs a power transfer system, figure 13-16, to insure high efficiency at part throttle and to provide for engine braking. The independent gasifier turbine and the power turbine shafts are equipped with a multiplate slipping clutch which is the heart of the power transfer system. At part load, a portion of the gasifier turbine power is transferred to the power turbine side of the engine. At less than full load, the system slows the power turbine as a slight amount of pressure is applied to the clutch. The governor on the gasifier turbine responds by increasing fuel output to increase speed. The net result is increased turbine inlet temperature and the higher turbine efficiency that can be gained with high temperatures. With power transfer, the gasifier turbine temperature is maintained at a constant high level, temperatures that will permit high thermal efficiency. Clutch pressure is controlled by a pressure programmer which senses gasifier turbine torque and speed as well as temperature and altitude.



Fig. 13-15 General Motors GT-309 turbine engine for heavy-duty vehicular applications (Courtesy General Motors Corporation)

Engine braking is accomplished by locking the power transfer clutch which causes the output of the power turbine to drive the compressor, dissipating the heat energy as air is pumped through the engine.

Efforts at the Ford Motor Company are in the area of passenger car applications for turbines, figure 13-17. Research is directed at finding materials and manufacturing processes that can produce turbine parts inexpensive enough for passenger car use. These parts must be able to withstand high turbine temperatures while maintaining exacting engine tolerances. Ceramic components are being considered to replace the expensive high-temperature metal parts. This permits an increase in engine temperature, allowing the engine to be made smaller and more economical to operate. Fuel economy is expected to be better than a comparable internal com-

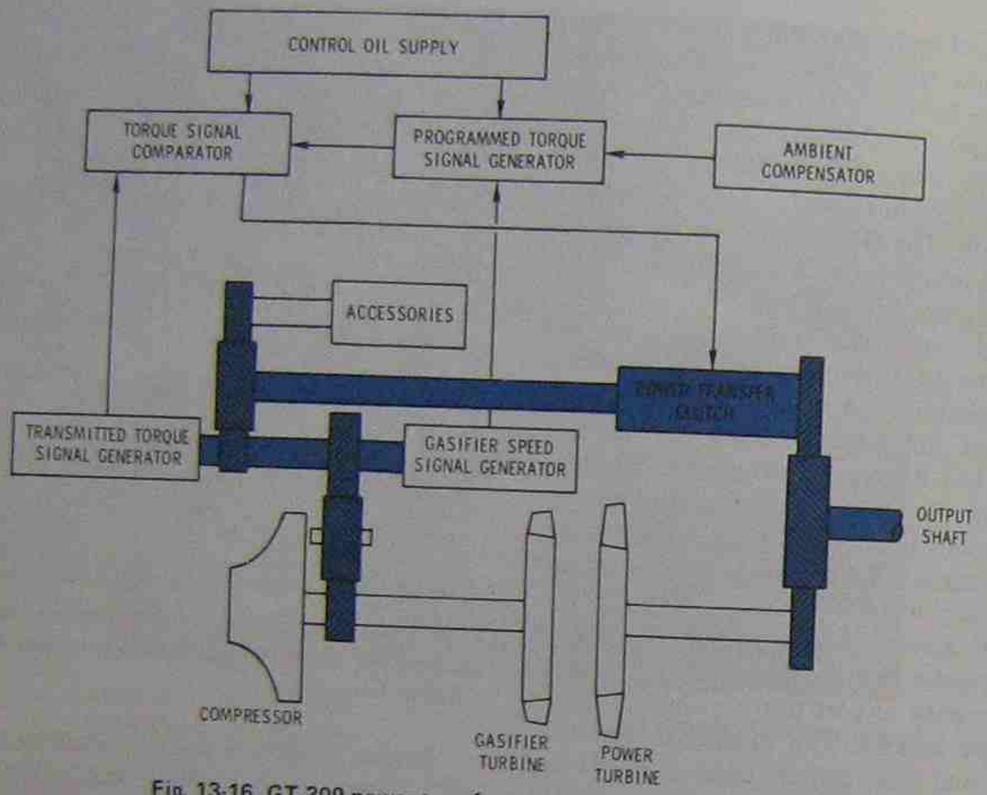


Fig. 13-16 GT-309 power transfer engine control system diagram

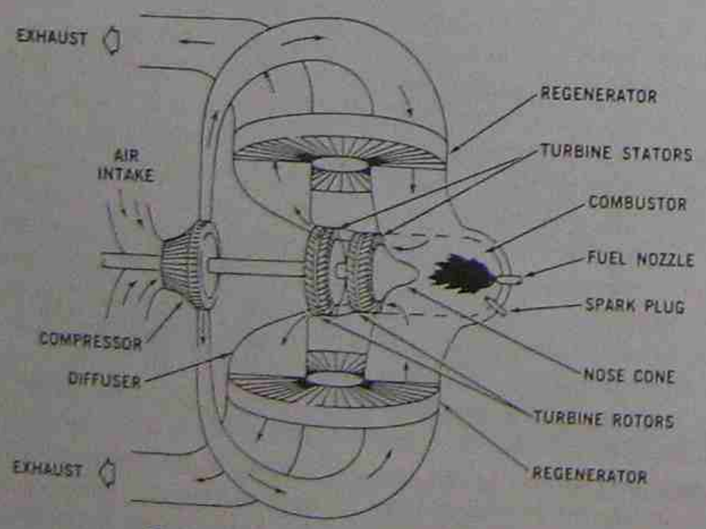


Fig. 13-17 Passenger car turbine engine

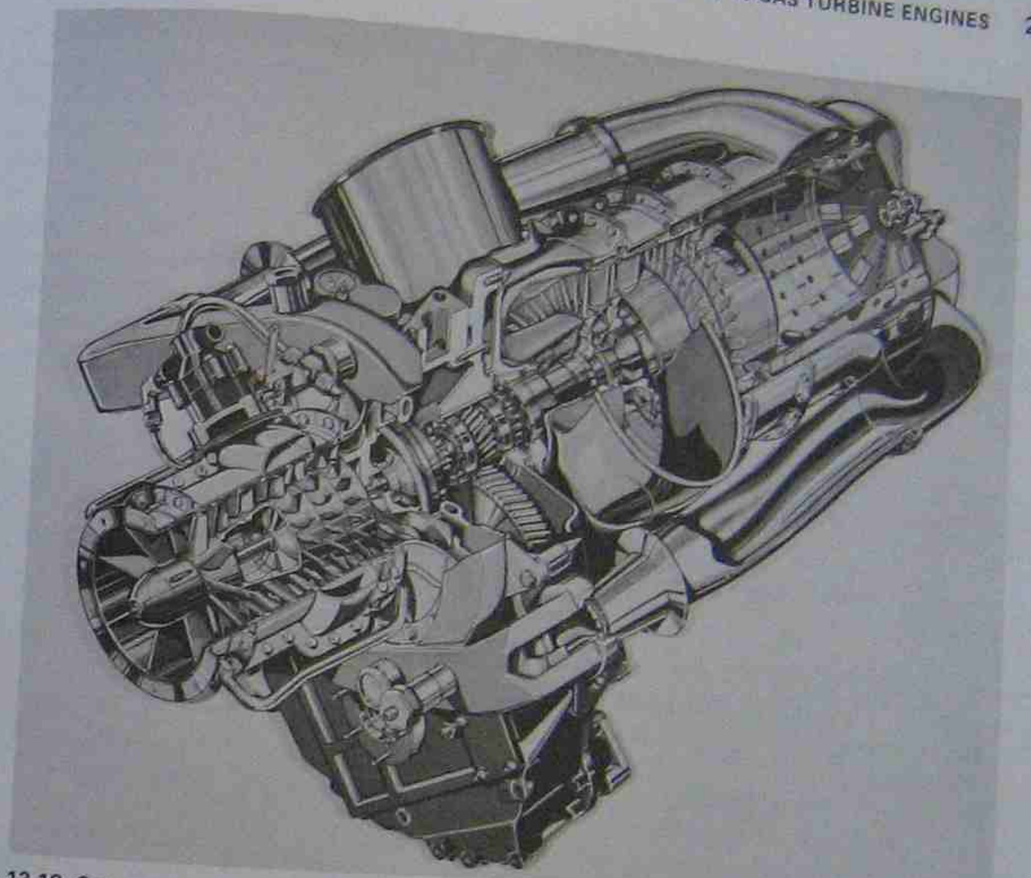


Fig. 13-18 Cutaway view of a Model 250 turboshaft engine (Courtesy of Allison Gas Turbine Division of General Motors)

bustion engine. New combustion systems are also being developed to reduce the emissions of nitrogen oxides. Turbines are already low in hydrocarbon and carbon monoxide emissions. It can take several years to determine if a competitive passenger car turbine is possible.

AIRCRAFT DEVELOPMENT

Jet engines revolutionized the field of commercial and military aviation with turbojet and turboprop engines. Gas turbine manufacturers developed gas turbine engines for smaller fixed-wing, propeller-driven aircraft and helicopters. In these applications, shaft power is used rather than jet thrust. The Allison Model 250 turboshaft light engine falls into this category, figure 13-18. The model 250 was designed specifically for the Army's new observation helicopter. The 250-C18 weighs only 136 pounds (62 kilograms), yet can develop 317 horsepower (236 kilowatts). The engine dimensions are a compact

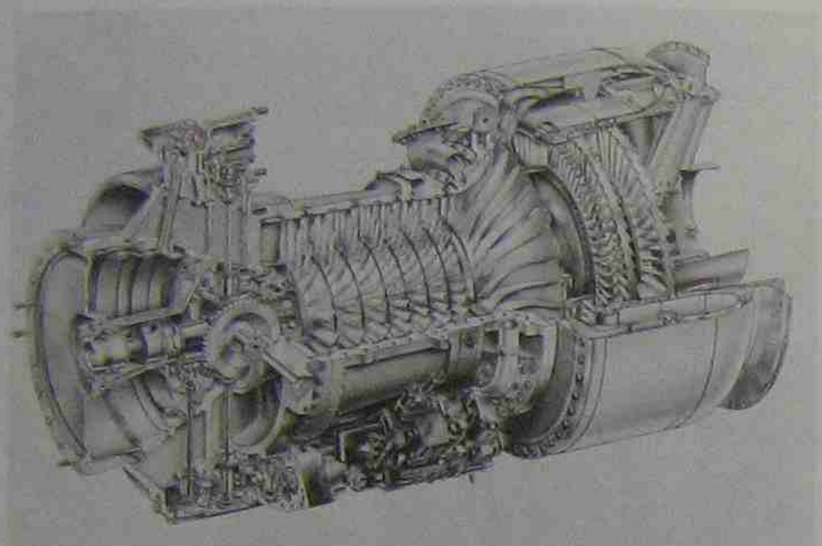


Fig. 13-19 Cutaway of the AVCO Lycoming T-53 gas turbine (Courtesy AVCO Lycoming Division)

40" long x 22 1/2" high x 19" wide (1016 mm long x 572 mm high x 483 mm wide). The power output shaft is geared down to 6000 revolutions per minute.

The incoming air is compressed by a six-stage axial flow and one-stage centrifugal flow compressor. Air is ducted to the other end of the engine and into the single large combustor. Gases pass through a two-stage gasifier turbine which drives the compressor, then to a two-stage power turbine which delivers power to the output shaft. Exhaust gases are ducted from the engine upward through twin ducts.

In the future, engines such as these may be equipped with regenerative devices which will increase the engine's thermal efficiency and the potential applications for the engine.

One of the outstanding universal-purpose turbines that has been developed is the T-53 by AVCO Lycoming, figure 13–19. Depending on the gearing, accessories, and hardware, the basic T-53 turbine can be used for turbofan, turboprop, geared helicopter, high-speed helicopter, marine, surface vehicle, or industrial applications.

The T-53-L-13 is a shaft turbine helicopter engine that develops 1400 shaft horsepower (1 megawatt) at 6300 revolutions per minute, yet weighs only 530 pounds (241 kilograms). The overall dimensions of the engine are 47.61 inches (1209 millimeters) along with a diameter of 23 inches (584 millimeters). The AVCO AFT-1500 is a vehicular version that develops 1500 brake horsepower (1.1 megawatts) at 3000 revolutions per minute. Again, the size is quite small. It is 28" high x 60" long x 40" wide (711 mm high x 1524 mm long x 1016 mm wide). It weighs 1600 pounds (427 kilograms).

The T-53 turbine has a five-stage axial compressor followed by a single centrifugal compressor. The compressed air is directed to the rear of the turbine and into the combustion chamber. Fuel atomizers ring the chamber and, after initial spark ignition, the burning is continuous. Gases pass through two compressor turbines and two power turbines. The power turbine shaft extends forward and concentrically through the compressor shaft, thus delivering shaft power at the forward or cold end of the engine.

ELECTRICAL POWER GENERATION

The field of large horsepower prime movers has long been dominated by the steam turbine. However, the gas turbine has in recent years been making its place in this important field, figure 13-20. Large, heavy-duty gas turbines may range in size from several thousand horsepower to more than 20,000 horsepower. Except for the fact that they use gas directly from combustion, these turbines closely resemble those using steam, figures 13-21 and

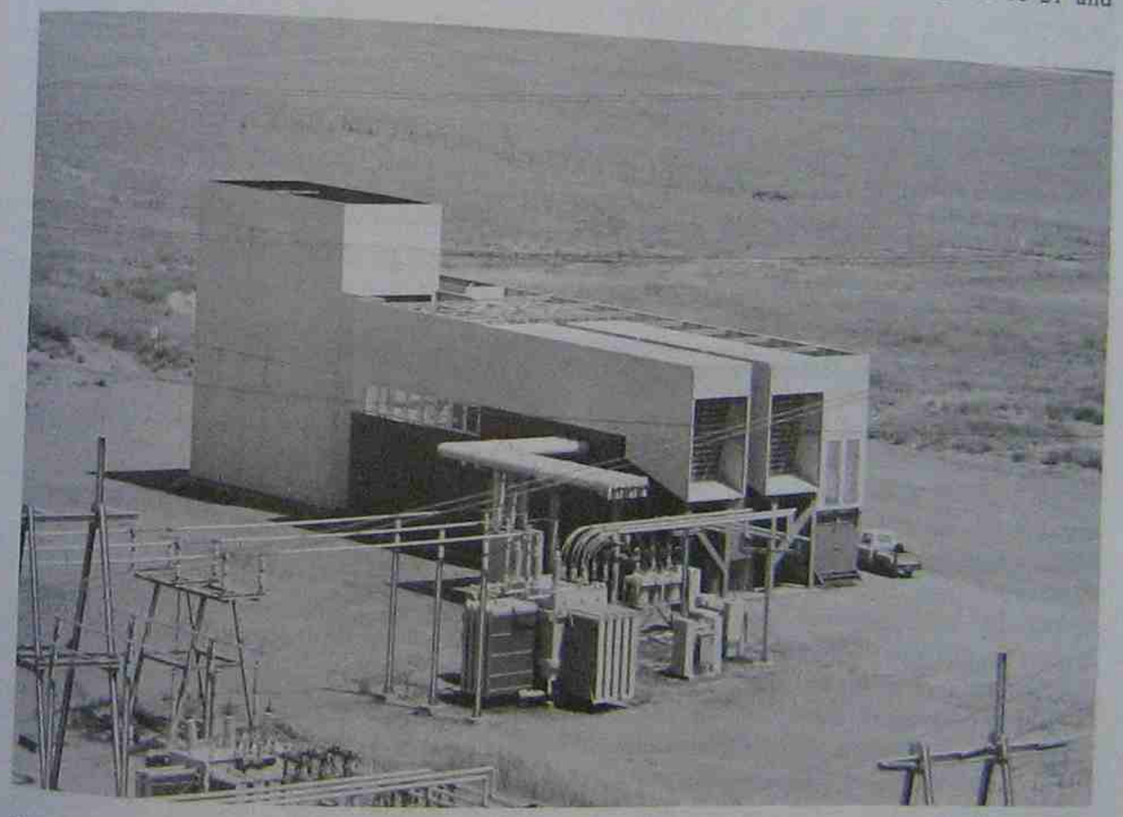


Fig. 13-20 Complete installation of Westinghouse gas turbine power plant (Courtesy Westinghouse Electric Corp. Power Generation Group)

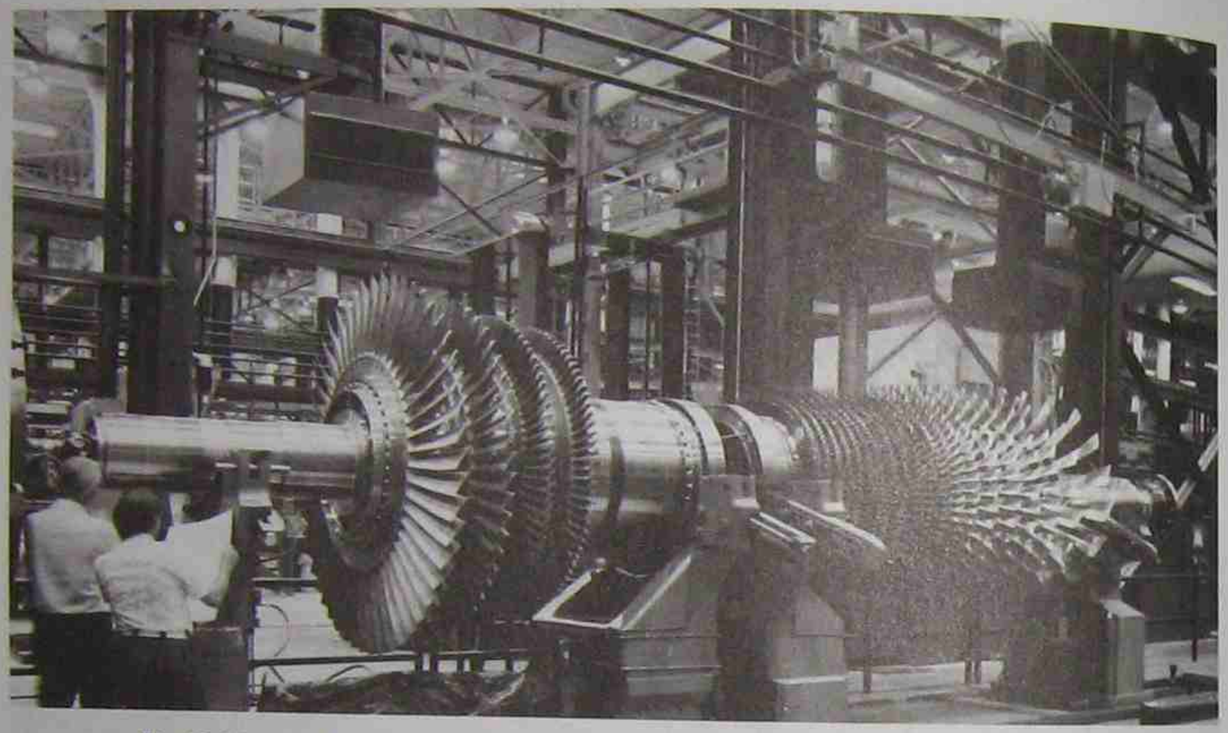


Fig. 13-21 Axial flow compressor and reaction turbine rotor for gas turbine power plant

13-22. The prime applications of these turbines is electrical power generation where, depending on the installation of the turbine, they may be used in base load generation or in peaking. *Peaking* refers to supplying the needed generation requirements during times of heavy demand on the system. In this application, the base load may be delivered by a conventional steam generator with a smaller gas turbine supplying peaking requirements. Here the gas turbine brings its advantages of quick start and low maintenance into play. Base load installations may be of a combined nature, steam turbine and gas turbine, using the gas turbine exhaust gases to preheat the air before it enters the boiler. Such a combined cycle may increase thermal efficiency as much as nine percent.

OTHER APPLICATIONS

Large gas turbines are used as the prime mover to supply the many phases of an industrial complex, providing electricity, hot water, and heat for the various industrial processes of the industry. By integrating the gas turbine into the process, industries such as chemicals, petroleum, petro-chemical, paper, and steel, among others, a complete power package can be provided. These industries require large amounts of heat and power and are natural targets for gas turbine installations.

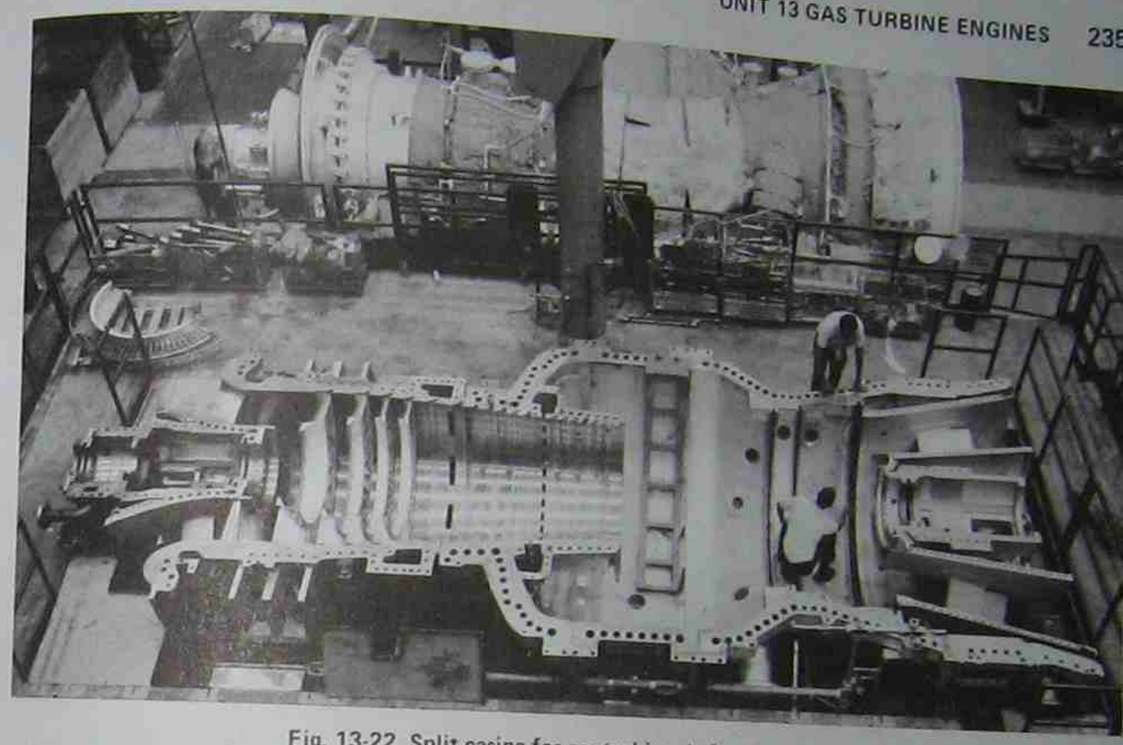


Fig. 13-22 Split casing for gas turbine shaft and turbine wheels

REVIEW QUESTIONS

1. Explain how the gas turbine's appetite for air is satisfied.
2. List several fuels that gas turbines are capable of using.
3. Explain the difference between a turboshaft engine and a turbojet engine.
4. Can a gas turbine use both turboshaft and turbojet principles? Explain.
5. List several applications for gas turbine engines.
6. Explain several of the advantages of gas turbine engines.
7. Explain the regenerative principle and the advantage of its use.
8. What is the function of the gasifier turbine?
9. What is the function of the power turbine?

10. Describe the systems that can be used to insure efficiency of the gas turbine at slow speeds and also provide for engine braking.
11. Explain how a gas turbine can be used in a combined cycle with a steam turbine.

SECTION 4
EXTERNAL COMBUSTION ENGINES

Unit 14 Steam Engines and Steam Turbines

OBJECTIVES After completing this unit, the student should be able to:

- Explain the difference between internal and external combustion engines.
- List the parts of a typical steam engine.
- Describe how an impulse turbine is different from a reaction turbine.
- Discuss the uses of steam engines and turbines.

The steam engine is classified as a heat engine. The chemical energy of a fuel is released in the form of heat energy which the steam engine is designed to harness. Unlike most engines, the steam engine can be made to operate on almost anything that will burn: wood, coal, petroleum, or their many variations. The steam engine cares little what fuel is used, just as long as the water is boiled and steam is produced. The reason why steam engines can operate on many different fuels is that the fuel is not burned within the engine itself. Fuel is usually burned in a fire box under a boiler, outside the working parts of the engine. The engine is called an *external combustion engine*.

The energy path of a typical steam engine starts with the chemical energy of the fuel being converted into heat energy. This heat boils the water to produce steam, which is confined in the boiler. High steam pressures build up and, when released and channeled,

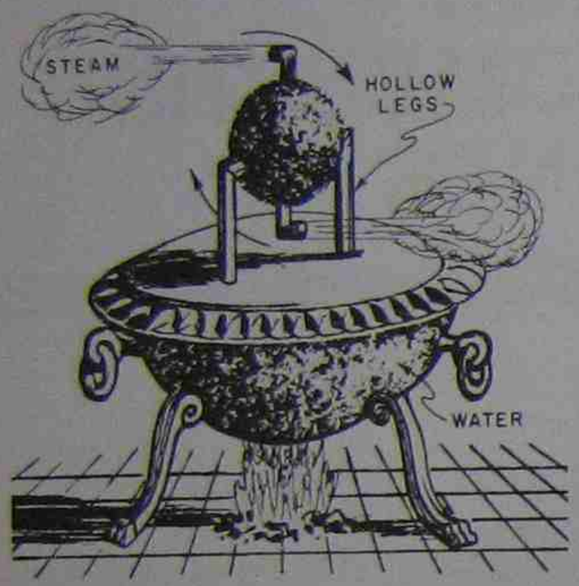


Fig. 14-1 Hero's aeolipile—steam put to work more than 2000 years ago

are able to move the engine's piston or turbine parts. It should be remembered that when water is converted into steam it expands at the rate of 1600 to 1. It is not difficult, therefore, to see how steam pressures can be built up in a closed boiler.

It is almost impossible to credit any one person with the invention of the steam engine. Many scientists, engineers, and inventors contributed their ideas down through the years, each person building upon the accomplishments of forerunners. Modern, powerful, efficient steam engines and turbines evolved from many crude, inefficient, and often unsuccessful efforts.

Hero's aeolipile which was devised 2000 years ago—and which was used in Unit 11 to illustrate jet propulsion can also be used here to describe the power of steam—the two illustrations are equally valid. Remember, the aeolipile was basically a hollow sphere that was spun around by jets of steam coming from within the sphere itself, figure 14-1. A boiler fed steam to the sphere. The action of the aeolipile can also be compared to water coming from a spinning lawn sprinkler. This novelty of the time could have been one of the first doors opened to the possibilities of steam power.

FIRST MAJOR DEVELOPMENTS

Further progress was almost nonexistent until about 300 years ago when Lord Worcester, Captain Thomas Savery, and Thomas Newcomen began to work on engines to pump water from coal mines in England, where the water, seeping into and flooding the mines, had created a need for a good pumping device. Thomas Newcomen built several hundred steam engines that were used throughout England's coal mines, figure 14-2. His pump had a rocking action: a large see-saw beam with the pump on one end and the steam engine on the other. Coal burned under the boiler, boiled the water and produced steam. Steam was let into the cylinder as the piston moved upward. The steam valve was shut off. Cold water was sprayed into the cylinder to condense the steam. Atmospheric pressure pushed the piston back down the cylinder; the pump on the other end raised water out of the mine. Since the power delivered was actually produced when the steam was condensed and atmospheric pressure, which was greater, pushed the piston down the cylinder, Newcomen's engine was more an atmospheric engine than a steam engine.

Newcomen's engines consumed an enormous amount of coal and, in spite of the large number of them in use, they were very

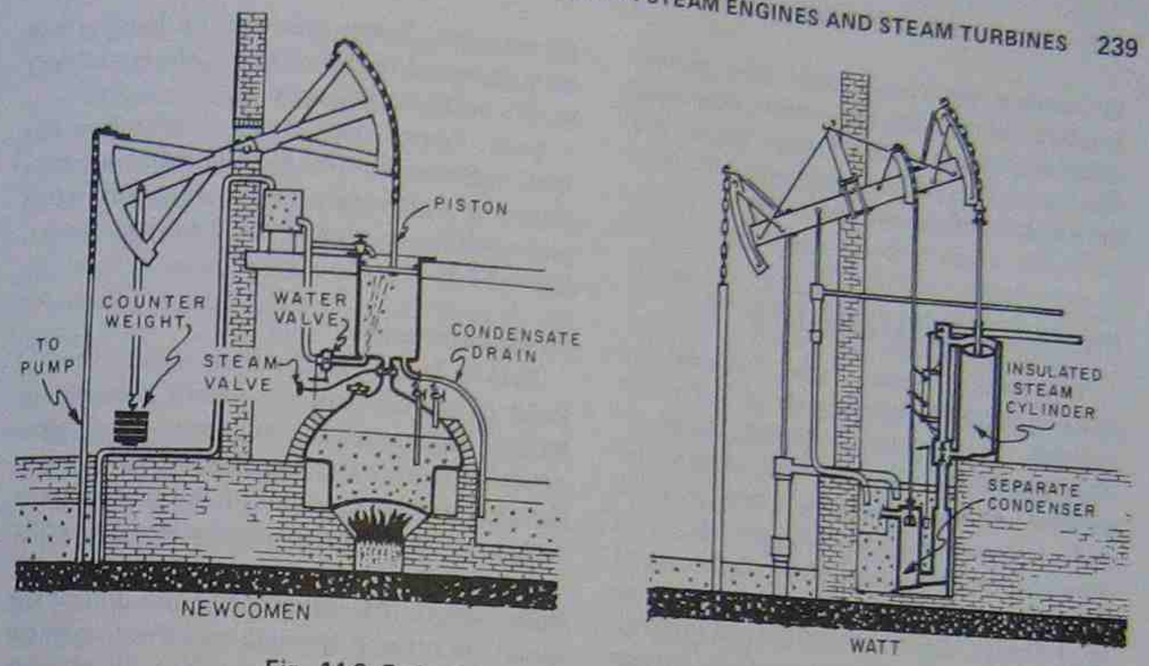


Fig.. 14-2 Early steam engines produced by Newcomen and Watt

inefficient. As coal prices rose, the cost of operating these engines became a problem.

James Watt studied Newcomen's engine and detected some of its faults. He reasoned that the principal cause of inefficiency was that the cylinder was first heated by the steam, then cooled by the condensing water. This alternate heating and cooling wasted much power. His solution was to connect a separate tank for condensing the steam. With this condensing tank connected to the cylinder, the cylinder could be kept hot all the time. Watt also devised a way to make the engine double-acting, that is, it would operate on both the push and pull strokes. The engines that Watt developed were more efficient than Newcomen's and widely used in England.

Methods were developed to convert the up and down motion of the engine into rotary motion. Engines became more versatile and were soon found powering the wheels of many industries: paper mills, corn mills, cotton spinning mills, breweries, and iron works. The steam engine was a contributing cause of the Industrial Revolution.

Watt's steam engines were heavy, so they were built to remain in one location. The eventual answer to reducing the size and weight of steam engines lay in the use of high-pressure steam, but higher pressures required boilers that could withstand these pressures without bursting. Richard Trevithick, an Englishman, successfully developed high-pressure boilers that operated at 60 pounds per square inch (408 kilopascals) pressure.

Lighter, high-pressure steam engines were adaptable to vehicles; the locomotive lent itself best to the use of steam. Trevithick built a steam locomotive and, though it was not entirely successful, it did work. George

Stephenson was the engineer who brought together all of the best steam propulsion ideas to build a practical steam locomotive. His locomotive, the *Rocket*, sparked the rapid development of the railroad industry.

MODERN DEVELOPMENTS

The modern steam engine has changed little in its *basic* components as it has developed. Two important factors, however, have contributed to the steam engine's increasing *efficiency*: higher steam pressure and higher steam temperature. A small amount of steam placed under conditions of high pressure and high temperature is capable of producing considerable power as it expands, pushing the piston down the cylinder. Steam locomotives that produce as much as 6500 horsepower (4850 kilowatts) have been built, for example. Steam pressures on locomotives have increased to the range of 300 pounds per square inch (2 megapascals).

Even though the steam locomotive has been replaced by the diesel-electric locomotive, it is worthwhile to consider what takes place within a typical railroad locomotive, figure 14-3.

Steam Locomotive

Fuel is burned in the firebox, and the hot gases of combustion are drawn through the boiler, which consists of many steel pipes surrounded by water. As the hot gases sweep through the pipes, some of the heat is transferred to the water in the boiler. The water boils and the steam rises to the top of the boiler where it is collected in the dome. The steam next travels through superheaters where its temperature is increased. The superheated steam is then introduced into the steam chest

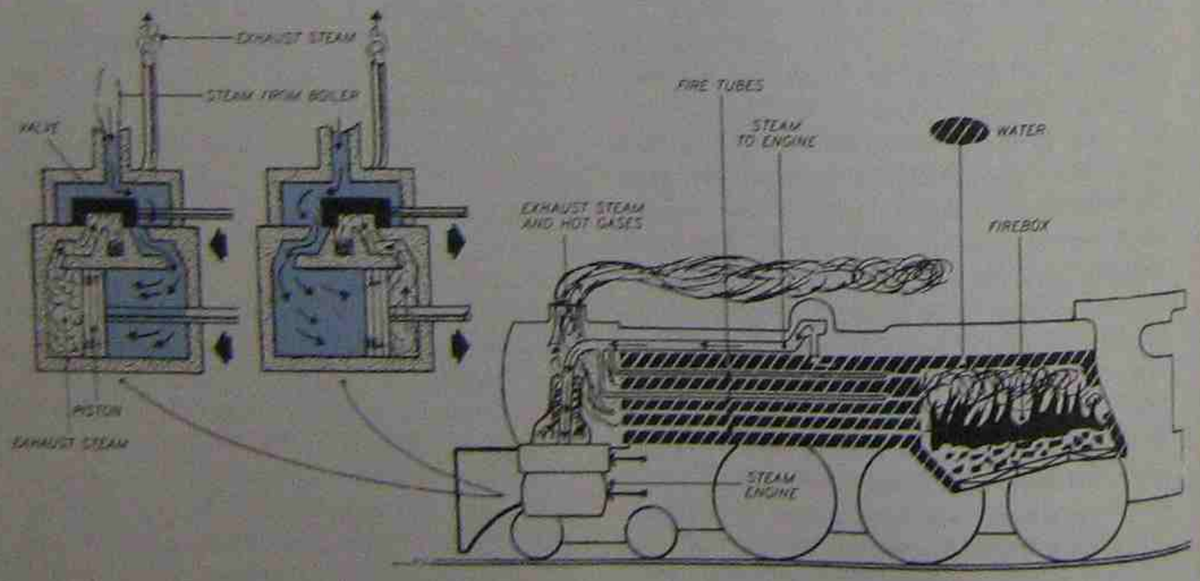


Fig. 14-3 A typical steam locomotive

and is ready to deliver its energy. The sliding valve within the steam chest is designed to deliver steam to one side of the piston. When the piston has completed its stroke, the sliding valve admits steam to the other side of the piston. Power is, of course, produced on both strokes of the piston. The steam is exhausted up the exhaust stack of the locomotive, helping to create a good draft through the engine.

Variations

Some steam engines are compound engines, that is, the exhaust steam from one cylinder is led into a second or third cylinder to expand further, extracting more of the steam's energy. On compound engines, each succeeding cylinder must be larger. Most steam locomotives are not of the compound type. Instead, they have one piston on each side of the locomotive.

Some steam engines are equipped with condensers to conserve the boiler's water supply. The steam engines on ships need condensers since salt water cannot be used in a boiler without building up large deposits in the fire tubes. Because it would not be practical to carry enough fresh water to replace the water that is boiled away, the used steam must be condensed back into water and returned to the boiler. The railroad locomotive does not need a condenser. It is more practical to stop periodically and take on more water for the boiler, replacing the water that is lost as steam.

STEAM TURBINE

The idea of a steam turbine can be traced back to 1628 when Giovanni Branca designed a steam turbine. Though his ideas are on record, it is not known if his turbine was actually built. Little was done with the turbine until some years after Watt's reciprocating steam engine was developed and in wide use. At that time, engineers and scientists again began to think in terms of steam turbines. They reasoned that much power was being wasted in driving the reciprocating engine's many cranks and connecting rods, and in the start-stop, back-and-forth motion of the piston.

The first person to build a successful turbine was a Swedish engineer, Carl DeLaval. DeLaval's turbine, built in 1882, consisted of a wheel with vanes mounted on the rim. Four nozzles directed jets of steam against the vanes to drive the turbine. The action was much the same as wind driving a windmill. The kinetic force of the steam struck the blades, giving up a portion of its energy to revolve the turbine. This type of turbine is called an *impulse turbine*, figure 14-4.

DeLaval designed a nozzle that takes advantage of the behavior of steam as it is released from a boiler. The steam expands,

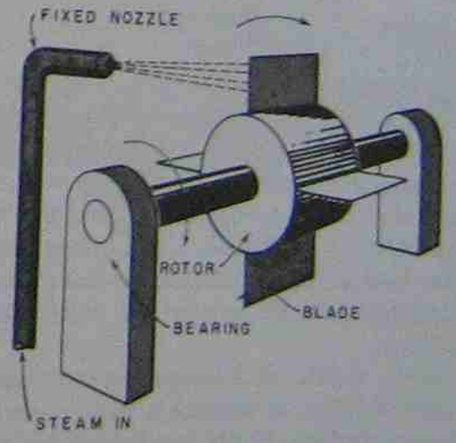


Fig. 14-4 Simplified impulse turbine

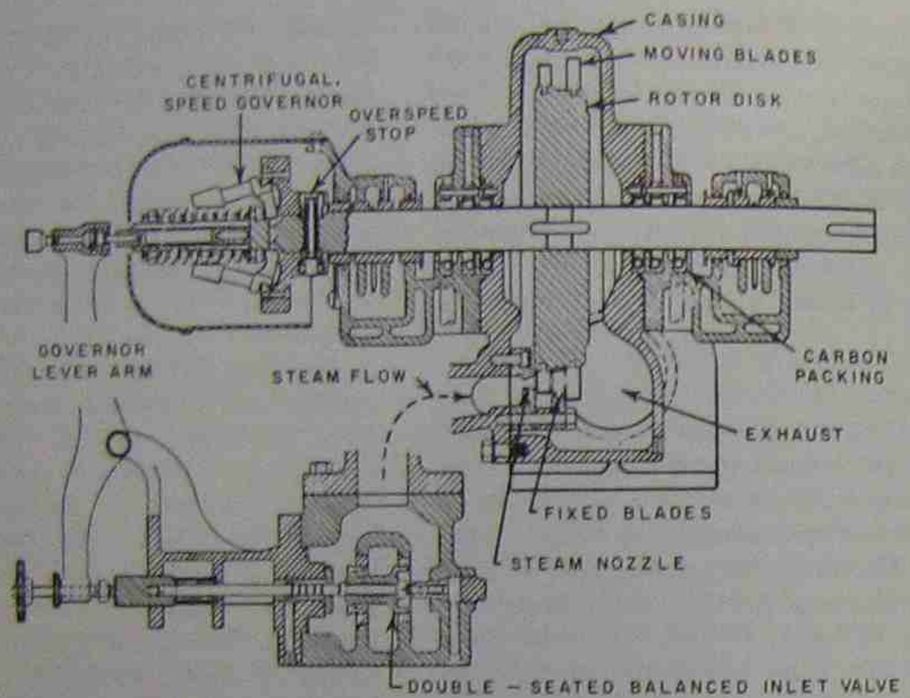


Fig. 14-5 Cross-sectional view of a small impulse turbine

but it also increases in speed or velocity as it is released. The DeLaval nozzle helps to increase the velocity and kinetic force of the steam.

In order to be efficient, the impulse turbine must rotate at about one-half the velocity of the incoming steam. This means that the turbine rotor turns 10,000 to 30,000 revolutions per minute. Such speeds create problems in themselves since the speed must be geared down to operate machinery. The characteristics of DeLaval type turbines make them best suited for installations that require a relatively small amount of power, figure 14-5.

C. G. Curtis, an American inventor, used DeLaval's ideas to produce a more powerful impulse turbine. Curtis constructed his turbine with a series of revolving and stationary blades, figure 14-6. In today's Curtis turbine, the steam hits the first rotor vanes, imparting motion to the rotor as the steam changes its direction of flow. The set of stationary vanes changes the steam direction back again and the steam strikes a second set of rotor vanes, giving up more of its kinetic energy. The next set of stationary blades reverses the steam

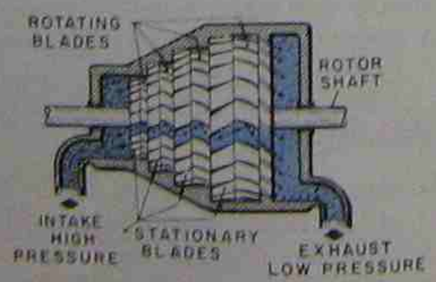


Fig. 14-6 A simplified steam turbine

direction again and the process continues as the steam travels through the turbine.

Often turbines are divided into two or more pressure sections to gain increased efficiency. Each diminishing pressure section has larger turbine rotors to accommodate the expanded steam. These turbines are the compound impulse type, figure 14-7.

Another type of impulse turbine in use today is the helical flow impulse turbine, figure 14-8. In this turbine the steam follows a spiralling path as it delivers its kinetic energy to the rotor, figure 14-9.

The *reaction* turbine was invented by C. A. Parsons of Ireland. His turbine is similar to Curtis's in that it has alternating and fixed blades, sometimes called diaphragms, but the design of the blades is different. Instead of having a symmetrical cross-sectional path to follow, the steam follows a converging cross-sectional path between the blades, figure 14-10. As a result, the steam is accelerated. All of the many turbine blades that surround the wheel produce this reaction. The principle is identical to that of a jet or rocket engine. The action of the accelerated steam causes the reaction of pushing the rotor forward, figure 14-11. Steam that enters a turbine at 75 miles per hour (120 kilometers per hour) under pressure leaves the turbine at 300 miles per hour (483 kilometers per hour) under low pressure. The steam passes through a 13-foot (4-meter) long turbine in 1/16 of a second.

In actual practice the reaction turbine does not derive 100% of its power from the reaction principle. About half comes from im-

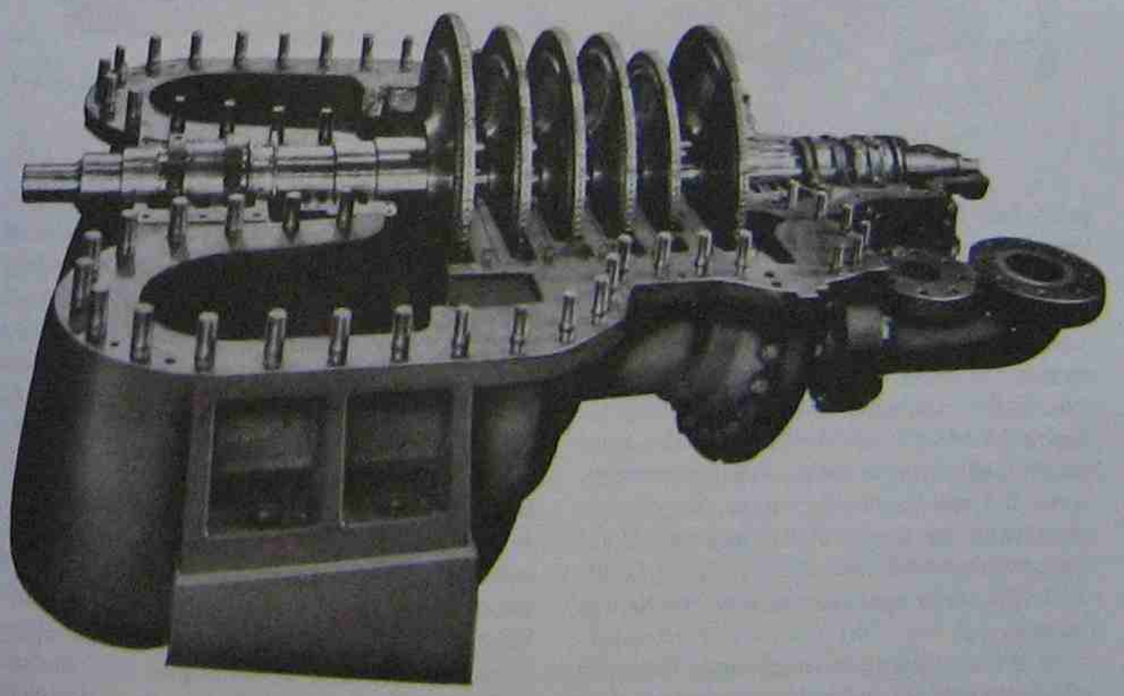


Fig. 14-7 A six-stage impulse turbine with the top half of the casing removed

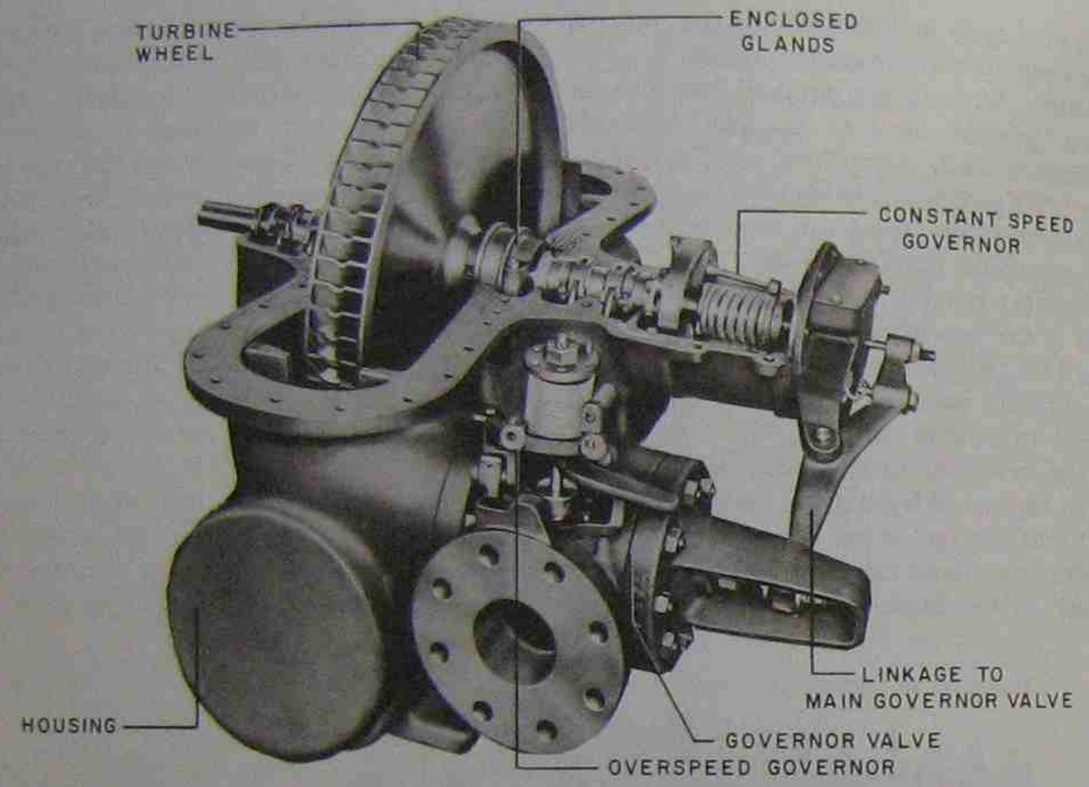


Fig. 14-8 Modern helical flow impulse turbine with the top half of the casing removed

pulse, half from reaction. Most modern steam turbines are a blend of impulse and reaction.

The typical turbine consists of: the rotor, including the main shaft and the turbine wheels and their blading, figure 14-12; the casing, including the nozzle passages, figure 14-13; the stationary blades or diaphragms, figure 14-14; a speed regulator or governor controlling the amount of steam allowed to enter through the nozzle; a lubricating system to satisfy the needs of a continuous high-speed rotor shaft and gearbox, figure 14-15; and, for some applications, a gear-reduction system.

A *non-condensing* turbine allows the spent steam to exit the turbine at atmospheric pressure or higher. In some cases this steam is further put to work in a variety of industrial processes. In the *condensing* turbine the spent steam is sent to a condenser for cooling and reuse. Cooling is accomplished by circulating large amounts of water through pipes in the condenser. This allows a low pressure to be maintained in the condenser, improving the expansion ratio of the steam and increasing the turbine's efficiency.

The general pattern in turbine construction is to reduce the steam pressure in many stages for slow-speed operation, or reduce the steam pressure in few stages for high-speed operation. A high-speed turbine used for driving a generator may reduce the steam pressure in



Fig. 14-9 Action of the steam in a solid wheel machine

50 steps while a low-speed turbine for propelling a ship may reduce the steam pressure in 200 steps.

The primary application of steam turbines is in the field of generating electricity, figure 14-16. The high-speed turbine is well suited to this purpose since generators also operate best at high speed. The steam turbine accounts for two-thirds of the total electrical output in the United States. Often the electrical generating plant is located near a river. This provides a constant source of fresh water and economical barge transportation of the coal or oil that is used as fuel. The coal is pulverized and blown into the fire chamber of the boiler where it literally explodes as its chemical energy is changed into heat energy.

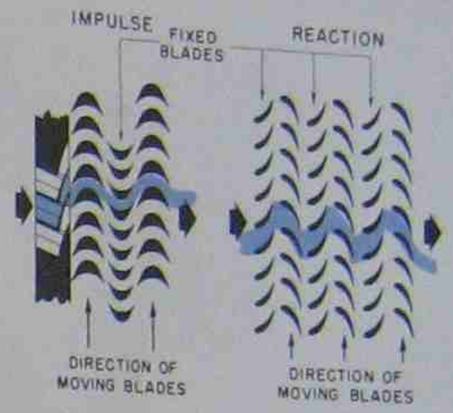


Fig. 14-10 Impulse and reaction blading

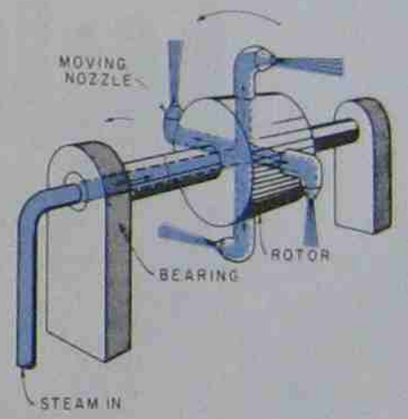


Fig. 14-11 Simplified reaction turbine

Steam is produced in the water tubes in the boiler and sent to the turbines which drive the generators. Steam turbine electrical generating plants have a high efficiency, 20 to 28%.

Modern turbines are designed for a variety of applications. To meet different speed and horsepower requirements, turbine manufacturers develop various turbine styles, although the basic operating principles remain the same. Many modern turbines use steam under as

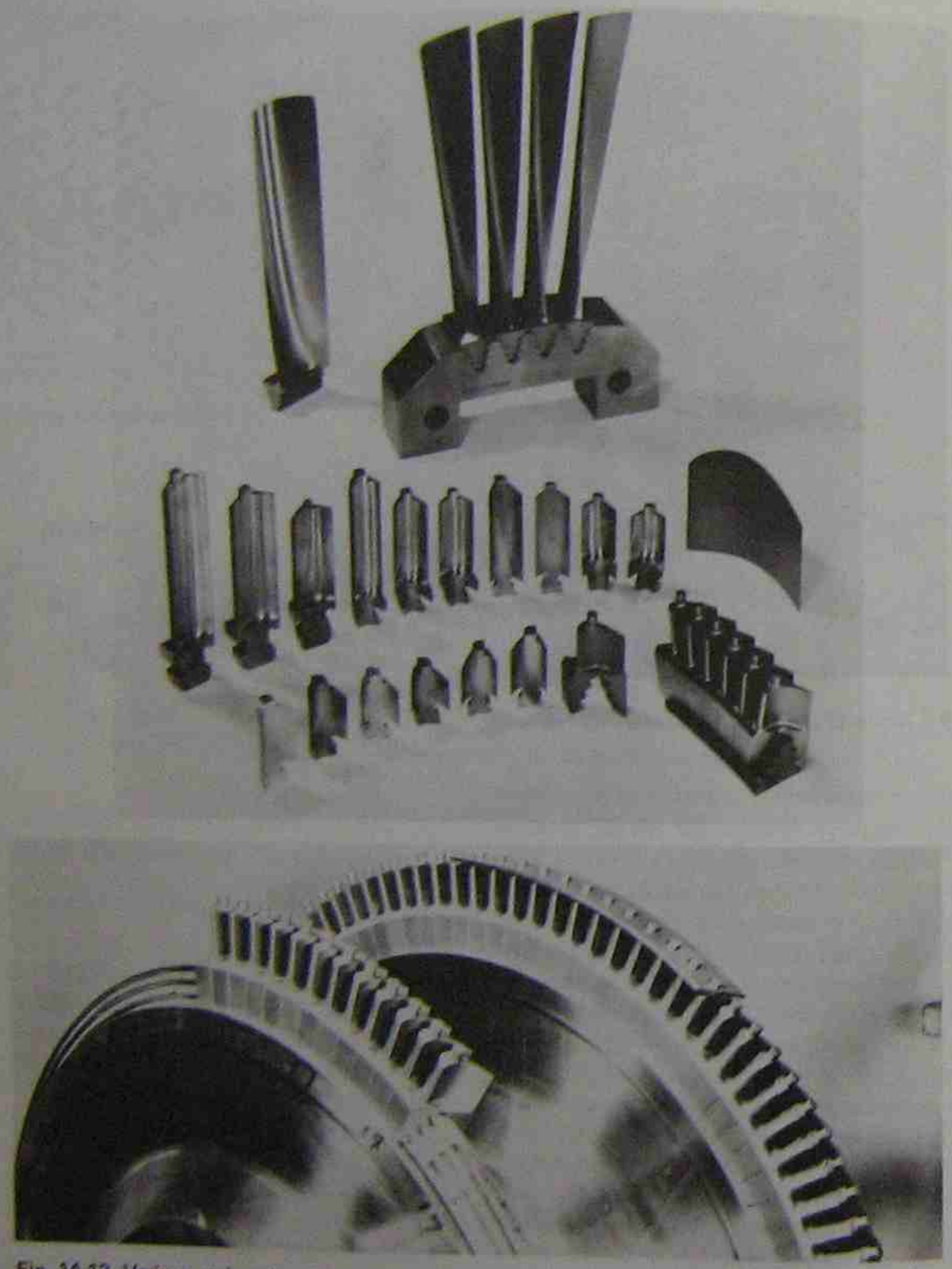


Fig. 14-12 Various styles of turbine blades shown individually and turbine blades partially installed on a turbine wheel

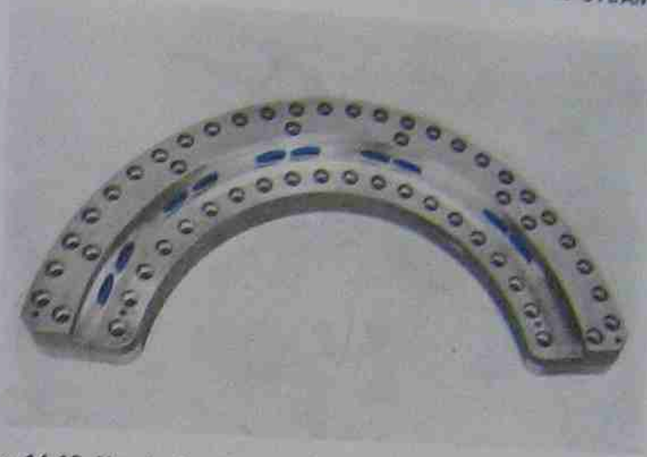


Fig. 14-13 Nozzles for admitting steam to turbine—only one-half shown

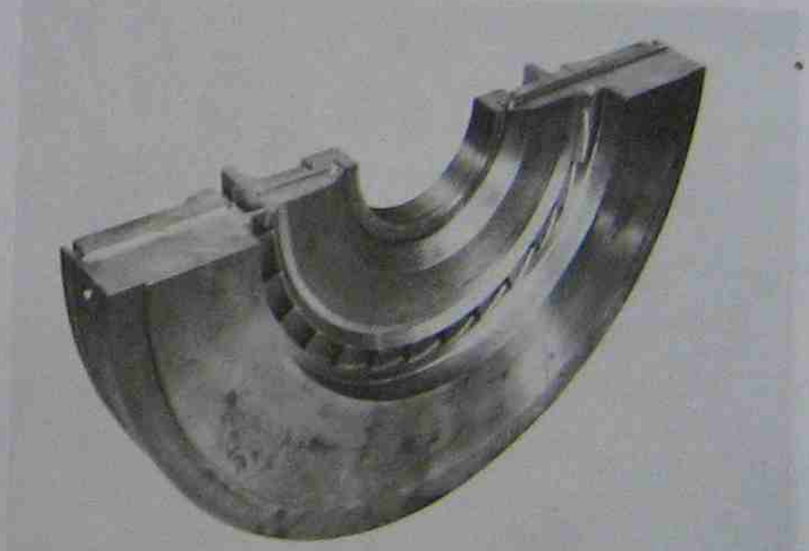


Fig. 14-14 Diaphragm of stationary blades—only one-half shown

much as 5000 pounds per square inch (34 megapascals) pressure and 1100°F (593°C) temperature. These extremes are possible because special alloys are now available for use that did not exist when turbines were first developed. Careful machining and workmanship go into every turbine, making it an efficient prime mover of watch-like precision.

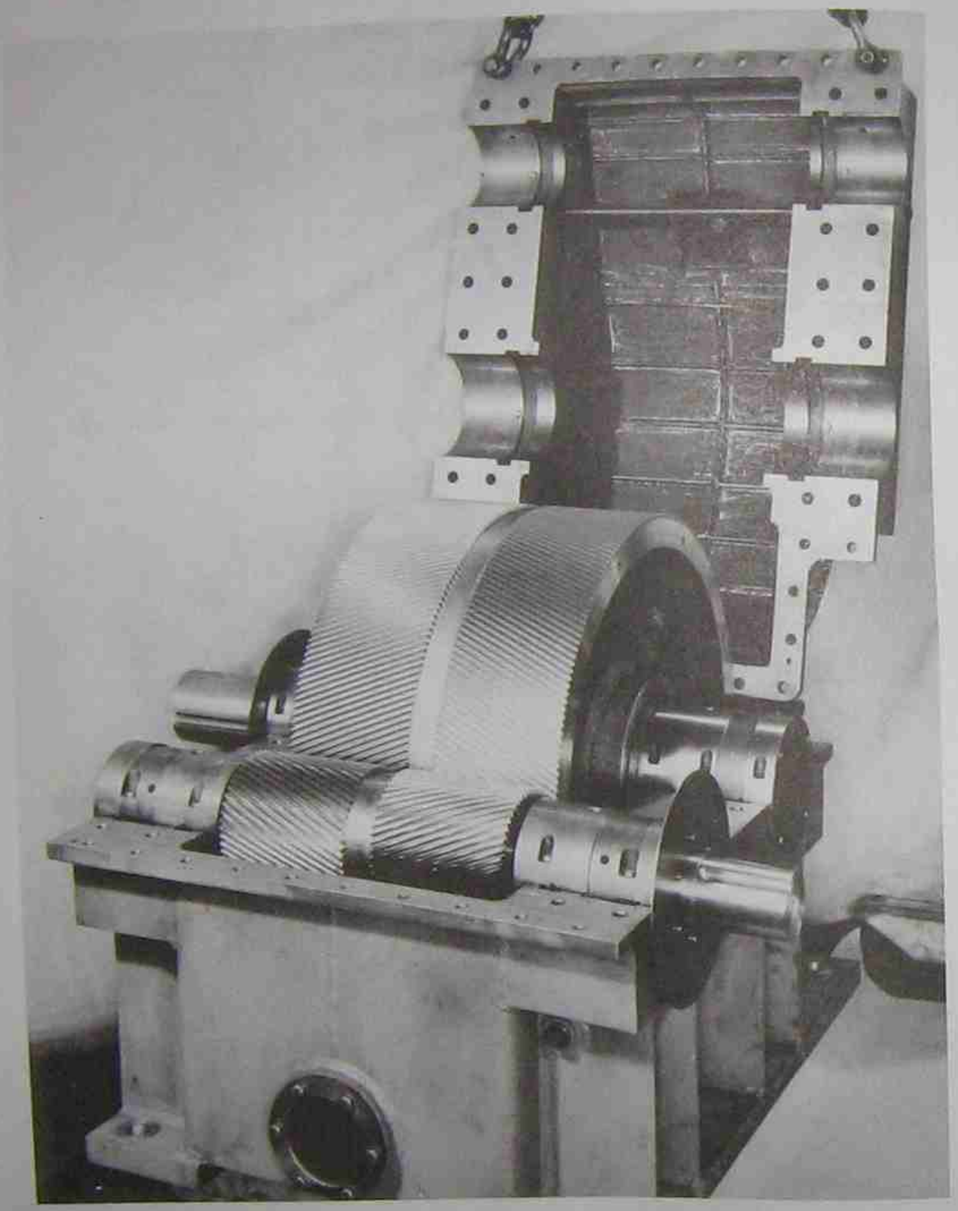


Fig. 14-15 High speed gears for pressure lubricating system

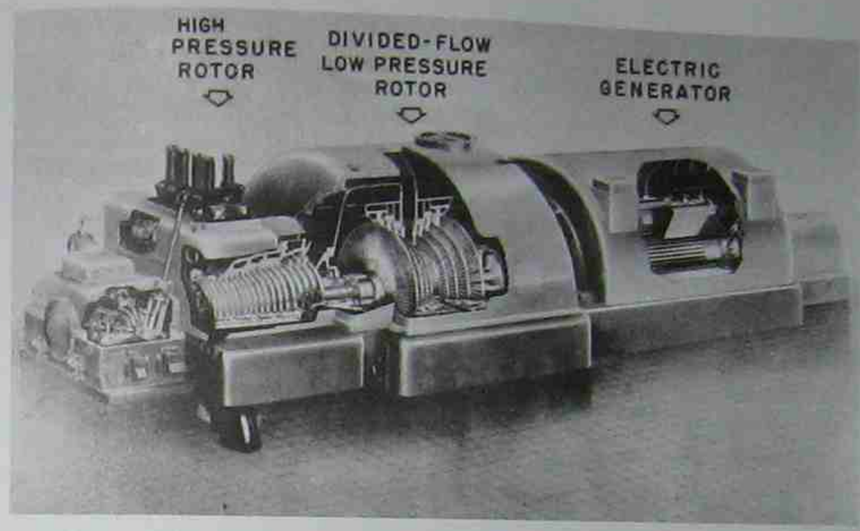


Fig. 14-16 A typical steam turbine generating plant

REVIEW QUESTIONS

1. Explain why a steam engine is classed as an external combustion engine.
2. Briefly trace the energy path within a steam engine or steam turbine.
3. What were the first steam engines used for?
4. Why is Thomas Newcomen's steam engine sometimes referred to as an atmospheric engine?
5. In what way did James Watt improve the steam engine?
6. What improvements made the reciprocating steam engine adaptable to locomotives?
7. Explain why some steam engines need a condenser and some steam engines do not.
8. Explain the action of the steam in an impulse turbine.
9. Trace the path of the steam through a Curtis-type turbine.
10. In what way is a reaction turbine different from an impulse turbine?
11. Are modern turbines pure impulse or pure reaction? Explain.
12. What is the most important use of steam turbines today?
13. What is the efficiency of a modern steam turbine?

SECTION 5
ELECTRICAL ENERGY

Unit 15 Principles of Electricity

OBJECTIVES After completing this unit, the student should be able to:

- Explain the principles of static electricity.
- Recognize series and parallel circuits.
- Discuss magnetism and electromagnetism.
- Identify and explain primary and secondary cells.
- Discuss the charging and discharging cycle of an automobile storage battery.
- Explain how alternators and generators produce electricity.

To appreciate electricity, try to place yourself at a time in history before electricity was commonly used. There were no electric lights, radios, television sets, telegraphs, telephones, or electric motors. There were no power household appliances like washers, driers, vacuum cleaners, toasters, electric coffee pots, or hair dryers. The machines of industry were powered by large, inefficient steam engines. The pace of life was slower before the era of electrical technology. However, both men and women worked harder than their modern counterparts do. Aided by electricity, our work load has been lightened.

Communication devices such as radio, telephone, telegraph, television, and computers have speeded communications and helped to shrink our world, because messages can be transmitted at the speed of light. While the world has, in a sense, been made smaller, our understanding of other people has been broadened as a result of these devices. Modern communication places ideas and pictures before us from all parts of the world. Today, we are made aware of community, state, national, and world affairs and have an opportunity to expand our understanding and knowledge.

Gone is the era of candle light and horse

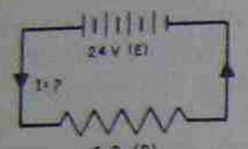
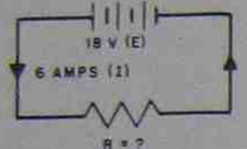
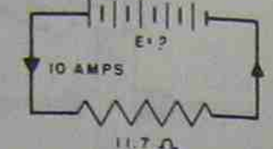
FIND CURRENT		FIND RESISTANCE		FIND VOLTAGE	
					
$I = \frac{E}{R}$	$I = \frac{24 \text{ volts}}{6 \text{ ohms}} = 4 \text{ amperes}$	$R = \frac{E}{I}$	$R = \frac{18 \text{ volts}}{6 \text{ amps}} = 3 \text{ ohms}$	$E = IR$	$E = 10 \text{ amps} (11.7 \text{ ohms}) = 117 \text{ volts}$

Fig. 15-3 Applications of Ohm's Law

Where:

I = Current intensity or amperes
E = Voltage or electromotive force
R = Resistance stated in ohms

Three simple diagrams, figure 15-3, show how Ohm's Law can be used to calculate electrical problems.

ELECTRICAL CURRENT

In discussing electrical circuits, we shall assume that we have *direct current*–(DC)–a continuous flow of electrons in one direction. Typical producers of direct current are batteries, DC generators and rectifiers. Rectifiers convert AC to DC. Current flows from a battery as long as there is a complete path for it to follow: a complete circuit. A switch is usually placed in the circuit to control electron flow. When the switch is closed, electrons flow and the light is on, for instance. When the switch is opened, current stops. The electrical potential is still present when the switch is open, but there is no way for it to be satisfied; the circuit is not complete. Recall that a complete circuit is necessary for electron flow.

There are two basic types of electrical circuits: series and parallel. If all the resistances in the circuit are in one path, the circuit is a *series circuit*. Current must pass through all of the resistances. Therefore, the total resistance of a series circuit is the sum of the individual resistances. Each resistance will create a voltage drop, so the total voltage is equal to the sum of the separate voltages. In figure 15-4, if one lamp burns out, the circuit is broken and all the lamps go out; this is one disadvantage of series wiring.

Remember: (1) although voltage is divided among the resistances, (2) current is the same

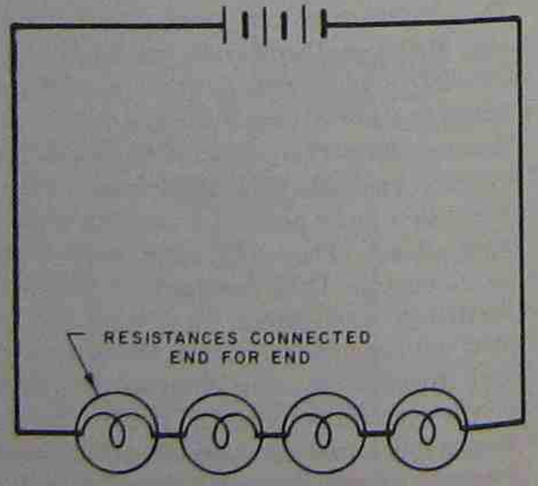


Fig. 15-4 Series circuit

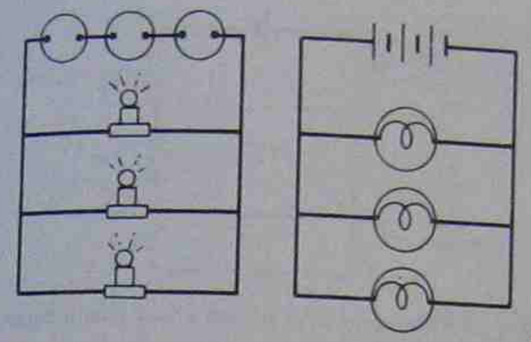


Fig. 15-5 Parallel circuit

through all resistances, and (3) resistance is the sum of the separate resistances.

If the resistances in a circuit are connected side by side, each having one end to the power source, the circuit is a *parallel circuit*, figure 15-5. Current divides itself to flow through the available paths. The amount of current that flows through any part depends on the resistance of that part. The resistance is divided up so that the total parallel resistance is less than the smallest single resistance in the circuit. The voltage across each resistance is the same, the full 117 volts on normal household installations.

Remember: (1) voltage is the same across all resistances, (2) current is divided among the resistances, and (3) total resistance is less than that of the smallest resistance.

MAGNETISM

The ability of certain metals to attract iron or steel is discussed in Unit 7. These metals, called magnets, can also attract nickel, cobalt, chromium, and magnesium. Although the first practical use for the magnet was the compass, this is not the main reason for studying magnetism. Magnetism has achieved greater importance because most of the electricity that is produced originates with the principles of magnetism.

In explaining the phenomenon of magnetism, it is known that atoms of iron and a few other substances have the *special ability* to line themselves up in a pattern whereby the magnetic qualities of each atom complements those of surrounding atoms. These atoms work together, combining their minute magnetic fields to produce a noticeable magnetic field. In nonmagnetic substances, on the other hand, atoms are arranged in a random manner and, therefore, do not exhibit magnetic properties.

Substances that are magnetic have a north-seeking pole and a south-seeking pole, corresponding to the earth's magnetic poles. In effect, each magnet has a magnetic field around it just as the earth does. As a reminder, the like poles of two magnets repel each other while the unlike poles attract each other, figure 15-6.

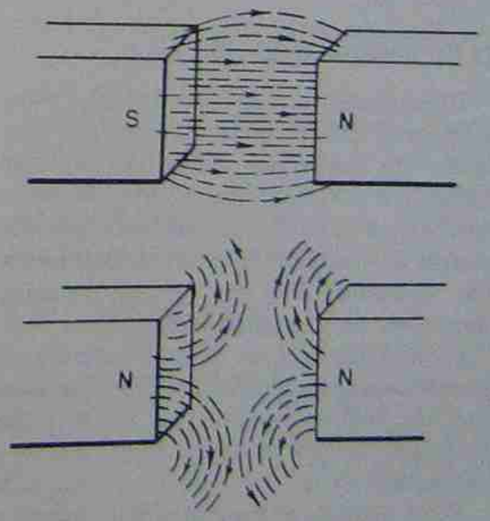


Fig. 15-6 Unlike poles attract each other; like poles repel each other.

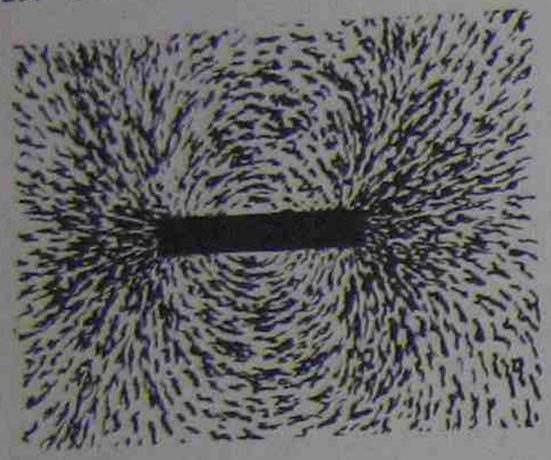


Fig. 15-7 Illustrating a magnetic field by using iron filings

The magnetic field is strongest at the ends of the magnet; in the center of the magnet the field is weak. A magnetic field can be seen by placing a magnet under a piece of paper and then sprinkling iron filings onto the paper. The iron filings line up to show the magnetic field and its concentration, figure 15-7.

ELECTROMAGNETISM

When electric current flows through a wire, a magnetic field is built up around the wire itself. This can be seen using cardboard, iron filings, and a current-carrying wire. With the wire passed through the cardboard and the current flowing, iron filings are sprinkled onto the cardboard. They can be seen arranging themselves in a magnetic field, figure 15-8. The magnetic field or lines of force are referred to as *flux*, and just as in a natural magnet, the field is strongest near the wire and decreases as the distance from the wire increases.

Flux around a wire also has direction; this is determined by the direction of electron flow within the wire. As shown in figure

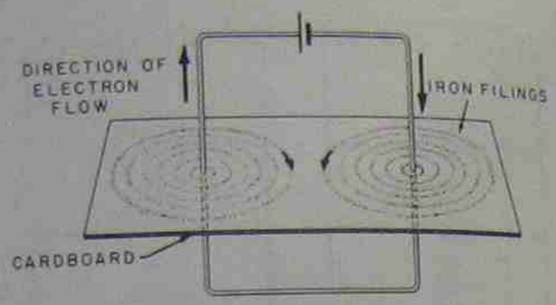


Fig. 15-8 Magnetic field around a wire that is carrying electric current

15-9, the north pole of the compass needle indicates the direction of flux around the wire. The dot in the center of the wire on the left indicates the point of the current-direction arrow coming toward the observer. The X at the right represents the tail of the current arrow pointing away from the observer. If the direction of electron flow within the wire is reversed, the compass needles will reverse themselves, indicating a change in flux direction.

The left-hand rule enables a person to determine either flux or current direction, providing one of the two is known. If current direction is known, point the left thumb in the direction of flow. When your fingers grasp the wire, they point in the flux direction. If the flux direction is known, wrap the fingers of the left hand around the wire in the direction of the flux. The left thumb will point in the direction of current, figure 15-10.

Unit 7 says that when a current-carrying wire is made into a coil, the whole coil becomes a magnet. A single magnetic field builds up around the coil. The magnetic flux around the turns of wire combines to form one large magnetic field; the coil is said to be electromagnetic.

The magnetic field of the electromagnet has a north pole and a south pole just as a

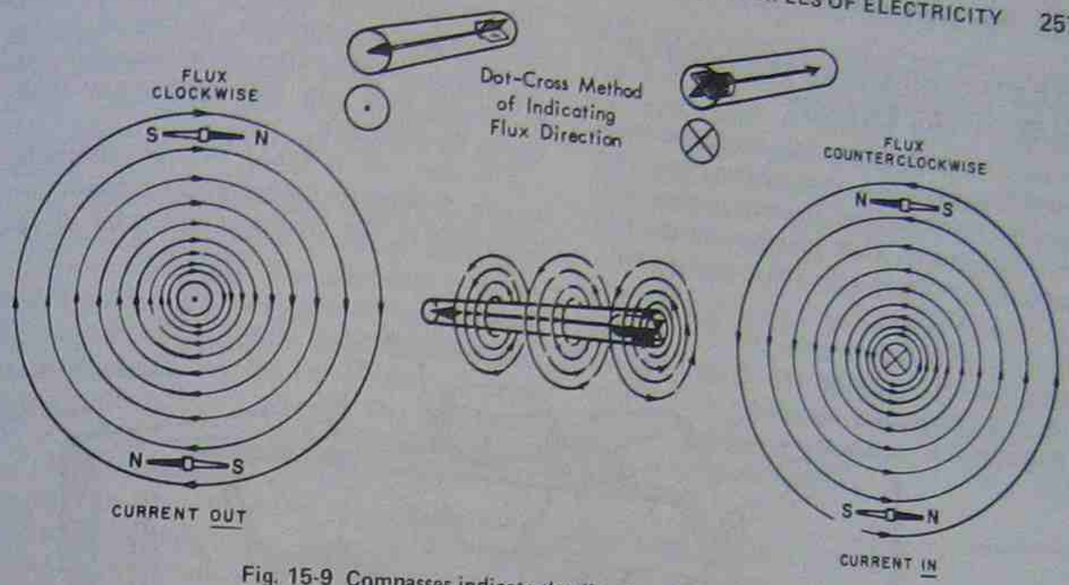


Fig. 15-9 Compasses indicate the direction of flux around a wire.

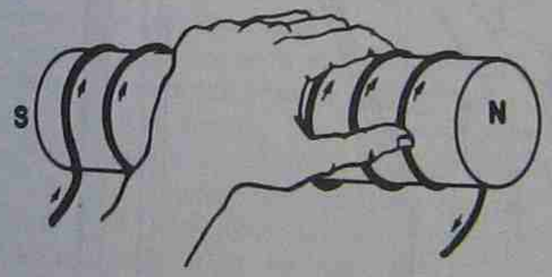


Fig. 15-10 The left-hand rule for determining flux direction or direction of electron flow

natural magnet has. The like poles repel and the unlike poles attract. Electrically speaking, the ends of the coils where the currents are parallel in the same direction are attracted to each other; the ends of the coils where the currents are parallel in the opposite direction repel each other, figure 15-11.

On the electromagnet, a soft iron core is used to strengthen the magnetic field. Electromagnets and other magnetic devices can be used for lifting iron and steel, magnetic separators, relays, bells, solenoids, sound producers, and many other items.

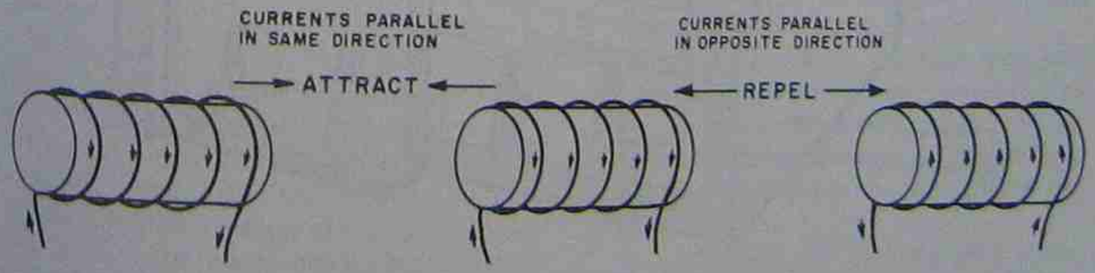


Fig. 15-11 Electromagnets attract or repel each other according to the direction of current in the coil.

ELECTROCHEMICAL SOURCES OF ELECTRICAL ENERGY

Dry cells and automobile storage batteries are perhaps the two most common examples of the conversion of chemical energy into electrical energy. They are separated into two categories, primary cells and secondary cells. The dry cell is a *primary cell*; once its chemical reaction is complete, it cannot be recharged. A storage battery is a *secondary cell*; it can be used and recharged many times during its useful life.

The dry cell is made of two electrodes and an electrolyte. Its operation depends on a difference in the electrical potential of the

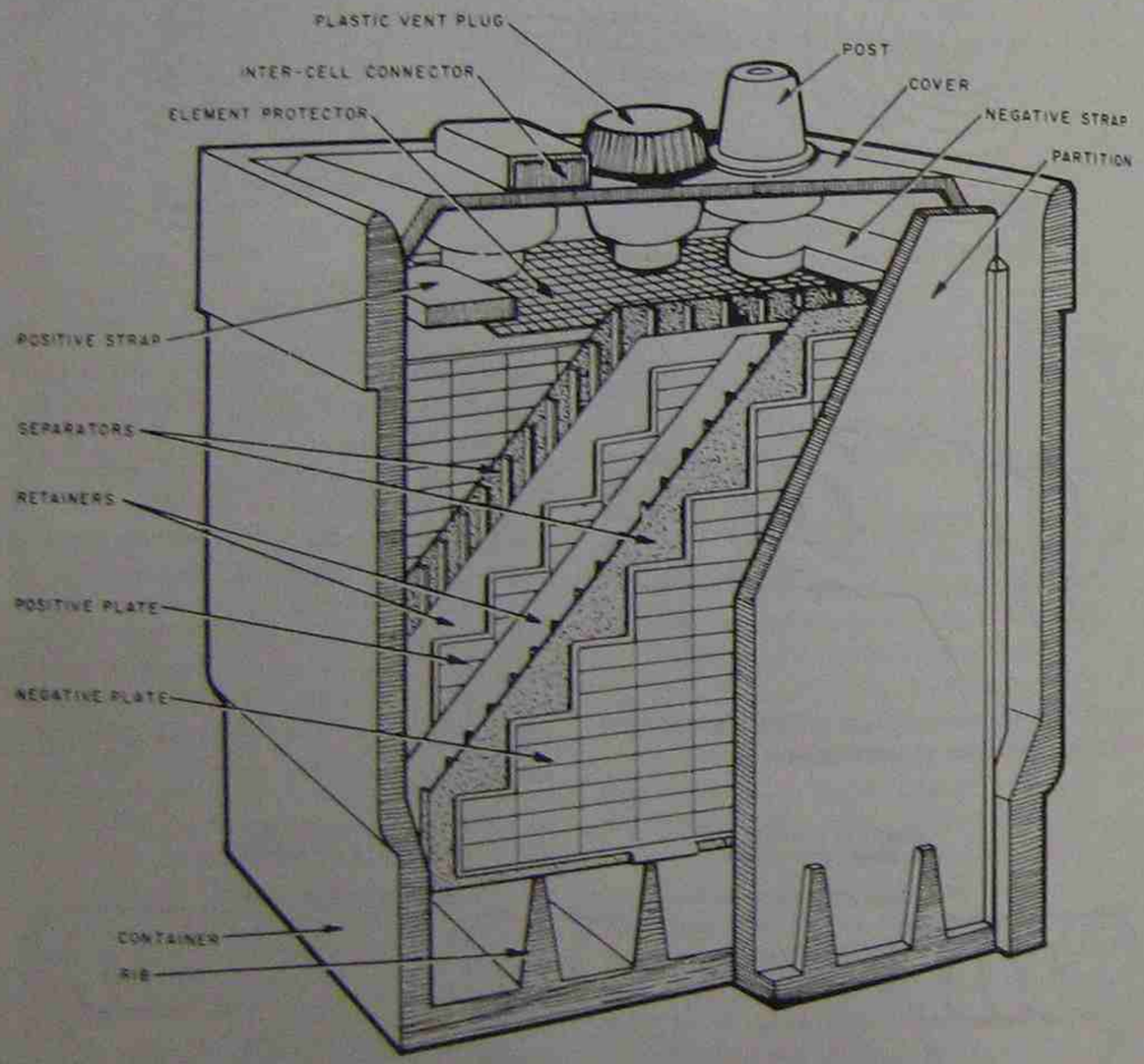


Fig. 15-12 The lead storage battery

two electrodes. Equally important, it depends on ionization for its operation. An *ion* is an electrically-charged atom or group of atoms; they may have lost or gained electrons. Many substances are capable of being ionized.

The dry cell—which really is not dry at all—is made of a zinc outside shell or container; this is one electrode. The container is filled with a thick paste of ammonium chloride dissolved in water; this is the electrolyte. Extended down the center of the cell is a carbon rod; another electrode. The top of the cell is sealed off, preventing evaporation of the electrolyte. In a complete circuit, free electrons in the zinc travel through the wire to the carbon electrode. These electrons are picked off by ammonium ions in the electrolyte. The zinc case is the negative terminal and the carbon rod is the positive terminal. There is a potential difference of 1 1/2 volts between the two electrodes.

Storage batteries such as those commonly seen on automobiles convert chemical energy into electrical energy. The storage battery may be either 6 or 12 volts. They are made of alternate plates of lead peroxide and spongy lead. The plates are prevented from touching each other by separators, figure 15-12. The electrolyte is a solution of sulfuric acid and water. The chemical action of the storage battery is discussed more fully in Unit 7, and additional illustrations show its construction.

It should be noted that many modern storage batteries are almost maintenance free. Little or no attention to the electrolyte level is required since the battery is designed to eliminate water loss. This is done by first moving the plates nearer the bottom of the battery case to allow more electrolyte to cover the plates. The lead grids or plates are

designed in a different manner to also reduce the amount of water lost by electrolysis. They are constructed of calcium lead instead of antimony lead, because calcium lead and sulfuric acid do not create the hydrogen gas that is formed in the presence of antimony and which is very explosive.

Cold, subzero weather can reduce the capacity of a fully-charged battery by 45%. In addition, the cranking load due to cold oil and parts might increase 3 1/2 times, figure 15-13. That is the main reason why it is important to have a properly-sized, fully-charged battery in the automobile.

DC AND AC ELECTRICAL GENERATORS

Very simply, generators are used to convert mechanical energy into electrical energy. The energy of free falling water or the energy of hot gases directed against a turbine blade produces mechanical energy in the form of a rotating shaft. This motion is used to turn the generator to produce electricity.

Whenever magnetic lines of force cut a wire, electric current is induced to flow in the wire. There must be a changing magnetic field in order to induce electron flow. If the wire is held stationary in a fixed magnetic field, there is no electron flow. Electron flow occurs only when the wire cuts into the magnetic field, or the magnetic field moves relative to the wire, figure 15-14.

Either an increasing magnetic field or a decreasing magnetic field can cause electron flow. More current can be induced by increasing the speed that magnetic lines of force are cut, or increasing the strength of the magnetic field.

In a generator, the magnetic field is stationary. The coil of wire is moved within the

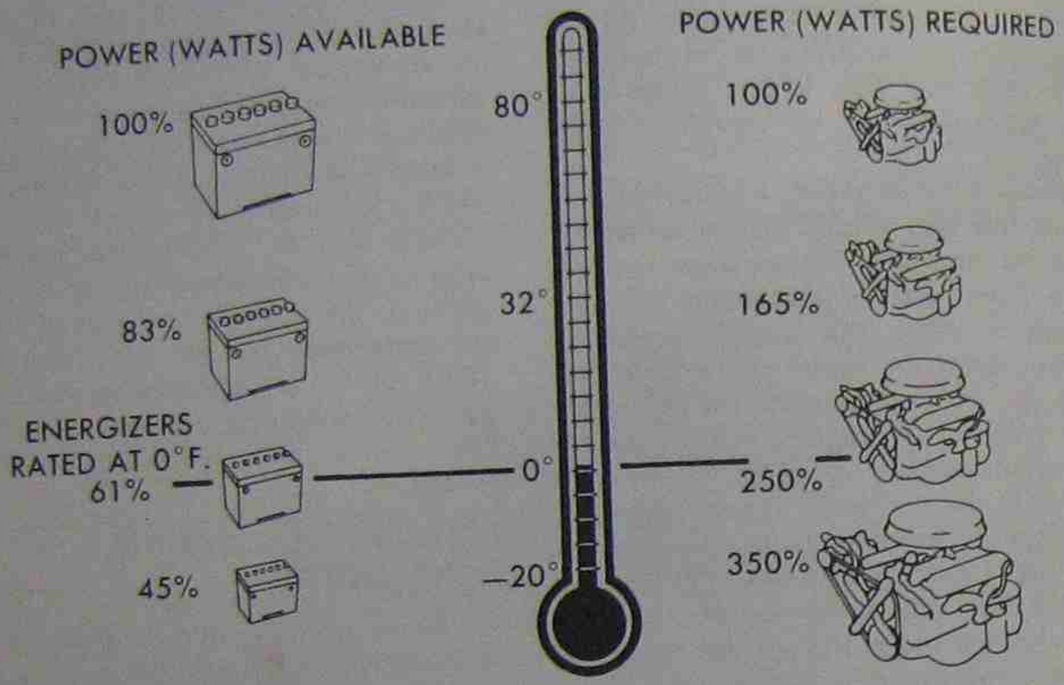


Fig. 15-13 Battery power goes down with temperature while engine starting requirements go up.

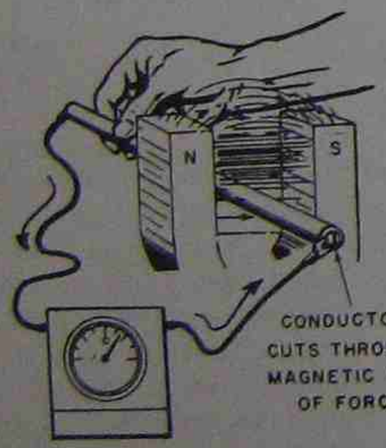


Fig. 15-14 Producing an induced current by moving a wire through a magnetic field

magnetic field, figure 15-15. In small generators, the magnetic field is created with permanent magnets. In large generators, it is normally produced by electromagnets that create a stronger magnetic field. The coils of wire on the armature rotate inside the magnetic field. Actually the *armature* is made of a shaft that has many iron laminations fastened to it that strengthen the magnetic action. Conducting wire is wound around the laminations. The two ends of the wire are connected to a slotted slip ring mounted on the armature. Two brushes, one on either side of the slip ring *(commutator)* provide the necessary path for electron flow.

For the sake of clarity, the drawings and

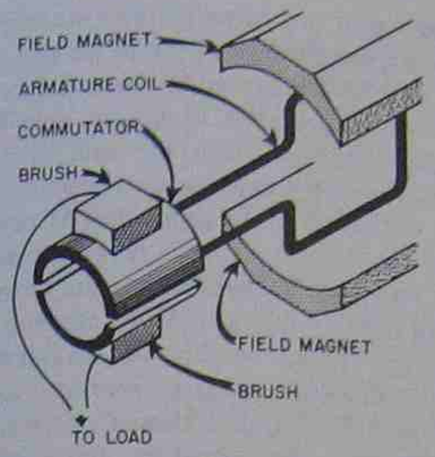


Fig. 15-15 A simplified DC generator

explanation of the DC *(direct-current)* generator have been simplified, figure 15-16. In position #1 there is no electromotive force produced since the wire is moving parallel to the field's magnetic lines of force. However, as soon as the armature begins to move toward position #2 it begins to cut magnetic lines of force. At position #2 the maximum number of magnetic lines of force are being cut; induced current has gradually built up. Electrons flow toward the right-hand brush. As the armature continues on toward position #3 induced current continues to flow in the same direction but at a diminishing rate. At position #3 there is no electromotive force generated. Also, the right-hand half of the ring will now touch the left-hand brush and vice versa. Now the armature moves up to position #4, again cutting lines of force. The direction of armature coil movement has been changed in relation to the magnetic field and the direction of electron flow has been reversed. However, since the commutator segments are touching opposite brushes, the effect is that the current continues in the same direction.

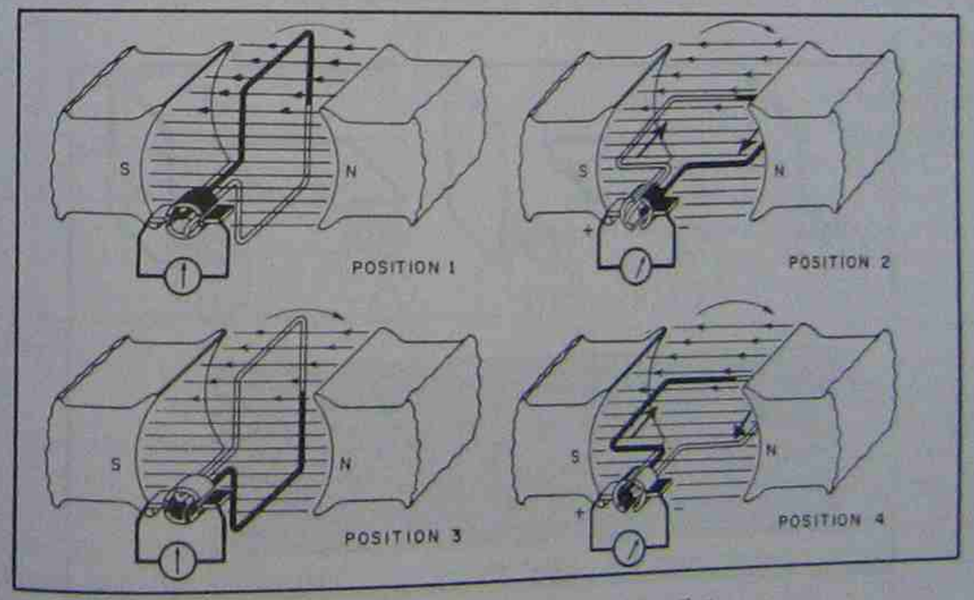


Fig. 15-16 Direct current generator rotation

As the armature continues its rotation, it produces a stream of electrons flowing in one direction: this is said to be a direct current or DC.

This output is not constant in the number of electrons that flow, figure 15-17. Every revolution of the DC generator produces two peaks. This is because, in actual construction, the DC generator is much more complex than these simplified diagrams indicate. In order to smooth out the operation of the generator and to produce a steady electromotive force, several coils of wire are wound around the rotating iron core. This means that the construction of the commutator must also be much more complex.

The AC *(alternating-current)* generator, called an alternator, is very similar in construction and operation to the direct-current generator. However, the current produced by the AC generator changes its direction with every revolution of the armature. Instead of having a split ring commutator, two complete rings are mounted side-by-side on the armature shaft and connected to the armature coil. A brush rides against each ring, one brush always in contact with the same ring. In figure 15-18, the basic action shown is the same as that of a DC generator. At position #1 of the armature there is no electromotive force produced, but as the armature moves on toward position #2 the induced electron flow increases. Current reaches its maximum at position #2, diminishing to zero as it arrives at position #3. The direction of electron flow reverses when the armature starts moving toward position #4. The induced electron flow reaches its maximum at position #4, diminishing to zero as it arrives back at position #1. The slip ring commutator enables the generator to produce a flow of electrons that changes its direction with every armature revolution or cycle, figure 15-19. Ordinary alternating current is supplied at 60 cycles.

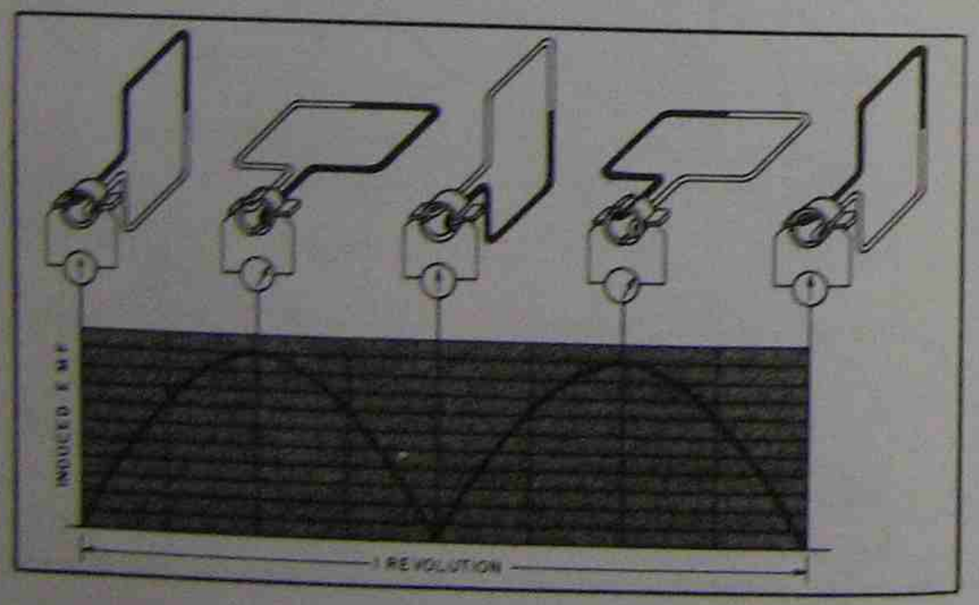


Fig. 15-17 Direct current induced electromotive force graph

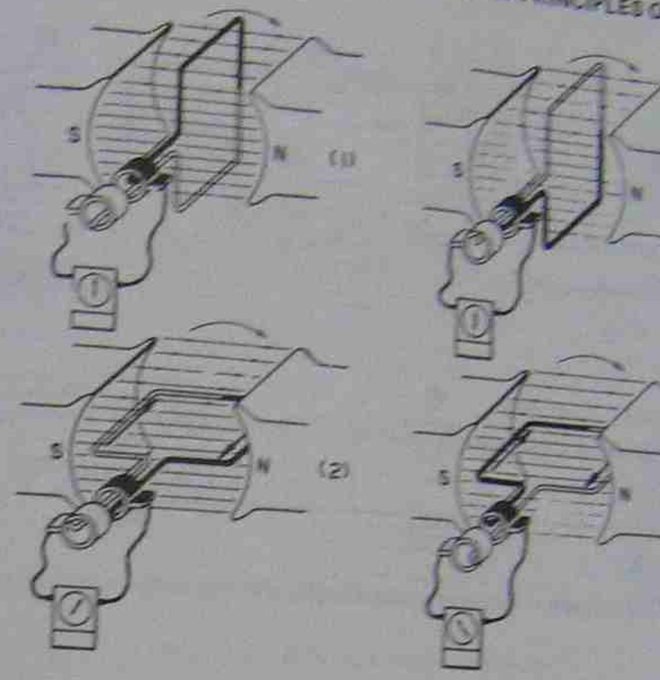


Fig. 15-18 Alternating current generator rotation

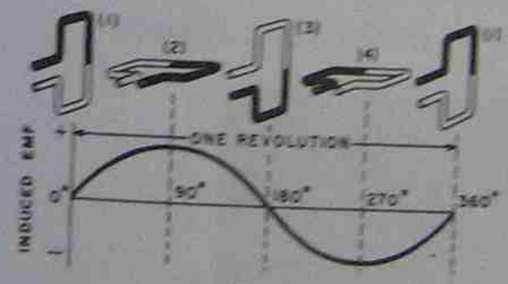


Fig. 15-19 Alternating current induced electromotive force graph

This means that there are 60 complete cycles or revolutions, 120 changes in current direction, every second.

Alternating current and direct current are in common use. Both are good for the operation of electric light, heating units, or universal electric motors. Direct current is needed for electroplating, electrolysis, or the charging of storage batteries. However, the use of alternating current is more widespread because it can be transmitted over long distances more easily than direct current, figure 15-20. The voltage of alternating current can be stepped up or stepped down by the use of transformers. Generally, the voltage from the power station is stepped up to be transmitted over a long distance and then stepped down near the point where it is to be used, figure 15-21. With alternating current, high-voltage transmission lines are made of smaller wires. This means that there is less power loss. Most generators deliver 13,200 volts. This voltage is stepped up as high as 250,000 volts for long distance transmission, and then eventually stepped down to the 120 or 240 volts for use in homes and industry, figure 15-22.

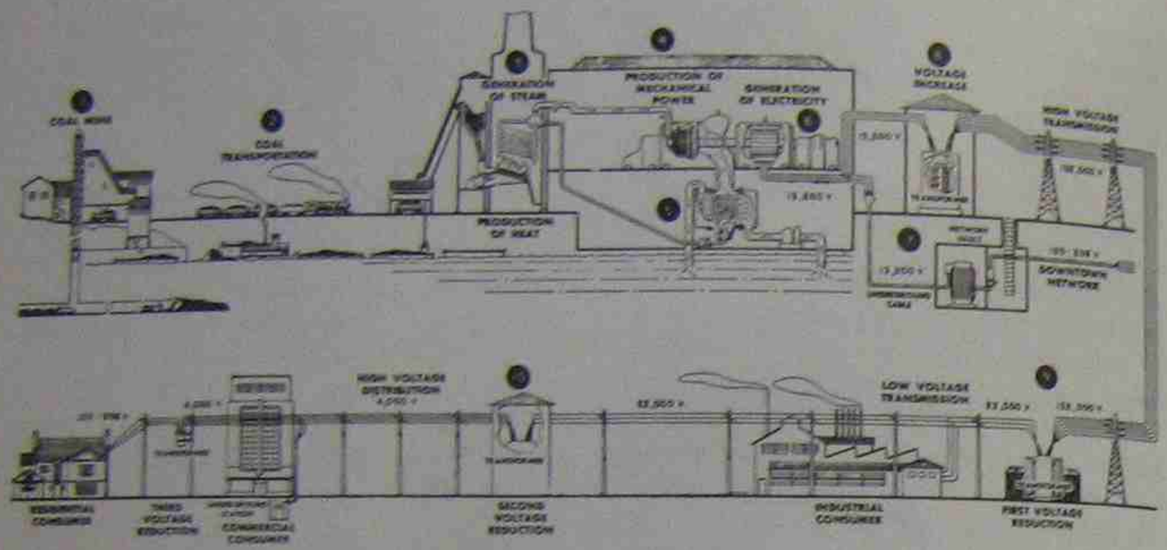


Fig. 15-20 Stages in generating, transmitting, and distributing electricity



Fig. 15-21 Conowingo hydroelectric power plant of the Philadelphia Electric Company (Courtesy Philadelphia Electric Co.)

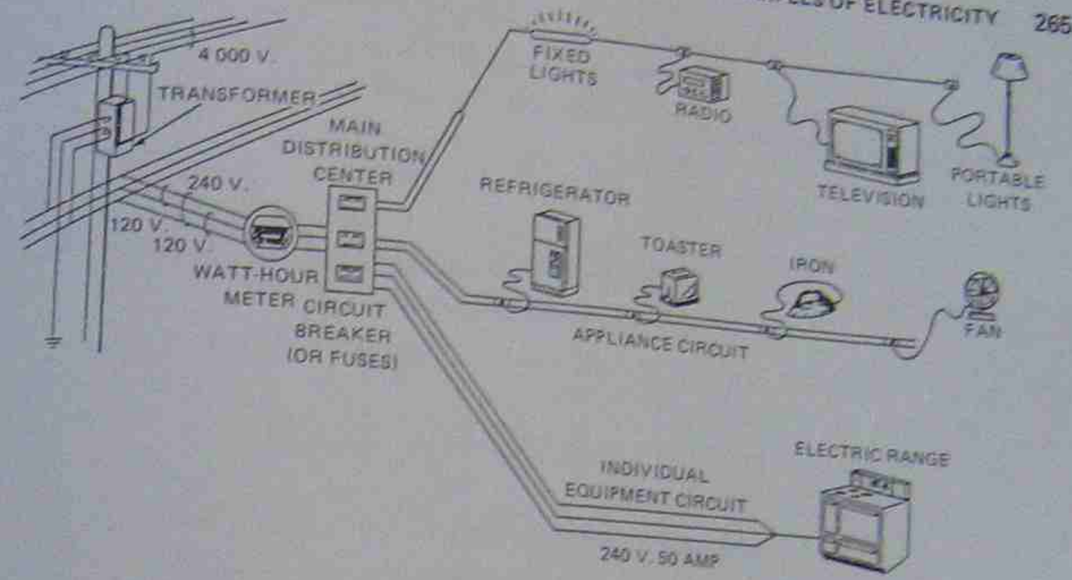


Fig. 15-22 A Typical distribution system

REVIEW QUESTIONS

1. Explain how a pencil or any other object is electrical in nature.
2. List the parts that make up an atom and tell the electrical characteristic of each.
3. What accounts for copper's ability to readily conduct electricity?
4. Why are elements whose atoms have almost complete outer shells poor conductors?
5. Do like charges of static electricity attract or repel each other?
6. Explain how a negatively charged rubber rod can charge an electroscope by contact.
7. Define an electrical current.
8. Define the following terms: amperage, voltage, resistance.
9. Using Ohm's law, calculate the following:
   E – when I is 0.02 ampere and R is 4000 ohms
   I – when E is 110 volts and R is 220 ohms
   R – when E is 120 volts and I is 6 amperes

10. Draw a simple series circuit that contains three resistances.
11. Draw a simple parallel circuit that contains three resistances.
12. How can you account for the magnetic characteristics of iron and steel?
13. State the laws of repulsion and attraction for magnets.
14. How can the left-hand rule be used to determine the direction of magnetic flux when the direction of current is known?
15. Describe how you could build a simple electromagnet.
16. Do electromagnets have any practical use? If so, list some common uses.
17. What is meant by primary and secondary cells?
18. What is electrochemical energy?
19. Explain the underlying principle of a generator.
20. Explain briefly how most generators are powered.
21. What is the basic difference in the construction of a DC and an AC generator?
22. Why is alternating current used in preference to direct current for home and industrial uses?
23. Explain the function of a transformer.

SECTION 6 TRANSMISSION OF POWER

Unit 16 Mechanical Transmission of Power

OBJECTIVES After completing this unit, the student should be able to:

- Explain the five simple machines.
- Recognize the three classes of levers.
- Calculate mechanical advantages of force, speed, and distance.
- Discuss ways of transmitting power to machines.

DIRECT TRANSMISSION OF POWER

The power of the engine must be *transmitted* to the machines. In some cases, the machine can be fastened directly to the prime mover. This is not only desirable and simple, but few power losses occur this way. When the drive shaft of the prime mover is directly connected to the driven shaft of the machine or device, an ideal situation exists as, for example, a blade fastened to the engine's crankshaft on a rotary lawn mower. Also, direct drive from the shaft can be seen in many machines that are driven by electric engines, such as grinders and polishers. The simple, ideal situation for power transmission can be found, but in most cases the machine application calls for something more complex.

INDIRECT TRANSMISSION OF POWER

Direct transmission of power may not cover all of the operating requirements of the given machine or mechanism. Factors such as speed changes, disengaging the machine from

the prime mover output requirements changes in direction of rotation, transmitting energy over long distance, transmitting energy around corners, or converting rotary motion to linear motion, cannot be satisfied by direct, positive linkage with the prime mover. The power transmission system requirements of the automobile point up several of these factors. Aggressive speed changes and direction changes would not be practical if the crankshaft were directly and positively fastened to the wheels with no mechanism in between.

Unit 9 provides a detailed explanation of the automobile drive system and it would be well to review it after studying this unit to see how mechanical transmission principles are applied.

Small engine applications—such as seen on a riding lawnmower—will also use many principles discussed in this unit, and so the power train of a typical riding lawnmower is covered at the end of this unit.

In addition to direct transmission of energy to machine, there are three primary methods of delivering the power of the prime mover to the machine that is to do the work:

- *Mechanical transmission* involves gears, pulleys, chain drive, levers, shafts, and fixed axles, as the transmission media.
- *Fluid transmission* involves the use of a liquid or a gas within a dynamic system as the transmission media.
- *Electrical transmission* involves the use of induction wire to deliver electric current.

Each of the three methods has its advantages and disadvantages. Engineers select the transmission system best for the requirements, often they use the systems in combination with each other. For example, coal is used to produce heat which converts water into steam. The steam is directed against the blades of the steam turbine. The steam turbine drives a generator producing electrical energy which is transmitted throughout the countryside by the use of wires. The energy arrives at a factory, for instance, where it is used to drive various electric motors. The power produced by the electric motors may be transmitted to the machine through gears, belts, or other mechanical arrangements, or the power of the electric motor may be transmitted to a fluid power system which, in turn, transmits the power to the machine. There is an infinite number of combinations. This section deals with the physical principles and some of the techniques involved in transmitting power.

MECHANICAL TRANSMISSION OF POWER

Mechanical transmission principles enable a person to do more with the power that is available. The principles do not increase the power coming out of the engine or other force-producing device because the total power being produced cannot be multiplied, the mechanical principles can adapt the power to a particular machine.

Several mechanical principles have been applied for centuries, long before engines were a source of power. The principles work well whether the source of power is an engine, a draft animal, a human, or a natural force. The principles discussed in this unit are often referred to as simple machines. These principles are isolated by engineers in thousands of variations as seen in transmission systems and the machines themselves. It is sometimes difficult to draw a firm line between transmission systems and the machine itself, since the two may often blend into an integral unit. Countless applications of the simple machine principles are seen but basically the principles can accomplish three things:

- Change the size of the applied force.
- Change the direction of the applied force.
- Change the speed that results from the applied force.

These simple machines include the lever, wheel and axle, inclined plane, wedge, and screw.

LEVER

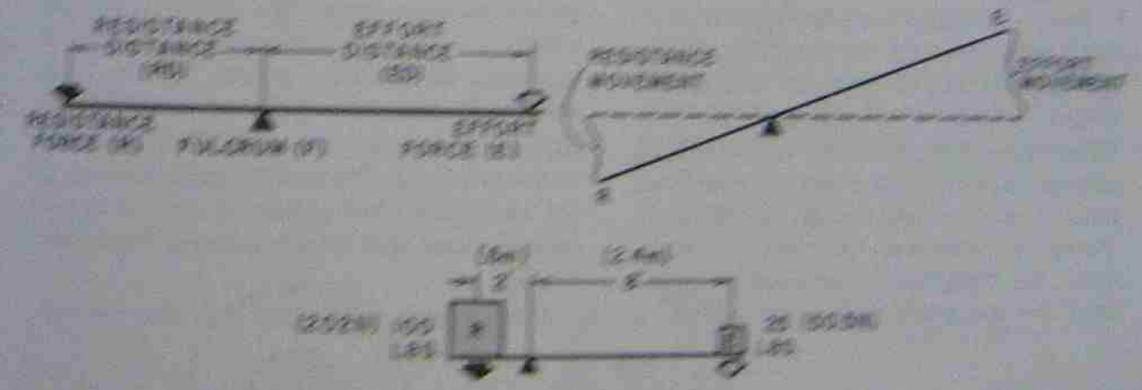
Levers allow a person to lift, move, or hold far more than is possible without them. They are commonly used. A mouse enables a small child to lift a man off the ground, a man uses a lever to move a boulder, a boy uses a pair of pliers to hold a bolt. Any long

bolt or board will do for a lever as long as it has a good point (fulcrum) to work against. In doing, a mechanical advantage with a lever, less force is used but it must apply over a greater distance to overcome and move the opposing object which totals movement.

Mechanical advantage is the number of times that force is multiplied. What a person in applied force is lost in having to apply the force over a greater distance. The principle of the lever does not allow both a larger force and smaller distance moved. One is sacrificed for the other. With the lever shown in figure 16-1, an effort or force of 25 pounds (25 newtons) can lift 100 pounds (100 newtons), a mechanical advantage of four.

Levers fall into three categories: first class, second class, and third class levers.

First class levers place the fulcrum between the resistance and the effort force. These levers multiply force with a sacrifice in the



ENGLISH	METRIC
R x RD = E x ED	R x RD = E x ED
(100 LBS) x (2FT) = (25 LBS) x (8FT)	(445N) x (4m) = (111.5N) x (2.4m)
(200FT-LBS) = (200FT-LBS)	(1.2J) = (1.2J)

Fig. 16-1 The moments of force around the fulcrum balance each other. Note that for larger force applied (R) or for greater distance applied (RD), the effort distance (ED) must be increased, or increase effort force (E).

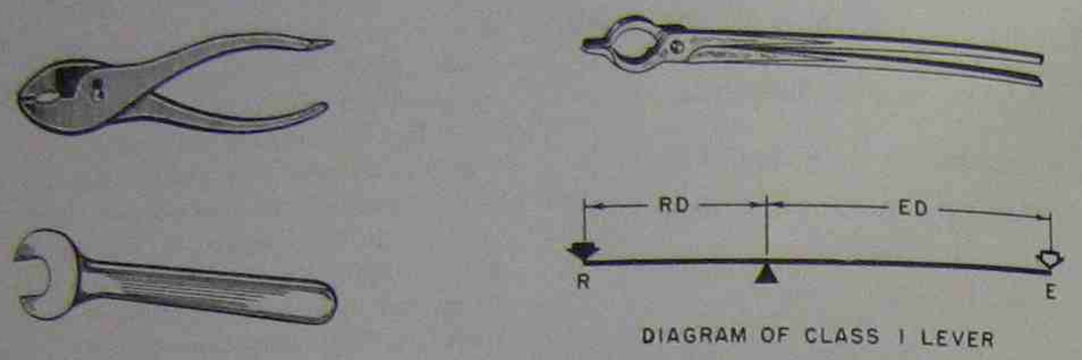


Fig. 16-2 Examples of first class levers

distance the object is moved. The direction of movement is reversed, figure 16-2.

Second class levers place the fulcrum at the end of the lever with the resisting weight at a point along the lever. These levers also multiply force with a sacrifice in the distance the object is moved. The direction of object movement is the same as that of the applied force, figure 16-3.

Third class levers place the fulcrum at the end of the lever with the resisting weight at the opposite end of the lever. The applied force or effort is at a point along the lever. These levers increase effort by multiplying distance moved by the object and, therefore, have a negative mechanical advantage. A fishing rod illustrates this principle. Sometimes the fisherman is mystified at how a small fish can create such a large pull on his rod. The fish has the mechanical advantage, figure 16-4.

WHEEL AND AXLE

Essentially the wheel and axle consists of two wheels firmly held together along the same axis. The axle may be short or it may be a very long shaft. Mechanical advantage is gained when the large wheel is moved through a distance. The axle moves also; its motion is less since its diameter is less, but the force twist, or torque on the axle is multiplied, figure 16-5. A boat trailer winch is an example of this principle. The mechanical advantage of the winch will allow a man of normal size to properly load and secure a heavy boat onto a trailer.

Study figure 16-6; note that the mechan-

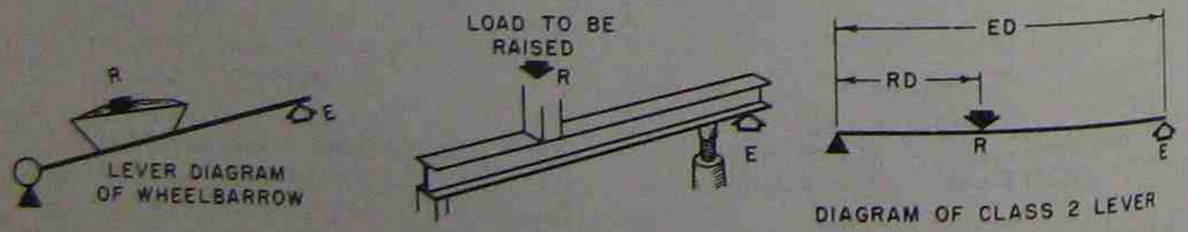


Fig. 16-3 Examples of second class levers

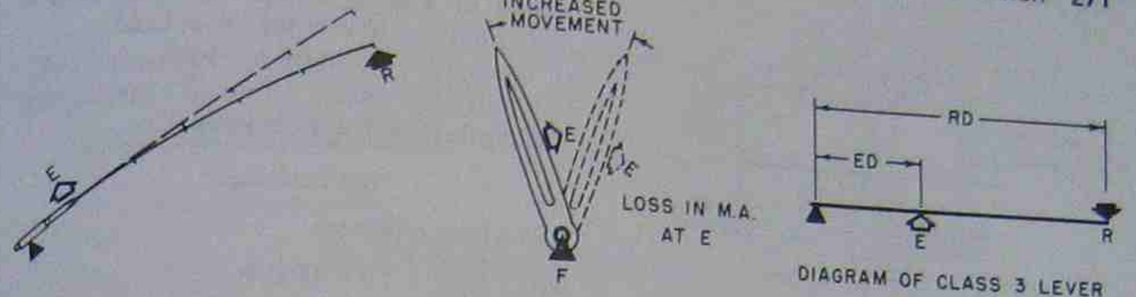


Fig. 16-4 Examples of third class levers

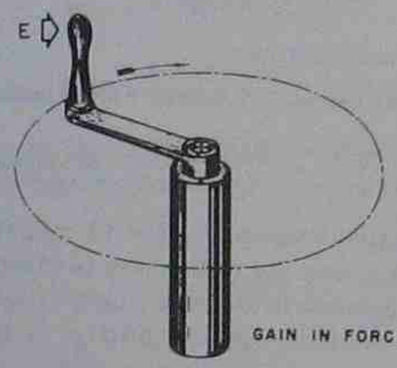


Fig. 16-5 Gaining mechanical advantage of force with the wheel and axle

ical advantage possible with the wheel and axle is essentially that of a Class 1 lever. The fulcrum is at the center of the wheel and the axle. The resistance distance, RD, is measured from the fulcrum to the perimeter of the axle, and the effort distance, ED, is measured from the fulcrum to the perimeter of the wheel.

In the perfect wheel and axle, these moments of force are equal: E X ED = R X RD.

Figure 16-7 shows an effort force of 10 pounds (44.5 newtons) applied to a 5-inch (127-millimeter) radius wheel. The resistance force acting on the axle of 1-inch (25.4-millimeter) radius which the effort force over-

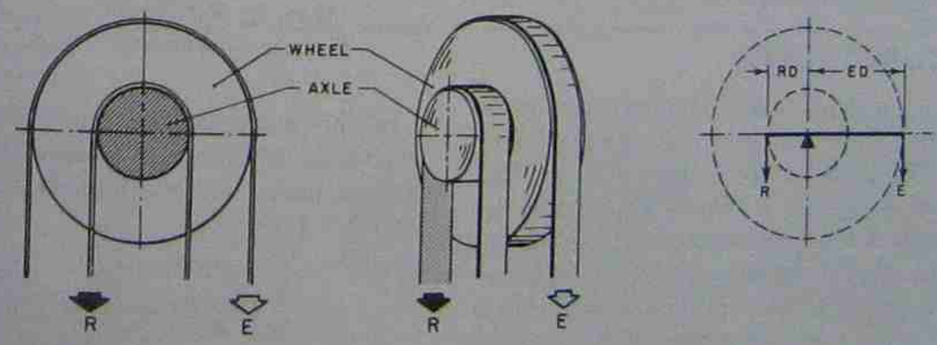


Fig. 16-6 Wheel and axle moments of force

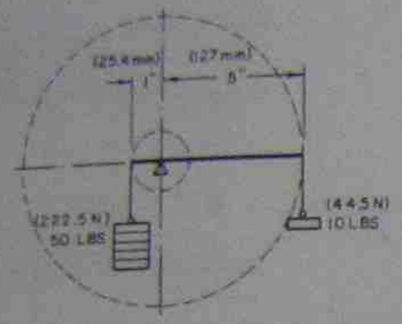


Fig. 16-7

comes is found by the moment formula:

U.S. Customary

E × ED = R × RD

10 pounds × 5" = R × 1"

$\frac{\text{50 pound-inches}}{\text{1 inch}}$ = R

50 pounds = R

Metric

E × ED = R × RD

44.5 newtons ×
127 millimeters = R × 25.4 millimeters

5651.5 newton-millimeters = R

222.5 newtons = R

With a wheel and axle combination, a smaller force may be used to produce or control a larger force.

INCLINED PLANE

The inclined plane also allows force to be applied over a longer distance in order to handle heavy objects, figure 16-8. This principle—as well as others—was used by the Egyptians in the construction of the pyramids. Stone blocks weighing several tons were rolled up a gently inclined plane and maneuvered into place. Upon completion of the structure, the earthen inclined planes were removed.

Inclined planes or ramps permit the application of a lesser amount of force over a longer distance to ease the job at hand.

Example: a boy lifts his 100-pound (445-newton) body onto a 3 foot (0.9 meter) high loading dock with a single jump.

U.S. Customary

Work = Force × Distance

Work = 100 lb × 3 ft = 300 ft-lb

$\text{Force} = \frac{\text{Work}}{\text{Distance}} = \frac{\text{300 ft-lb}}{\text{3 ft}} = 100 \text{ lb}$

Metric

Work = Force × Distance

Work = 445 newtons × 0.9 meter = 400.5 joules

$\text{Force} = \frac{\text{Work}}{\text{Distance}} = \frac{\text{400.5 joules}}{\text{0.9 meter}} = 445 \text{ newtons}$

By walking up a 10 foot (3 meter) long ramp, less than the 100-pound (445-newton) force required in a single jump is applied, but it must be applied through a greater distance.

U.S. Customary

$\text{Force} = \frac{\text{Work}}{\text{Distance}} = \frac{\text{300 ft-lb}}{\text{10 ft}} = 30 \text{ ft-lb when walking up ramp}$

Metric

$\text{Force} = \frac{\text{Work}}{\text{Distance}} = \frac{\text{400.5 joules}}{\text{3 meters}} = 133.5 \text{ newtons when walking up ramp}$

In this example, the boy actually has a mechanical advantage of force when using the inclined plane. The mechancial advantage of force is 3 1/3.

U.S. Customary

$MA_f = \frac{\text{R (Resistance Force)}}{\text{E (Effort Force)}}$

$MA_f = \frac{\text{100 lb}}{30} = 3\ 1/3$

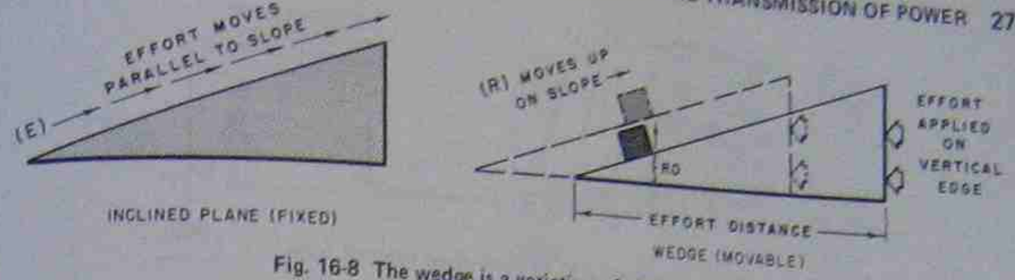


Fig. 16-8 The wedge is a variation of the inclined plane.

Metric

$MA_f = \frac{\text{R (Resistance Force)}}{\text{E (Effort Force)}}$

$MA_f = \frac{\text{445 newtons}}{133.5} = 3\ 1/3$

The mechanical advantage of distance can also be calculated.

U.S. Customary

$MA_d = \frac{\text{RD (Resistance Distance)}}{\text{ED (Effort Distance)}}$

$MA_d = \frac{\text{3 ft}}{\text{10 ft}} = .3$

Metric

$MA_d = \frac{\text{RD (Resistance Distance)}}{\text{ED (Effort Distance)}}$

$MA_d = \frac{\text{0.9 meter}}{\text{3 meters}} = .3$

The mechanical advantage of speed is calculated with the same formula:

$MA_s = \frac{RD}{ED}$

Note that these mechanical advantage formulas apply to all simple machines.

WEDGE

The wedge is a variation of the inclined plane. It is driven under or into an object and applies its force through a longer distance. Many cutting tools are actually made up of a series of wedges which are called teeth. Under magnification these wedge teeth get under and break away the material they are cutting, figure 16-9. Axes and chisels are also wedges. In addition, wedges make excellent holding devices; the simple doorstop is one example.

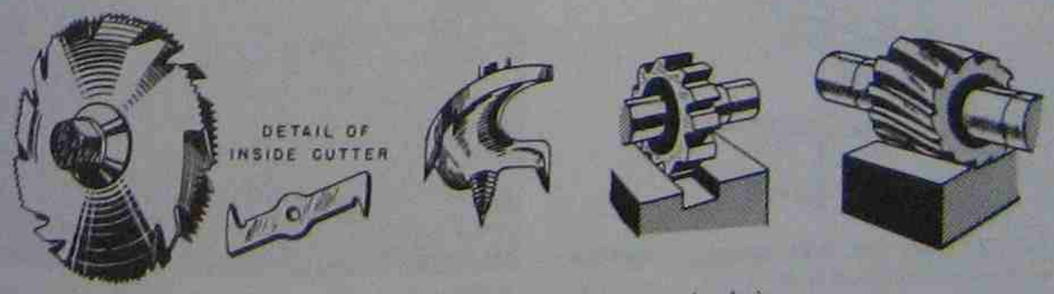


Fig. 16-9 Applications of the wedge as a separating device

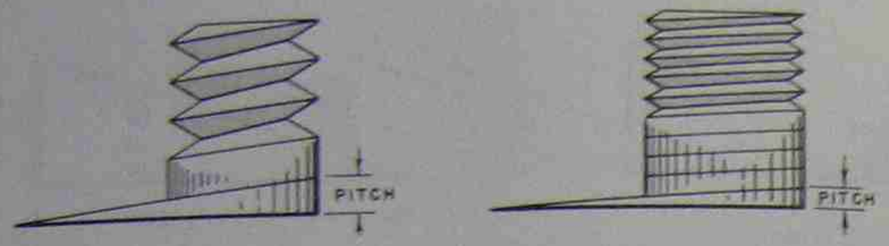


Fig. 16-10 The screw is an inclined plane in spiral form.

SCREW

The screw is also an inclined plane. However, it is one that has been put into a round form and appears as a continuous spiral, figure 16-10. Its most common application is in fasteners such as nuts, bolts, and wood screws. However, screw principles are used in jacks, worm gears, some pumps, and to convert rotary motion to linear motion. The mechanical advantage that a screw applies can be tremendous since the pitch of the screw is usually quite small (RD) and the distance the effort is applied through (ED) is usually quite large by comparison. A jack screw illustrates this very well, figure 16-11.

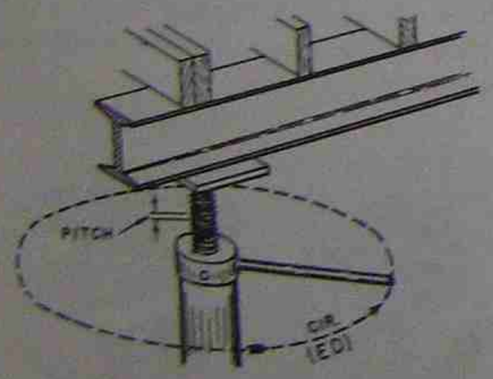


Fig. 16-11 The jack screw applies a tremendous mechanical advantage of force.

PULLEYS

Pulleys in various arrangements create a mechanical advantage which can aid in the movement of heavy objects. In gaining the mechanical advantage, distance moved is sacrificed in the interest of applying less force. The number of ropes supporting the object determines the mechanical advantage. If four ropes support the weight, then the rope is pulled four feet in order to move the object one foot; but the force, disregarding friction, required is one-fourth the weight of the object, figure 16-12.

GEARS

The gear uses the same principles as simple machines. It is merely a wheel with special notches or teeth cut into its perimeter to provide positive contact with another gear. In a sense, two meshing gears are like two levers working against each other.

V-belts and pulleys, or chains and sprockets, have the same mechanical function as do gears, figure 16-13. They are useful if power is transmitted between shafts that are separated by a distance. If construction permits close spacing of the shafts, then gear teeth can mesh against each other, a simpler arrangement.

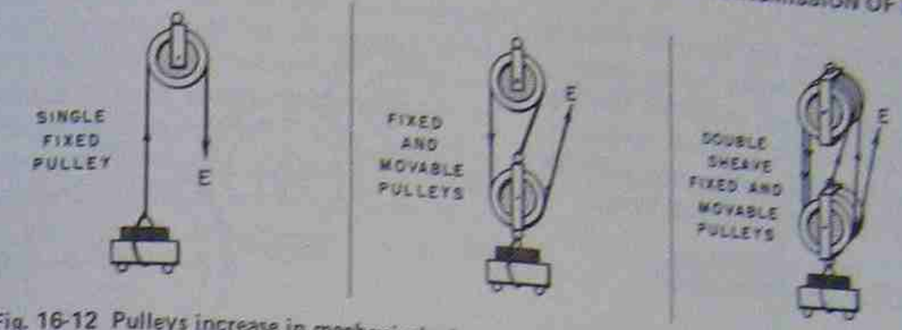
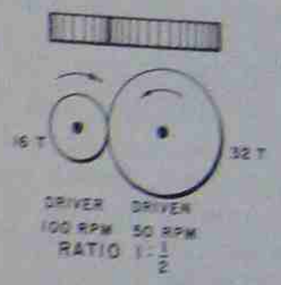


Fig. 16-12 Pulleys increase in mechanical advantage as the number of turns of rope (ED) increases.

Gears of different sizes change speed in proportion to the number of teeth on each gear, figure 16-14. A gear with 24 teeth will drive a gear with 12 teeth at double its speed.

$$MA_S = \frac{\text{Teeth in Driving Gear}}{\text{Teeth in Driven Gear}}$$

$$MA_S = \frac{24}{12} = 2$$



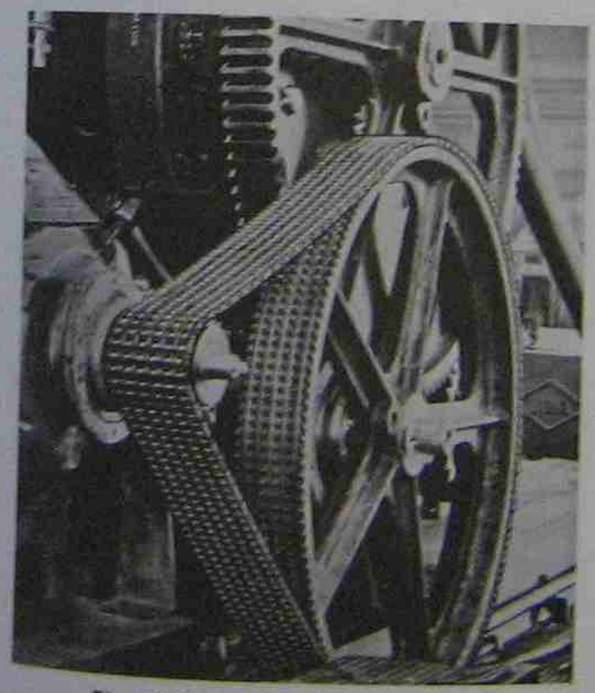


Fig. 16-13 A chain-driven gear train

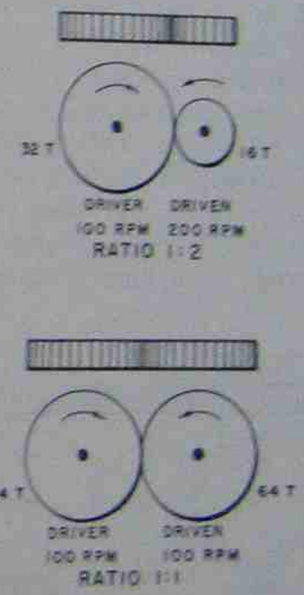


Fig. 16-14 Gears may be used to change speed a
force.

When speed changes, the torque or twisting force also changes. Gearing up to increase speed reduces the torque produced. Gearing down to decrease speed increases torque. A gear with 24 teeth will drive a gear with 48 teeth at half its speed, but twice its force.

$$MA_f = \frac{\text{Teeth in Driven Gear}}{\text{Teeth in Driving Gear}}$$

$$MA_f = \frac{48}{24} = 2$$

The gearing in an automobile is an excellent example of this. At low speed it is geared down to gain the torque needed to get the auto moving. At highway speed, the auto is moving nicely and is geared up. Less torque is needed, but more speed is required. The power transmission principles of the automobile are discussed in more detail in Unit 9.

Gears also change the direction of rotation as the power is transmitted from one to another; from clockwise rotation to counterclockwise rotation and so forth, figure 16-15.

Gears are arranged in a gear box in the proper sizes and combinations to satisfy the needs of the machine that is powered, figure 16-16. Sometimes the positions and gear combinations are fixed, but often provision is made to shift the gears around in various combinations as is done in an automobile transmission. Gears in no way change the total power that is developed by the prime mover, they just change the speed or torque.

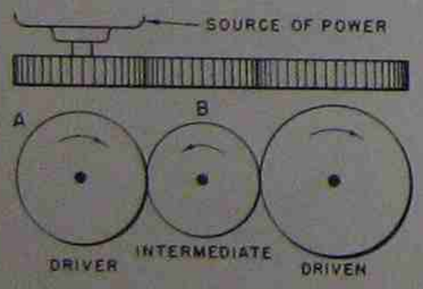


Fig. 16-15 Changing direction of rotation

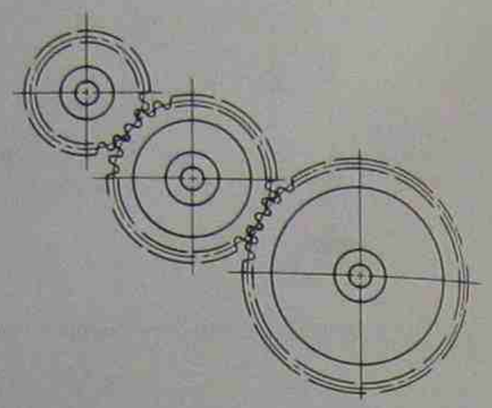


Fig. 16-16 Representation of simple gear train

Mechanical transmission of power is seen in everyday machines and mechanisms. It is important to understand some of the basic principles of machines and power transmission. This takes some of the mystery out of the devices that at first appear too complicated to be understood. Mechanical transmission is the world of gears, wheels, levers, belts, pulleys, chains, shafts, and screws. They are positive linkages between the prime mover and the mechanism. Through years of improvement and research they have become very efficient and reliable in their service.

THE POWER TRAIN

Many uses of engines involve getting the power to the wheels as well as getting power to the machine. For example, a riding lawnmower engine must move the entire machine along as well as turn the blades for mowing grass. A wide variety of applications of levers, gears, pulleys, V-belts, shafts, chains, and sprockets are used to transmit the power of the engine's crankshaft at the correct speed and torque for the machine's requirements. Sometimes it is as simple as the direct drive of a rotary push-type mower. However, many uses are more complex and require a clutch, transmission, universal joint, and differential. These mechanisms are referred to as the power train.

- *Clutch* – connects and disconnects the power without stopping the engine.
- *Transmission* – provides for different speeds and directions (forward and reverse).
- *Universal Joint* – provides a flexible drive shaft.
- *Differential* – allows the wheels to rotate at different speeds for turning corners.

Clutch

The clutch engages or disengages the engine from the rest of the power train. When the engine is started and the machine is standing still, the clutch is disengaged. When the machine is moving, the clutch is engaged. Think of two pie plates, each on the end of a shaft, figure 16-17. One plate and shaft can rotate without the other plate and shaft rotating. However, if the rotating plate is moved into contact with and held against the nonrotating one, both will rotate.

A very simple clutch arrangement is sometimes used on V-belts and pulleys. By having no belt tension the engine is disengaged. Tightening the belt tension with an idler pulley engages the machine, figure 16-18.

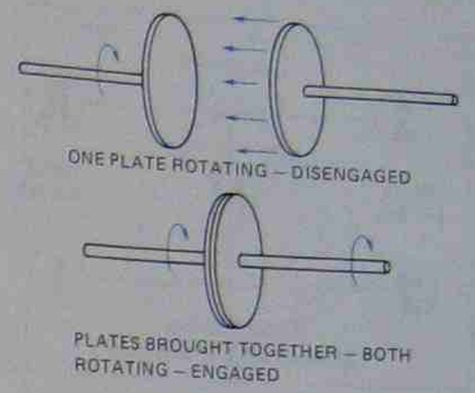


Fig. 16-17 When a nonrotating plate is held against a rotating plate, both plates will rotate.

Transmission

Gears are arranged in a transmission in the proper sizes and combinations to satisfy the operating requirements of the machine that is being powered. Provisions are made to engage or shift the gears into various combinations which provide different output speeds and directions.

A typical transmission for small gasoline engines has three forward speeds and one

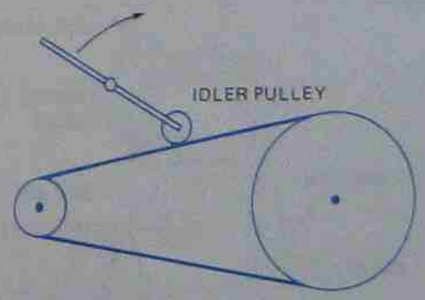


Fig. 16-18 Moving the idler pulley against the belt engages the drive.

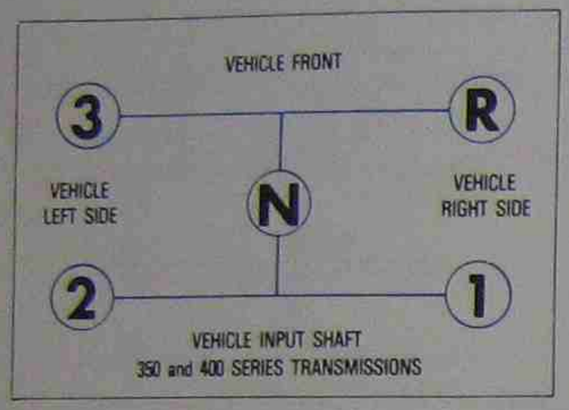
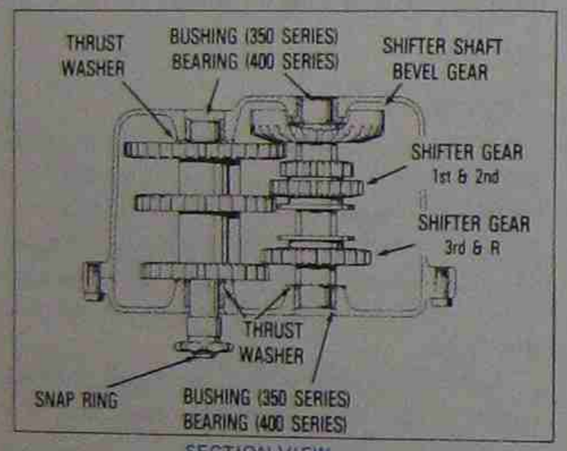
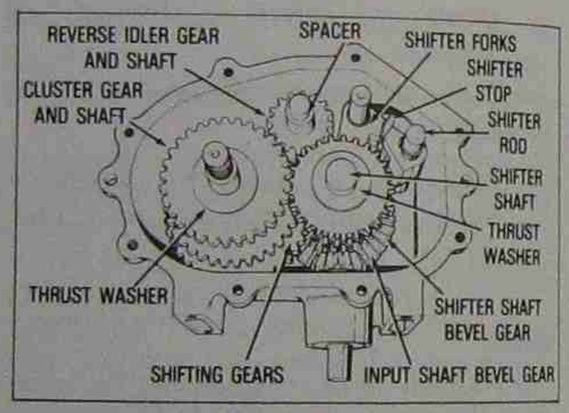


Fig. 16-19 Transmission shifting pattern

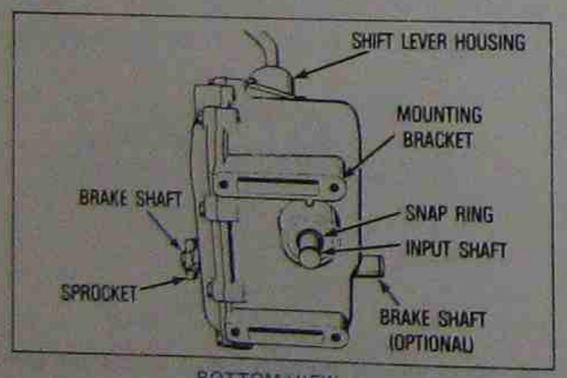
reverse speed, figure 16-19. The Tecumseh/ Peerless model 350 shown in figure 16-20 is a good example of a typical small gasoline engine transmission. Power input is to the large bevel gear. A shifter fork mechanism shown in figure 16-21 slides the gears into mesh as required and power is transferred to the companion or output shaft. When the transmission is put into reverse, an idler gear is brought into mesh. This "third" gear reverses the direction of rotation on the output shaft.



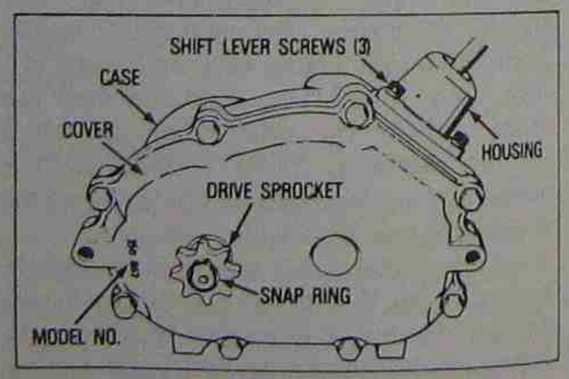
SECTION VIEW



TOP VIEW



BOTTOM VIEW



SIDE VIEW

Fig. 16-20 A typical small gasoline engine transmission

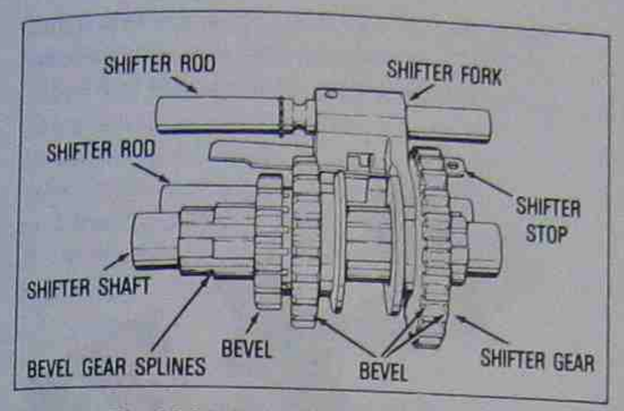


Fig. 16-21 Shifter fork, gears, and shaft

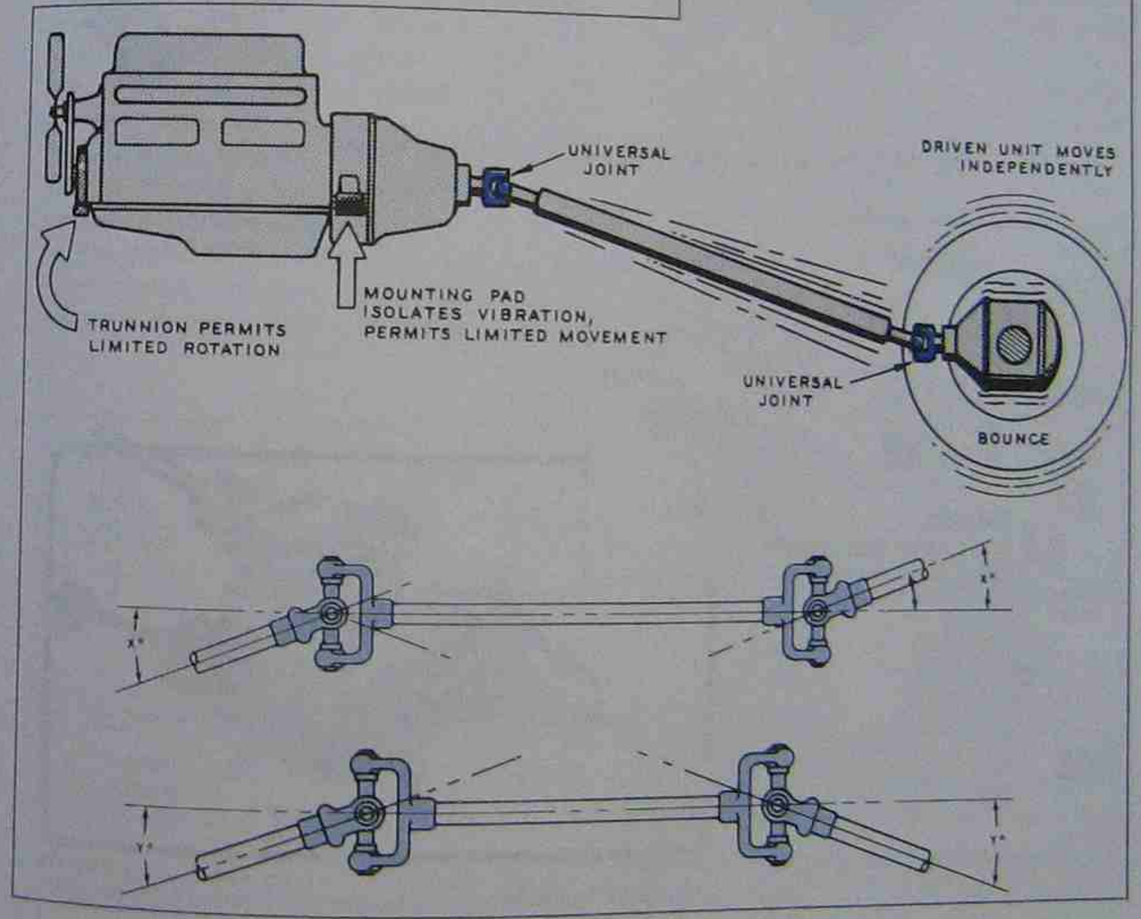


Fig. 16-22 Universal joint

Universal Joint

Universal joints add flexibility to the mechanical transmission of power by connecting shafts that do not share the same axis, figure 16-22. The most common use for universal joints is between the transmission and differential. The universal joint compensates for misalignment, bouncing, and movement between the transmission and differntial. The action of the universal joint is similar to the action of the human wrist. In addition to universal joints, flexible couplings can be used to transmit power if there is a small amount of misalignment or motion between two units, figure 16-23.

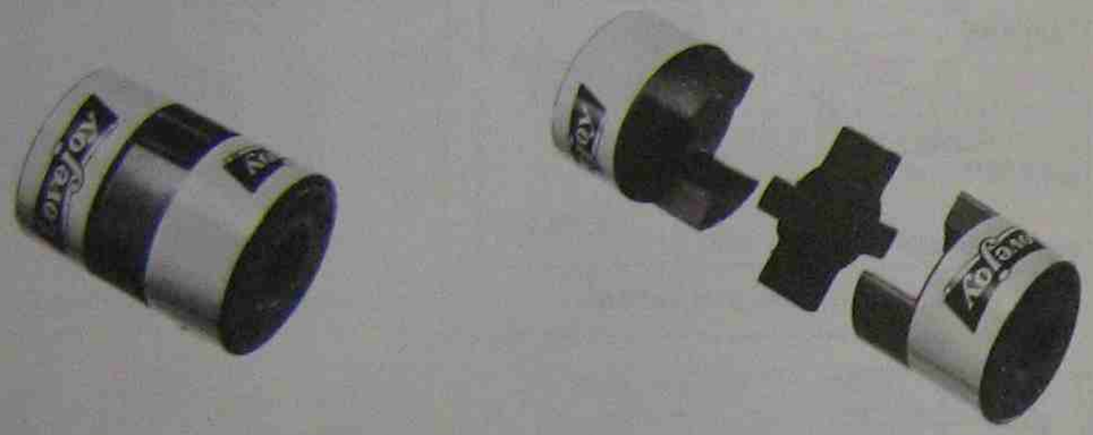


Fig. 16-23 Flexible couplings (Courtesy Lovejoy, Incorporated)

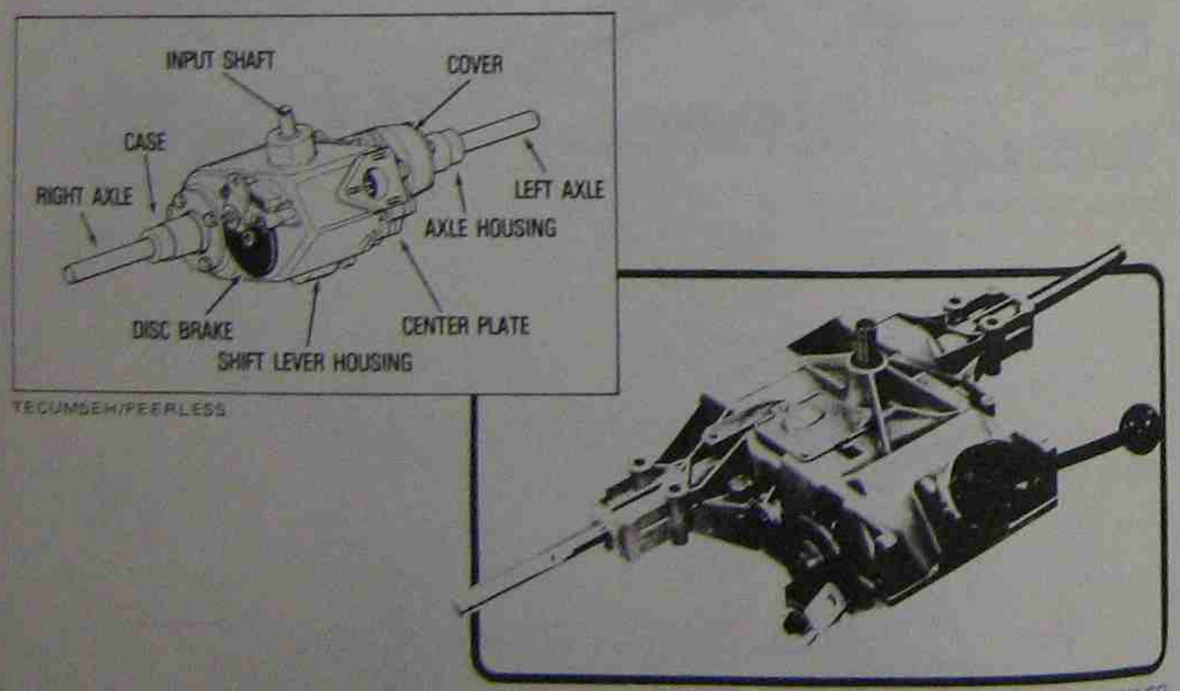


Fig. 16-24 Transaxles

Differential

The drive shaft and universal joints carry the power to the differential. The differential transmits the power to the axles and also enables the wheels to revolve at different speeds when a corner is turned. The wheel on the inside of the turn needs to travel less distance than the wheel on the outside of the turn, just as a column of marching soldiers do in turning a corner.

The parts of the differential are the case, drive pinion, ring gear, differential side bevel gears on the end of the axles, and pinion gears mounted in the differential case. Details of the differential operation are covered in Unit 9.

Transaxles

Transaxles are a combination of the transmission, differential, and axles within one housing, figure 16-24. This results in a more compact and lighter weight unit. Transaxles are very common for riding lawnmowers, lawn tractors, and similar machines. A transaxle unit with the top housing removed is shown in figure 16-25. The transaxle shown in figure 16-26 has five speeds forward and reverse. Power input is to the bevel gear. The shifter collar moves the key into the shifter spur gear cluster to engage a particular gear. The remaining four shifter spur gears turn freely on the shifter and brake shaft. The spur gear at the end of the shifter and brake shaft turns the output gear; the output pinion engages the differential ring gear. The sprocket and chain drive are engaged for reverse.

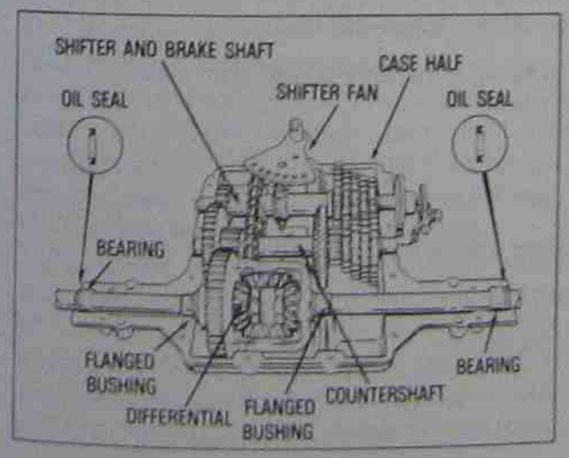


Fig. 16-25 Transaxle with top housing removed

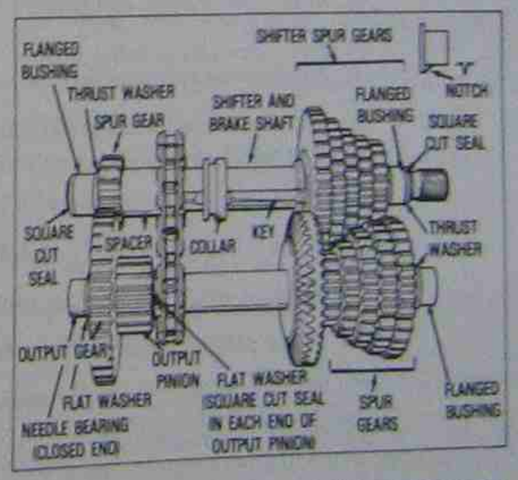


Fig. 16-26 Basic parts of a typical transmission portion of a transaxle

REVIEW QUESTIONS

1. Can direct or fixed transmission of power between the prime mover and the machine satisfy all machine applications? Explain.
2. What are the three basic power transmission systems?
3. List one example of each class of lever: first class, second class, third class.
4. Calculate the force necessary to move a 200-pound (890-newton) weight using a first class lever. The weight is 3 feet (0.9 meters) from the fulcrum. The lever's total length is 13 feet (4 meters).
5. Calculate the mechanical advantage of force found in carrying a 50-pound (222.5 newton) box up a 10-foot (3-meter) ramp that is 2 feet (0.6 meters) from ground level.
6. Compare a conventional wedge to the wedge formed by a cutting tooth.
7. What could be said about the mechanical advantage that is created by the use of the screw as a simple machine?
8. What determines the mechanical advantage of a pulley?
9. When are V-belts and pulleys or chains and sprockets used instead of gears?
10. Explain the relationship that exists between speed and torque.
11. What is the mechanical advantage of speed between a driven gear with 12 teeth and a driving gear with 96 teeth?
12. Explain the term *power train*.
13. What is the purpose of a clutch?
14. Explain why many engine applications need a transmission.
15. When might a universal joint be used?
16. Why do wheeled vehicles need a differential?
17. What is a transaxle?

Unit 17 Fluid Transmission of Power

OBJECTIVES After completing this unit, the student should be able to:
Explain the difference between hydraulics and pneumatics.
List and discuss the parts of a typical hydraulic system.
Discuss the advantages of the hydraulic system.
List and discuss the parts of a typical pneumatic system.
Explain the applications of a vacuum.

Fluid power involves the use of a fluid—in either liquid or gas form—to operate a mechanism. The fluid might be air-directed, as wind captured by the sail of a ship, or it might be water flowing in a river, its energy tapped by a water wheel. In the ancient civilizations of the Romans, Cretans, Persians, Indians, and Chinese, water was stored in reservoirs, channeled in aqueducts and pipes, and used for domestic purposes and irrigation. Civilization did not progress beyond these applications of fluid power for many centuries. These, then, give modern fluid power its foundation. To better understand modern uses, two key words must be introduced. These words are the two basic terms that are associated with fluid power: hydraulics and pneumatics.

Hydraulics is that branch of fluid power that deals with the use of liquids, usually oil, to transmit power from one place to another. The hydraulic system receives and controls the power delivered by the prime mover, generates a hydraulic force, transmits the force, and converts the force to power which is delivered to the work load.

Pneumatics is that branch of fluid power that deals with the use of gases, usually air or nitrogen, to transmit power from one place to another. The pneumatic system receives and controls the power delivered by the prime mover, generates a pneumatic force, transmits the force, and converts the force to power which is delivered to the work load.

Hydraulics and pneumatics share many common characteristics:

- Both use a fluid media; a liquid takes the shape of the vessel in which it is contained, and a gas completely fills the vessel in which it is contained.
- Both liquids and gases can flow through a pipe or a hose.
- The rate of flow of both liquids and gases is easily controlled with valves.
- Both liquids and gases can be caused to flow by various types of pumps.

There is one basic difference between liquids and gases which makes the separation of the two areas into different study units easier to follow. Liquids are virtually incompressible, while gases can be compressed. A hammer blow on the piston of a liquid-filled cylinder is like hitting the end of a steel shaft. A hammer blow on the piston of a gas-filled cylinder is like hitting a spring-loaded cylinder; it gives and then bounces back. Although there are many similarities that exist between hydraulic and pneumatic systems, for the sake of clarity and because of their one basic difference, the two are discussed separately.

HYDRAULICS

The key principle for modern hydraulics was formulated by Blaise Pascal in the seventeenth century. Pascal's Law states that pressure set up in a confined liquid acts equally in all directions and *always* at right angles to the containing surfaces. As an example, consider a flat fire hose which becomes cylindrical when it is filled with water. Pascal theorized, "There is a vessel

1. that is filled with water,
2. The vessel is closed on all sides.
3. It has two openings.
4. One opening is one hundred times as large as the other.
5. Each opening is supplied with a piston that *fits exactly*.
6. A person is pushing on the small piston.
7. The force exerted *equals* that of 100 people pushing on the large piston.
8. If *one* of the 100 people leaves, the force exerted by the person on the small piston will *overcome* the remaining 99 people pushing on the large piston.

This law even more simply stated means the pressure at any point in a static liquid is the same in every direction and exerts equal force on equal areas, figure 17–1.

Pascal's Law is an application of mechanical advantage to a liquid. Just as a lever can multiply force at the sacrifice of distance, so can hydraulics.

In the illustration of the lever and the weight, figure 17–2, a force of 2 pounds (8.9 newtons) moves through 100 inches (2540 millimeters) to produce 200 inch-pounds (22.6 joules) of work. This work is capable of producing equal work on the other end of the lever and can move 100 pounds (445 newtons) through a distance of 2 inches (50.8 millimeters), or 200 inch-pounds (22.6 joules).

The hydraulic creation of mechanical advantage is similar to that of the lever, figure 17–3. Two pounds (8.9 newtons) of force pushing the piston down the cylinder 50 inches (1270 millimeters) is equal to 100 inch-pounds (11.3 joules) of work. The two pounds (8.9 newtons) of force is transmitted

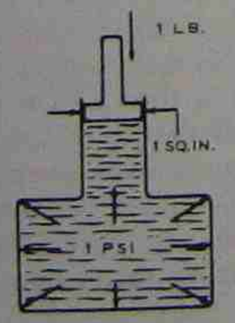


Fig. 17-1 Pressure is transmitted equally in all directions.

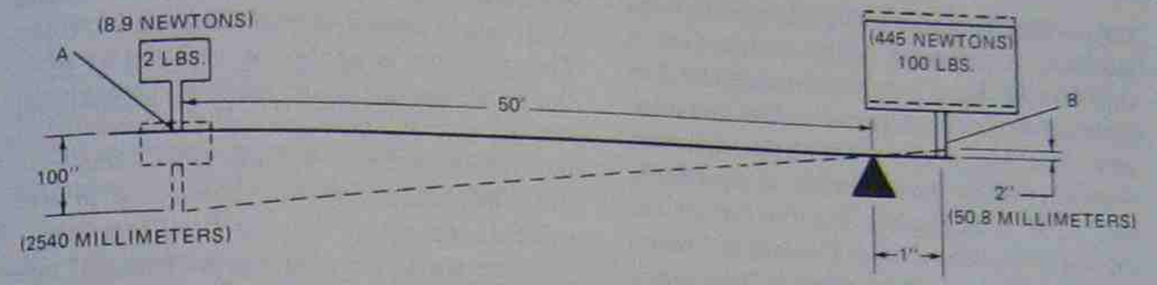


Fig. 17-2 The mechanical advantage of a lever also applies to hydraulics.

undiminished in all directions and pushes against the 50 square inches (32 258 square millimeters) of the large piston with a total force of 100 pounds (445 newtons). Work = Force × Distance:

U.S. Customary

$$\text{Distance} = \frac{\text{Work}}{\text{Force}} = \frac{100 \text{ inch-pounds}}{100 \text{ pounds}} = 1 \text{ inch}$$

The large piston moves upward one inch.

Metric

$$\text{Distance} = \frac{\text{Work}}{\text{Force}} = \frac{11.3 \text{ newton-meter}}{445 \text{ newtons}} = 25.4 \text{ millimeters}$$

The large piston moves upward 25.4 millimeters.

Pascal's Law deals with *static liquids*, that is, liquids that are not in motion; the *dynamics of liquids*, or liquids in motion, is quite another thing. As indicated earlier, friction is not taken into account, but friction is a factor in fluid transmission of power just as it is in the mechanical transmission of power. Friction in dynamic fluids is always present but it can be minimized if (1) the pipes or hoses are large enough to prevent excessive velocity and the resulting turbulence, (2) the lengths of the pipes or hoses are not excessive, (3) the number of bends in the pipe or hoses is not excessive, and (4) the corners are not too sharp.

The principle of how friction affects liquid

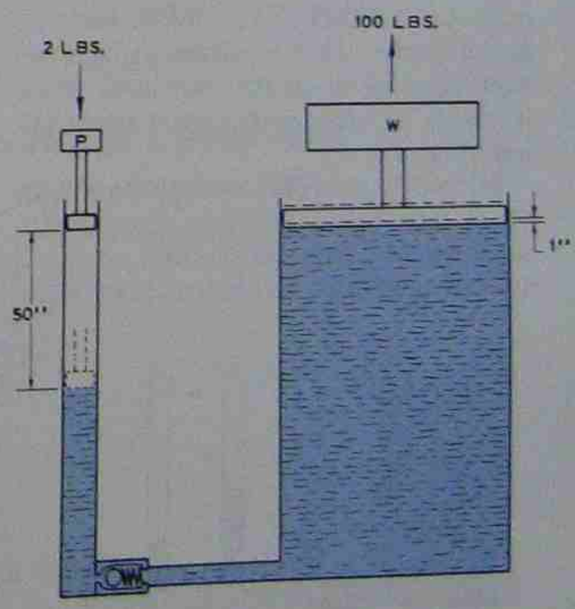


Fig. 17-3 Creating a mechanical advantage in hydraulics

flow is seen in figure 17–4. The main body of the liquid between A and C creates what is called *static head pressure*. When point B is opened up, the water is free to flow and dissipate the entire pressure. Notice that the water does not rise to the level of A in pipes D, E, and F. It is noticeably less the further the pipes are from the source. The drag of friction prevents the water from rising in these pipes, because friction has robbed some of the static head pressure.

Turbulence is another factor in fluid dynamics. A smooth laminar (in layers) flow of liquid is the most efficient. The layers of moving fluid are parallel to each other, but layers near the center of the pipe are moving more rapidly than those near the surface of the pipe where friction creates some drag. Therefore, if the velocity becomes too great due to a pipe that is too small, the laminar flow is disturbed and then efficiency-destroying turbulence sets in. Laminar flow might be compared to the smooth flow of traffic on a superhighway under moderate traffic load. Rush hour traffic—on the other hand—slows, it is more turbulent, and therefore slower and less efficient.

Bernoulli's principle concerns itself with the dynamic behavior of fluids. This principle states that the static pressure of a moving liquid varies inversely to its velocity. The static pressure on the surface of the pipe or hose decreases as the velocity of the fluid increases. This principle is applied in carburetors when the fluid flowing is air rushing through the venturi section. Low pressures are created in the venturi section. Figures 17–5 and 17–6 show how static pressure is reduced in constricted areas where the velocity is increased.

These are some of the principles that provide guidelines for engineers to follow as they design various hydraulic units that make up hydraulic systems of power transmission. Hydraulic systems are commonplace today, and, in terms of history, is a young industry. Modern hydraulics is not water flowing in aqueducts; it is liquid under high pressure in high-pressure pipes and hoses and in close tolerance machines with leak-proof pistons and cylinders. The development of reliable fluid power transmission systems had to wait for

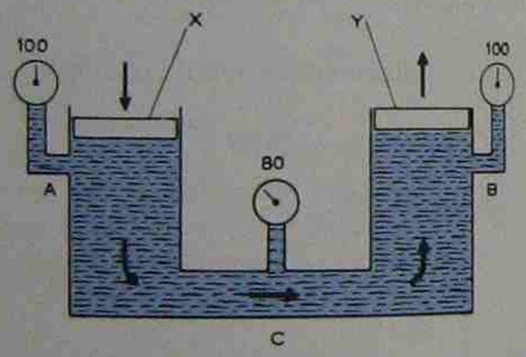


Fig. 17-5 Static pressure decreases as velocity increases.

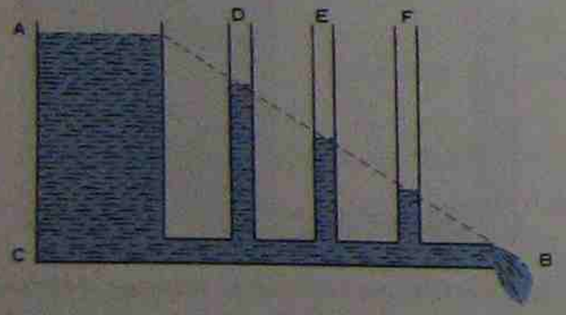


Fig. 17-4 The drag of friction also applied to liquids.

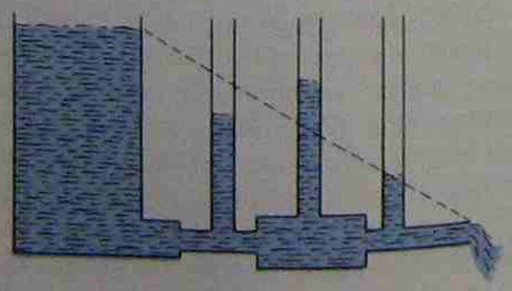


Figure. 17-6 Bernoulli's principle in action

improved materials and manufacturing techniques before it became a reality.

HYDRAULIC COMPONENTS

The average person is probably unaware of the many hydraulic systems in common use. Such uses include the automobile brake system, power steering, a garage hoist, or a dump truck, figure 17–7. There is also the wide application of hydraulics to the manufacturing industries such as machine tools, food and chemical processors, die casting, plastics,

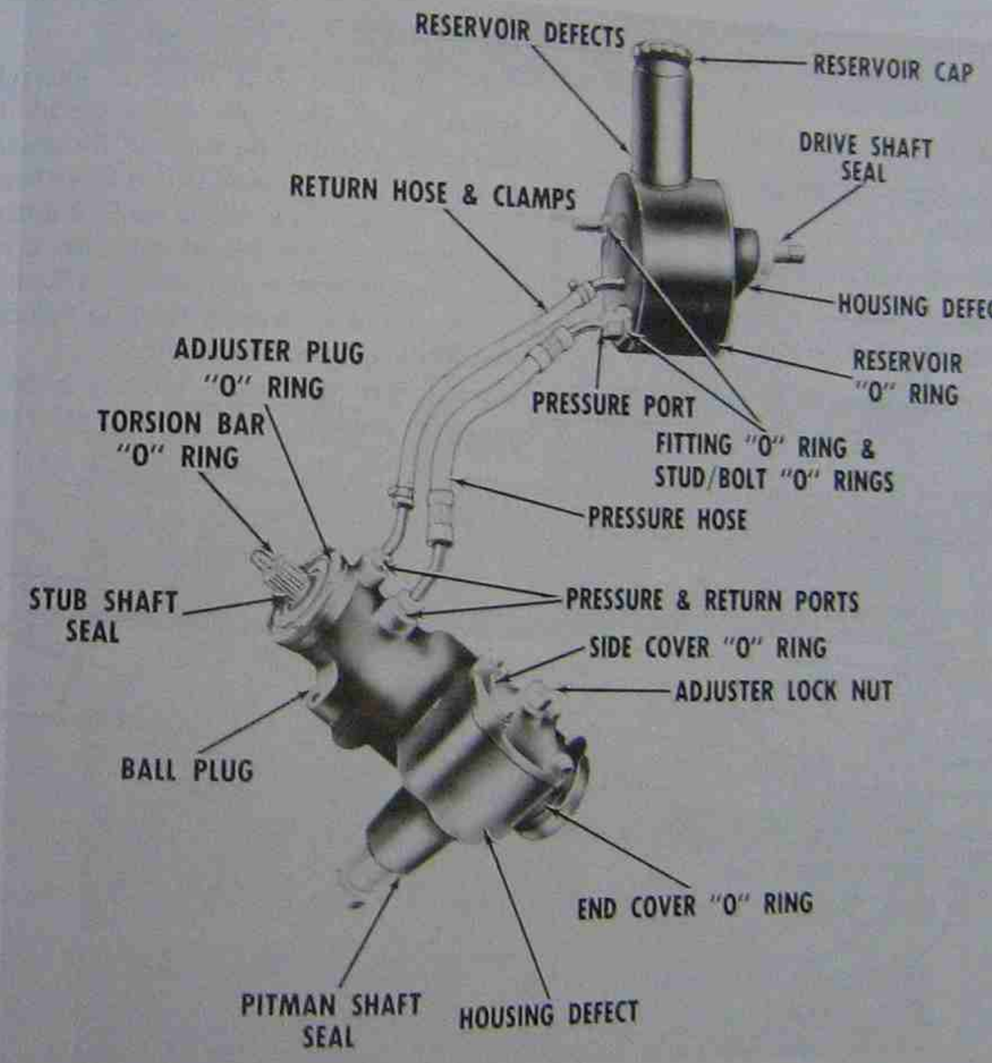


Fig. 17-7 Automobile power steering uses hydraulics. Points to check if a leak occurs are illustrated.

presses, glass machinery, textile mills, paper products, ordnance, and deck machinery. Applications in the aerospace industries include commercial and military aircraft, rockets, satellites, and helicopters. Applications for mobile equipment include lift trucks, earth movers, farm machinery, log skidders, trucks and buses, utility vehicles, mining, and railroad equipment, figures 17–8 and 17–9.

The components of a hydraulic system, figure 17–10, include:

- the hydraulic fluid itself.
- filters and strainers that increase its useful life.
- a reservoir or storage tank for liquid.
- tubing, pipes or hose to transmit the liquid through the hydraulic circuit.
- a pump driven by the prime mover to move the hydraulic fluid under pressure.
- valves to change direction, pressure, or amount of flow.
- motor or cylinder which is acted on by the hydraulic fluid, converting hydraulic power back into mechanical power for use by the mechanism.

Let us now cover these one by one.

HYDRAULIC FLUID

The fluid used most often in hydraulic systems is oil. Hydraulic oil is specifically formulated to satisfy the needs of the system. Its viscosity must be such that it flows freely through the system at the designated operating temperature, but not so thin that it can leak from the system and reduce efficiency. It must also be sufficiently thick to lubricate the various components properly.

Over a period of time, oil may begin to oxidize or combine with air just as other sub-

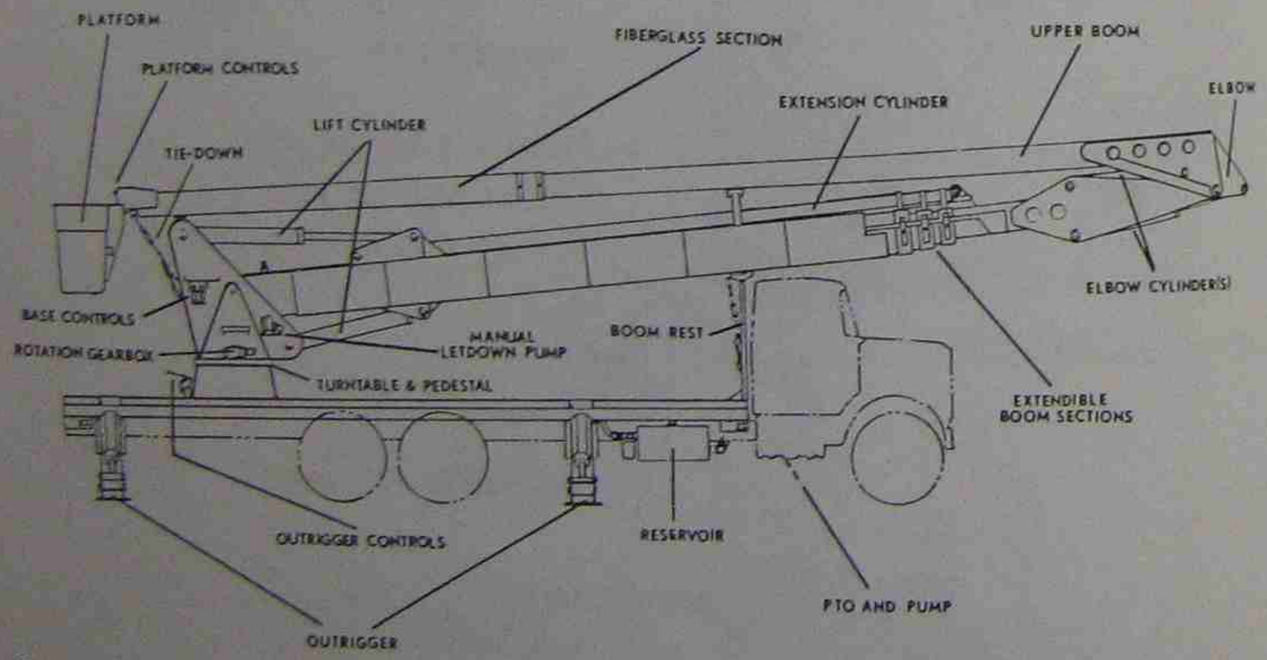


Fig. 17-8 Where would this aerial basket be without hydraulics? (Courtesy of Reach-All Manufacturing and Engineering Company)







Fig. 17-9 Typical applications of hydraulics (Courtesy Massey-Ferguson)

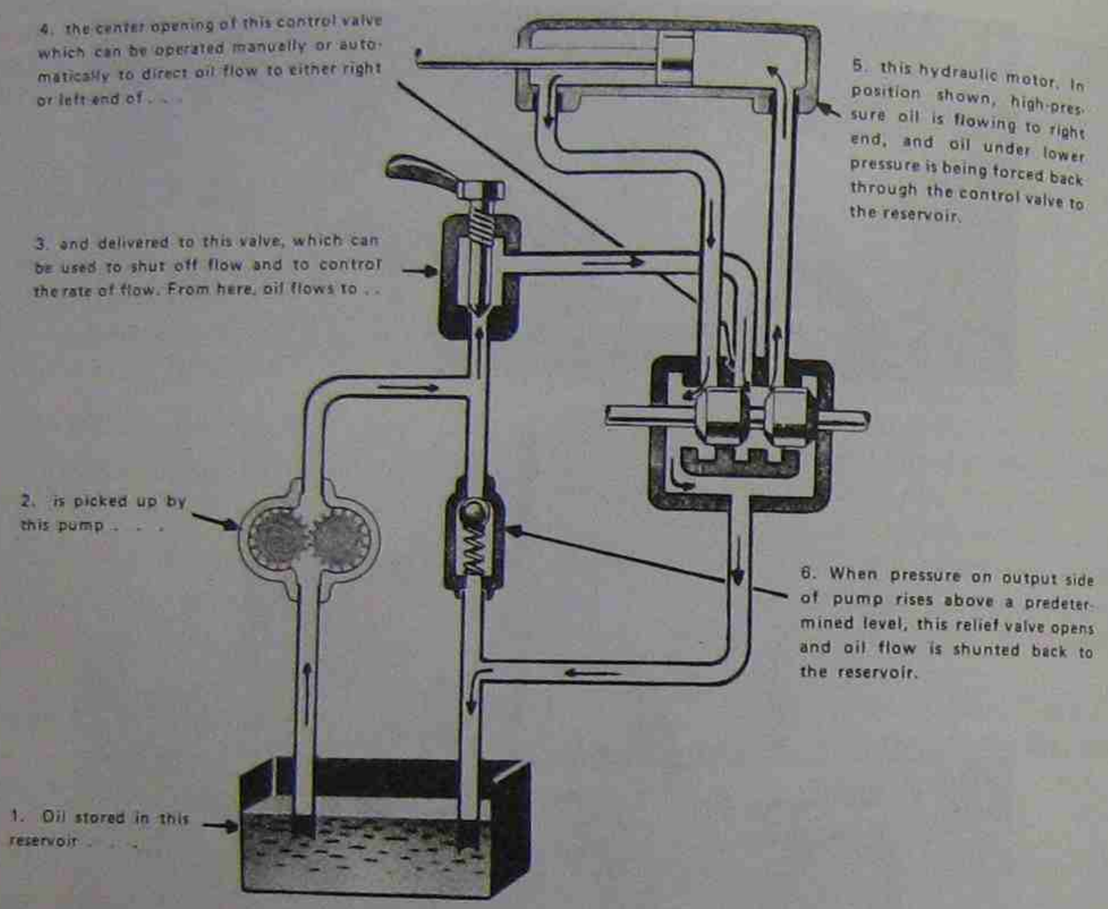


Fig. 17-10 A typical hydraulic system

stances do. This must be controlled because it causes the development of resins, varnishes, lacquers, and sludges. High operating temperatures increase the rate of oxidization in oil, and the contaminants caused by oxidization are corrosive acids. Therefore, corrosive effects on the precision hydraulic components can be minimized by using equipment that works at moderate pressure and temperature, and by careful preventive maintenance.

FILTERS AND STRAINERS

Filters and strainers are important in every system to prevent excessive wear, figures 17-11 and 17-12. Since small particles of dirt in the oil cause an abrasive action in hydraulic parts just as they do in engine parts, strainers are usually made of fine wire mesh capable of removing coarse foreign matter. Filters–by comparison–remove much smaller impurities, such as combustion byproducts and water.

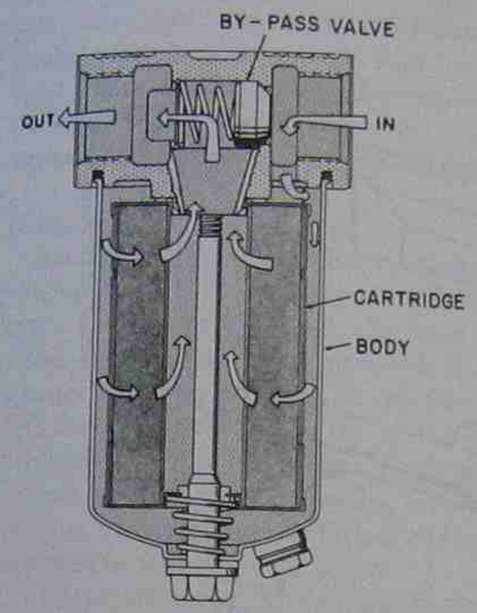


Fig. 17-11 Full flow oil filter

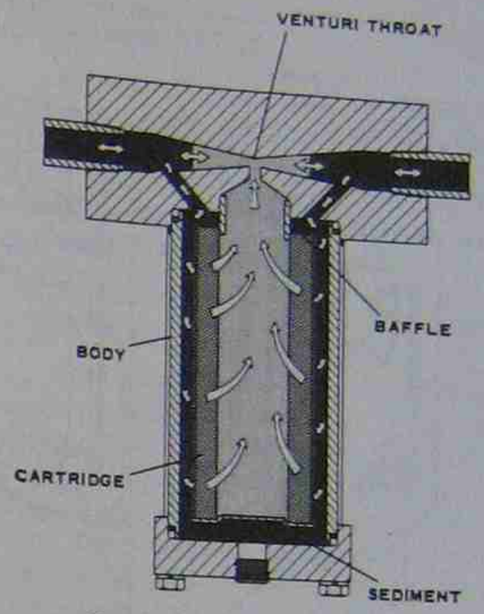


Fig. 17-12 Proportional flow oil filter

Most filter elements can be removed and replaced much the same as automobile filters. Today's filters remove particles as small as 78 millionths of an inch (2 nanometers).

RESERVOIR

The reservoir is a tank large enough to hold a sufficient reserve supply of hydraulic oil, figure 17-13. Most reservoirs are vented to the atmosphere to prevent a vacuum from forming as the oil level varies. The vent is fitted with an air breather or filter to prevent foreign materials from entering the system. As the oil returns to the reservoir, it enters with a good deal of force and turbulence. Baffle plates slow down the oil and allow time for air bubbles to rise to the top and the oil to cool before it is recirculated.

PUMPS

The hydraulic pump is driven by the prime mover or electric motor, and converts mechanical energy into hydraulic energy. It picks up the hydraulic fluid and forces it along its way. People often think of these pumps as *building up* an oil pressure, but since oil is virtually incompressible, it is better to think of the pump as delivering a driving rod of solid oil through the piping of the system. The pump generates both the flow and the resulting force. Pressure or resistance to the flow occurs further down the line as the machine places a load against the hydraulic force.

Pumps are rated or sized by the volume of hydraulic fluid they can deliver within a given time. This output varies with the speed of the

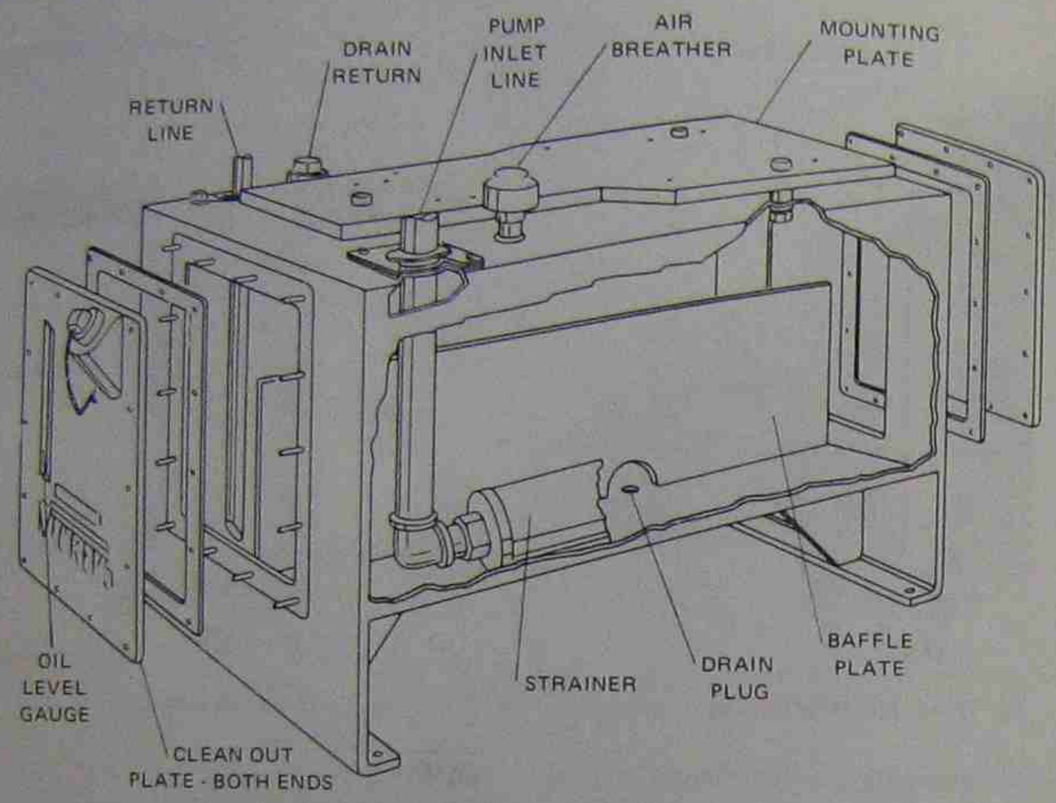


Fig. 17-13 A typical reservoir

pump, so the pump speed must be established as a factor in a pump rating. Some pumps are rated by their displacement or the amount of oil they will move during one cycle.

Pumps operate on either of two basic principles: nonpositive displacement or positive displacement.

Nonpositive Displacement Pumps

The nonpositive displacement pump is characterized by the centrifugal pump, figure 17-14. The speed of the pump and the resistance to flow determine how much fluid is delivered. The principle is simply that centrifugal force throws the fluid from the eye of the pump—where it first enters—to the outside perimeter of the spinning impeller, and through the pump outlet. If the pump discharge was completely

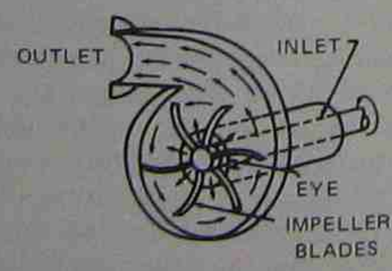


Fig. 17-14 Operating principle of a centrifugal pump which is a nonpositive displacement pump

shut, the pump would churn through the liquid, producing only heat. With the centrifugal pump 100% slippage is possible. These pumps are used in applications that require a large volume of flow at relatively low pressures.

Positive Displacement Pumps

Positive displacement pumps deliver a fixed volume of fluid at any given speed. If resistance to flow is increased, the force of the liquid and its velocity is increased. If the resistance becomes absolute or the flow is cut off, then pressure builds up to the stall or breaking point. A relief valve which opens at a predetermined pressure setting prevents this possible damage. There is little if any slippage in a positive displacement pump.

The pump speed is usually not varied to meet differing operating requirements. If the application calls for flexibility in the volume of the fluid flow, then variable displacement pumps are used. In these pumps the physical relationship between the pump components can be changed to provide for different volume requirements. Flow control valves can also change the volume of fluid flow.

Rotary pumps are of the positive displacement type and include gear, lobe, vane, and piston pumps. In any of these pumps the hydraulic fluid is allowed to enter the pump chamber, trapped by the closing pump chamber, and then moved to the discharge side of the pump where it is forced out. The key parts may be gears or lobes rotating against each other, movable vanes that work against the walls of the pump housing, radial pistons in a rotating off-center cylinder block, or axial pistons in an offset or tilted cylinder block. Several simplified drawings of these pumps are shown in figure 17-15A through E.

ACCUMULATORS

An accumulator is a device sometimes use to store oil under pressure for use when faste than-normal delivery is required. Also, th accumulator absorbs and cushions shocks o surges in the system. Accumulators are sprin or weight loaded, or gas charged.

TUBING

Fluid from the pump is transmitted through pipes, tubing, or flexible hose. These trans mitting lines are strong enough to contain the hydraulic fluid at its working pressure and ac cept higher surges in pressure should they oc cur. Often hydraulic lines contain a pressure as high as 5000 pounds per square inch (34 megapascals).

VALVES

Valves are located in the hydraulic circuit to control the rate of fluid flow, the pressure of the system, or the direction of the fluid flow.

Flow Control Valves

Rate valves, commonly known as flow control valves, operate on valve principles that are rather well known and commonly used in handling many different fluids. Rate valves include gate, plug, globe, and needle valves, figure 17-16. Gate and plug valves are normally ON-OFF valves. They are not suited for use as a throttle since in a partially-opened position they cause excessive turbulence. The globe valve is also normally ON or OFF, but it can be used as a throttle since the liquid flows on all sides of the globe and

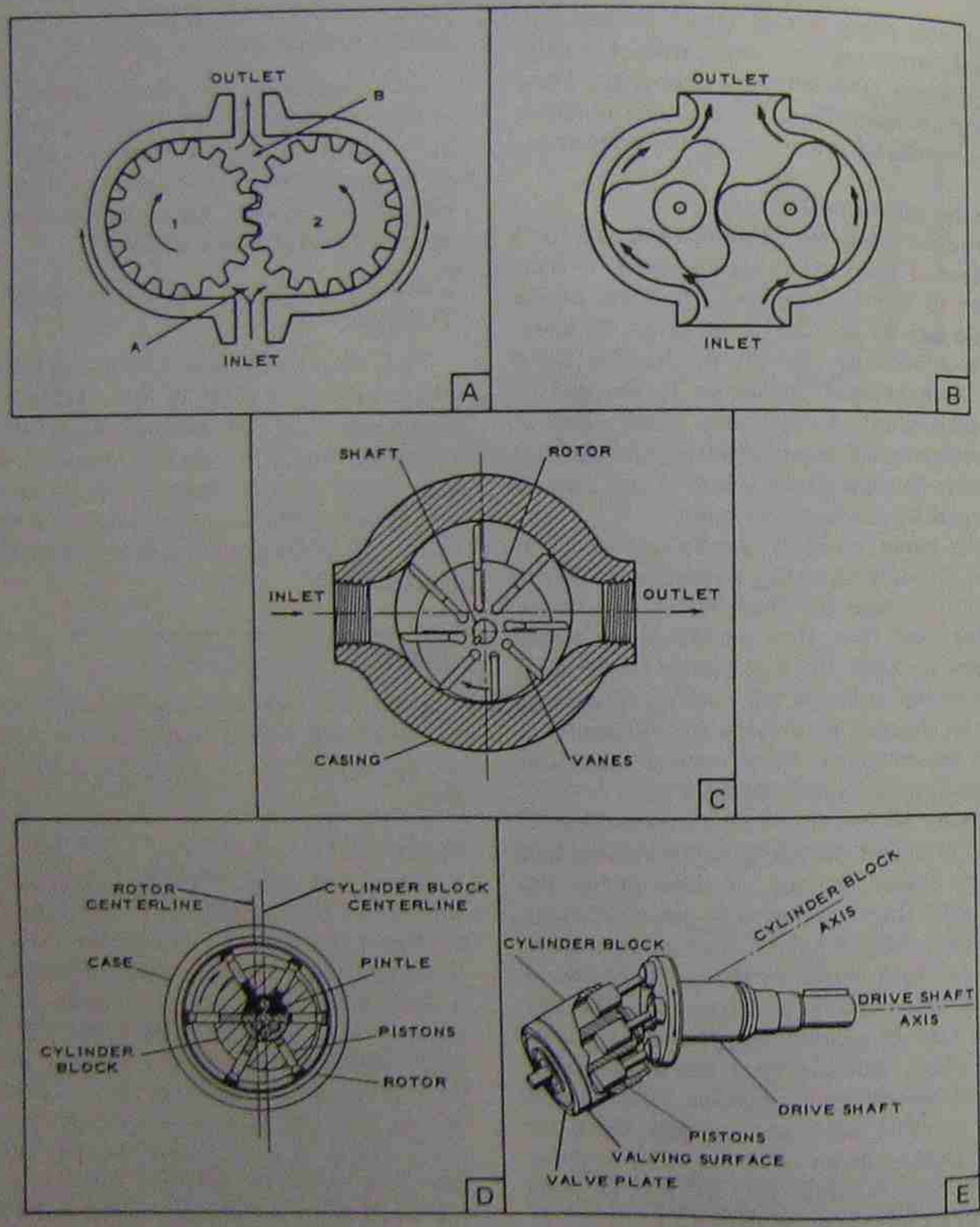


Fig. 17-15 Positive displacement hydraulic pumps: (A) gear pump, (B) lobe pump, (C) vane pump, (D) radial piston pump, and (E) axial piston pump

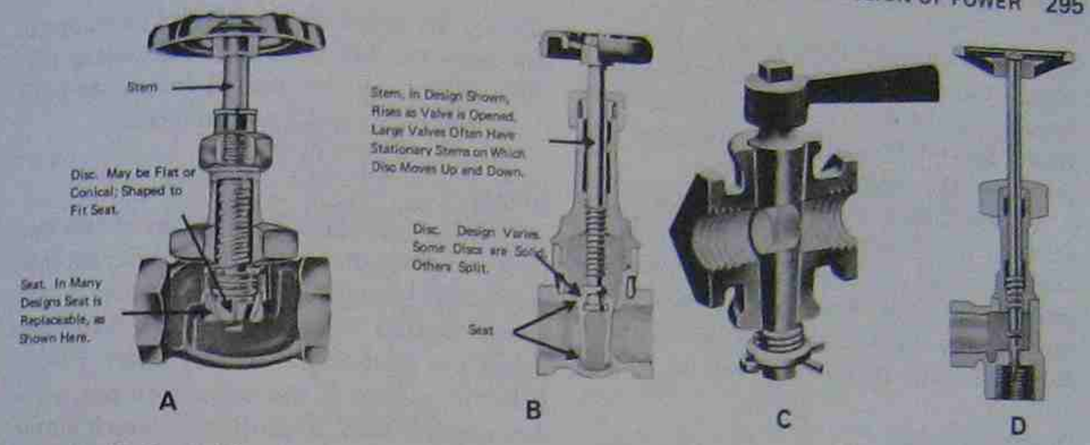
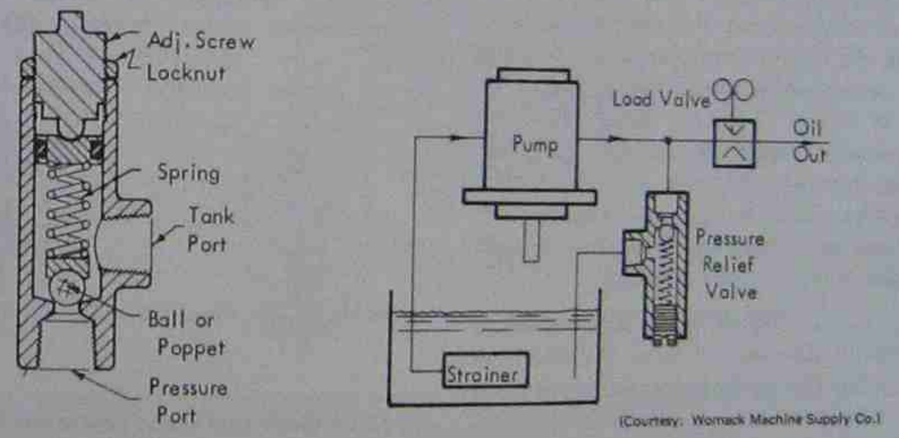


Fig. 17-16 Typical flow control valves: (A) globe valve, (B) gate valve, (C) plug valve, and (D) needle valve



(Courtesy: Womack Machine Supply Co.)

Fig. 17-17 Pressure relief valve and its application

it is more balanced in operation. Needle valves are well suited to vary the amount of flow through small openings.

Pressure-compensated flow control valves accomplish the same basic task as a governor does on an engine. These valves provide a constant pressure and hence a constant speed at the working machine, even though the load on the machine may vary. A spring-loaded piston moves to increase the valve opening when the pressure begins to drop at the discharge side of the valve. The pressure balances the spring to provide a uniform rate of fluid flow.

Relief Valves

Pressure relief valves, figure 17-17, are set to open at a predetermined pressure. They are a safety feature which prevents excessive pressure from building up. They are spring-loaded; the valve is closed when the spring pressure is equal to or greater than the pres-

sure of the hydraulic fluid. At fluid pressures higher than the spring pressure, however, the valve is pushed open and a portion of the fluid is bled off, thereby reducing the force or pressure in the system.

Another type of relief valve is the pressure-reducing valve which allows a branch of the main hydraulic circuit to operate at a lower pressure than the main circuit. These are spring-loaded valves which bleed off fluid to balance the valve at a preset pressure.

Directional Valves

The check valve is perhaps the most common directional valve. This valve permits flow in one direction only. As soon as pressure in the opposite direction is applied, the valve mechanism is forced tightly against its seat. In figure 17-18, the check valve is a spring-loaded piston. If the force of fluid flowing through the valve is stopped, the spring (A) pushes the piston (B) against the valve seat preventing any fluid flow through the valve in the opposite direction.

Spool Valves. Spool valves are designed to control the direction of flow, figures 17-19 and 17-20. The liquid flows around the spool shaft when and where a path is provided. Shifting the spool shaft back and forth opens and closes the various paths. These valves, like many others, can be located in remote positions and be actuated by solenoids.

Motors

The hydraulic fluid now arrives at the motor where hydraulic energy is reconverted into mechanical energy. If linear motion is the desired output of the system, a hydraulic cylinder is used as the motor, figure 17-21. If rotary motion is the desired output, a rotary motor is used. Regardless of which motor is used, its output is converted into power that moves against the work load at the machine. Rotary motors perform the opposite

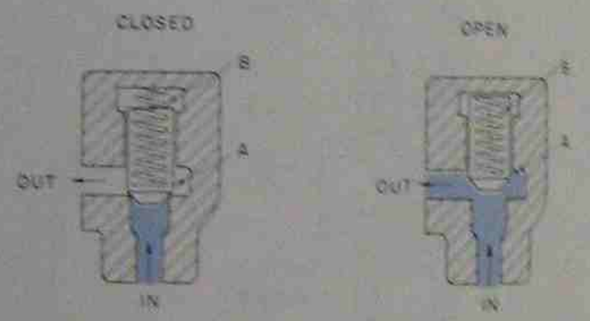


Fig. 17-18 Check valve allows flow in one direction only.

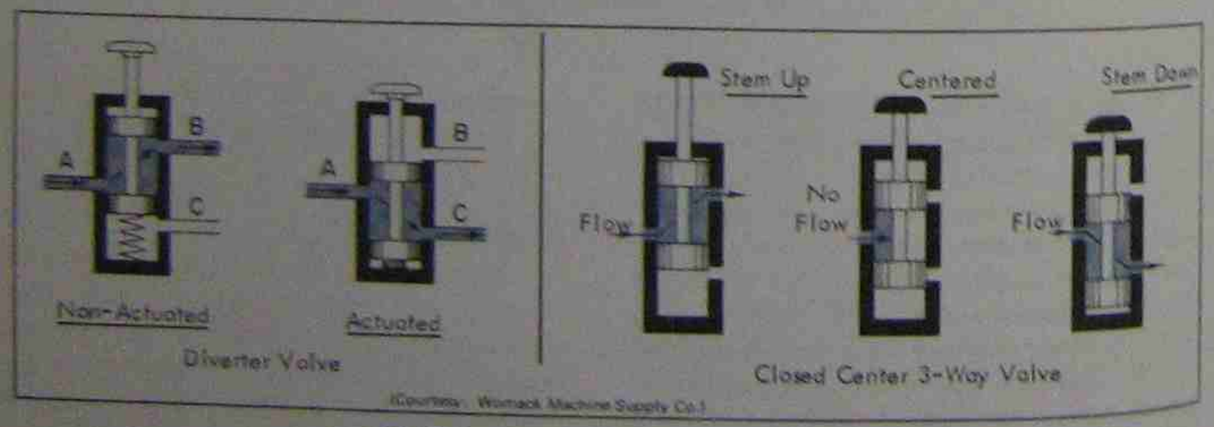


Fig. 17-19 Spool-type valves have many applications.

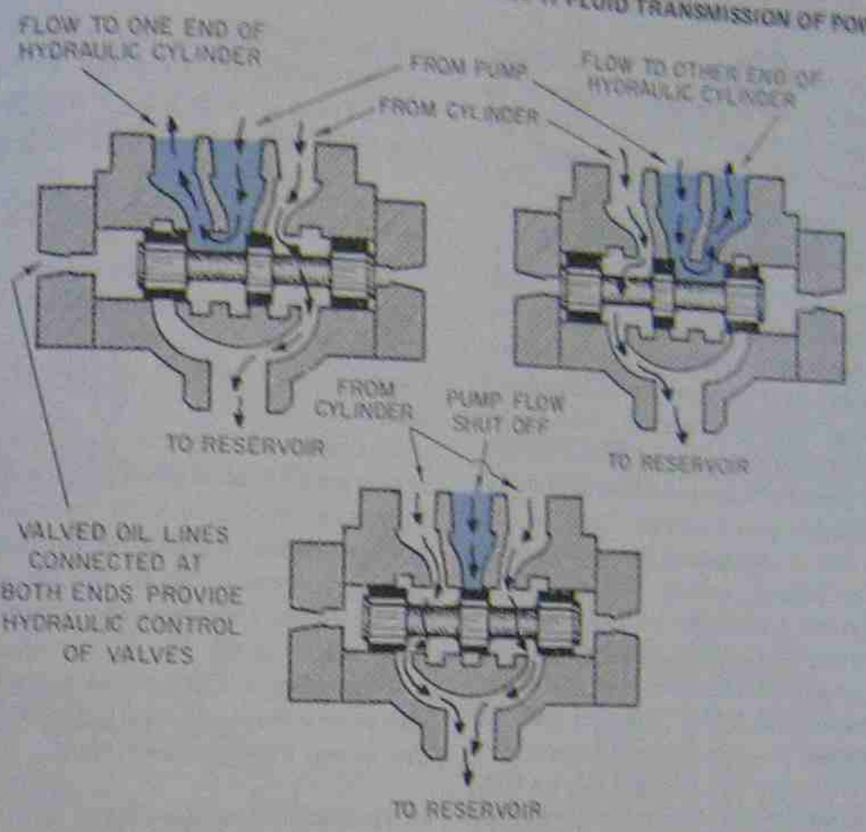


Fig. 17-20 Spool valves are directional valves that provide quick, positive action.

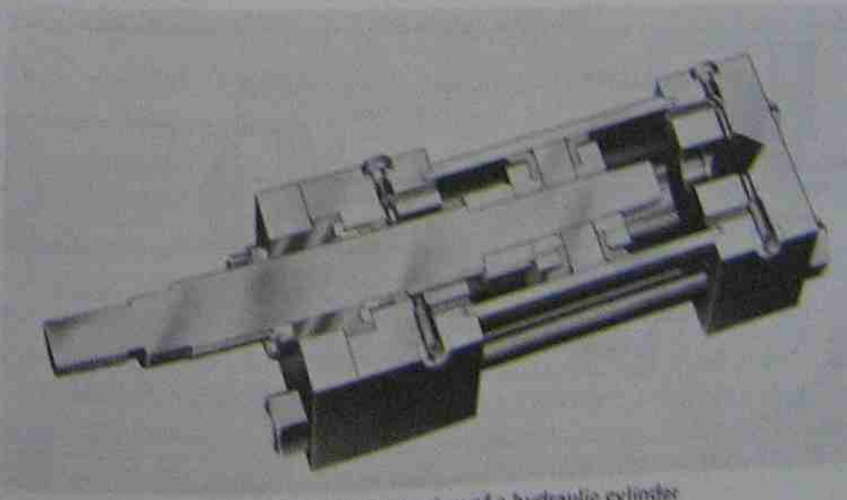


Fig. 17-21 Cutaway view of a hydraulic cylinder.

function of rotary pumps, and, in many cases, pumps can be used as motors with little or no modification. Motors are selected on the basis of the speed and torque that are required.

HYDRAULIC CYLINDER ACTION

In a hydraulic cylinder, figure 17–22, the fluid applies a force in all directions inside the cylinder, but only the piston is free to respond to the force, which it does by sliding down the cylinder. This linear motion of the piston produces work at the machine. When the cylinder has completed its stroke, the fluid direction is changed and hydraulic force on the opposite end of the piston moves the piston back to its original position. The area of the piston face has a lot to do with the speed the piston travels. The choice is speed and long distance, or larger force. As the size of the piston increases, the speed decreases and the force is applied through a shorter distance.

If the efficiency of a cylinder is to be high, it must be well sealed at both the rod and the piston. The development of superior packing and sealing materials was a problem in the hydraulics industry for many years, but modern materials prevent leakage within the cylinder. There are a surprising number of applications for cylinders, figure 17–23.

SUMMARY OF HYDRAULICS

The complete hydraulic system consists of the reservoir, pump, transmission lines, pressure, flow, and directional valves, and motor. Figure 17–24 shows a typical hydraulic system.

Hydraulic circuits are usually drawn with symbols rather than with picture or cutaway-type drawings. Fortunately, hydraulic symbols are standardized throughout the industry. The graphical diagram, figure 17–24, is the usual way to show the hydraulic components and their relationships.

Hydraulics is a large and growing field. It can offer advantages which make it an attractive power transmission system.

- Hydraulics produces linear or rotary motion without the use of gears, chains, or belts which require more maintenance.

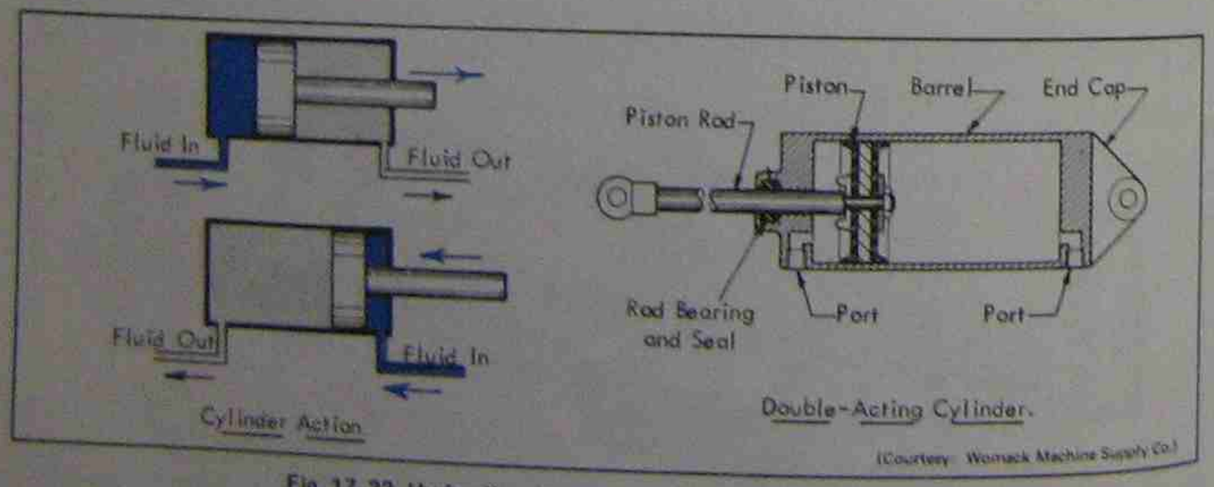
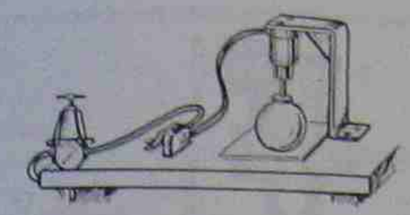
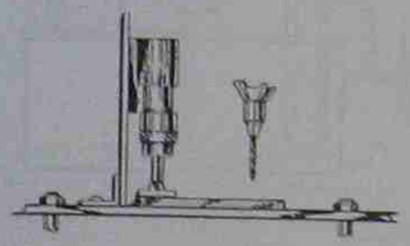


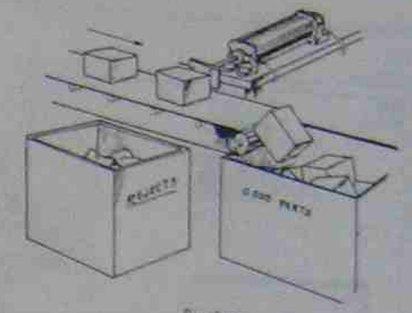
Fig. 17-22 Hydraulic cylinder action and basic construction



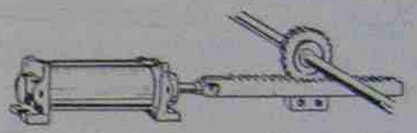
Delicate Parts.



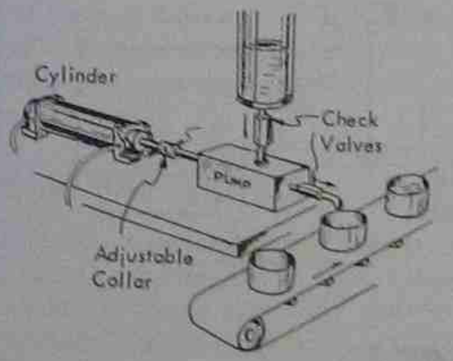
Drill Press Clamp.



Sorting.

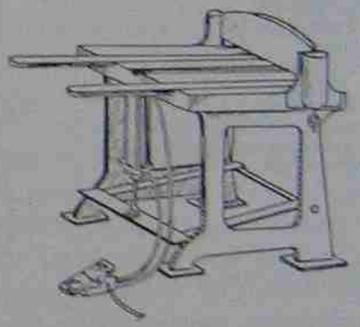


Rack and Pinion.



Metering.

(Courtesy Womack Machine Supply Co.)



Metal Shear.

Fig. 17-23 A few of the many applications for hydraulic cylinders

- Hydraulic components lubricate themselves with hydraulic oil.
- Hydraulic power is flexible. A hydraulic hose can go around corners, flex with the machine motion, or go across the room.
- Hydraulics are capable of exerting forces to fit the need, either tremendous forces or very delicate forces.
- Hydraulic power is smooth. Since hydraulic oil is virtually incompressible, instant power response is possible.

PNEUMATICS

Pneumatics and hydraulics–as mentioned before–are both fluid power systems. Much that has been said about hydraulics also applies to pneumatics. Pneumatics does with gases what hydraulics does with oil to transmit

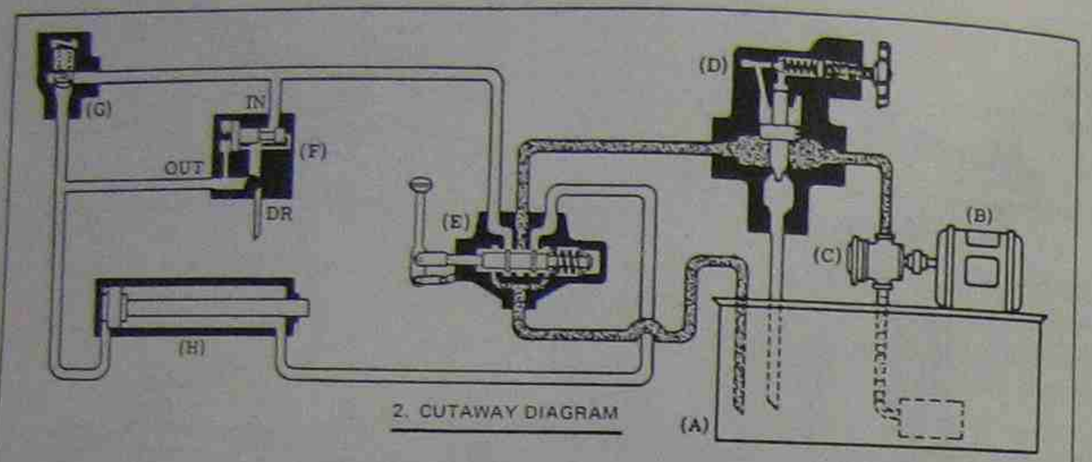


Fig. 17-24 Four types of hydraulic drawings: 1. graphical diagram, 2. cutaway diagram, 3. pictorial diagram, and 4. combination diagram

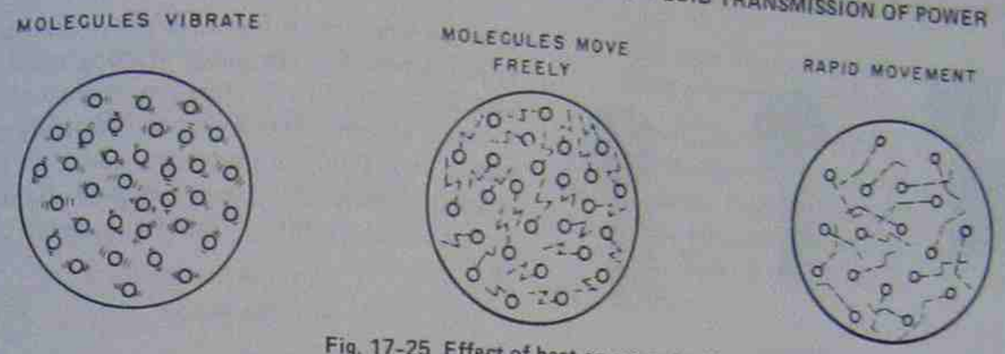


Fig. 17-25 Effect of heat on gas molecules

power from one point to another. The pneumatic system generates the pneumatic force, transmits, and controls the power it receives from the prime mover. Modern pneumatics goes beyond many of the historical applications of gases in motion such as sailboats and windmills because it involves generating and transmitting the gaseous flow within the pneumatic system itself.

LAWS OF PNEUMATICS

Pneumatics is controlled by physical principles just like hydraulics. Pascal's Law, the pressure at any point in a static fluid is the same in every direction and exerts equal force on equal areas, applies to both liquids and gases under pressure. Pneumatics can gain a mechanical advantage just like hydraulics.

The molecules of a gas are far apart and very light. When a gas is heated, molecular activity increases, figure 17-25. Since there is more motion of the molecules, they tend to strike or bump into each other more often. If the gas is in a container, the molecules strike the sides of the container more often and this is seen as an increase in pressure. Temperature has more effect on the expansion of gases than it does on either liquids or solids.

The temperature behavior of gases was observed by Jacques Charles, and his findings resulted in the physical law that bears his name. Charles' Law states that all gases expand and contract in direct proportion to the change in the absolute temperature, provided the pressure is held constant. This means: if the volume is held constant, then the pressure varies in accordance with the temperature, figure 17-26.

Boyle's Law is one of the most common gas laws applied to pneumatics. This law states that "the absolute pressure of a confined body of gas varies inversely as the volume, provided the temperature remains constant." That is to say, double the pressure on a gas and its volume is reduced in half. Quadruple the pressure and the resulting volume is one-fourth

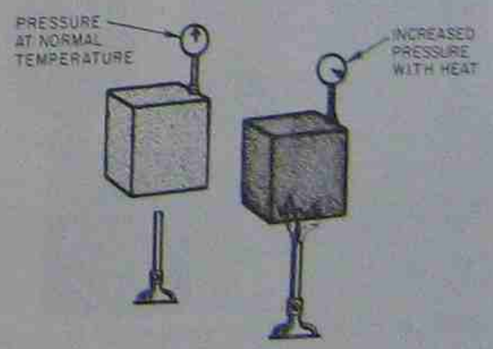


Fig. 17-26 Temperature rise affects movement and pressure.

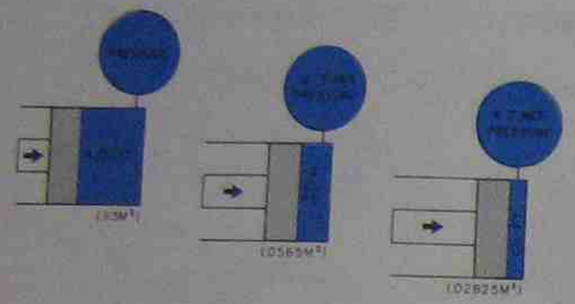


Fig. 17-27 Boyle's Law on the volume of gases

the original volume, figure 17-27. P_1 and V_1 are the original pressure and volume. P_2 and V_2 are the pressure and volume after expansion or compression.

$$P_1 \times V_1 = P_2 \times V_2$$

The formula can also be written as:

$$P_2 = \frac{P_1 \times V_1}{V_2} \quad \text{or} \quad \frac{V_2 = P_1 \times V_1}{P_2}$$

When these formulas are used in actual problems the pressures on the gauges that are in the system must be converted to absolute pressure. Gauges are calibrated at sea level pressure which is 14.7 pounds per square inch (100 kilopascals). The gauge starting point or zero is therefore 14.7 (100) less than absolute pressure of zero. Therefore, 14.7 pounds per square inch (100 kilopascals) is added to the original pressure, P_1, converting it to absolute pressure. For example, find P_2 in figure 17-28.

U.S. Customary

$$P_1 \times V_1 = P_2 \times V_2$$

$$P_2 = \frac{P_1 \times V_1}{V_2}$$

$$P_2 = \frac{(15 \text{ psi} = 14.7 \text{ psi}) \times 5 \text{ cu ft}}{1 \text{ cu ft}}$$

$$P_2 = \frac{29.7 \times 5}{1} = 148.5 \text{ psi}$$

$$\begin{array}{r} \text{Absolute} = 148.5 \text{ psi} \\ -\ 14.7 \\ \hline 133.8 \text{ psi} \end{array}$$

P_2 = 133.8 psi gauge pressure

Metric

$$P_1 \times V_1 = P_2 \times V_2$$

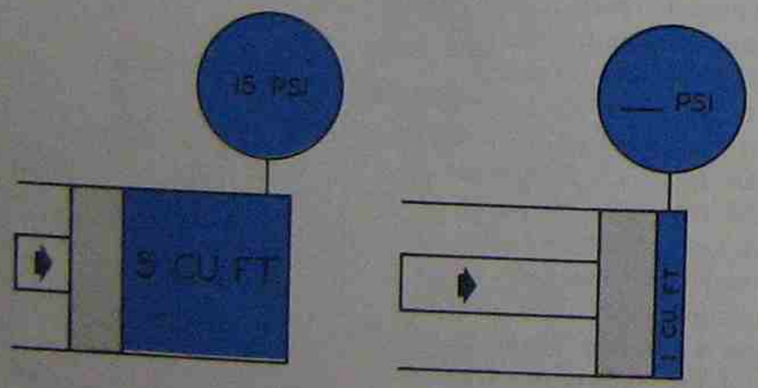


Fig. 17-28 A problem in volume and pressure

$$P_2 = \frac{P_1 \times V_1}{V_2}$$

$$P_2 = \frac{(102 \text{ kPa} = 100 \text{ kPa}) \times 0.14 \text{ c}^3}{0.028 \text{ c}^3}$$

$$P_2 = \frac{28.28}{0.028} = 1010 \text{ kPa}$$

$$\begin{array}{r} \text{Absolute} = 1010 \text{ kPa} \\ -\ 100 \\ \hline 910 \text{ kPa} \end{array}$$

P_2 = 910 kPa gauge pressure

The same parts are required in a pneumatic system that are required in a hydraulic system. The main difference is that the transmitting media, a gas, is not rigid like a column of confined oil. However, under pressure and in motion, gas can exert a force and produce work.

PNEUMATIC COMPONENTS

Physical laws govern the design of the parts that make up a pneumatic system which must have these components:

- pump or compressor to supply pressurized gas.
- receiver, storage cylinder, air cylinder, or air bottle to act as a reservoir for the pressurized gas.
- actuators.
- dryers.
- hoses or pipes to channel the air.
- valves to control pressure and direction of flow.
- motor which is acted on by the pneumatic fluid, converting pneumatic power back into mechanical power for use by the mechanism or machine.

Some of the components of a pneumatic system are identical to hydraulic components. Nearly all are similar in their construction and operation. They are just designed to handle a different type of fluid, figures 17-29 and 17-30.

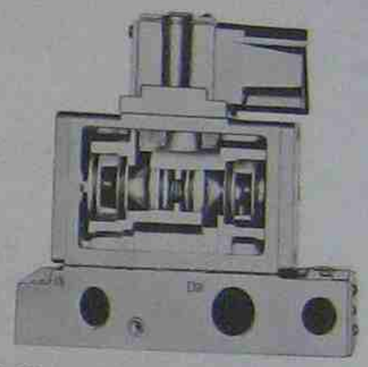


Fig. 17-29 A piston poppet pressure-actuated air valve

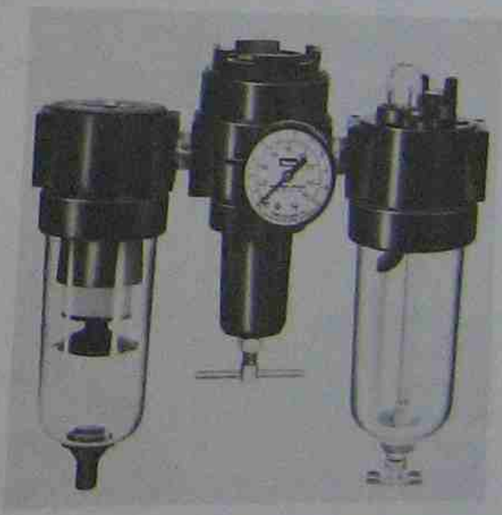


Fig. 17-30 A three-way unit for filtering air, lubricating air, and regulating the air pressure

Compressors

Air compressors are driven by an electric motor or by a prime mover. Compressors are centrifugal, rotary, or reciprocating types, figure 17–31. Air compressors often build up their final pressure over a series of stages, figure 17–32. For example, in a three-stage reciprocating air compressor, the air travels successively through three cylinders before it arrives at the air receiver or reservoir. The size of the cylinders and the piston displacement is progressively reduced as the volume decreases and the pressure increases. Special attention is given to the lubrication of the parts of all air compressors. Many of the same techniques used in reciprocating internal combustion engines are used, such as splash oil systems and oil pumps.

Compressing air creates heat, and a certain portion of the heat is carried away to prevent damage to the compressor. Air cooling, water cooling, or oil cooling systems are used.

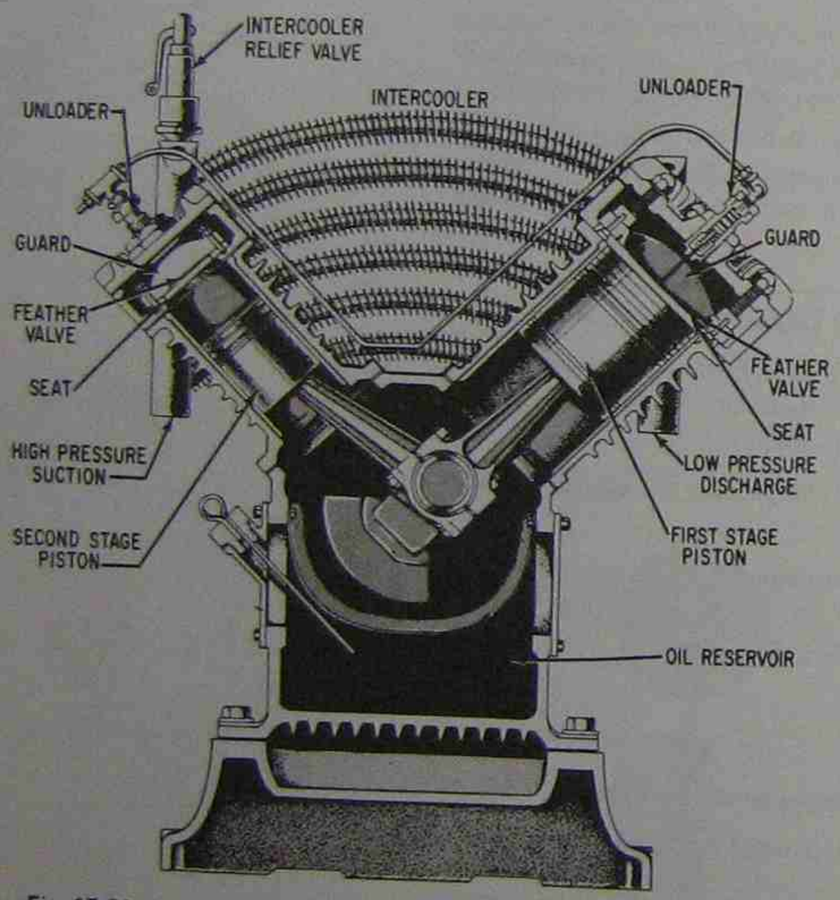


Fig. 17-31 A simple two-stage reciprocating low-pressure air compressor

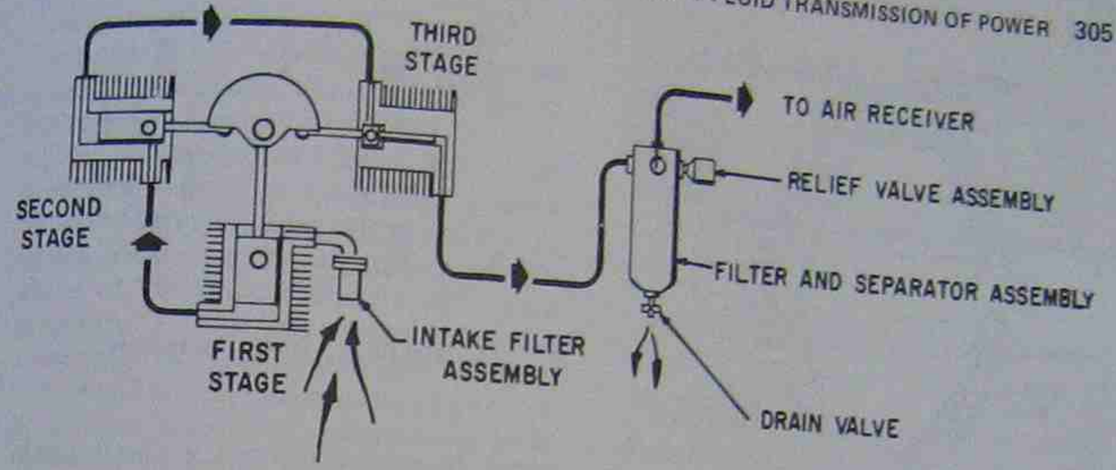


Fig. 17-32 Air compressor assembly

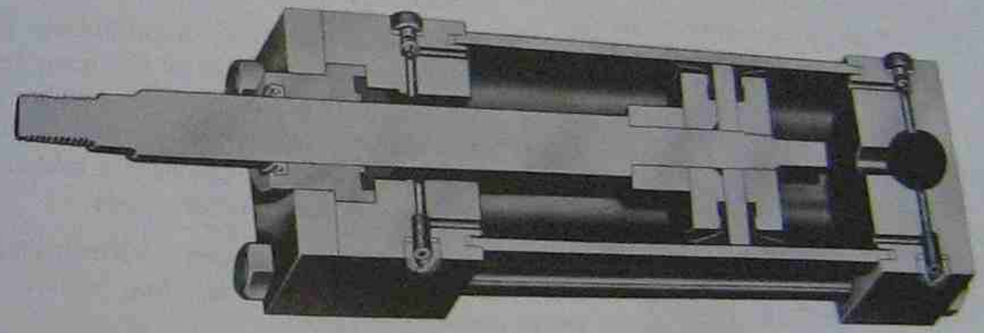


Fig. 17-33 Air cylinders are very similar to hydraulic cylinders.

Air Cylinders

Motors use the compressed gas to apply force to the machine and its work load. Air cylinders are very similar to hydraulic cylinders, figure 17–33. They are single-acting, double-acting, or telescoping cylinders. The double-acting cylinder is the most common. Air is directed to either side of the piston, giving power alternately in each direction.

Turbine Motors

If rotary motion is the desired output of the pneumatic system, a turbine motor is usually employed. Jets of air are directed against the turbine blades. The construction principles are much the same as those found in steam turbines or gas turbines, but usually the application is much smaller and lighter. Both single stage and multiple stage turbines

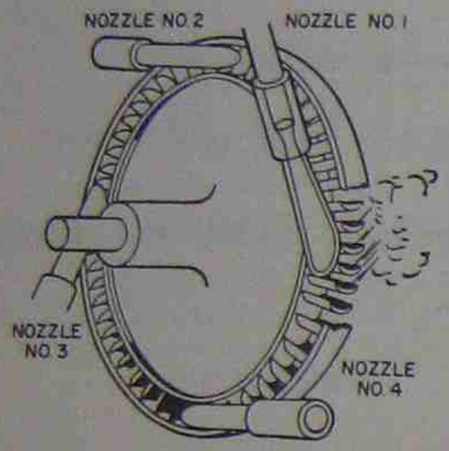


Fig. 17-34 Single-stage turbine

are used, figures 17–34 and 17–35.

Another turbine is the pinwheel turbine which is simply jet action applied to pneumatics. Its action is like that of a lawn sprinkler, figure 17–36.

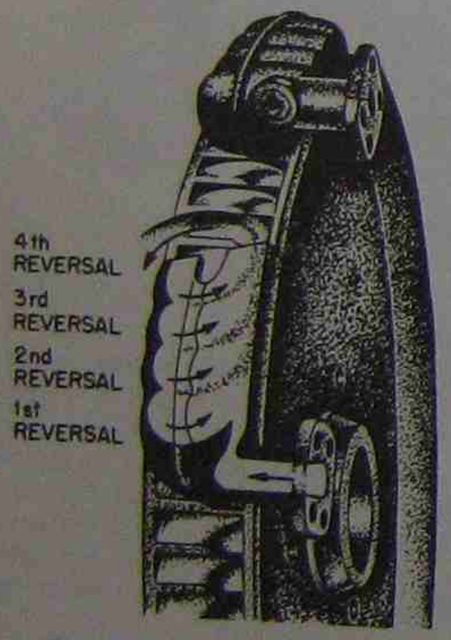


Fig. 17-35 Multiple-stage air turbine

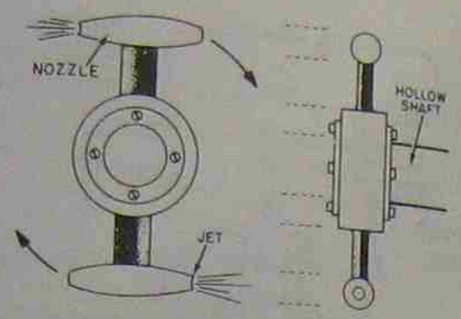


Fig. 17-36 Pinwheel air turbine

SUMMARY

Pneumatics has many applications. Most persons can identify some of the many pneumatic applications, such as air hammers or compressed air tools used in manufacturing operations, but these are only a few of the many modern uses. Others include:

- Tools such as grinders, buffers, sanders, drills, screwdrivers, nut setters, and wrenches
- Air hoists
- Rivet, chipping, and sand hammers
- Clamping devices
- Blast cleaning
- Spraying
- Air control circuits
- Pneumatic systems as backup or emergency systems for hydraulic systems
- Air gauging
- Pneumatic conveying of materials

Vacuum Applications

Another phase of fluid power involves vacuum applications. Vacuum is just the opposite of fluid under pressure. It is fluid, usually air, removed from a space. Vacuum applications depend on atmospheric pressure. Simple vacuum principles can be seen in a collapsing soda straw. Reducing pressure on the inside of the straw allows the atmospheric pressure of 14.7 pounds per square inch (100 kilopascals) to push in and collapse the straw.

Atmospheric pressure working against areas of very low pressure or partial vacuum can be used to clamp and lift materials, figure 17–37. Vacuum cups can lock on to any smooth surface.

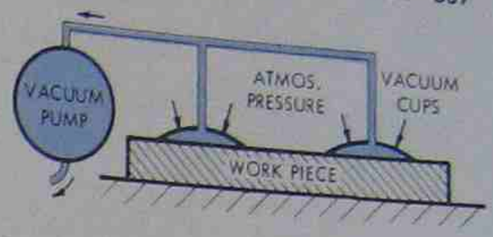


Fig. 17-37 Lifting concrete by vacuum clamping

The vacuum forming of pliable plastic sheets is another application. A vacuum pump produces the low pressures that are necessary to put this principle to work, figure 17–38.

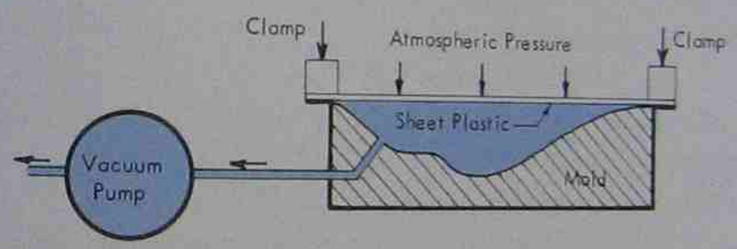


Fig. 17-38 Vacuum molding of plastic

REVIEW QUESTIONS

1. Explain several ways in which fluid power has been used throughout history.
2. Define the term hydraulics.
3. Define the term pneumatics.
4. What can be said about the compressibility of liquids?
5. The hydrostatic principle tells us that $P_1 = P_2 = F/A = Y/B$, assuming no pressure deviation. If A = 1 square inch (6.45 square centimeter), F = 1 pound (.45 kilogram), and B = 10 square inches (64.5 square centimeter), what is "Y", in figure 17-39?

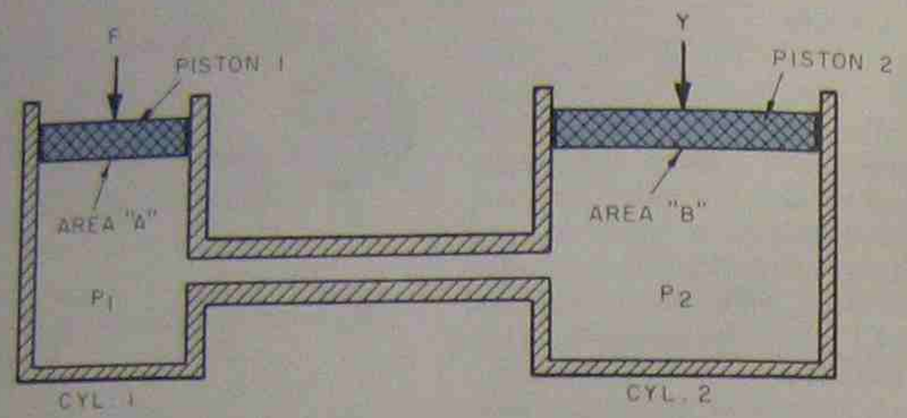


Fig. 17-39

6. How can the mechanical advantage possibilities of hydraulics be compared to that of a lever?
7. What can cause excessive friction on fluids flowing in hoses or pipes?
8. What effect does turbulence have on the efficiency of fluid dynamics?
9. What does Bernoulli's principle deal with?
10. List several common, everyday applications for hydraulic systems.
11. List the basic components of a typical hydraulic system.
12. Why are filters of particular importance to a hydraulic system?
13. What is the basic difference between a positive displacement pump and a non-positive displacement pump?
14. What three purposes can valves be designed to satisfy?
15. What hydraulic device is used to provide rotary hydraulic power at the load?
16. List several applications for hydraulic cylinders.
17. List several advantages that the field of hydraulics can offer.
18. Why does an increase in temperature have more of an effect on the pressure within a pneumatic system than it does in a hydraulic system?
19. State Boyle's Law in a brief, basic form.
20. What basic components are necessary for a pneumatic system?
21. Prepare a list of several modern uses for a pneumatic device.

SECTION 7 ALTERNATIVE ENERGY SOURCES

Unit 18 Solar Energy

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the role of government in developing alternative energy sources.
- Briefly explain the operation of a solar collector.
- Explain how solar heat can be stored.
- Explain the term passive solar heating.

INTRODUCTION

Until the 1880s, the main energy source was wood. Coal took over during the early 1900s. In the 1950s the United States was using more oil than coal. Today, oil and natural gas are used in about equal amounts. At present 95% of the energy the United States uses comes from fossil fuels: coal, oil, and natural gas. For millions of years the deposits of fossil fuels have been built up by the photosynthesis in plants as the sun's energy has been converted into plant growth.

For generations fossil fuels have been used at an ever-increasing rate as our culture became more industrialized. People have surrounded themselves with countless energy demanding devices and machines. The energy has been cheap and abundant and, because of this, has been used wastefully. Recent history, however, including alarming political developments in the Middle East and oil shortages have convinced many that, unless solutions and alternative energy sources are developed, increasing fuel shortages and higher prices are certain.

Development of other energy sources provides alternatives to fossil fuels. Some alterna-

tive energy sources are new; some are quite old and time tested, while some have been discarded in favor of cheap, convenient fossil fuels. This section discusses the most significant of these energy sources.

- Solar (Unit 18)
- Wind (Unit 19)
- Hydroelectric (Unit 20)
- Biomass (Unit 21)
- Geothermal, Wood, Tidal (Unit 22)
- Nuclear (Unit 24)
- Direct Conversion (Unit 25)

At present it is not expected that all of the alternative energy sources can solve the energy crisis. The solution will come from (1) the intelligent conservation and use of present fossil fuel reserves, (2) increasing the efficiency of engines and other prime movers, (3) changing life-styles to reduce consumption, and (4) increasing the use of alternative energy sources. All four of these elements are needed to bring energy demands in line with the energy available.

Government research activities are being directed by the Energy Research and Development Administration (ERDA). In 1975 the Atomic Energy Commission was abolished and replaced by two new agencies, the Nuclear Regulatory Commission and the Energy Research and Development Administration. ERDA's mission is to do research and development in nuclear and other fields of energy. Its goal is to make the nation self-sufficient in energy while protecting the environment and the public welfare. Currently ERDA is giving its highest priority to energy conservation.

SOLAR ENERGY

The sun has poured its energy upon the earth day in and day out for millions of years. The existence of fossil fuels is traced to the sun. The wind, tides, running water, wood, and plant life are also created by the sun's energy. It is predicted that the sun will continue to send its radiant energy to the earth for another four billion years. For all practical purposes, the sun is an ever-present, renewable, free source of energy.

This massive amount of energy can be used for heating and cooling as seen in figure 18-1. It has been estimated that an average of 1400 Btus (British thermal units) per square foot (16 megajoules per square meter) falls on the United States every day. Recall that a Btu is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit. Take that 1400 Btus per square foot, look at the area of the solar collectors in the figure, and it's easy to see that there is a lot of energy that is being trapped by those collectors instead of being wasted. It also makes it easy to understand why solar heat is an important alternative energy source because it conserves fossil fuels. About 20% of the total energy used in the United States is for residential heating, cooling, and hot water. A 20% energy savings is an enormous amount to consider.

The use of solar heating does present problems, however. The problems of cloudy days, night, and seasonal changes are basically solved by storing the extra heat during the day for use at night and cloudy periods.

The sun's radiant energy is collected and transferred in the form of heat through air or water. The water is stored in large water tanks, figure 18-2. The heated air is

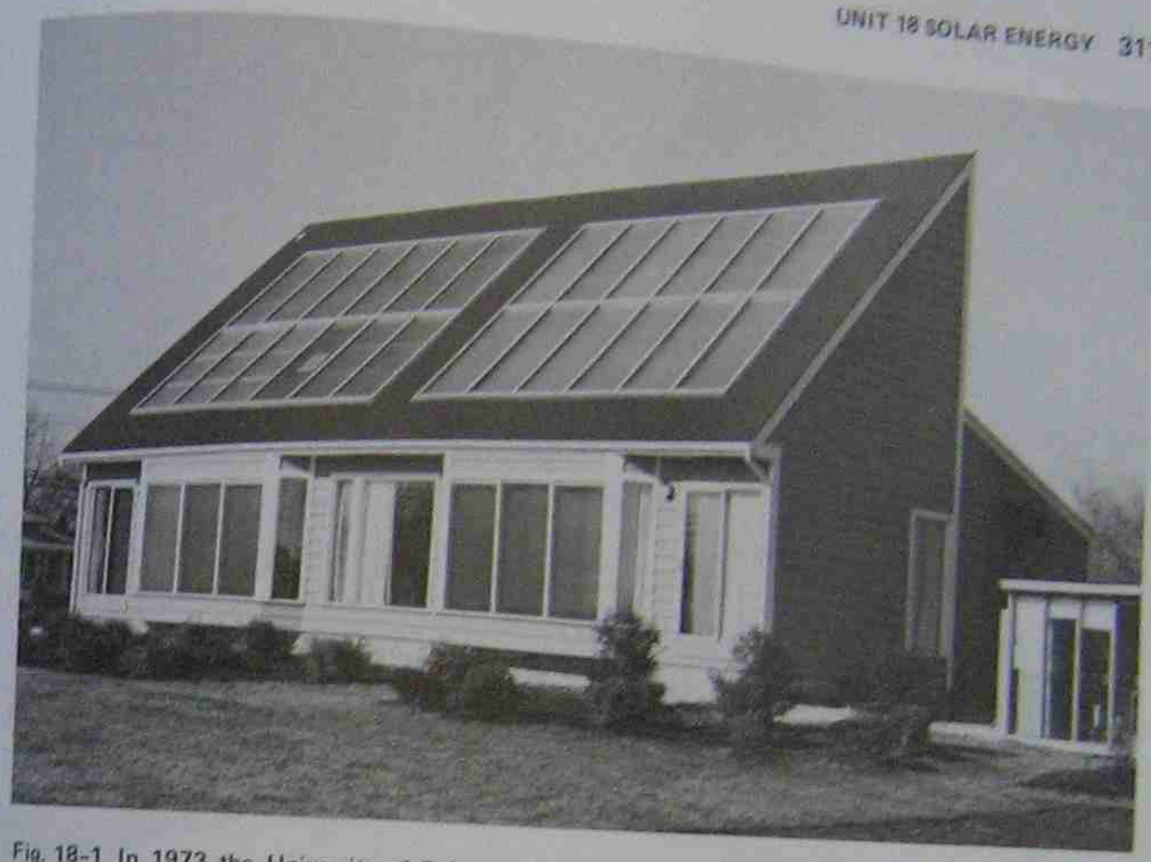


Fig. 18-1 In 1973 the University of Delaware built this house to experiment with active and passive solar systems. Hot air collectors, some containing experimental cadmium solar cells, were integrated into the roof and south walls; phase change storage for both heating and cooling was located in the basement. Research was continued in the house for about a decade.

stored in a container filled with fist-sized rocks. The stored heat energy is returned to the living spaces when needed by hot-water heating or through the rocks by a forced-air heating system. For very cold or extended cloudy periods, a backup heating system is provided.

A basic solar collector consists of window glass, a black metal panel, and insulation, figure 18-3. The principle of operation is commonly called the greenhouse effect. Ordinary glass allows the short wavelengths of visible sunlight to pass through. When they are absorbed by the collector panel, the sunlight changes to longer wavelength heat waves which do not pass back through the glass. The collector panel is metallic and coated with black paint to help gather the heat. If a water system is used, tubes or pipes are bonded to the collector panel where water flowing through the system picks up the heat. On air systems the collector is corrugated to increase the collecting area. Insulation under the

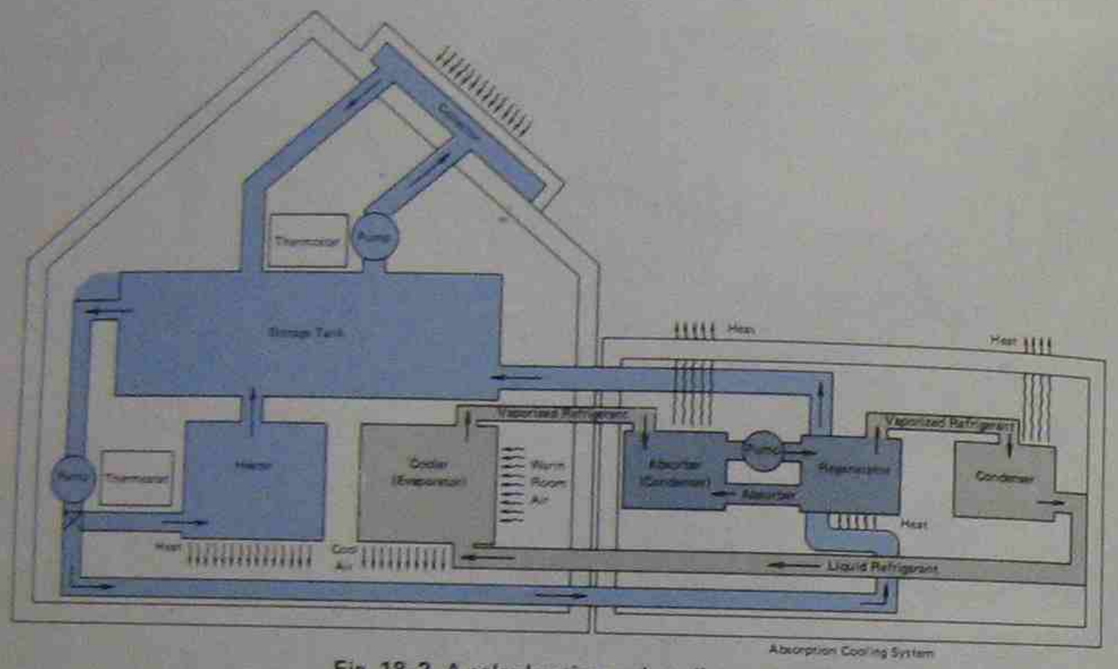


Fig. 18–2 A solar heating and cooling system

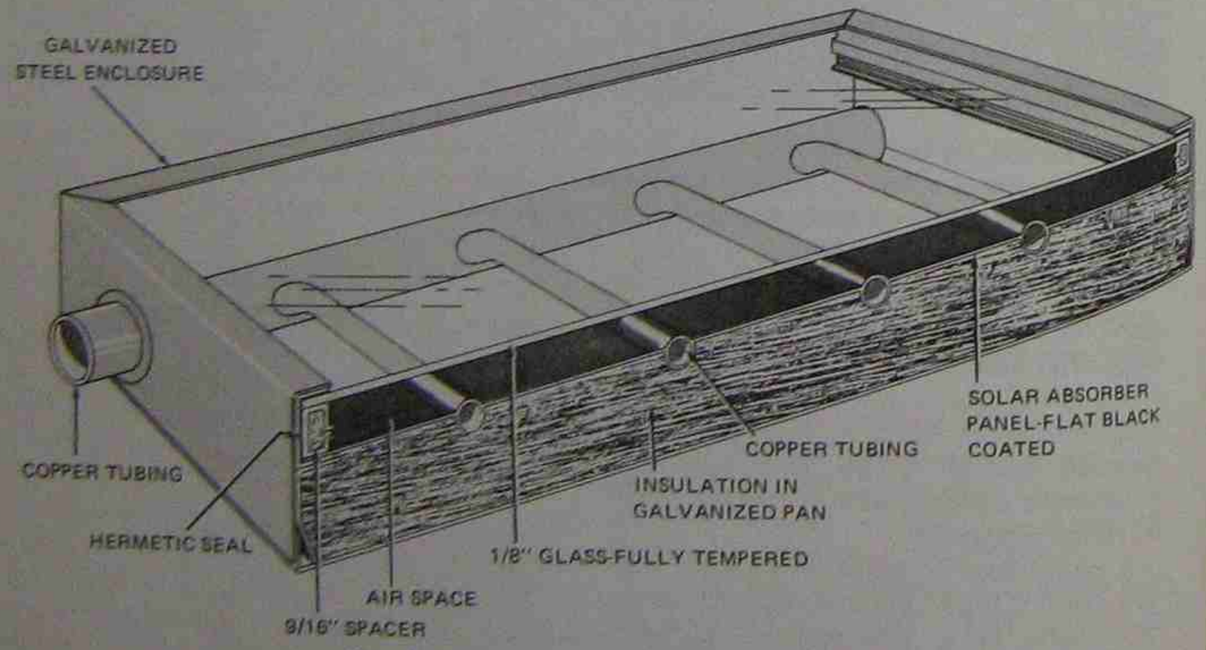


Fig. 18–3 A commercially-made solar collector

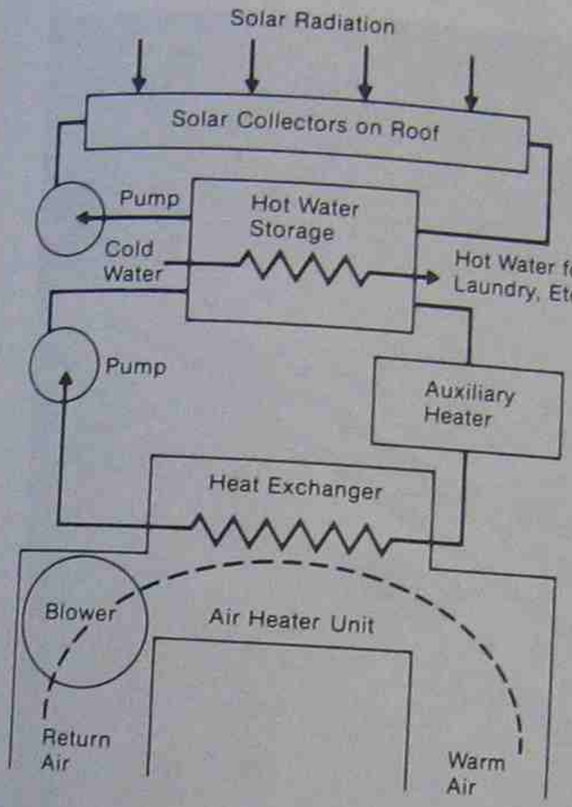


Fig. 18–4 Major elements of solar heating concept

collecting panel prevents heat loss. The collecting panel can reach a temperature of 300°F (149°C) with this simple but effective system.

The collected heat can be stored in a large water tank, perhaps 2000 gallons (7570 liters) or more. One cubic foot (0.028 cubic meter) of water stores 62.4 Btu's of heat for each degree Fahrenheit (0.47° Celsius) above the desired room temperature. This heat can be returned to the living area as needed, figure 18–4. If rock storage is used, the rock size must allow air to be blown through the system of rocks, but rocks are not as effective as water in absorbing heat. Therefore a large amount must be used, 25 to 50 tons (22½ to 45 metric tons). This is often stored in the basement of the building to be heated. Of course, using air and rock storage does have the advantage of being free of plumbing and freezing problems. Certain salts are even better for holding heat. Glaubers salt, sodium sulfate decohydrate, is being carefully tested. Five tons can store heat equal to 25 tons (22½ metric tons) of water or 125 tons (112½ metric tons) of rock.

Many solar heated homes are operating today, although they are far from being common. It is difficult, but not impossible, to convert a conventional older home into a solar home; a group of solar collectors as large as a billboard must face the south and be elevated at the angle of latitude plus approximately 10°.

In the future it is possible that the largest users of solar heating will be public, industrial, and commercial buildings. The school shown in figure 18–5 is a large scale solar heating and cooling installation. It is designed to provide 60 percent of the energy requirements and 80 percent of the hot water.

Solar cooling uses the absorption-refrigeration method, figure 18–6. This is the same principle that refrigerators use. Ammonia is the refrigerant and water is the absorber. Evaporating ammonia picks up heat and the water easily picks up the ammonia. The heat indoors is thereby absorbed. Solar heated water is used to boil off or vaporize the ammonia from the heated water absorber. The ammonia is then condensed and returned to the system to again evaporate and pick up the heat from inside the house.

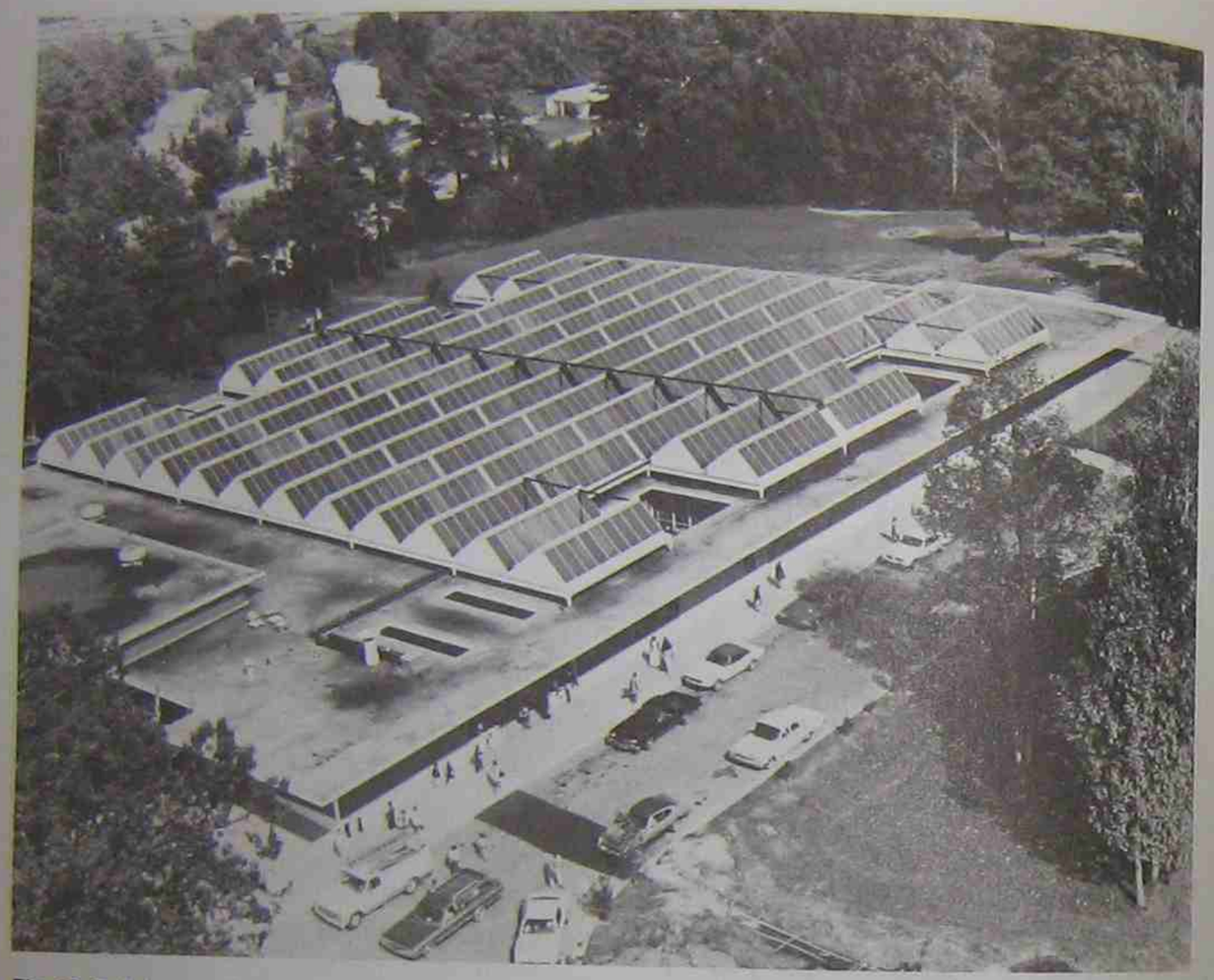


Fig. 18-5 A large scale solar heating and cooling installation at the George A. Towns Elementary School in Atlanta, Georgia (Courtesy Westinghouse Electric)

PASSIVE SOLAR SYSTEMS

Passive solar heating systems are the most simple. They consist of a home designed to make the most of the solar energy striking the building. They are not mechanical in nature; pumps and fans are not used. Simply having a large amount of window area facing the winter sun will help to heat the living area through the greenhouse effect. When the amount of overhang of the roof is correct the low angle of the winter sun will permit the sun's rays to strike the windows while the overhang will shade the windows during the summer when the sun is higher in the sky. Passive solar heating usually involves the extensive use of

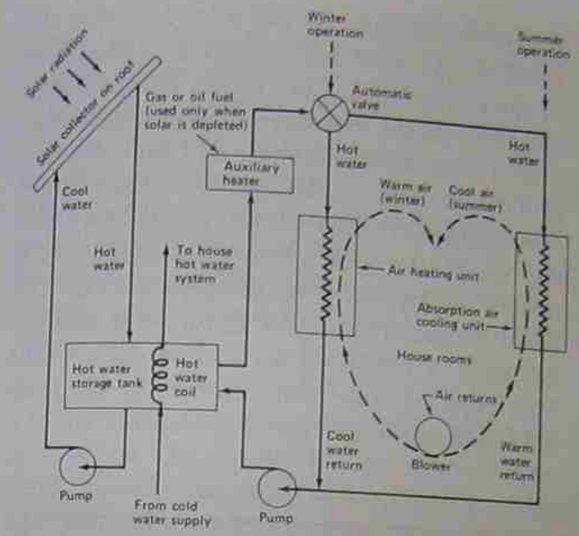


Fig. 18-6 A system that uses solar energy for heating and cooling

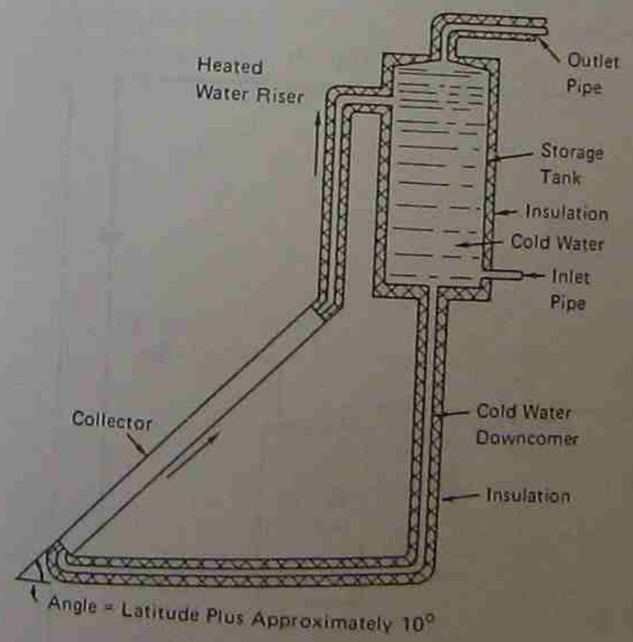


Fig. 18-7 Thermosyphon solar water heater



Fig. 18-8 The "Sun Shower" for campers is made of clear plastic on one side and black plastic on the other. When placed in the sun with the clear side up for a few hours, water will be heated enough for a comfortable shower. (Courtesy Basic Designs Inc.)

brick and stone inside the home. The materials will absorb a good deal of heat during the day and then slowly release the heat during the evening. Large drums of water can also be used to store heat during the day. Most passive solar heating techniques are built into the home at the time of construction.

A passive solar water heater is small and simple. The most common heater operates on the thermosyphon principle, figure 18–7. It consists of a solar collector, an insulated storage tank mounted above the collector, a heated water riser pipe, and a cold-water downcommer pipe. As the solar rays heat the water in the collector, it rises up the system to the storage tank. Cool water, being heavier, moves from the bottom of the storage tank, through the downcommer, and into the bottom of the collector. Using this method, about 40 to 50 gallons (150 to 190 liters) of water a day are heated with a 4 by 8 foot (1.2 by 2.4 meter) collector. The temperature of the water reaches 165°F (74°C) on a hot summer day or 115°F (46°C) on a cold winter day. This type of solar water heater is ideal for mild climates where freezing weather is not a problem. The system can be simplified, as in figure 18–8 or made more complex for better control, figure 18–9.

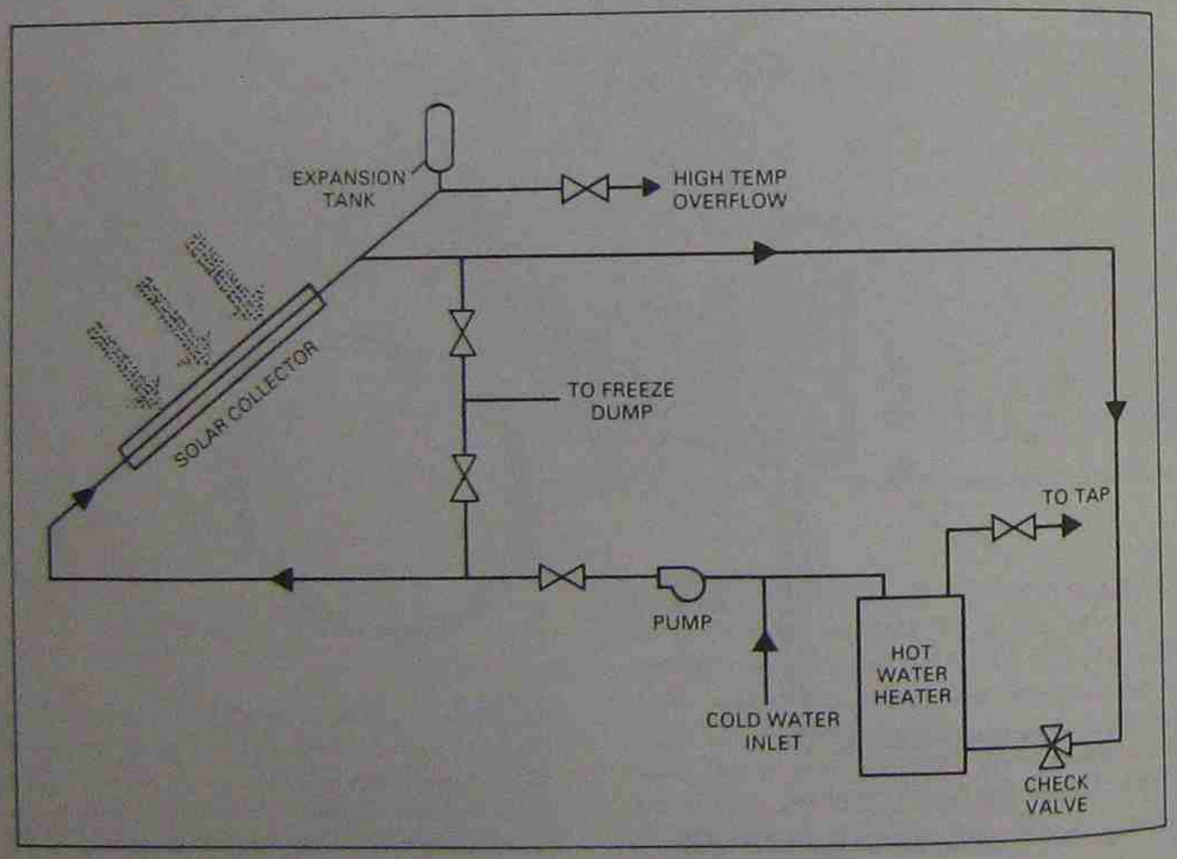


Fig. 18–9 Solar hot water heater using a pump to circulate the water

Solar cooking is an old idea that has been used for years in areas where the sun is dependable and fuel is scarce. A solar oven is little more than an insulated box with a hinged double glass top. The inside of the box is lined with aluminum foil to reduce heat loss. Cooking is done in a blackened pot to help absorb the heat. A solar oven can reach a temperature of 400°F (204°C).

Reflector-type solar cookers use a parabolic reflector to concentrate the sun's rays at one point, usually the grill that supports a pot. The parabolic reflector must face the sun; some solar cookers can automatically turn to follow the direction of the sun as it moves across the sky. Concentrating collectors represent a safety hazard to the eyes and also a burning hazard.

On a large scale, the sun's rays are reflected by mirrors to a central receiving point, figures 18–10 and 18–11. The heat received boils the water, producing steam for mechanical work or the generation of electricity. In the sunny southwest it is estimated that 10 square miles (26 square kilometers) of solar reflectors could operate a 1,340,000 horsepower (1000 megawatt) power plant. If such a plant were working at 60 percent capacity, it could supply the needs of a city of one million people. Building costs would be high, but the fuel would be free. A five-megawatt solar thermal installation is now under construction at ERDA's Sandia laboratories in New Mexico. A megawatt is one million watts, or the equal of 10,000, one-hundred watt light bulbs.

Solar cells convert solar energy directly into electricity when light falls onto their silicon surface. These solar cells are used in nearly all of our space vehicles. They are very dependenable, but at this time too expensive to compete with other sources of electricity. Solar cells and batteries are discussed in Unit 24.

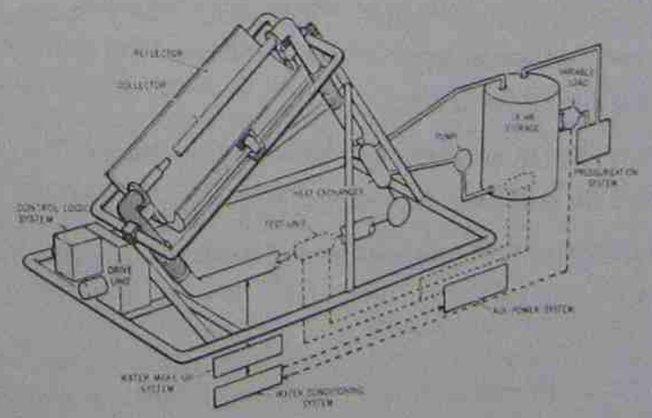


Fig. 18-10 Curved metal plates on the collector cause the sun's rays to focus on a glass collecting tube in which water or other fluid is flowing.

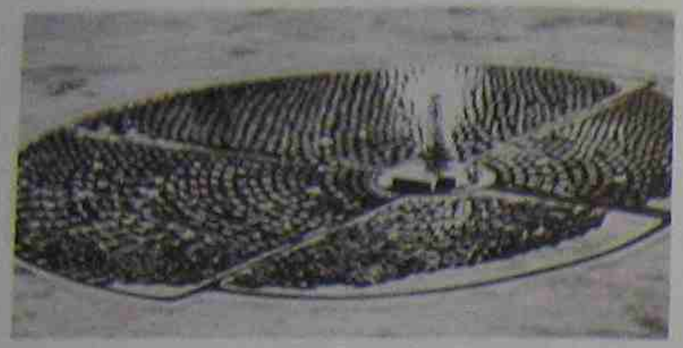


Fig. 18-11 Large solar farm collector system (Courtesy Olympic Resource Management)

REVIEW QUESTIONS

1. How is the sun used as the source of 95 percent of our energy?
2. Discuss how people have been wasteful with energy.
3. Will fossil fuel ever run out? Explain.
4. Discuss how changing a person's life style can conserve energy.
5. What government agency is responsible for developing alternative energy sources?
6. Solar energy is most likely to be used for what purposes?
7. What are the three main parts of a solar collector?
8. Discuss the greenhouse effect.
9. How can heat be stored in a solar home heating system?
10. Explain the principle of the thermosyphon water heater.
11. Is it possible to cook with solar energy? Explain.
12. What is a solar cell?

Unit 19 Wind Energy

OBJECTIVES After completing this unit, the student should be able to:

- Explain the problems associated with wind energy.
- Discuss the potential for using wind energy.
- Describe the conditions necessary for the successful operation of a wind turbine.

The topic of wind energy brings to mind the days of sailing ships and windmills. The vision of old Dutch windmills for pumping water and grinding grain usually comes to mind—part of the lifestyle of another country—but windmills were once on virtually every farm in the United States. Six million windmills were in operation, and even today it is estimated that there are still 150,000 working.

These windmills had metal fan blades of 12 to 16 feet (3.6 to 4.9 meters) in diameter and could develop about 1/6th horsepower (124 watts) in a 15 miles per hour (24 kilometers per hour) wind. Such windmills were commonly used for pumping water and for generating electricity. Their DC output was sometimes used to charge batteries. Special wind generators were also developed. At one time more than 300 companies were producing generators to power radios and electrical devices.

The Rural Electrification Administration strung wires and brought electricity to most United States farms in the 1930s. This convenient energy from a central power plant caused the windmill to temporarily lose its importance as a source of power.

Today the energy of the wind is an almost unlimited, untapped resource. It is calculated that the energy of the winds blowing across the continental United States is twenty-eight times greater than the estimated total power needs of 1986. But the trememdous potential of wind energy is not easy to use. Storage of the wind generator output is often necessary, figure 19-1. Sometimes there is too little wind blowing to be productive, and, on occasion, the wind blows with destructive force; contrary to much popular belief, with wind energy, more is *not* better.

Winds come from the uneven heating of the earth's surface, figure 19-2. Usually the land heats more rapidly than the water. As the warm air rises, the cool air from the water moves in under it as an on-shore breeze. In the evening, the land cools more quickly than the water, and breezes move from the land to the water. Mountain and valley breezes occur when hot air travels up the mountain slopes during the day, and cool air travels back down the mountainside at night. The prevailing winds are created by the cool polar air moving toward the equator, and the heated equatorial air rising to the upper atmosphere and moving toward the poles.

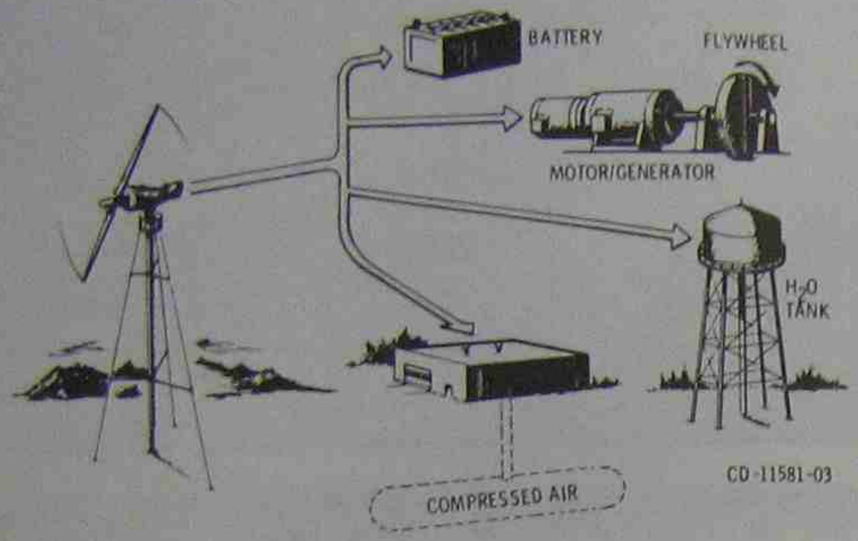


Fig. 19-1 How wind energy might be stored

To operate a wind generator, a minimum wind of 6 miles per hour (10 kilometers per hour) is needed. Twelve to 25 miles per hour (19 to 40 kilometers per hour) winds provide the best wind energy. The energy of the wind is proportional to the cube of the wind speed. This means if the wind speed is doubled, the power output will be eight times greater. Short periods of high wind speed are more effective than long periods of low or moderate wind speed.

Small wind generators are on the market

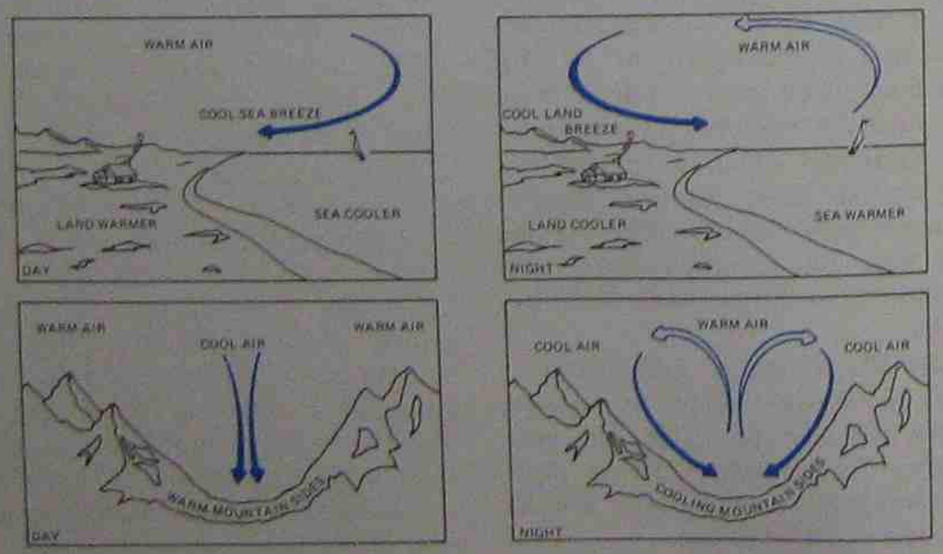


Fig. 19-2 How winds are created

for farms, ranches, cabins, and remote locations. Often these can compete economically with the cost of bringing wires to a distant location. Such generators are usually 12- or 24-volt systems, delivering their energy to storage batteries, figure 19-3. These systems are large enough for lighting, light refrigeration, and small appliances. However, electric heating, cooking, or air conditioning will overload all but the most expensive systems.

Homes designed to use wind generators are usually wired for both AC and DC. Incandescent lights, some electric motors, and some hand-held electric tools can use DC power directly from the batteries. For certain appliances that cannot operate directly from batteries, a solid-state inverter converts the DC into 110-volt AC.

The wind system must have (1) a tower that is at least 30 feet (9 meters) above the ground in a clear area, (2) special batteries, referred to as stationary or houselighting, which have a long life and can be charged and discharged up to 2000 times, (3) a slow speed generator or alternator and (4) blades and a hub.



Fig. 19-3 A 500-watt generator for battery operation (Courtesy Senecbaugh Wind Electric)

All modern wind systems use two or three propeller blades. Propeller wind generator will rotate five to ten times faster than the older style, multiblade windmill. Propeller speeds are in the range of 300 to 400 revolutions per minute. If high winds threaten to increase the propeller speed beyond its designed limit, the pitch of the blades is automatically changed. Reducing the pitch changes the angle of the blade into the wind, reducing the speed of the generator.

The largest wind generator ever constructed was the Smith-Putnam machine located on a 2000-foot (600-meter) hill known as Grandpa's Knob, Rutland, Vermont. This machine, designed by Palmar Putnam, was to feed energy into the Central Vermont Public Service Corporation electrical system. This huge machine had a 110-foot (34-meter) tower and a 175-foot (53-meter) diameter blade. Rotor speed was 28.7 revolutions per minute with an adjustable pitch blade. At wind speeds of 30 miles per hour (50 kilometers per hour) or greater, the generator would produce 1250 kilowatts. While technically successful, wartime shortages, a bad main bearing, and an overstressed blade plagued the project. It was halted in 1945 after only 1100 hours of logged time.

Serious efforts and experiments are again underway with large scale wind generators, figure 19-4. ERDA and the National Aeronautics and Space Administration, NASA, have constructed a 100-kilowatt wind turbine at the Lewis Research Center's Plum Brook facility in Sandusky, Ohio.

Two 62.5 foot blades are designed to rotate at 40 revolutions per minute. In an 18



Fig. 19-4 The Mod-2 wind turbine generates 2,500 kW of power at its Goodnoe Hills, Washington location. The rotor is 300 feet in diameter with a center of rotation 200 feet above ground.

mile per hour (29 kilometers per hour) wind, it produces 133 kilowatts. The slow speed and high torque of the hub are changed into low torque and high speed for the generator with a 45:1 ratio gearbox, figure 19-5. The assembly rests on a 100-foot (30-meter) tower, figure 19-6.

Wind energy can be tied into existing power systems. Figure 19-7 shows wind turbines supplementing an existing hydroelectric plant. Similarily, a home owner with a wind generator can feed any unused electrical power into the local utilities systems–selling his extra power to the utility.

Wind energy is clean and free and when well designed and constructed the generators are not even visually polluting, figure 19-8. Wind turbines are no longer a novelty–they are successfully operating in many areas, figure 19-9. They are especially practical and competitive in rural or remote areas where electrical power is expensive, figure 19-10.

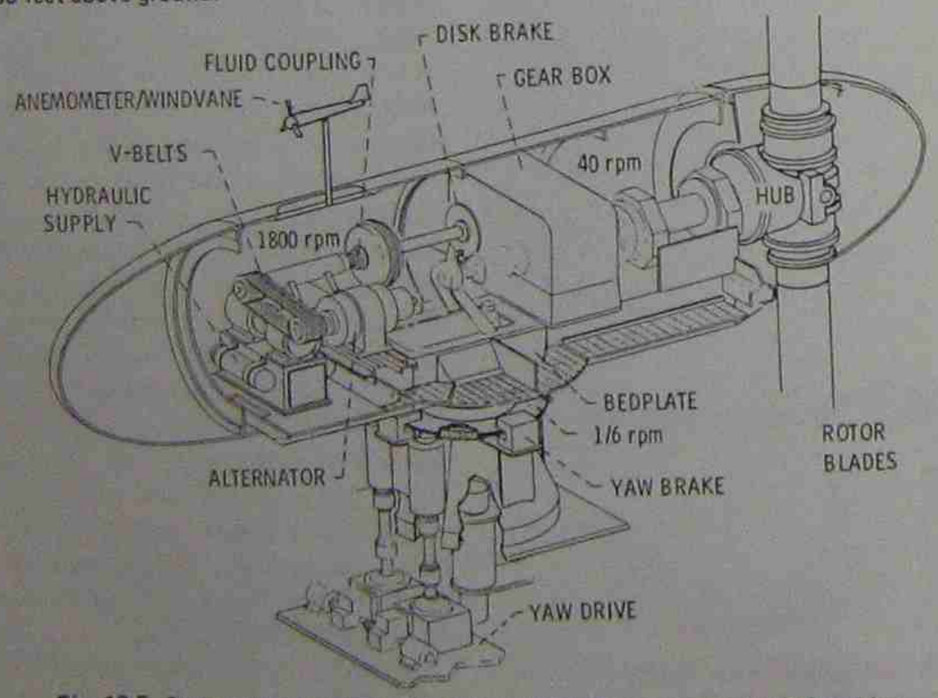


Fig. 19-5 Cutaway view of the DOE/NASA 100-kW experimental wind turbine



Fig. 19-6 DOE/NASA 100-kW experimental wind turbine (Courtesy NASA, Lewis Research Center)

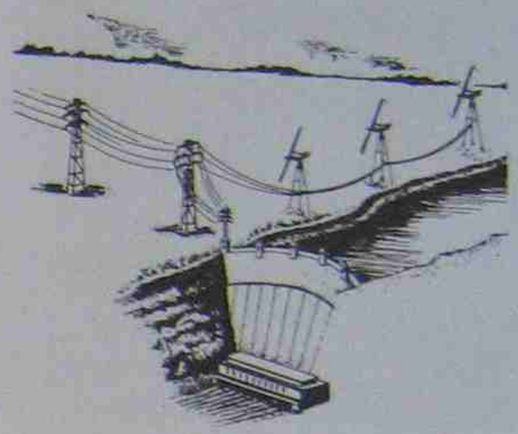


Fig. 19-7 Wind turbines working with a hydroelectric plant



Fig. 19-8 The Darrius style of wind generator has foils that react to wind from any direction



Fig. 19-9 World's largest vertical axis wind turbine. It can produce 250 kilowatts in a 35-kilometer per hour wind, enough for lighting and appliances for 50 homes. (Courtesy of National Research Institute of Canada)



Fig. 19-10 Wind-powered turbine is used to power a stripper oil well in the Texas panhandle. (Courtesy Phillips Petroleum Co., by the American Petroleum Institute)

REVIEW QUESTIONS

1. Why were windmills used on farms in the United States? What happened to them?
2. Why is it difficult to harness wind energy?
3. What wind speeds are best for wind turbines?
4. How is the electricity from small wind generators usually stored?
5. How can wind turbine blades be protected from high winds?
6. Explain what ERDA/NASA is doing in the field of wind turbines.

Unit 20 Hydroelectric Energy

OBJECTIVES After completing this unit, the student should be able to:

- Explain the difference between impulse and reaction turbines.
- Discuss the importance of hydroelectric energy to our nation.
- Explain the uses of several types of turbines.
- Explain the use of the hydraulic ram.

Water does not qualify as a new and little used alternative energy source. Rather, water energy is the oldest source of motive power. Today the technology of hydroelectric plants is highly developed, figure 20-1. However, although water power is an alternative to fossile fuels, it is currently contributing a great deal to fill the electrical generation needs of our country. About 15 percent of the electric energy used in our country is from hydroelectric plants, figure 20-2.

The United States uses about 1/3 of the electricity generated in the world, and the demand for electricity has doubled about every ten years. However, the limits of hydroelectric energy are being approached since most of the best sites have already been developed with power plants. That means that hydroelectric expansion in the future will be modest.

The water turbines that drive electric generators operate on either the *impulse* or *reaction* principle. Impulse can best be demonstrated by directing the force of a garden hose against a cupped hand. Hit by the force of the water, the hand moves in the direction of the stream of water. Impulse turbines usually operate with high water pressures. The reaction principle can be seen from the force a person needs to use to hold the hose. If the hose could be mounted on the rim of a wheel, its motion would be opposite that of the water stream.

The most common impulse turbine designs are the Pelton and turbo. The Pelton wheel, figure 20-3, has buckets cast or bolted on its perimeter. One or more jets of water are directed against the buckets. The buckets are shaped somewhat like an open walnut shell. Water striking the buckets splits into two streams which fall clear of the wheel or runner. This type of turbine must be run in air. If surrounded by water, its motion would be slowed. More than any other turbine, the Pelton wheel resembles the old fashioned water wheel on the grist mill. While used very little today, this type of turbine does produce a tremendous amount of power. For example, a large Pelton wheel using water jets 12 inches (0.3 meter) in diameter produces 20,000 horsepower (15 megawatts). A turbo-type impulse turbine directs the water at the runner from the side.

Common types of reaction turbines are the Francis, Kaplan, and Deriaz; reaction turbines are more widely used than impulse

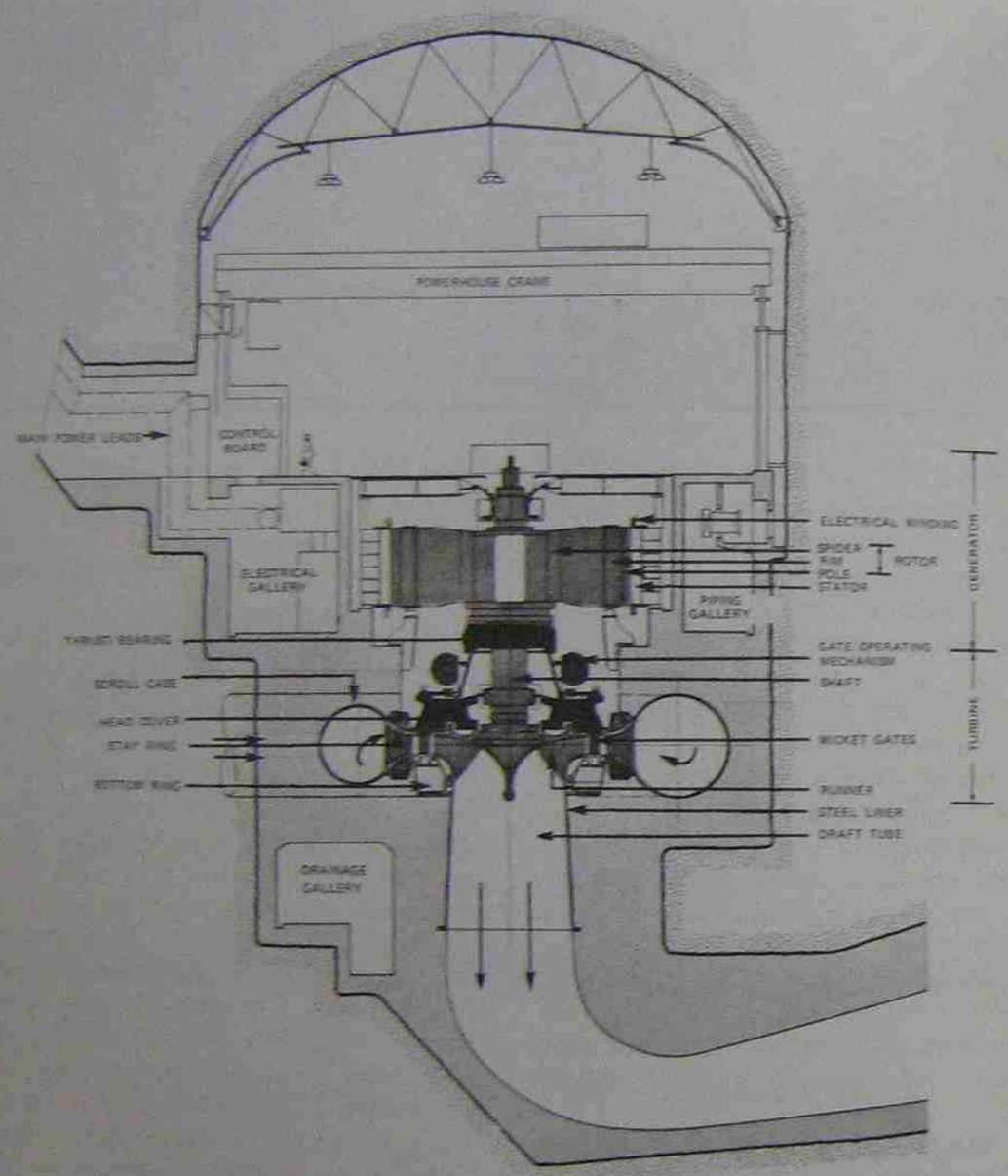


Fig. 20-1 Cutaway view shows the turbine and generator section. Note the size of the man by the control board.

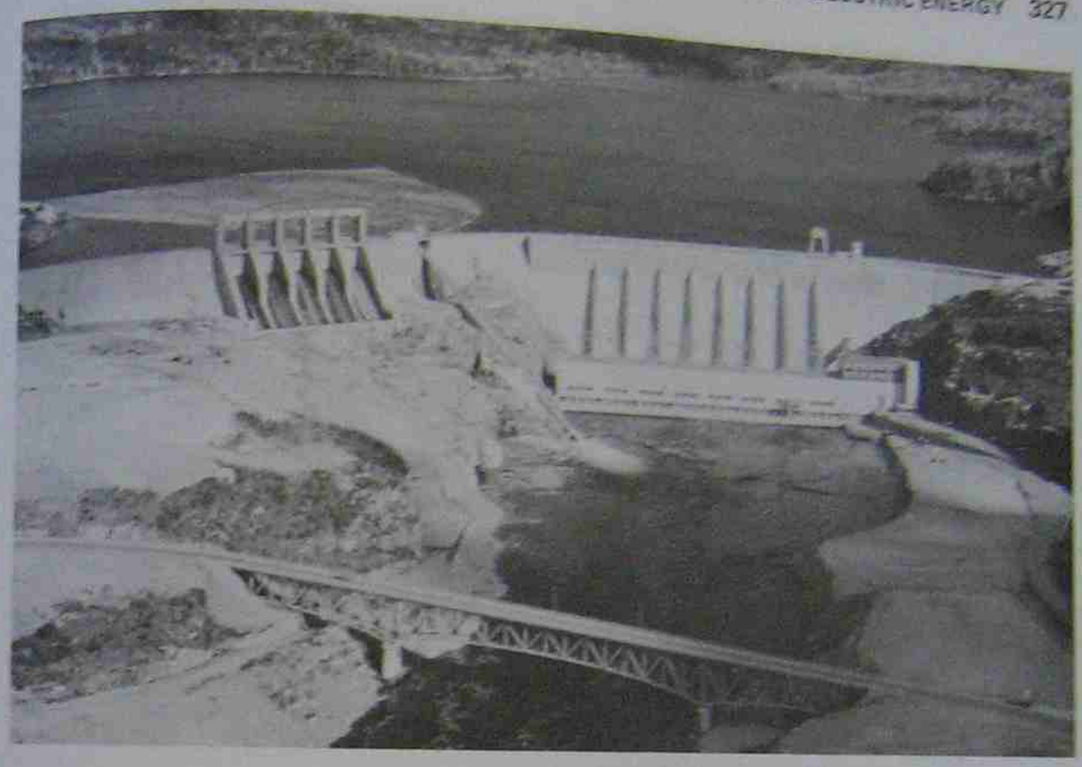


Fig. 20-2 Hydroelectric projects contribute 15% of our electricity (Courtesy Dominion Engineering Works, Montreal, Canada)

turbines. The Francis turbine brings the water to the runner in a spiral casing, figure 20-4, that has a snail shell appearance. The runner, figure 20-5, is usually operated horizontally, rotating on a large vertical shaft. The flow through the runner is radial; water goes from the outer edge of the turbine towards the middle. The water exit is axial, flowing from the center of the turbine downward. Moving gates or wickets, figure 20-6, in the casing can regulate the quantity of water flow. When water strikes the curved vanes of the runner, it changes direction. The acceleration of the water by this direction change moves the wheel. Francis turbines are well suited for power sites that have low water pressure, but still have a large quantity of water flow.

Larger turbines are more economical than several smaller turbines at one site, and three of the largest turbines ever installed are located at the new third power house at Grand Coulee Dam, and are of the Francis type. Each of these turbines is capable of delivering over one million horsepower (750 mega-

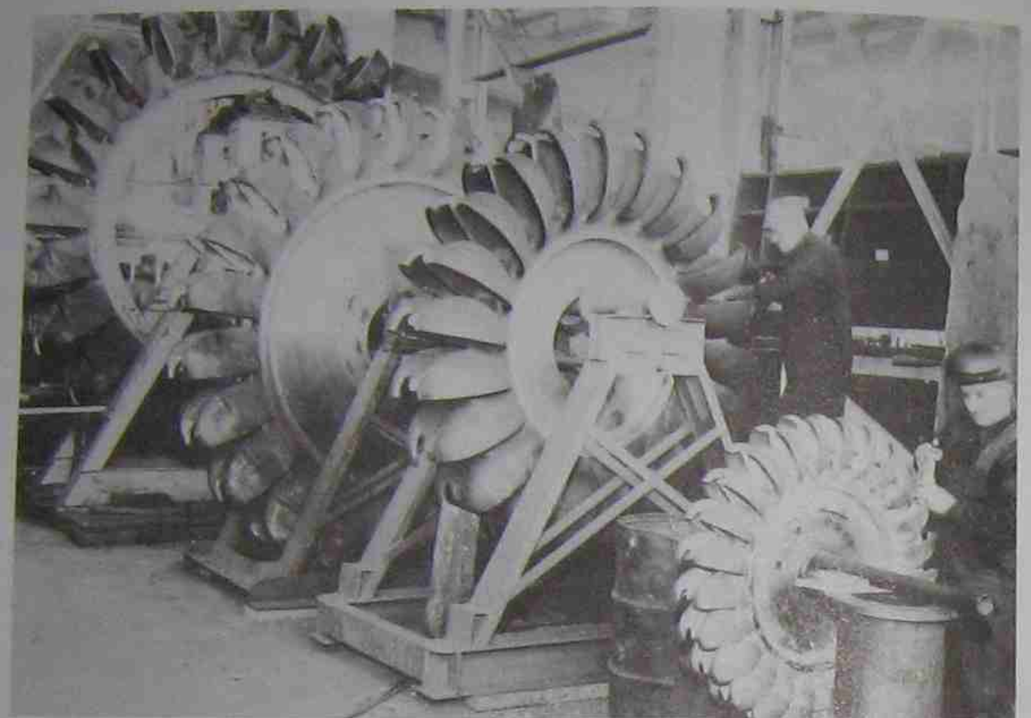


Fig. 20-3 A variety of impulse turbine runners ranging in output from 3500 horsepower (2600 kilowatt) in the foreground to 150,000 horsepower (110 megawatt) in the background.

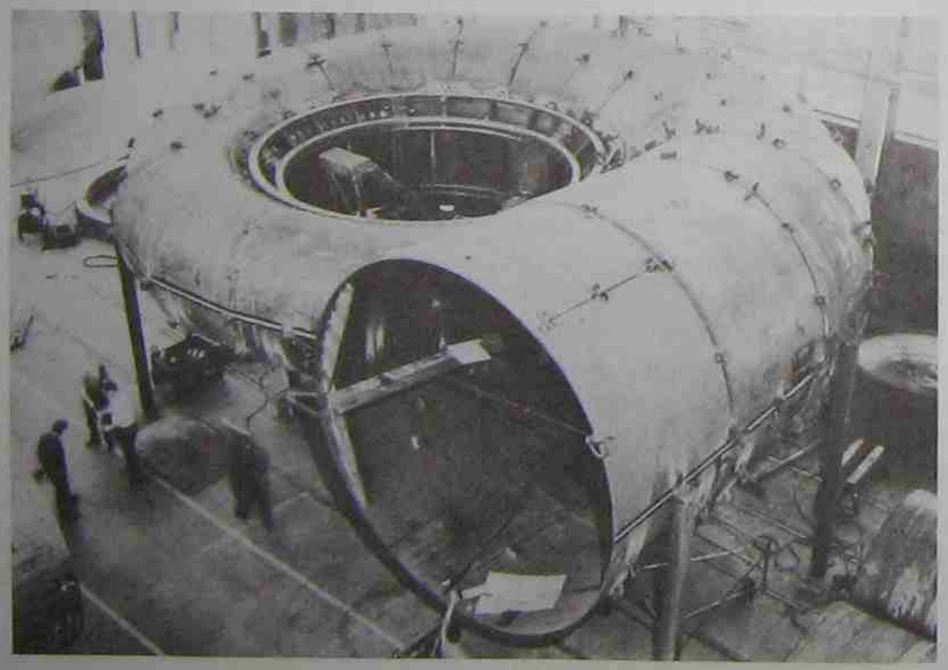


Fig. 20-4 Casing brings water to the turbine.

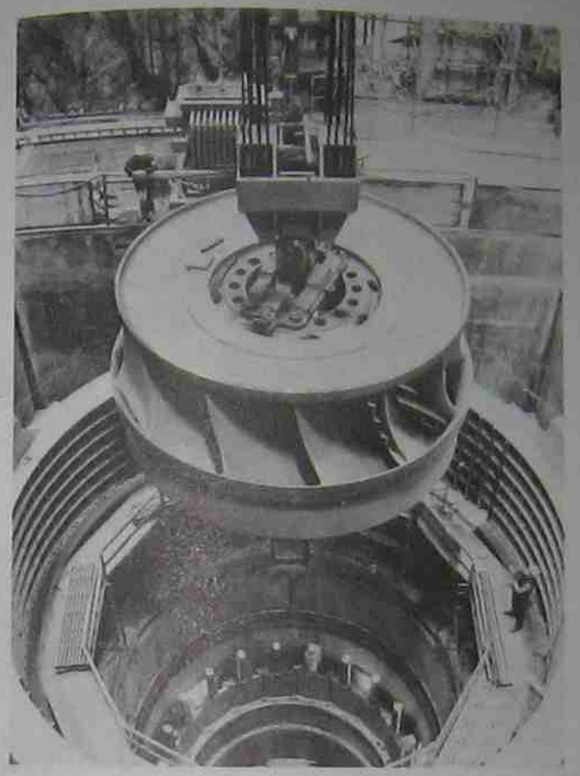


Fig. 20-5 Runner for a Francis turbine



Fig. 20-6 Wicket gates control the quantity of water entering the turbine.

watts). The assembled runner is 32 feet (10 meters) in diameter and weighs 1,100,000 pounds (500 000 kilograms). Each of the 32 wicket gates weighs 14,000 pounds (6400 kilograms).

The Kaplan style turbines, figure 20-7, have the appearance of a ship's propeller. With low water pressure, the Kaplan turbine has the advantage of higher speeds than the Francis turbine. The Kaplan turbine blades are movable to correctly match the blade angle to the amount of water flow, figure 20-8. Another type turbine, the Deriaz, also has movable blades to adjust the pitch.

An interesting water pumping device is the *hydraulic ram*, figure 20-9. It uses the fall or head of water, 20 inches (0.5 meter) or more, with a flow rate of 1.5 gallons (6 liters) or more per minute. It will pump water to a height of 25 feet (7.6 meters) for each foot (0.3 meter) of fall. The ram does this pump-



Fig. 20-7 Cutaway showing the construction of a hydroelectric power unit

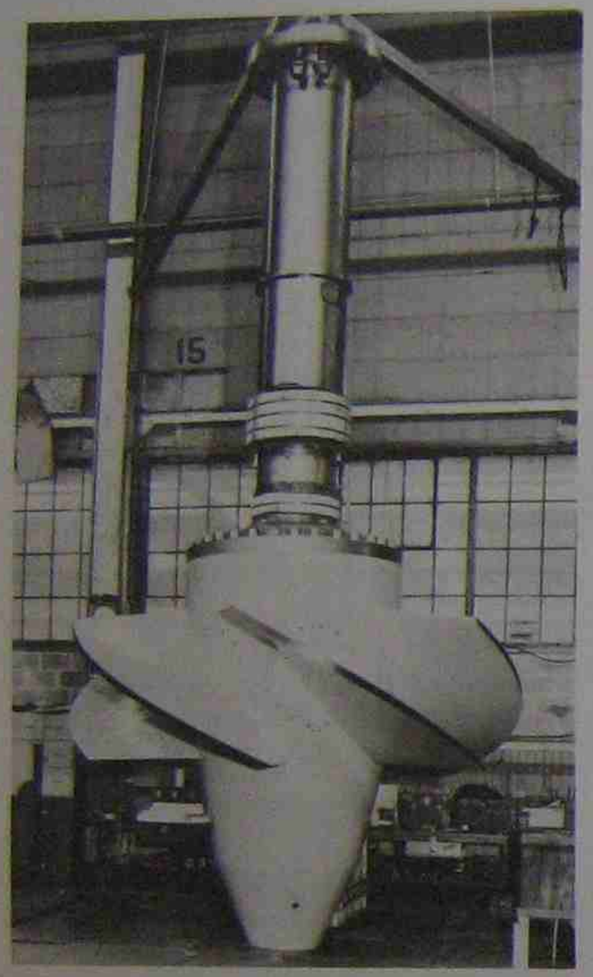


Fig. 20-8 Runner and shaft assembly of a Kaplan turbine (Courtesy Dominion Engineering Works, Montreal, Canada)

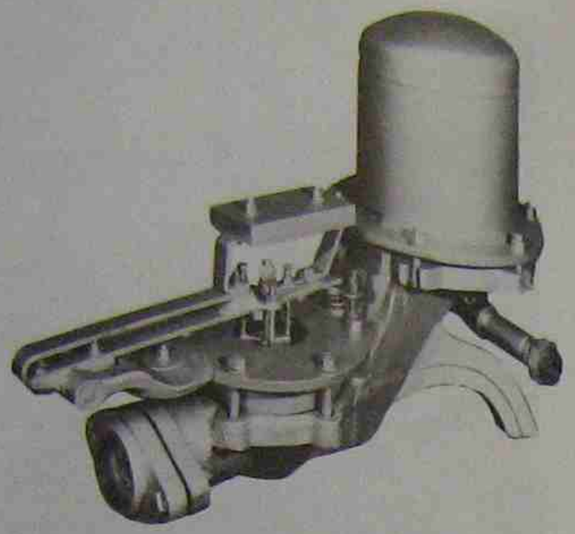


Fig. 20-9 Rife No. 40 heavy-duty universal ram, 4-inch inlet, 2-inch outlet (Courtesy Rife Hydraulic Engine Manufacturing Co.)

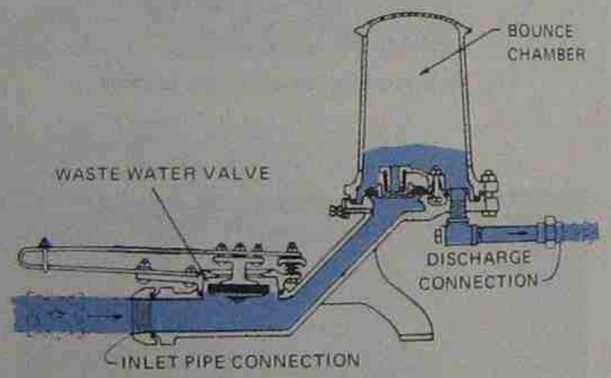


Fig. 20-10 Section drawing of series B ram

ing action on its own; no outside power is required. Water flows to the ram through an inlet pipe, figure 20-10, and out a waste water valve. At a certain speed the waste water valve automatically closes. The downward movement of the water column opens a second valve leading to the air-bounce chamber. When air pressure and water pressure equalize, the second valve closes. This action is repeated and, after several strokes, pressure in the bounce chamber will be pushing water to a considerable height. This type of pump is ideally suited for farm operations and can be used at springs, wells, and river sites, figure 20-11. Although not hydroelectric in any way, the ram can substitute its action for electric or gasoline engine pumps.

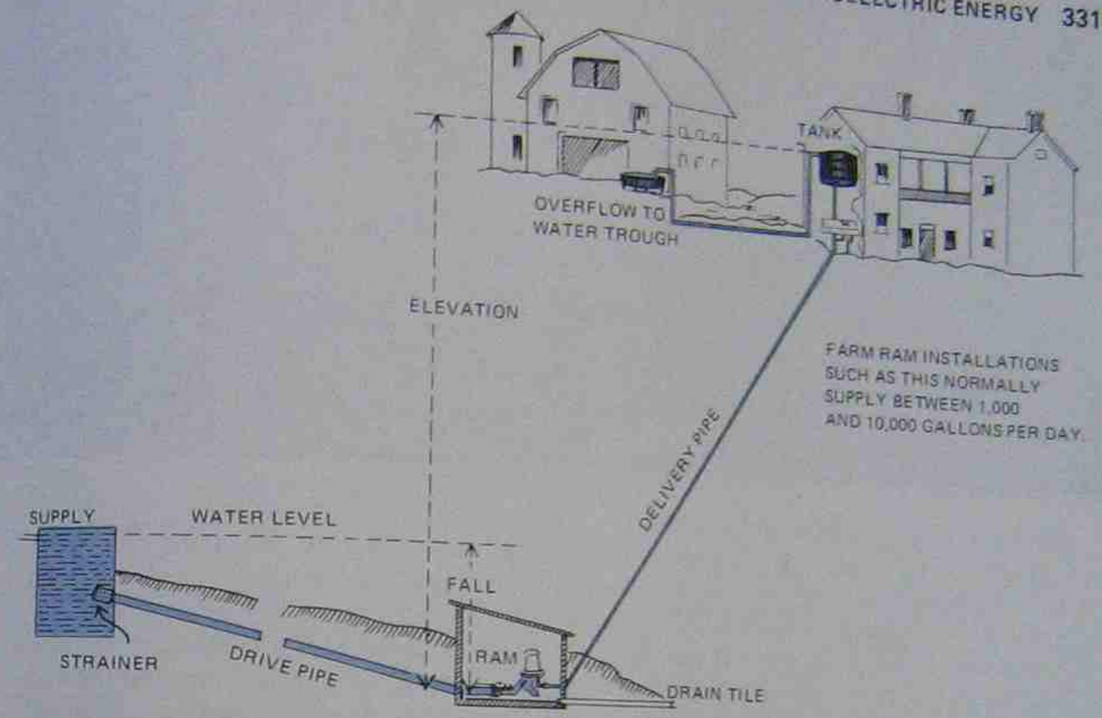


Fig. 20-11 Installation of a hydraulic ram on a farm

REVIEW QUESTIONS

1. What percentage of our electricity is generated by hydroelectric power?
2. Explain the impulse turbine principle.
3. Explain the reaction turbine principle.
4. What type of turbines are installed at the Grand Coulee Dam?
5. What is the main advantage of a Kaplan style turbine?
6. What is the source of energy to operate a hydraulic ram?

Unit 21 Energy From Biomass Sources

OBJECTIVES After completing this unit, the student should be able to:

- Define biomass.
- Explain what photosynthesis has to do with biomass.
- Discuss biomass burning.
- Explain how biomass can be distilled into alcohol.
- Understand the difference between ethanol and methanol.

Obtaining energy from biomass has been accomplished for many years. Its primary importance today is to provide a fuel source to supplement our diminishing fossil fuels. The Department of Energy estimates that biomass is now supplying about 1% of our energy. There is a great possiblity that this percentage will be raised.

Simply stated–biomass is organic material. All vegetation or plant material that is grown can be used as biomass. For energy usage biomass is usually converted in one of three ways: (1) biomass may be directly burned, (2) biomass may be converted into alcohol, and (3) biomass may be converted into a gas called methane which is also the principle ingredient in natural gas.

DIRECT BURNING

All trees and plants grow by the chemical process called photosynthesis. Plants capture light energy and use it to create carbohydrates within the chlorophyl-containing portions of the plant. A direct result of this process is the formation of oxygen, which the plant gives off as a waste product. Carbohydrates–if you remember–are molecules containing carbon and hydrogen. Of course, there are also hydrocarbon molecules in fossil fuels which causes them to burn. Dry plant material will also burn; we do not have to wait millions of years for them to be transformed into fossil fuels. Studies show that a pound of dried plant material can produce up to 7,500 Btus of heat energy. This is more than half the amount of heat energy obtained from burning one pound of coal.

Collecting a significant amount of organic material for large scale burning for energy is possible but not entirely practical. For example, an electric power plant would require several hundred square miles of a forest "tree farm" to operate. Remember that before the widespread use of fossil fuels many countries had almost exhausted their supply of trees that they had been using for energy sources. Also, such a use competes directly with the lumber and wood products industry; really quite a major consideration.

Research is directed toward producing the maximum amount of biomass for the least cost. Eucalyptus trees are very productive with yields of 8 to 25 tons of biomass per acre.

Burning the solid wastes in garbage and trash to produce energy is very practical but, as of this date, there are fewer than 30 processing plants in the country. This means that less than 1% of the 150 million tons of garbage and trash we throw away each year is burned to produce heat energy for electrical generation. In Sweden, Denmark, and the Netherlands–on the other hand–some 40% of their municipal waste is burned for energy.

The production of energy by burning biomass is too rich a resource to neglect. It is a renewable source and if it is soundly managed it will do no harm to the environment. Wood as a *home* heating fuel is making a serious comeback, however, and is discussed in Unit 22.

ALCOHOL FROM BIOMASS

Alcohol, as just mentioned, can be produced from all organic material. Two important types of alcohol can be distilled: ethyl alcohol (ethanol or grain alcohol), and methyl alcohol (methanol or wood alcohol). Both processes also produce useful by-products other than the alcohol.

Ethanol is produced from the distillation of plant sugars; many fruit and grain crops are commonly used. The biomass is ground and mixed with water to form a mash. The mash contains starch which must be converted to sugar. This is done by adding malt which contains an enzyme that changes the starch to sugar. Another enzyme which is contained in yeast is added; this enzyme ferments the sugar into ethyl alcohol.

To remove the alcohol from the mash it is distilled; heat is applied and the alcohol, which boils at 171°F, vaporizes and can be condensed on a cool surface and separated from the mash. A bushel of corn can yield up to 2.4 gallons of ethanol. The byproducts from the process can be used as feed for livestock.

Ethanol has many industrial uses in plastics, solvents, drugs, and food processing. Today ethanol is also much in the news as a motor fuel. When combined in the proportions of 90% gasoline and 10% ethanol it is commonly called gasohol, figure 21-1. Adding ethanol not only stretches the gasoline supply, it also helps to raise the octaine rating of the fuel. Gasohol sales are on the increase; more than 270,000 barrels are sold each day.

Methanol is accomplished by the *destructive* distillation of the biomass. Wood, sawdust, or other material is dried, placed in an oven, and heated to between 400 and 500°F. Gases are driven from the material and are condensed into a liquid. Chemical processes are then used to separate out the methanol. Charcoal remains in the ovens after all the liquids and gases are driven off by the heat. Methanol has much the same industrial uses as ethanol, however it does contain more heat energy.

Ethanol and methanol are the principle types of the many types of alcohol that can be produced from biomass. Both of the al-



Fig. 21-1 A service station attendant filling a tank with gasohol (Courtesy of the American Petroleum Institute)

cohols can also be produced directly from petroleum. Today 30% of the alcohol used by industry comes from biomass. None of the alcohols discussed in this unit are beverage alcohols, since they are treated with toxic materials to make it unfit—to say nothing of downright deadly—for human consumption.

METHANE GAS FROM BIOMASS

The production of methane gas has received considerable attention as an alternative energy source. Many experiments involving the production of methane are underway with several successful installations already at work in the U.S., figure 21-2. In fuel-short India, some 2500 units are operating in farms and villages. During World War II, because of massive gasoline shortages, intensive research on methane was carried out by the Germans as an alternate source of fuel. Methane plants are in operation today at locations throughout the world.

The production of methane offers other advantages besides the production of a combustible gas for heating and engines. It also yields high quality organic fertilizer and helps to reduce the problems of waste disposal.

The source of methane gas is organic matter that is decomposed (broken down) by bacteria. Manure, organic garbage, or leaves are mixed into a watery paste called a slurry and fed into a digester tank. The digester tank might be as small as a 55-gallon (190-liter) oil drum or it might take on the dimensions of a 3000-gallon (11 000 liter) pit.

When *aerobic* (with air) decomposition of plants, animals, and manure take place in nature, the byproducts are ammonia, carbon dioxide, and the solid we call humus. However, methane is produced by a biological disgestion in which two type of *anaerobic* (without air) bacteria break down organic substances. Anaerobic bacteria can live and grow without oxygen, while aerobic microorganisms require oxygen to live and grow. Acid-producing bacteria are capable of breaking the matter into materials such as acetic acids. The other anaerobic microorganisms produce methane. The digester must have the proper balance of these organisms. The bacterial action works best at 95°F (35°C).

The gas produced is sometimes referred to as bio gas, marsh gas, or sewer gas. It contains about 70% methane, carbon dioxide, and traces of sulfurated hydrogen. The trace of sulfurated hydrogen gives the gas an odor of rotten eggs.

The slurry in the digester will begin to produce methane within several days; the entire process taking about 40 days. In that amount of time, 95 percent of the methane will be given off. If the digester is to be operated continuously, 1/40 of the digester capacity should be renewed each day, with an equal amount of sludge removed.

On a large scale, the production of methane is economically sound. Sewage treatment plants can produce energy and power, and fertilizer as a byproduct. Increasingly, large livestock feeding operations are faced with the dilemma of waste disposal. Here methane digesters have a real potential. At the individual home site, the practicality is in question since there is the initial large cost involved. Also regular feeding and monitoring of the digester is required. Unless an individual has the time and an interest in methane, he may not wish to start up a home unit.

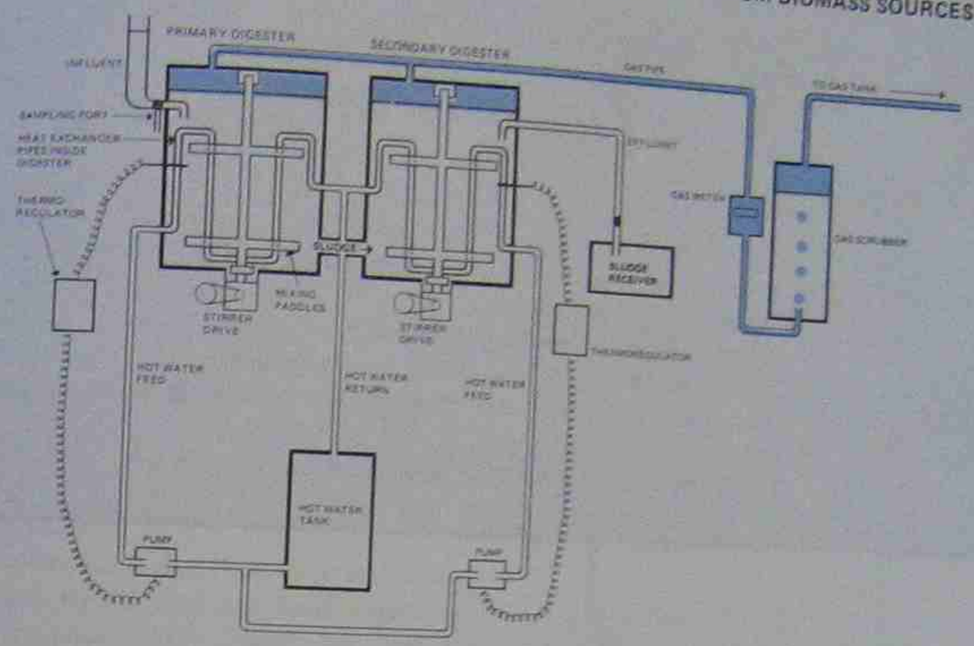


Fig. 21-2 Diagram of experimental livestock waste digester

REVIEW QUESTIONS

1. Explain how biomass and fossil fuels are related.
2. Compare the heating value of biomass with that of coal.
3. What biomass materials can be burned in addition to wood?
4. Explain why burning biomass has its limitations.
5. Briefly outline the distillation of ethanol.
6. What is gasohol made of?
7. What are the advantages of gasohol?
8. What types of biomass are often used in methane production?
9. What is the difference between aerobic and anaerobic decomposition?

Unit 22 Geothermal, Wood, and Tidal Energy

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the term geothermal.
- Locate several major geothermal areas.
- Discuss the problems of using wood for home heating.
- Explain the advantages and disadvantages of several wood burning methods.
- Explain how the energy of the ocean tides can be harnessed.

GEOTHERMAL ENERGY

The internal heat of the earth is referred to as *geothermal energy*. The thickness of the earth's crust varies from 6 to 30 miles (10 to 50 kilometers). Below this crust lies the magma at a temperature of 6000° to 8000°F (3300° to 4400°C). This intense heat radiates very slowly to the earth's surface. As a mine shaft goes down, a temperature rise of 100°F per mile (24°C per kilometer) can be noted. Drilling technology has not reached the magma, and scientists are not sure how to harness this energy even if they could reach it.

At the base of the continental crust, a layer just above the magma, the temperature is 400° to 1800°F (200° to 980°C). It is at this level that interest in geothermal energy lies. Geysers, such as Old Faithful, figure 22-1, hot springs; and bubbling mud pots are found in the United States and around the world. Water seeps into the underground cracks in the rocks or through porous rocks, picks up heat, and returns to the surface. It

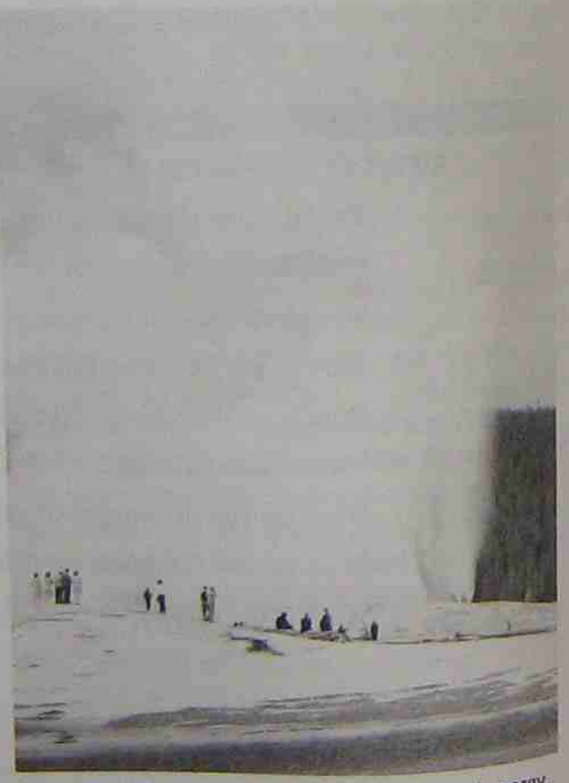


Fig. 22-1 Old Faithful displays geothermal energy.

is possible for the water to return as dry steam or as wet steam, a combination of steam and water.

Dry steam is the most useful because, on a commercial basis, it can be fed directly into standard steam turbines to generate electricity. Dry steam is not found in many places throughout the world. The geyser region near San Francisco, California, figure 22-2, is one such dry steam field. Steam is collected from over 100 wells and sent to the turbines where about 500 megawatts of power are produced. While it already provides San Francisco with about one-half of its electricity, the capacity of this site is currently being increased.

In Larderello, Italy, there is a dry steam geothermal region that has been producing electricity since 1913. Today the area is working at capacity with thirteen generating plants producing 365 megawatts.

Superheated underground water is under sufficient pressure to keep it liquid. When it is brought to the surface through a well, some of it will boil into steam as the pressure is reduced. Geothermal fields that have this structure are called wet steam fields, figure 22-3. They are far more common than dry



Fig. 22-2 The Geysers, a geothermal steam field in California

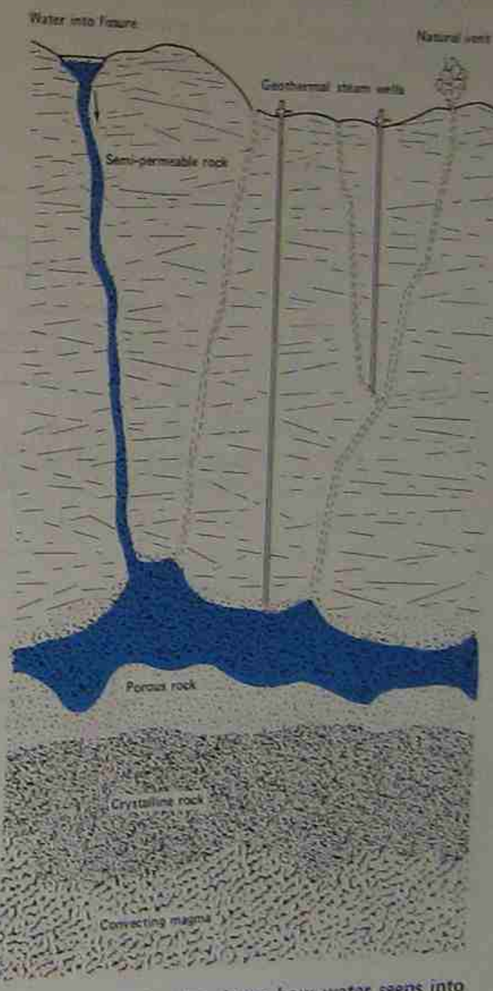


Fig. 22-3 This drawing shows how water seeps into the earth to pick up the heat in the porous rocks above the crystalline rock and magma.

steam fields; this steam is used primarily for heating. Interestingly enough, Iceland was developing wet steam fields in the 1930s. Ninety percent of the homes in the capital city of Reykjavik are heated with geothermal power. In the United States, wet steam heating is used in Klamath, Oregon and Boise, Idaho.

The secondary fluid cycle, figure 22-4, brings superheated water up, but keeps it under pressure and does not allow it to boil. This high-pressure secondary fluid is directed against the turbine and blades. The spent fluid from the turbine is condensed and recycled through the heat exchanger. Most of its heat is given up in the heat exchanger where a fluid like isobutane or freon, which has a lower boiling point, is vaporized. The hot water, having lost a good deal of its heat, is reinjected into the ground to conserve the total heat of the well area.

Wet and dry steam systems are in operation today. They are successful and economical, but limited to those hot spots on the

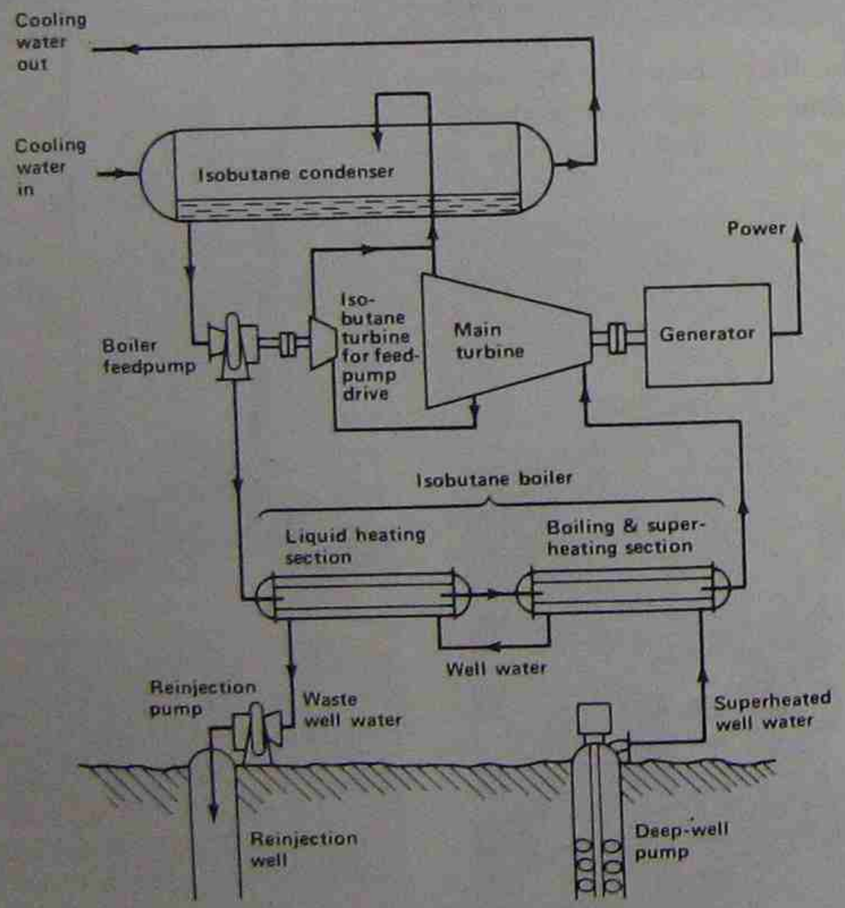


Fig. 22-4 Diagram of a vapor-turbine cycle for geothermal power generation

earth's surface where the heat is easy to reach. Dry hot rock deposits also exist, representing a potential for energy probably ten times that of known wet and dry steam fields. When such dry fields are found, a well is drilled down to the hot rock area. Cold water—pumped under high pressure down the well—opens a vertical crack in the granite above the hottest area. A second well is drilled to intersect with the cracked area. Cold water poured down into this hole continues to crack the hot rocks and allow the water to pick up heat. This water returns to the surface through the first hole in the form of steam and water. Here it is harnessed with a turbine. Hot rock technology is still in the experimental stages, but it does hold much promise. Government agencies hope that by 1986, 2% of the electric heating needs of the nation will be from geothermal sources.

WOOD—ENERGY FOR THE HOME

Can it be true that in our space age society some people are seriously returning to wood to heat the family home? Yes, more than just a few are renewing their interest in wood heating. The reasons include fear of oil and natural gas shortages, the rising costs of fossil fuels, and a nostalgic return to some of the old values and ways.

This renewable energy source can have an impact by conserving other fossil fuels. No one will pretend that heating homes with wood is right for everyone. Some want wood heat, using their conventional system as a backup. Others want conventional heat, with wood heat as a backup. Most people living in metropolitan areas will probably not even consider wood heat, because, ideally, a person interested in wood heat has a wood lot or lives on acreage that has an abundance of trees. Clearing fallen trees, limbs, and diseased trees can also yield considerable wood, as can thinning trees. However, it would take the yield from several acres of woods to heat a home in a cold climate. Therefore, wood could not be a total alternative fuel source for a nation.

In the 1600s, before coal came into use in England, there was an energy crisis because most of the forests had been cleared for firewood. Likewise, in the Mediterranean countries, many of the forests had been harvested clean with serious environmental results in the form of erosion and ecological damage.

Since many persons purchase wood for fireplace and recreational burning, it should be mentioned that wood is sold by the cord, figure 22-5. A stack 8 feet (2.4 meters) long, by 4 feet (1.2 meters) wide, and 4 feet (1.2 meters) high is a cord. A face cord is 8 feet (4.2 meters) long, by 4 feet (1.2 meters) high, and cut to any desired length. A rick is a face cord of 16-inch (0.4 meter) logs.

Buying wood by the cord does not consider the heating value of the type of wood. Among the hardwoods: ash, red oak, white oak, beech, birch, hickory, hard maple, pecan, and dogwood are high in heat output. Aspen, basswood, cottonwood, chestnut, and yellow

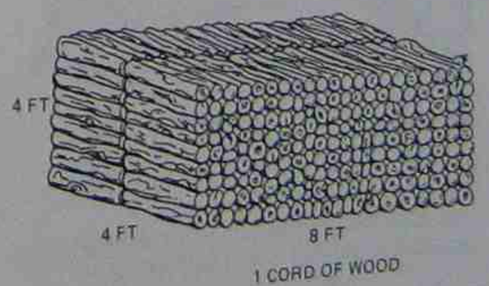


Fig. 22-5 Diagram of one cord of wood

poplar are low in heat output.

In the burning of wood, the cellulose and lignin of the wood are heated to the point where they break down into a gas. This gas, combined with oxygen, is heated to ignition temperature. Upon ignition, heat is given off. The heat supports the fire and warms the room.

The way the wood is burned is important.



Fig. 22-6 There is renewed interest in home heating stoves. (Courtesy Portland Stove Foundry)

Generally, open fireplaces are the least efficient. It is pleasant to watch the burning logs, but much of the heat goes up the chimney. A poorly designed fireplace an even result in a loss of heat because it draws warm air in the house up the chimney, especially after the fire has died down and the damper is left open.

A Franklin stove—with its flue fitted into an existing fireplace—has an advantage over a fireplace because it has doors. When the doors are closed, the rate of combustion can be controlled for longer, more even burning of the wood. The cast-iron construction of the Franklin stove helps hold and spread the heat throughout a room. Many other heating stoves of interesting designs, in addition to the Franklin, can be found on the market, figure 22-6. There are, for instance, fireplace *inserts*, made of a heavy cast iron that fit snugly inside the existing fireplace. The only part that shows is an attractively designed heavy cast door. They feature a damper for controlling the rate of burn and operate similar to a complete combustion heater.

Complete combustion heaters, figure 22-7, are the most efficient. They are airtight, with the cold air being preheated as it comes into the combustion area. Smoke is forced back through the combustion area before it goes up the chimney. Wood can also be burned in complete combustion heaters set up as central heating units, much the same as any other furnace. Furnaces are on the market that can use several different fuels: wood, oil, or natural gas. Thermostatically controlled dampers regulate the rate of burning by allowing the correct amount of air to enter the fire box. This type of heater can be loaded in the evening and burn through the night unattended until morning, or even longer.



Fig. 22-7 Complete combustion wood heater (Courtesy Riteway-Dominion Manufacturing Inc.)

figure 22-8. In the basement, this furnace can be installed into the central hot air duct system. While they are efficient, they are not usually as pleasant to view as a fireplace or heater of old fashioned design.

Wood smoke in small amounts is usually not a problem and, in fact, is low in irritating pollutants. For example, wood smoke contains no sulfur dioxide. Wood as an alternative energy source does have a place in the total energy picture, if used wisely.

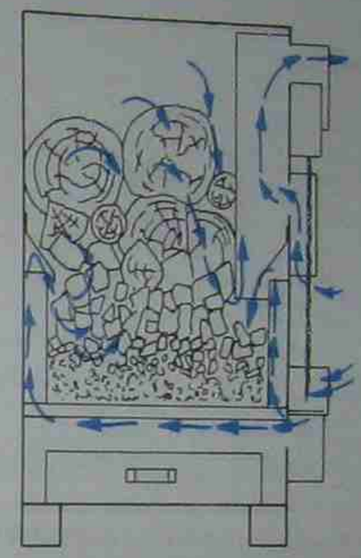


Fig. 22-8 Airflow through a complete combustion heater

TIDAL ENERGY

Anyone who lives near or has visited the ocean is familiar with the tides. Tides are caused by the gravitational pull of the moon on the earth's large bodies of water. What is known as the cycle of the tides occurs twice a day. This means that water beginning at high tide will go down to low tide and then back up to high. This also means that the interval between low tide and high tide is about six hours. Tides are generally higher the further the location is from the equator. The difference between low tide and high tide is sometimes as much as forty feet. If water flows into an estuary, bay, or up a river, and if a dam is built and equipped with water

turbines, electricity can be produced, figure 22-9.

Interest in tidal power continues but, to date, only one large scale plant is in operation. The plant is located at the junction of the Rance River and the Gulf of St. Malo, Brittany, France. This plant consists of a dam and 24 reversible Kaplan turbines that drive 10,000-kilowatt alternators. Turbines can produce electrical energy when the tide is rising, and also when the tide is going out. In order to best match the production of electricity to the community demand, the turbines can also be used as pumps for filling the river behind the dam during slack electric demand, thereby providing additional water for the turbines when it is needed. The tidal rise and fall at this location averages 26 feet (8 meters).

To be considered for a tidal power plant, an area must have a great difference between high tide and low tide, and be a tidal river or bay that contains considerable water volume.

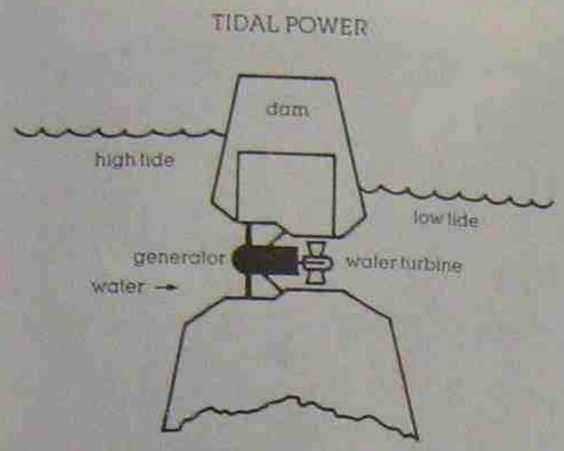


Fig. 22-9 Water turbine uses the tides to generate electricity. (Courtesy of Standard Oil Company of Indiana)

REVIEW QUESTIONS

1. Is geothermal energy practical? Are any geothermal systems in operation today?
2. How thick is the earth's crust?
3. What is the temperature of the magma?
4. Who is the ideal person to use wood as a home heating fuel?
5. What are the measurements of a cord of wood?
6. What types of woods have a high heat output?
7. Explain how an open fireplace can create a net loss of heat.
8. Where will tidal dams be most likely located?

Unit 23 Nuclear Energy

OBJECTIVES After completing this unit, the student should be able to:

- Discuss matter, atomic structure, and radiation.
- Explain nuclear fission.
- Compare a fossil fuel power plant to a nuclear power plant.
- Discuss the workings of a nuclear reactor.
- Explain nuclear fusion.

Nuclear energy as an energy source is by far the most promising, the most awe-inspiring, and the most fearsome that civilization has yet uncovered. The tremendous energy reserve of nuclear power promises to be an economical power source for all nations for centuries to come. Nuclear power can be relied on long after conventional power reserves of coal and oil are exhausted. When nuclear energy is used, natural resources of coal and oil can be conserved.

It is difficult to comprehend the energy locked within the atom. It is almost inconceivable that enormous energy exists within something that small. Yet the potential energy that lies within a pound (.45 kilogram) of uranium is nearly equal to 3,000,000 pounds (1364 metric tons) of coal, about twenty-five railroad cars full of coal, figure 23-1.

An appreciation of nuclear or atomic en-

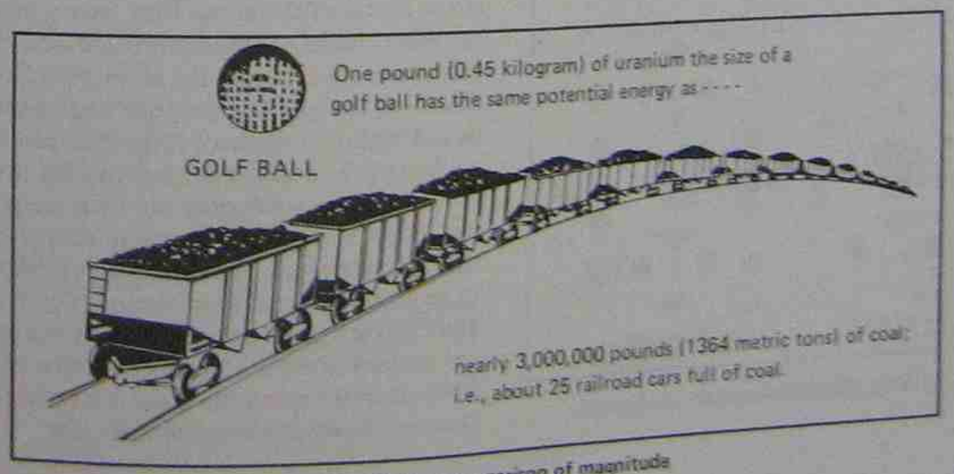


Fig. 23-1 A comparison of magnitude

ergy and an understanding of how it is produced and controlled is important. Basic knowledge of the structure of matter should be gained, however, before a more detailed investigation of nuclear energy is begun.

NATURE OF MATTER

The smallest complete unit of matter is called the *atom*; they are the building blocks of all substances. If it were possible to magnify any substance an infinite number of times, it would be seen as being made up of atoms. Some substances, in turn, are made up of all the same type of atoms. These substances are therefore *pure* and are known as the *elements*. There are ninety-two different elements that occur naturally; additional elements have been man-made.

Other substances could be magnified and found to be made up of *different kinds* of atoms that are bound together in a cluster—known as a molecule, figure 23–2. A *molecule* is the smallest group of different atoms that retain the properties of the substance. When

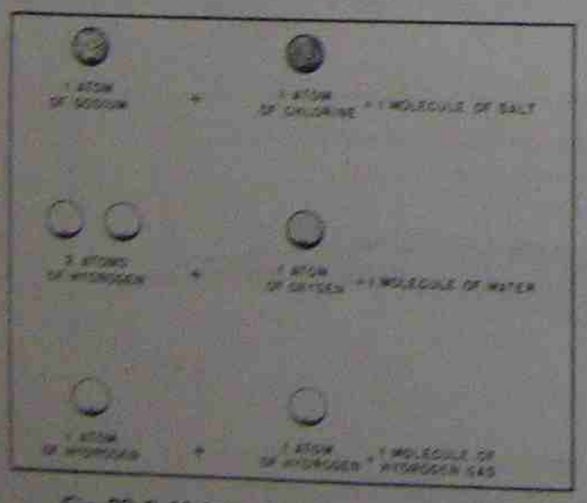


Fig. 23–2 Molecules are made up of atoms.

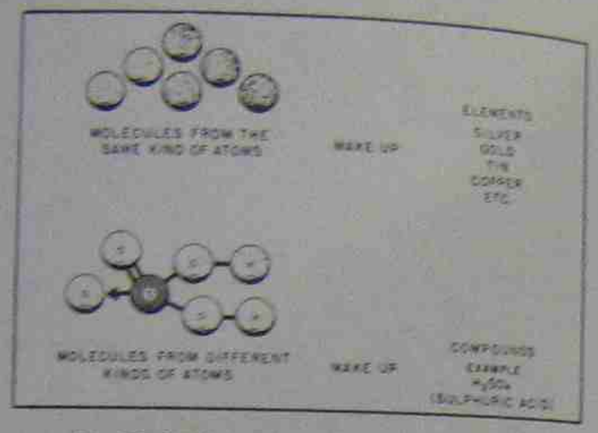


Fig. 23–3 Matter is made up of molecules.

two or more different atoms make up a molecule, it is referred to as a *compound*, figure 23–3. There are many ways that atoms can arrange themselves to form many different compounds. Over 400,000 different combinations are known, among these: wood, cloth, water, coal, and rock.

The Atom: Structure and Characteristics

The atom itself is made up of protons, electrons, and, with the exception of hydrogen, neutrons. The *protons* are heavy particles at the center of the atom; they have a positive electrical charge. The *neutrons* are also heavy particles at the center of the atom; they have no electrical charge. The protons and neutrons, bound tightly together, form the center or *nucleus* of the atom. The *electrons* are in orbit around the nucleus; they are extremely light and carry a negative electrical charge. With these facts in mind, the atom might be thought of as a solar system in miniature, figure 23–4. Electrons are held in their orbits by the pull of the protons in the nucleus. The number of electrons in orbit around the nucleus is equal to the number of protons in the atom.

The electrons are arranged in neat and predictable patterns called shells around the nucleus of the atom. Some elements are chemically *satisfied*, and since all of their shells are complete, they do not react with other elements; they are *inert*. Most elements

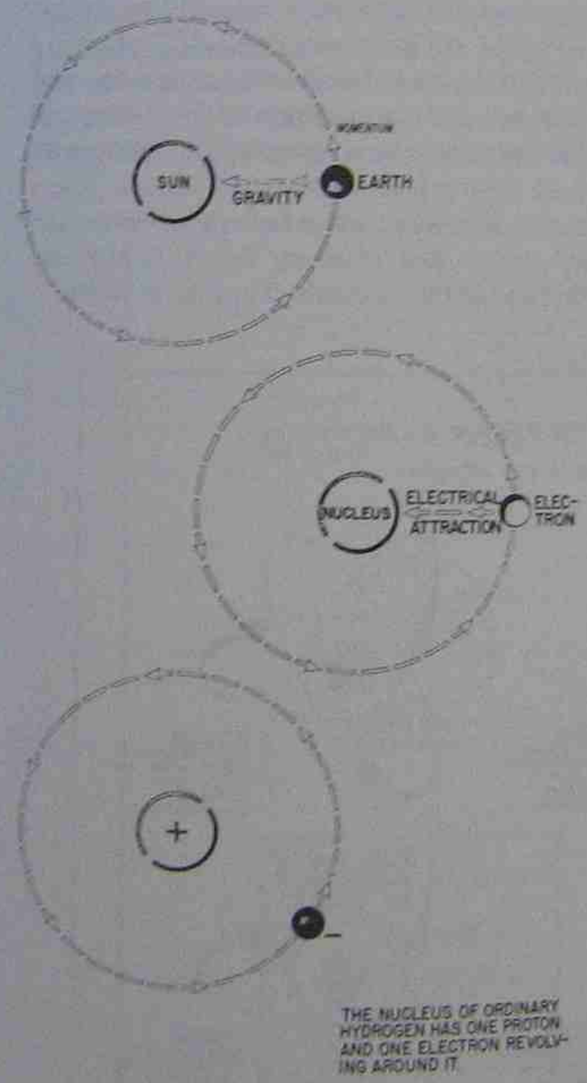


Fig. 23–4 An atom of hydrogen

have atoms with incomplete outer shells, however. The electrons in these outer shells are loosely held and they are capable of combining with other atoms. As these atoms share the electrons of their incomplete outer shell with those of other atoms, they form a molecule. This sharing of electrons produces chemical compounds. A good example is sodium chloride—common table salt—figure 23–5. As you can see, the chlorine atom has only seven electrons in its outer shell; it is one short. The sodium atom has only one electron in its outer shell. These two atoms share their outer shell electrons. Each outer shell is now complete, and a stable compound is formed.

To explain further, chlorine normally has only seven electrons in its outermost range or shell. For an atom to be chemically inert (satisfied) it should have eight electrons in this shell. Sodium has only one electron in its outermost shell. Now, if one atom of sodium combines with one atom of chlorine in such a way that the single atom in the sodium shell is shared with the outer shell of chlorine, then each atom is considered to have eight electrons in its outermost shell. In effect, then, the sodium loaned its one electron to the

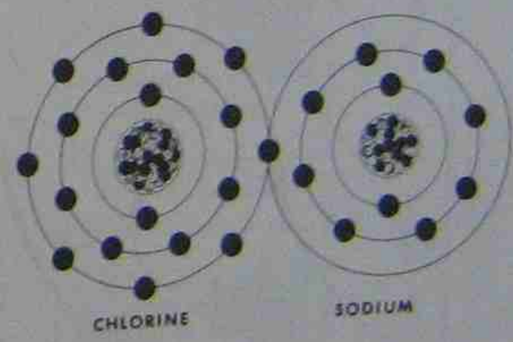


Fig. 23–5 Molecule of sodium chloride

chlorine to complete the eight electron outer shell and the chlorine loaned its seven electrons to do the same thing for the sodium. Under these conditions, a stable chemical compound results from the chemical reaction between sodium and chlorine and a molecule of sodium chloride is formed.

There is space between the molecules of any substance. Some molecules are very close together; some are very far apart. Gases have the most space between molecules, liquids have less space between their molecules, and molecules of solids have the least space between them; they are the most dense.

Molecules do not remain still; they are in constant motion. In gases there is tremendous movement of the molecules, while in solids the movement is reduced to a slight vibration. Also, the molecule's speed increases as it is heated. This can be seen on even a simple–supposedly solid–concrete road surface. The road surface is not laid in one piece, rather there are spaces between sections–expansion joints–so that the surface, heated and expanding under the summer sun, has room to move without creating stress cracks or *heaving*. This type of road construction is seen more frequently in southern states where heat can be more of a problem to a road surface. It can also be seen when water boils; some molecules get so hot and move so fast that they are thrown off the surface and appear as steam.

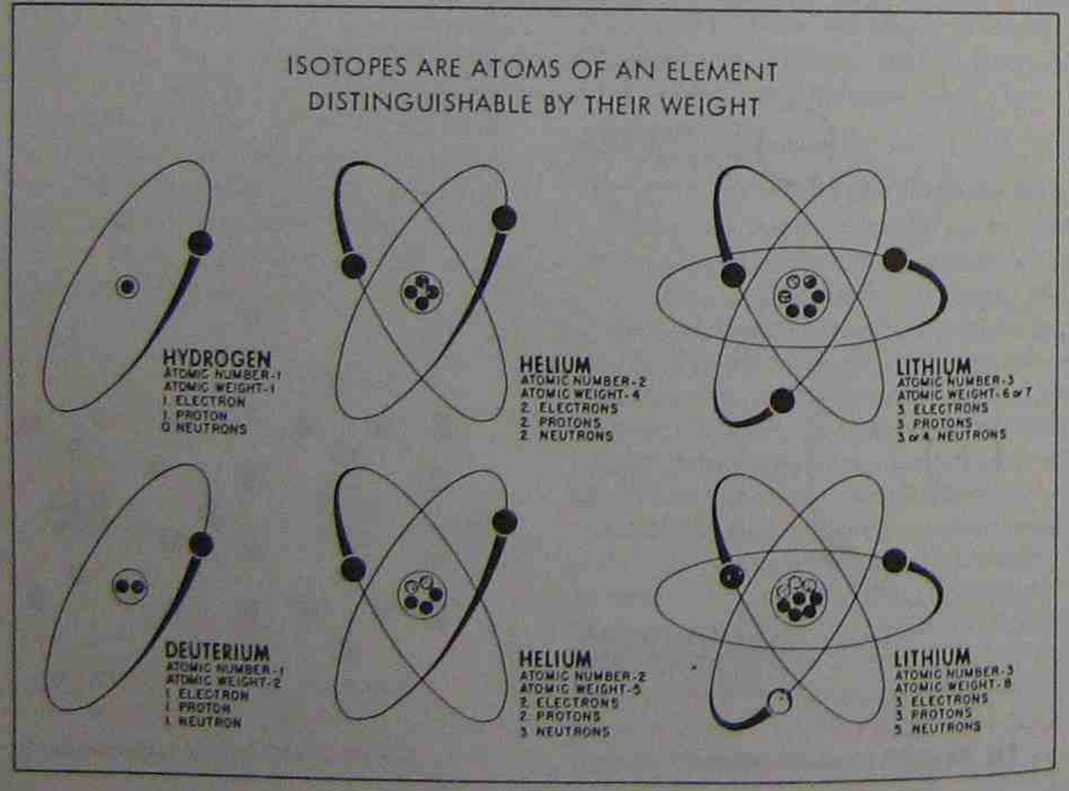


Fig. 23–6 Isotopes

The atom of each element has an *atomic weight*. This weight is the weight of the nucleus, or the combined number of protons and neutrons. Hydrogen, the lightest element, has one proton; its atomic weight is 1. Zinc has 30 protons and 35 neutrons; its atomic weight is 65. Uranium, a very heavy element, has 92 protons and 146 neutrons; its atomic weight is 238. The electrons are infinitely light and are not considered in atomic weight. Elements are also assigned *atomic numbers*, the number of protons in the nucleus. The atomic numbers for these elements then would be: hydrogen, 1; zinc, 30; and uranium, 92.

Another point in the understanding of atomic energy is isotopes. *Isotopes* are forms of the same element that have different atomic weights. The isotopes of an element are chemically alike and have the same atomic number, yet their total weight is different. The difference is in the number of neutrons in the nucleus. Isotopes are common; all elements have them. There are more than 1000 isotopes known today, figure 23–6.

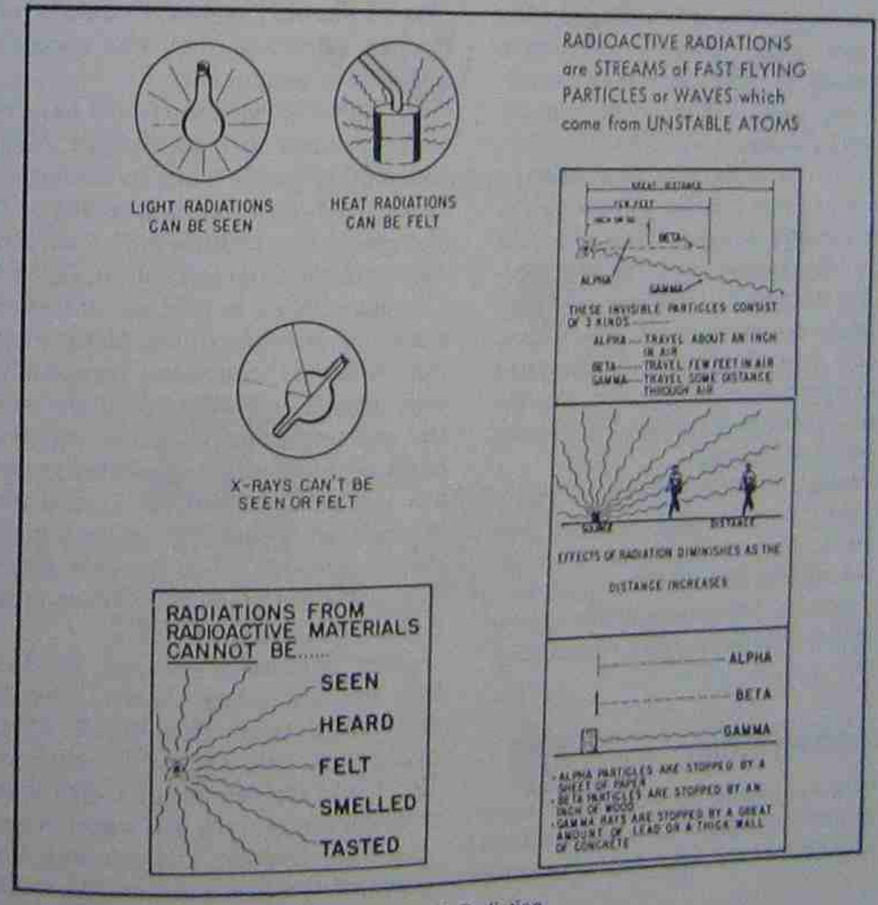


Fig. 23–7 Radiation

Radiation

Radiation is not new; we have always been exposed to it. It comes from the stars that are intensely radioactive and from the earth which is slightly radioactive. There are many *types* of radiation: light radiation which can be seen, heat radiation which can be felt, X-rays which can neither be seen nor felt, and radiation from radioactive material, figure 23–7. Our senses cannot detect radiation from radioactive material. Until recently, this last type of radiation occurred only in nature; now there are many man-made materials.

Radiation is a stream of fast-flying particles (waves) coming from atoms. There are three types: alpha, beta, and gamma. The *alpha* particle is heavy, travels a short distance, and can be stopped by human skin or a piece of paper. The *beta* particle is the same as an electron; it too can be easily shielded. However, alpha and beta particles are dangerous if taken into the body. The *gamma* ray is the most penetrating and dangerous. It is the radiant energy from the excess energy in the atom's mass. Great care must be taken to protect living tissue from gamma rays. Radiation, like fire or electricity, can be dangerous. It is a matter of the degree of exposure.

Uranium is a naturally radioactive element. The uranium atom loses protons in the form of radiation as it ages. The uranium slowly becomes radium and then finally becomes lead, a stable element. This process of one element changing into another is called *natural transmutation*.

NUCLEAR FISSION

As scientists studied the atom, they found that the atomic weight of each atom was less than the weight of the total mass of protons, neutrons, and electrons that it is composed of. Some of the mass appeared to have disappeared, contrary to the law of the conservation of matter which states that matter can be neither created nor destroyed, but only altered in form. As early as 1905, Albert Einstein reasoned that energy and mass were two forms of the same thing. He thought that the loss in mass was converted into energy. When free protons and neutrons were formed into a nucleus, they lost some mass. This loss in mass was converted into the energy that binds the nucleus together. If the atom could be broken or split, this binding energy could be released. Einstein calculated that this energy release would be tremendous.

Uranium-235 has been found to be the only natural element that can be split. An atom of uranium-235 is split when its nucleus is struck by a free neutron that is traveling at the correct speed. This neutron *bullet* can strike the nucleus of the atom and split it, figure 23–8.

Suppose that free neutrons are bombarding a mass of uranium atoms. Many of the neutrons will miss their target completely. However, when a neutron does hit the nucleus of the uranium atom, the atom will split. The result of this split is two smaller atoms, krypton and barium, figure 23–9. Also two more neutrons are freed. The process of splitting the uranium-235 atom is called *fission*. Just as Einstein had predicted, tremendous energy is released during the process.

Other isotopes of uranium, U-234 and U-238, will not undergo fission. That makes it unfortunate then, that 99.3% of uranium occurs as U-238. Only 0.7% is the valuable U-235, and the amount of U-234 is too small to be significant, even if it were fissionable.

A chain reaction is begun with the initial fission of the first uranium-235 atom, figure

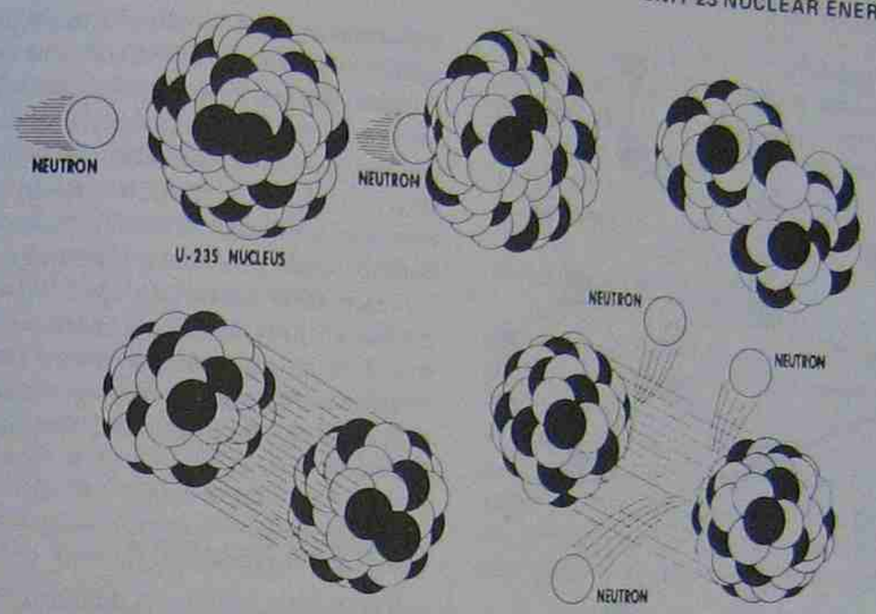


Fig. 23–8 Fissioning of uranium-235

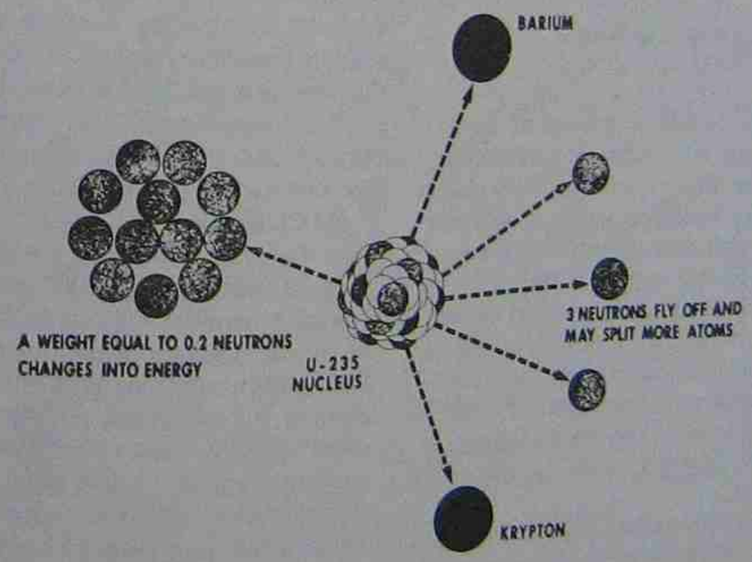


Fig. 23–9 Weight into energy

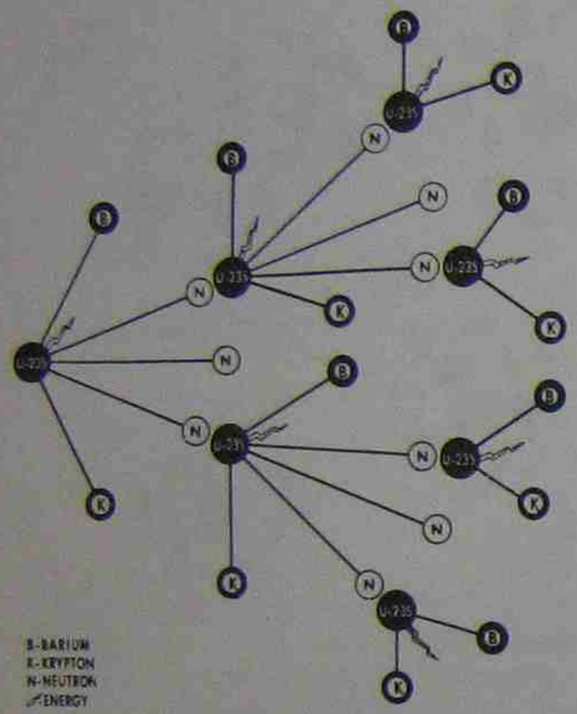


Fig. 23–10 Chain reaction

23–10. The free neutrons released in the fission travel until they strike and split other uranium atoms. With each fission in the chain reaction, energy is released and more neutrons are set free to strike and split still more atoms. An almost unlimited number of free neutrons can be released in an incredibly short amount of time. The result is an enormous release of energy. If the chain reaction is left uncontrolled, we have an atomic bomb, a destructive release of energy. The chain reaction can be controlled, however, with the use of an atomic reactor.

A chain reaction cannot be supported by a single atom. Neither can the reaction be supported by only two, three, or four atoms. There must be a large enough mass of uranium atoms present to support and propagate a chain reaction. If the mass is too small, the reaction will die out because too many neutrons are escaping from the surfaces. A mass where neutrons escape from the surfaces rapidly is said to be *sub-critical*. In order to maintain a productive chain reaction, there must be more than one additional atom split for each atom previously split. When a productive chain reaction is maintained, the mass is said to be *super-critical*. When the process of nuclear fission is proceeding at a controlled rate, as in a nuclear reactor, the mass is said to be *critical*.

NUCLEAR REACTOR

The nuclear reactor is designed to provide a controlled fission of the uranium atoms, releasing energy at a constant rate for a long period of time. The chain reaction is slowed down by diluting the uranium with another substance such as graphite. As fission occurs, the free neutrons are slowed down by the graphite *moderator*. This combination of uranium and graphite is referred to as a *pile*. The first atomic pile was built at the University of Chicago in 1942.

In figure 23–11, the initiating neutron works it way through the graphite atoms, striking a uranium nucleus at A, and causing its fission. Two more neutrons are emitted. The neutron following path #1 collides with graphite nuclei. These collisions reduce its speed until it causes the disintegration of another uranium nucleus at B. The disintegrating nucleus gives two more neutrons. The neutron following path #3 passes through the uranium mass C without causing disintegration, and proceeds to D, where it causes further reaction. The neutron proceeding along path #2 is captured by the uranium nucleus at E, since it is moving at a relatively high speed. The neutron following path #4 escapes through the surface of the pile.

The neutrons released by the fission of the U-235 may do one of three things. First, if the chain reaction is to be maintained, at least one of the neutrons must strike the nucleus of another U-235 atom causing its fission. Second, some of the neutrons that have been slowed down may be captured by the U-238 isotope. There are 140 of this heavier uranium isotope for every one U-235 isotope. When U-238 captures a neutron it becomes U-239. Neptunium U-239, which is radioactive, soon decays into a more stable form of U-239, plutonium. The formation of plutonium is important because it, too, is fissionable. Plutonium then can be used to help sustain the chain reaction at a later date. Third, the neutron can escape the pile. This is undesirable and should be kept to a minimum since it represents a loss.

Reactor: Parts and Function

The nuclear reactor itself is made up of several main parts. Atomic fuel, uranium U-235, is distributed within tons of U-238. The moderator, usually carbon in the form of graphite, or heavy water, has the effect of slowing the neutrons and also slowing the chain reaction. The control and safety rod mechanism regulates the chain reaction properly. Boron and cadmium rods are moved in

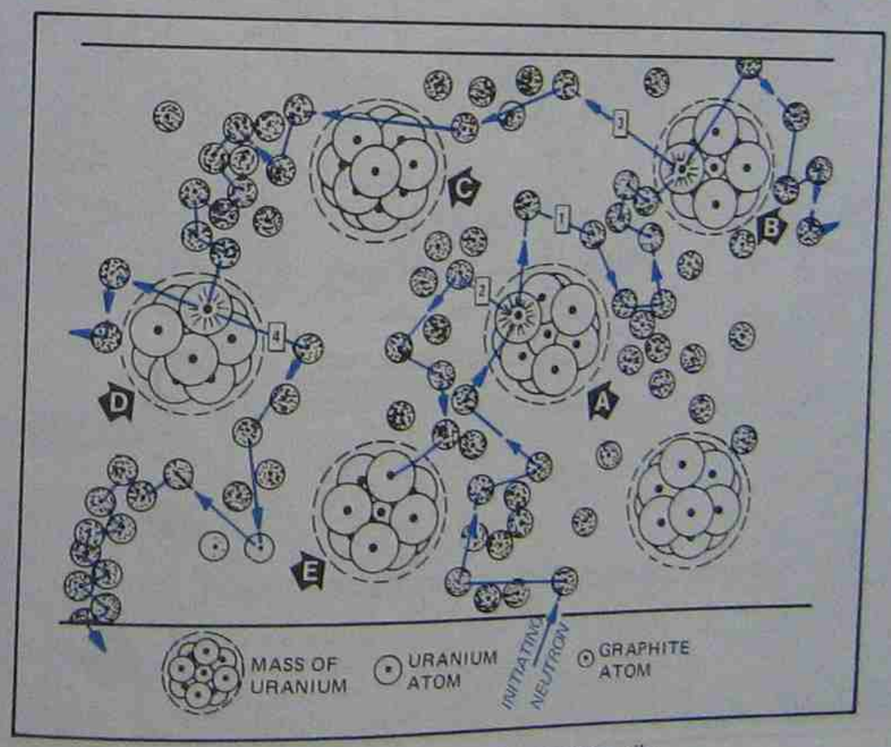


Fig. 23–11 Action of uranium-graphite pile

and out of the atomic pile to control fission, figure 23–12. Both of these elements have a strong ability to capture neutrons. When they are well into the pile they capture so many neutrons that there are not enough left to sustain the chain reaction. If the rods are all the way out of the pile, the chain reaction can reach sufficient intensity to burn up or melt down the materials. The rods are positioned to allow the desired level of reaction. The shield of a reactor is important for the protection of operating personnel. Concrete, several feet thick, and iron are used to completely enclose the reactor. The fission process emits neutrons and gamma rays that are very dangerous. The shield traps these dangerous rays and particles. The coolant is necessary to keep temperatures in the reactor low enough to prevent heat damage. The coolant is water or other fluids.

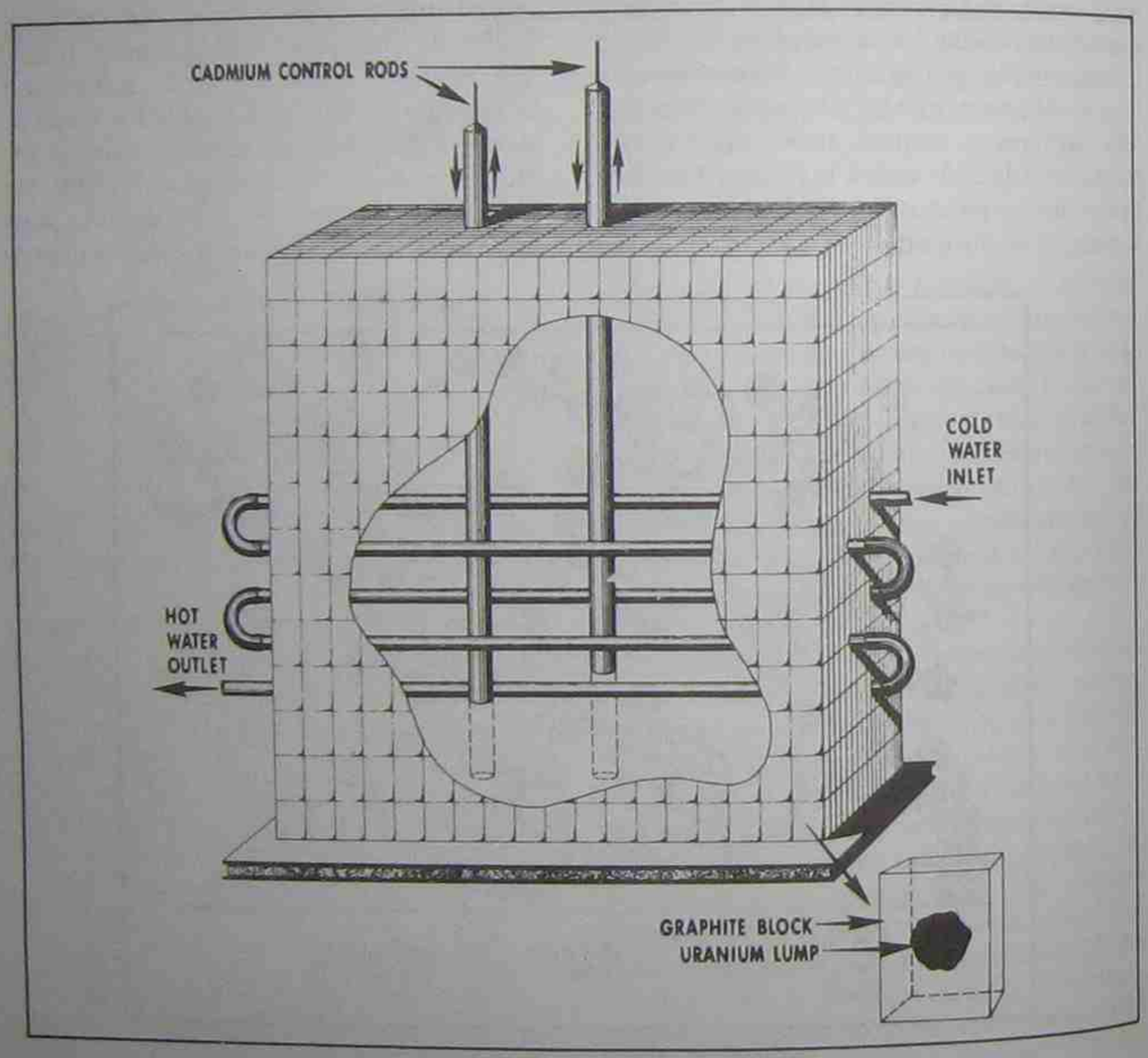


Fig. 23–12 Uranium-graphite pile

In power reactors, the coolant picks up this heat energy and uses it to produce power, which is perhaps the greatest potential use for the nuclear reactor, figure 23–13. Further, the

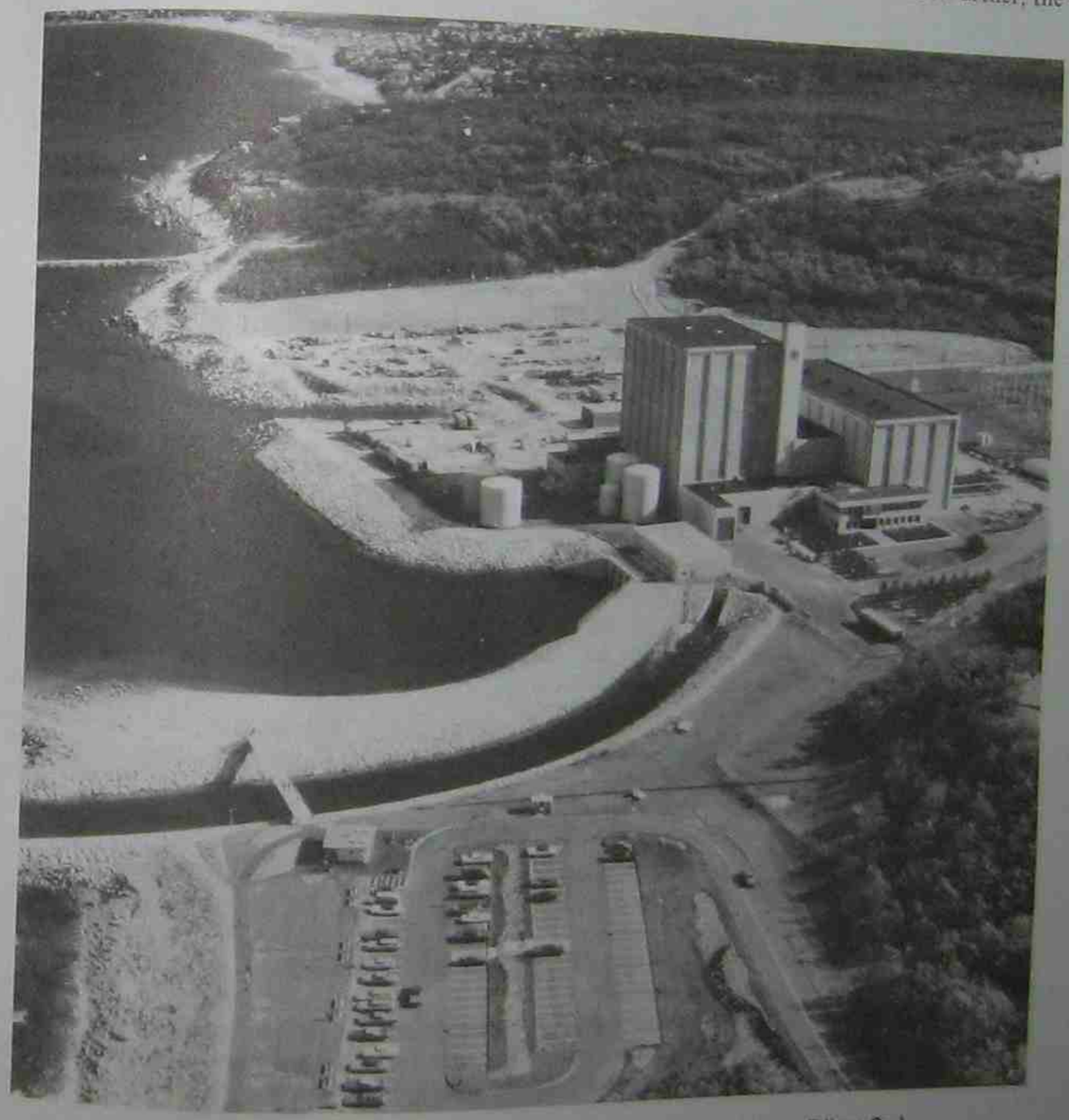


Fig. 23-13 Nuclear power plant—Pilgrim Station Unit 1 (Courtesy Boston Edison Co.)

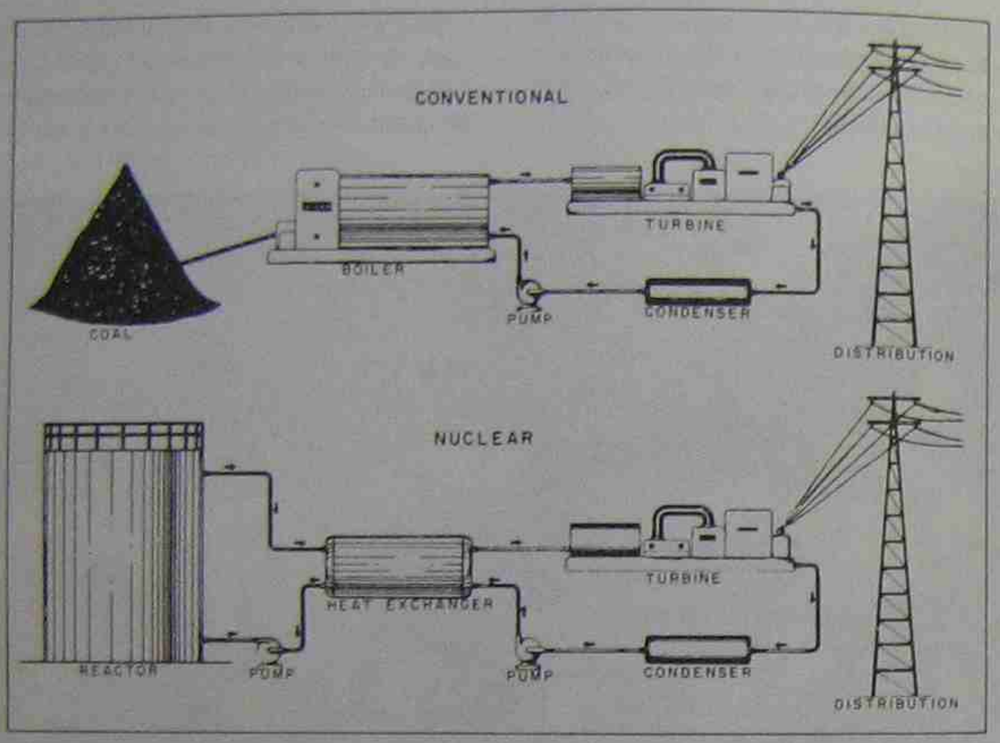


Fig. 23-14 Electrical power plants

intense heat energy of the reactor can be converted into electrical power because the action of a nuclear reactor used to produce electricity is very similar to that of a coal or oil-fired electrical generating station, figure 23-14.

As you can see in the figure, the intense heat energy inside the reactor is picked up by the coolant or heat exchange medium that flows through pipes within the pile. When heat is transferred to ordinary water in a heat exchanger or boiler, high-pressure steam is produced. The high-pressure steam is directed against the turbine blade, revolving the turbine which drives the electrical generator; power is produced. The coolant then returns



Fig. 23-15 Nuclear powered aircraft carrier Dwight D. Eisenhower (Courtesy Newport News Ship Building by American Petroleum Institute)



Fig. 23-16 Uranium mine and mill in northern Saskatchewan, Canada (Courtesy Gulf Oil Corporation by American Petroleum Institute)

to the reactor by way of a condenser, through the heat exchanger, and then to the reactor, where it is ready to begin a new cycle.

Eighty-five nuclear reactors are in operation throughout the nation producing almost 13% of our electrical energy. Fifty-seven more nuclear power plants are under construction. There are many other uses for nuclear reactors, such as nuclear-powered submarines and ships, figure 23-15. Nuclear locomotives and airplanes are also a possibility of the future. There is only a limited supply of uranium-235 available, but the known reserves of U-235 are expected to be adequate well into the next century, figure 23-16.

FAST BREEDER REACTOR

The liquid-metal fast breeder reactor is one of the answers to the long-term energy problem, hopefully stretching the uranium supply of several decades into several hundred years. To date, the breeder reactor is the only method that can extend our use of uranium, but at present the United States is lagging behind other countries in developing breeder reactor plants. Our Clinch River Breeder Reactor Project near Oak Ridge, Tennessee was scheduled to be in operation by 1980. Although 1.4 billion dollars has been spent on the project and plant design is almost 90% complete, political decisions have stalled the project.

The fast breeder reactor, figure 23-17, can use U-238, a non-fuel and convert it into U-239, a fuel. The breeder reactor does this by using fast, high-energy neutrons created by fission. They are captured, in turn, by U-238 (uranium) to create a new element, U-239 (plutonium) which is fissionable.

The liquid metal used in the fast breeder reactor is sodium. It allows neutrons to travel in the reactor with less interference. Liquid sodium does not degrade the neutrons, and it is the medium that cools the fuel and transfers the heat energy for electrical generation. The breeder reactor will not only replenish its own fuel supply but will also produce plutonium fuel for other nuclear plants.

NUCLEAR FUSION

If the goal of nuclear fusion is reached, the world may never face an energy crisis again. Fusion means coming together, while fission means splitting apart. The fusion process is the method the sun and the H-bomb use to create heat and light. Under controlled fusion, our own miniature suns can be created right on earth.

Fusion takes place when the nuclei of light elements collide and merge. The mass of the new nuclear particle is less than the total of the two separate masses. For example, if two

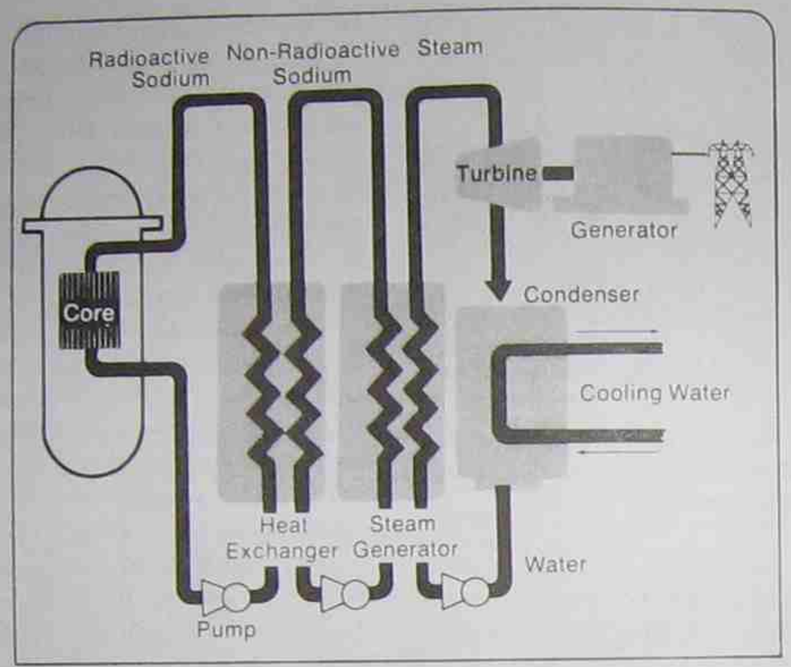


Fig. 23–17 Schematic of liquid metal fast breeder reactor

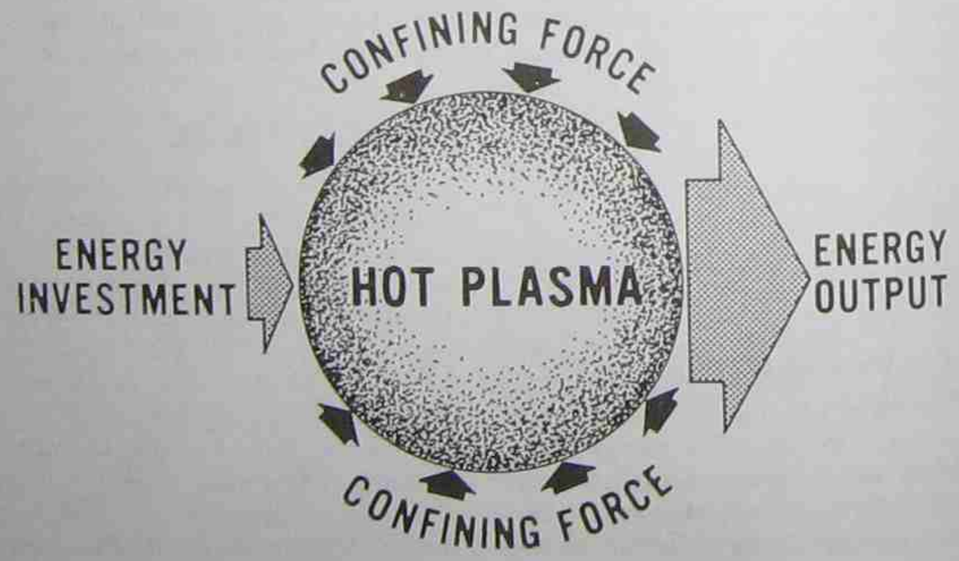


Fig. 23–18 Fusion requirements

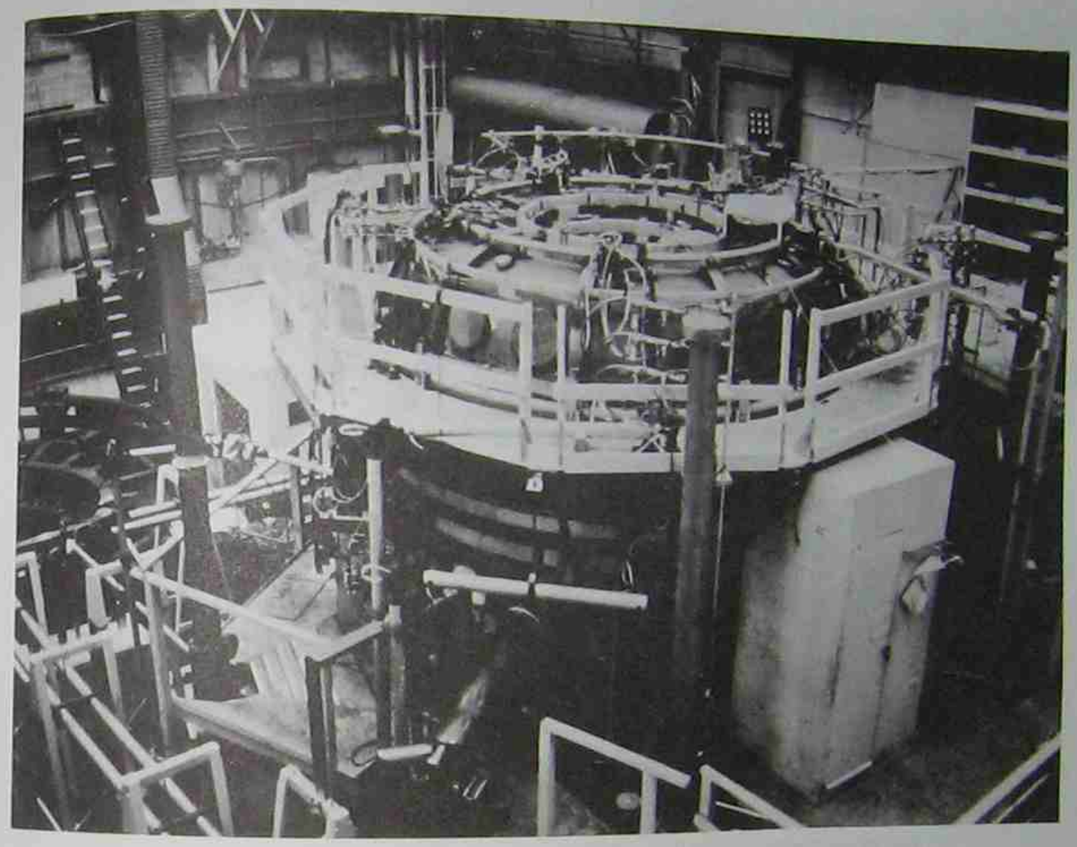


Fig. 23-19 Tokamak fusion reactor at Princeton University Plasma Laboratory (Courtesy of Electric Power Research Institute)

isotopes of hydrogen, deuterium and tritium, collide and merge, the result is a nucleus of helium and a free neutron. Just as in fission, mass has been changed to energy in the fusion process.

However, fusion does not take place easily because the positive nuclei will repel each other. In order to get the nuclei to fuse, very high temperatures are needed to speed up their movement. Also, the nuclei are densely packed to increase the chances for collision. The high temperature and high density is maintained long enough for the fusion to become self-sustaining, figure 23–18.

Several methods are being developed to produce the high temperatures necessary for fusion, figure 23–19. In magnetic confinement, a gas is heated inside a magnetic field. The gas looses its electrons, which form an envelope around the nuclei mass. Temperatures are fantastically high, 50 000 000°K. The container which is shaped like a hollow

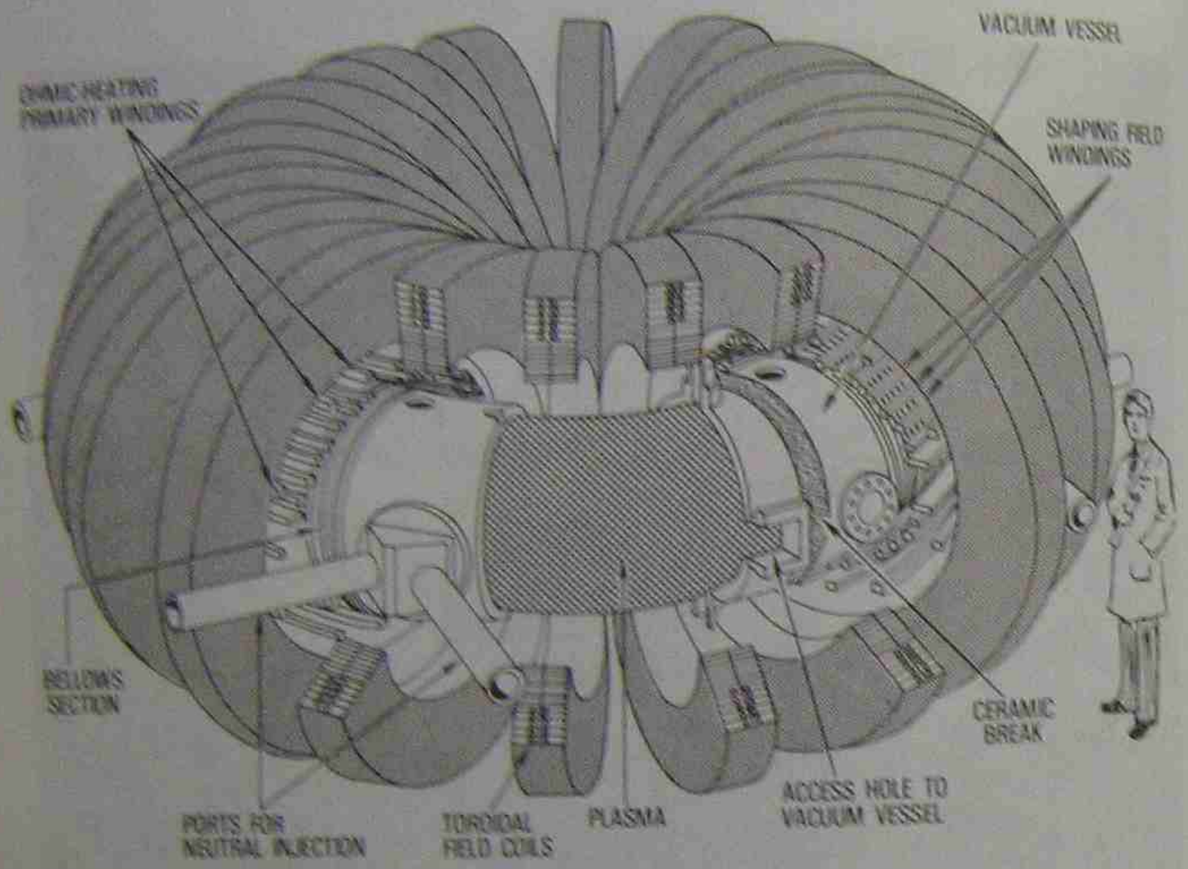


Fig. 23-20 Princeton Large Torus (PLT) is a toroid utilizing the tokamak concept

doughnut, is called a *toroid*, figure 23-20. Laser devices are also being developed to produce and contain the high temperature required for fusion.

It is possible that fusion power plants could become a reality early in the next century, figure 23-21. The fuel sources of deuterium and tritium can be found in sea water and, for all practical purposes, can be considered an inexhaustable fuel. When the energy of the sun is produced on earth through fusion, our energy needs can be met without relying on fossil fuels.

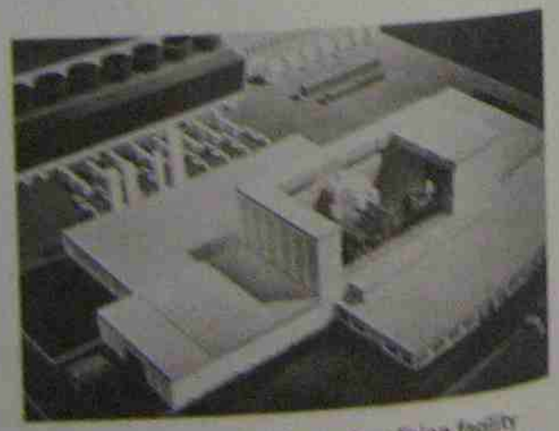


Fig. 23-21 Drawing of a nuclear fusion facility (Courtesy Standard Oil Company of California)

REVIEW QUESTIONS

1. Define the following terms: (a) atom, (b) molecule, and (c) compound.
2. What parts make up an atom? Explain their location in the atom.
3. What happens when atoms share their electrons?
4. Define atomic weight.
5. Define atomic number.
6. Define isotopes.
7. What is radiation? What are the three types of radiation?
8. What is fission?
9. List the products of uranium-235 fission.
10. Explain how a chain reaction takes place.
11. What is a nuclear reactor designed to accomplish?
12. What is plutonium?
13. List the main parts of a nuclear reactor and briefly explain the function of each part.
14. Explain how the heat energy within a nuclear reactor can be converted into electrical energy.

Unit 24 The Direct Conversion of Energy

OBJECTIVES After completing this unit, the student should be able to:

- Explain why direct conversion of energy is more efficient than other systems.
- List and discuss the methods used to produce electricity directly from primary energy sources.

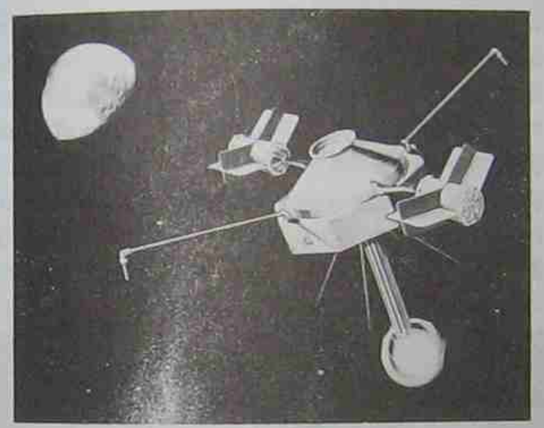
Energy should be put to work in as direct a manner as possible. The long route of changing energy through several different states is costly and wasteful. Under usual circumstances energy cannot be destroyed, but it can be lost to friction, or be converted into other forms that are not involved in producing the desired power. For example, notice the waste of energy involved in producing electricity, which is the most universally used type of power for home and industry.

TO → / FROM ↓	ELECTROMAGNETIC	CHEMICAL	NUCLEAR	THERMAL	KINETIC (MECHANICAL)	ELECTRICAL	GRAVITATIONAL
ELECTRO-MAGNETIC		Chemiluminescence (fireflies)	Gamma reactions (Co^{60} source) A-bomb	Thermal radiation (hot iron)	Accelerating charge (cyclotron) Phosphor	Electromagnetic radiation (TV transmitter) Electrolumines-cence	Unknown
CHEMICAL	Photosynthesis (plants) Photochemistry (photographic film)		Radiation catalysis (hydrazine plant) Ionization (cloud chamber)	Boiling (water/steam) Dissociation	Dissociation by radiolysis	Electrolysis (production of aluminum)	Unknown
NUCLEAR	Gamma-neutron reactions ($Be^9 + \gamma \rightarrow Be^8 + n$)	Unknown		Unknown	Unknown	Unknown	Unknown
THERMAL	Solar absorber (hot sidewalk)	Combustion (fire)	Fission (fuel element) Fusion		Friction (brake shoes)	Resistance-heating (electric stove)	Unknown
KINETIC (MECHANICAL)	Radiometer Solar cell	Muscle	Radioactivity (alpha particles) A-bomb	Thermal expansion (turbines) Internal combus-tion (engines)		Motors Electrostriction (sonar transmitter)	Falling objects
ELECTRICAL	Photoelectricity (light meter) Radio antenna Solar cell	Fuel cell Batteries	Nuclear battery	Thermoelectricity Thermionics Thermomagnetism Ferroelectricity	MHD † Conventional generator		Unknown
GRAVITATIONAL	Unknown	Unknown	Unknown	Unknown	Rising objects (rockets)	Unknown	

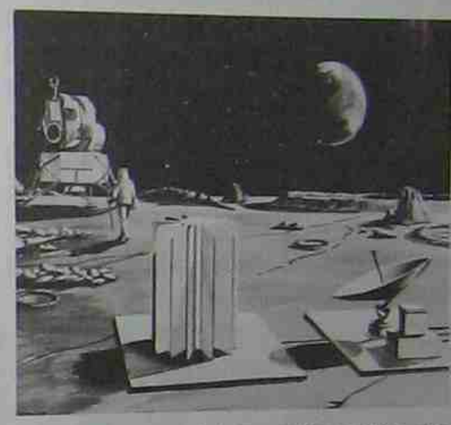
†Magnetohydrodynamics

Fig. 24-1

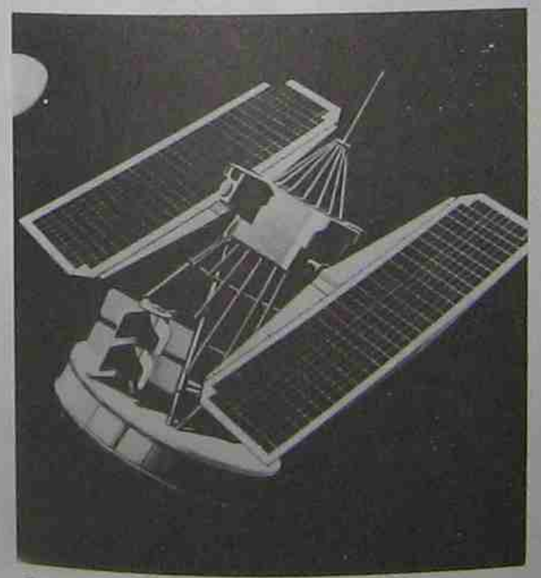
1. The chemical energy of coal is converted into thermal energy as it burns.
2. This thermal energy is absorbed
   water.
3. Steam is produced and directed ag
   the blades of a turbine, converting
   thermal energy into mechanical ene
4. The mechanical energy of the tur



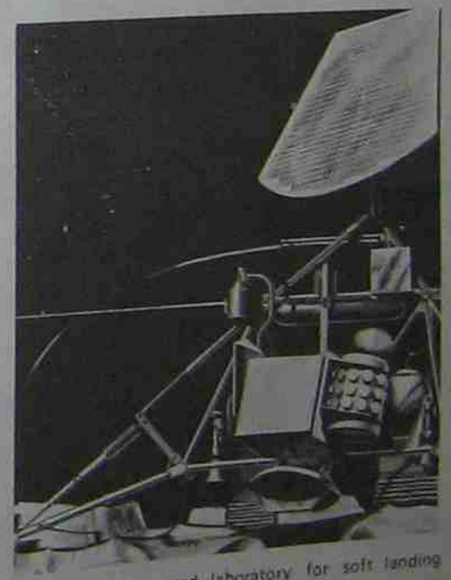
A. Atomic generators convert heat from radioactive fuel into electricity to power radio transmitters of satellites.



B. A nuclear-powered device, center, supplied elec-trical power for explorations on the moon.



C. Atomic fuel provides the power for instrumenta-tion of this weather satellite.



D. A nuclear-powered laboratory for soft landing on the lunar surface.

Fig. 24-2 U.S. atomic energy SNAP program (Systems for Nuclear Auxiliary Power) utilize direct energy verters. (Courtesy Atomic Energy Commission)

rotates the generator and the energy is at last converted into electrical energy for transmission and use.

5. The electrical energy may again take many forms as it is used by the consumer.

The described method is good; it is reliable; it produces the vast portion of all electrical energy, but it does represent the long route of energy conversion.

Imagine how much more efficient it would be if an energy form could be converted directly into electrical energy. The idea is not impossible, and it is certainly not new. Several direct conversion techniques have been demonstrated by scientists in the laboratory for many years, figure 24-1. The conventional battery has also been converting chemical energy directly into electrical energy for a long time, but it does have limitations of weight and length of service.

In our space age technology, many of the laboratory phenomena of direct energy conversion are under constant, intensive development. The result has been a whole new family of direct energy conversion devices. A good deal of the development of these energy conversion devices has come from the nation's space program, figures 24-2 and 24-3.

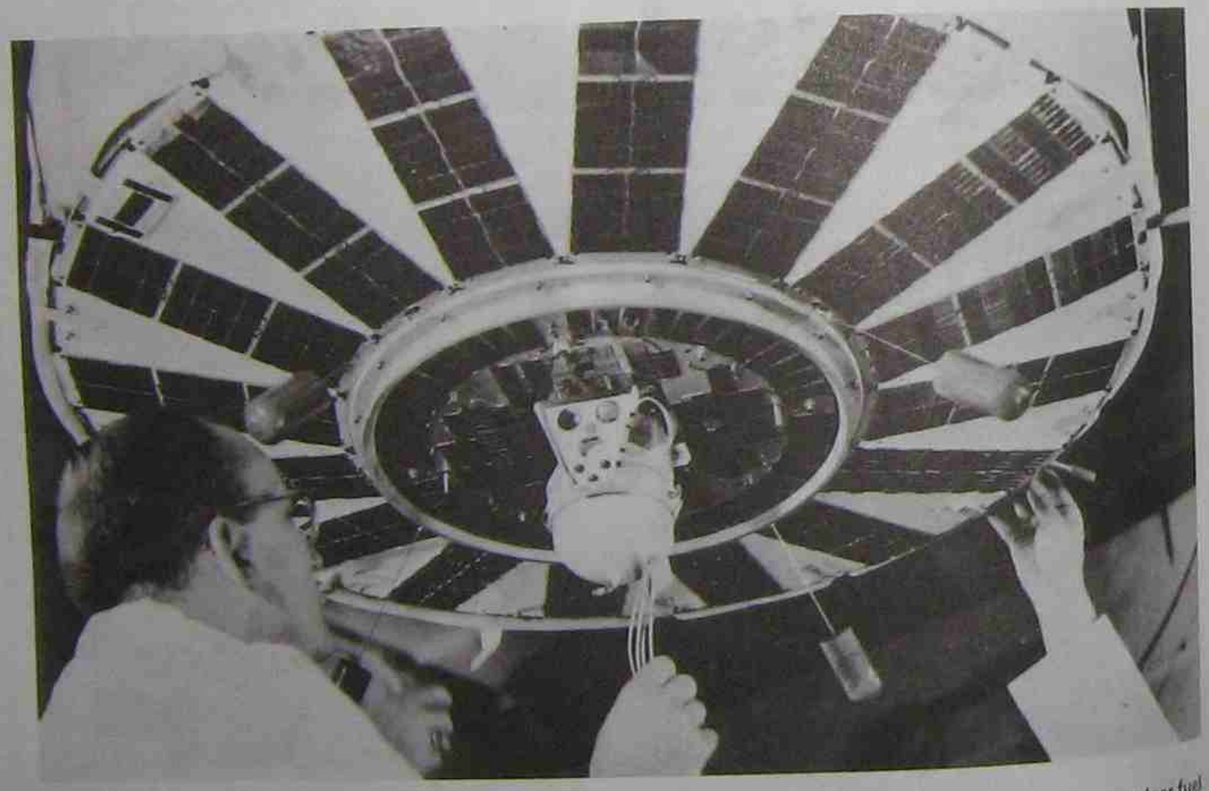


Fig. 24-3 Tiny nuclear generator is fastened to base of a TRANSIT satellite. In the orbiting generator, nuclear fuel generates heat which is converted through thermocouples to electrical energy. (Courtesy Atomic Energy Commission)

Space systems need rockets for basic propulsion, but, in addition, they need electrical systems that fit the requirements of long service life, low weight, and high reliability. Direct energy converters can meet these requirements. They play a part in meeting the electrical, electronic, and life support functions involved in outer space projects.

The direct energy conversion devices also have applications beyond their uses in space exploration. They can be used wherever long life, low weight, and high reliability are of great importance. These energy converters are now the heart of several rapidly maturing industries. In many cases, these products are out of the laboratory, off the drawing board, and are being manufactured and put into space, military and commercial use.

When direct energy converters are discussed, the topic concerns various devices that are capable of producing electricity directly from one of the primary energy sources. Several direct energy converters are discussed in this unit:

- *Solar cell*, electrical energy from the sun; electromagnetic energy
- *Thermophotovoltaic (TPV) converter*, electrical energy from thermal photons
- *Fuel cell*, electrical energy from chemical energy
- *Nuclear battery*, electrical energy from nuclear energy
- *Thermoelectricity and Thermionics*, electrical energy from thermal energy
- *Magnetohydrodynamic (MHD)generator*, electrical energy from kinetic energy

These energy converters do not rely on the dynamic conversion of energy through reciprocating or rotary machines. Quietness of operation is inherent in these energy converters since there are no moving parts. These techniques are highly sophisticated in their manufacture, but still very reliable and safe under normal operating conditions.

While heat engines are basically the domain of the mechanical engineer, direct energy converters are more the domain of the electrical engineer, chemist, physicist, and nuclear scientist.

The sun gives the earth heat and light. This huge, intensely hot body of gases is responsible for most of the energy we use, such as fossil fuels, wind, and water power. Section 7, Alternative Energy Sources, discusses solar heating, hydroelectric, and wind energy. In this unit, the aspect of solar energy discussed is the direct conversion of solar energy into electricity.

Devices that directly convert the sun's radiant energy into electrical power have been in existence for many years. The photogalvanic cell had its beginning in 1839. The barrier-layer photovoltaic cell was developed around 1876. These devices still have many applications today, but they do not produce much electricity. They are, therefore, suitable for measuring instruments and controlling devices that require small voltages. The devices mentioned are generally unsuitable for producing electricity in quantity or in competition with conventional electrical generators. At best, these units are only one percent efficient when converting solar energy into electrical power.

The *photogalvanic cell* is made of two electrodes suspended in an electrolyte. When light falls on only one of the electrodes, an electromotive force is produced.

The *photovoltaic cell* produces an electromotive force when it is exposed to light. A

light-sensitive semiconductor, such as selenium, is used in this cell. The photocell is often used in photographic exposure meters, photoelectric eyes, and photoswitches.

No significant breakthroughs in the search for ways to directly convert more of the sun's radiant energy into electricity were recorded until 1954. In that year, three scientists from the Bell Telephone Laboratories reported that they had improved the photovoltaic cell and increased its efficiency to six percent. The scientists, D. M. Chapin, C. S. Fuller, and G. L. Pearson, later succeeded in raising the efficiency of their silicon photovoltaic cell to eleven percent. A device with an efficiency of eleven percent does have possibilities of becoming a practical electrical power source. For example, on a clear day in Phoenix, Arizona, if 1000 watts of solar energy falls on a square meter of the silicon photovoltaic cell, 110 watts of electrical power can be provided.

THE SOLAR CELL

The photovoltaic cell, commonly called the solar cell or battery (and made of semiconductive materials) is now a reality and has found important uses in providing electricity for more than 80 communications satellites that can relay telephone conversations, radio, and television around the world, figure 24-4. Space communications of all types rely heavily on the solar cell. For the consumer, the solar cell is seen in the millions of economical solar-powered calculators sold almost everywhere. Their solar cell needs just ordinary daylight or artifical light to produce sufficient electrical energy to operate the device.

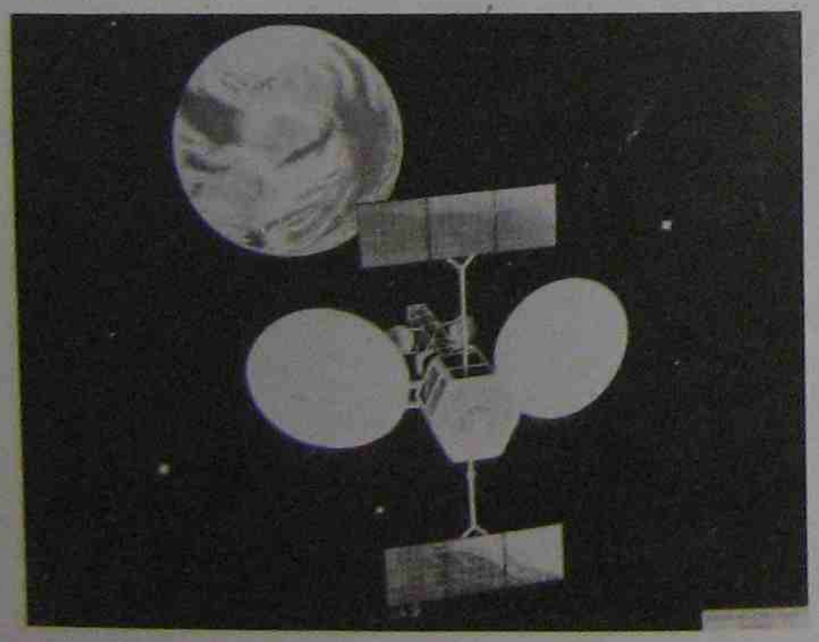


Fig. 24-4 Solar cell array on a communications satellite (Courtesy NASA)

Conductors, Insulators, and Semiconductors

The previous paragraph stated that solar cells were made up of semiconductive materials. At this point, it will be wise to review the various qualities of this and other materials to determine why semiconductor construction is the best choice.

Conductors, as you remember, are materials with loosely bound electrons that can easily move about. Insulators are materials with tightly bound electrons that cannot move about easily. Ninety percent of the substances we know are either conductors or insulators. However, there are a few substances that cannot be classed as either conductors or insulators. They are called semiconductors; silicon and germanium are examples, figure 24-5.

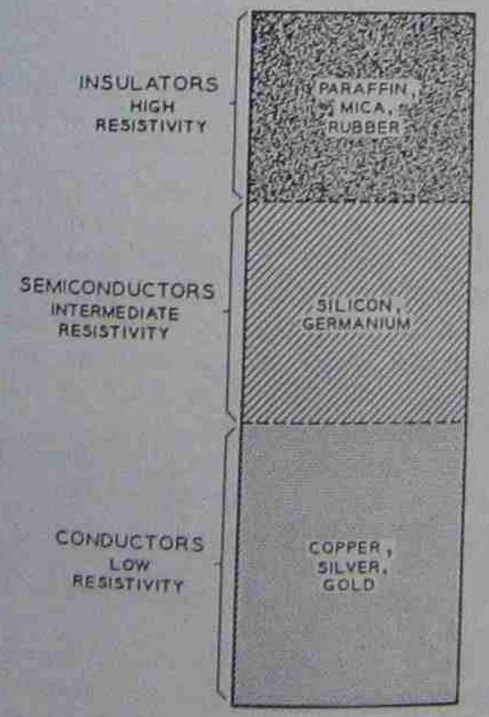


Fig. 24-5 Resistivity of insulators, conductors, and semiconductors

Insulators have a high resistance to the flow of electrons while conductors have a low resistance to the flow of electrons. Semiconductors, because they are artificially made in the laboratory, can have any amount of resistance designed into them.

The conducting qualities of semiconductors change with the temperature of the material. As a semiconductor is heated, it becomes a better conductor of electricity. More electrons are free to leave their atoms and move about. The reverse is also true. Cooling the semiconductor makes it a better insulator since fewer electrons break out of their orbits and become free electrons.

Figure 24-6 shows what takes place in a semiconductor. Though oversimplified, the drawings do illustrate the point. Drawing (A) shows a tray with ball bearings covering its bottom. The ball bearings represent the semiconducting material. Drawing (B) illustrates the semiconductor at absolute zero. The tray is tipped (electrical field), but the electrons will not flow and so the material will not conduct. In (C) the semiconductor is heated, the tray is shaken (thermal energy) and an electron hops out of orbit. The material becomes conductive. In (D) a potential is again applied. The free electrons can now move. The ball bearing moves to the lower end, leaving a hole at the upper end.

Semiconductors are heat sensitive and photosensitive. Light falling on a semiconducting material causes more electrons to leave their orbits, creating free electrons and electron holes which lack electrons. Photons are light energy and their effect on a semi-

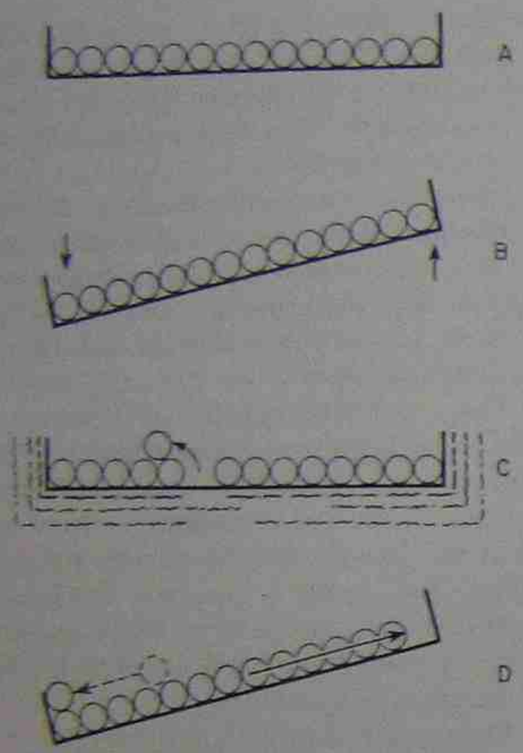


Fig. 24-6 Ball bearings in a tray illustrate the action of a semiconductor.

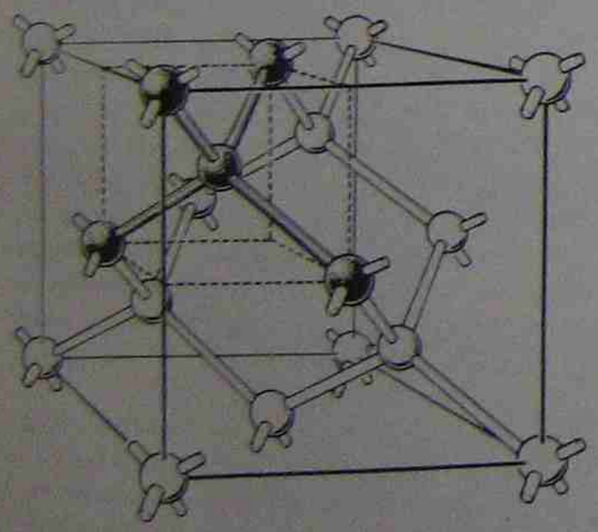


Fig. 24-7 Crystal lattice structure of silicon or germanium

conductor could be compared to pellets striking a tray of ball bearings.

Silicon and germanium are good semiconducting materials. They can be made very pure and both have a very desirable crystalline structure, figure 24-7. Electrons can be set free in both of these materials by the action of thermal energy or by striking the materials with photons of light energy.

Construction of the Solar Cell

A solar cell is made by combining pure silicon with a minute amount of arsenic by a special process. The combination of silicon and arsenic creates a new lattice pattern containing a free (extra) electron and is called an N-type (negative) semiconductor. The addition of boron in a later stage of the battery's construction produces yet another lattice pattern with a missing electron and is called a P-type (positive) semiconductor, figure 24-8. The area of the battery where the two semiconductors meet is referred to as the PN-junction.

Ultra pure silicon is *doped* (mixed with an impurity) with a minute amount of arsenic. The two materials are melted together and cast in the form of a small ingot, a single crystal of silicon. The addition of the arsenic makes the silicon rich in electrons. Silicon treated in this manner is called an N-type semiconductor.

The single silicon crystal is then sliced into very small, thin wafers. Rectangular in shape, these wafers are cut about 1/25th of an inch (1 millimeter) thick by a special crystal cutting machine. The silicon wafers are then polished to a high degree.

Boron is added to the surface of the silicon wafer. The wafer is placed in a quartz tube with a vapor containing boron. The boron is diffused into the surface of the silicon. Boron

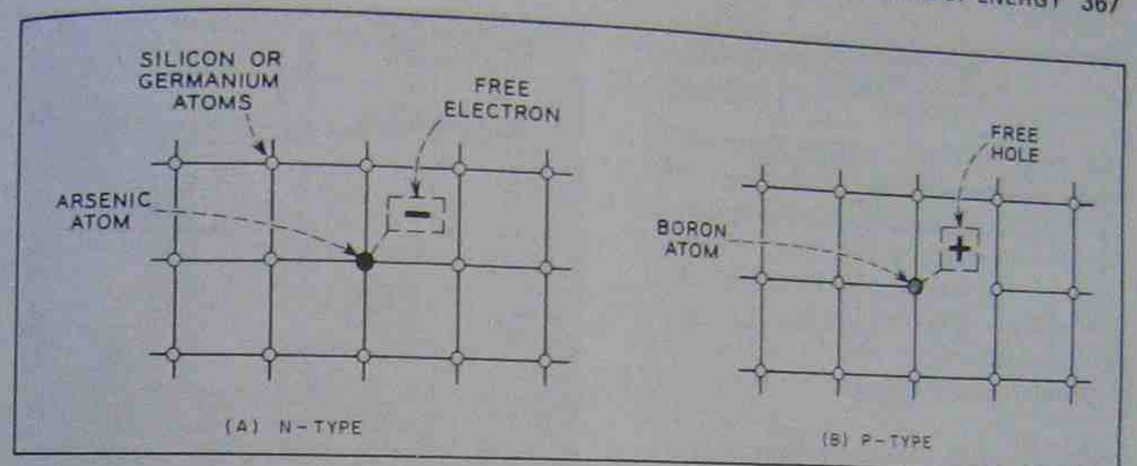


Fig. 24-8 Semiconductors

has the effect of reducing the total number of electrons that are potentially free. The boron-treated area of the wafer is said to be a P-type semiconductor. The boron penetrates only a small distance into the wafer, about 1/10,000 of an inch (.0025 millimeter). The area where the N-type semiconductor and the P-type semiconductor meet is called the PN-junction. The PN-junction is the heart of the solar cell.

Finally, the wafers are cleaned and then plated so that conducting wires can be attached to the wafer. Connected in series, several wafers are combined to form a solar-energized power source of electrical energy, figure 24-9.

Operation

The PN-junction is important to consider. The N-type silicon is, by nature, electron rich while the P-type silicon is hole rich. When light strikes the solar cell, and particularly the PN-junction, photons break electrons away from their atoms. Electrons and holes are

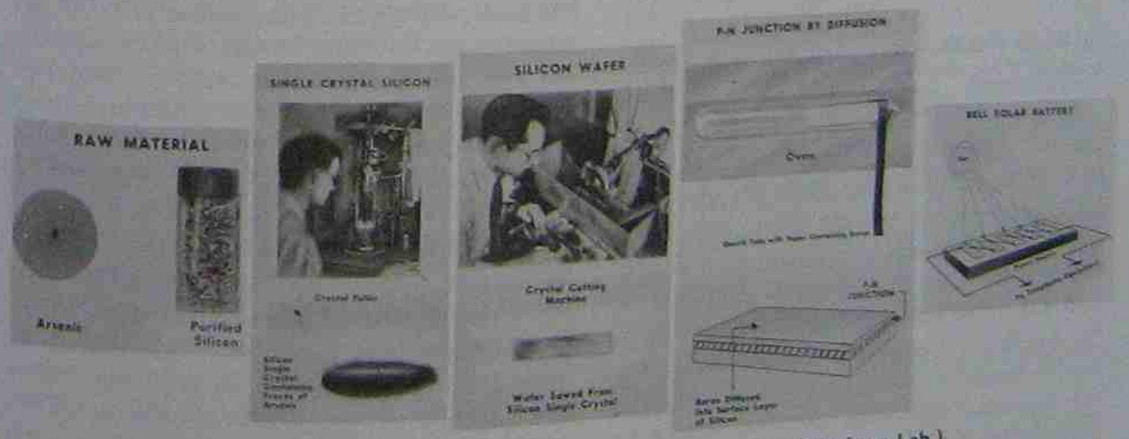


Fig. 24-9 Steps in constructing a solar battery (Courtesy Bell Telephone Lab.)

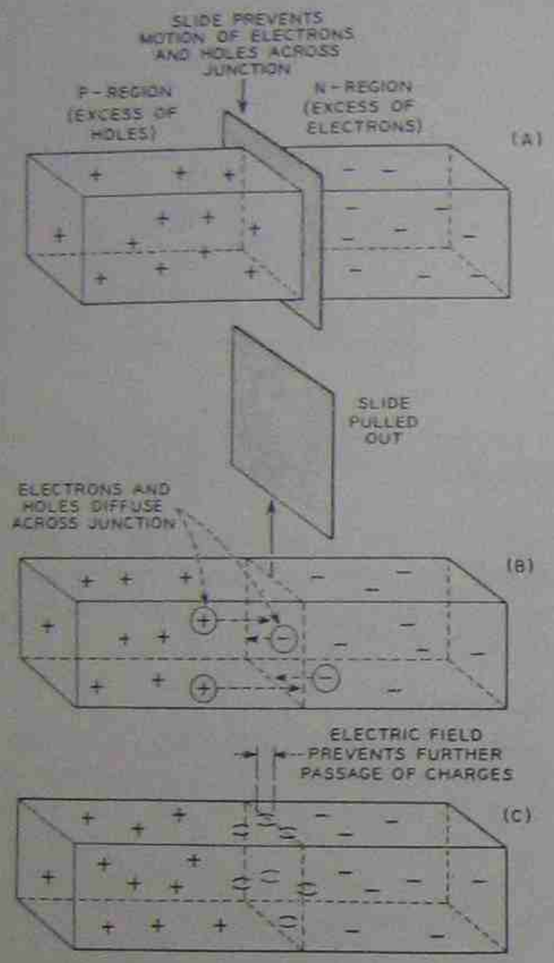


Fig. 24-10 Electric field is being built up at the PN junction.

created, electron hole pairs. The electric field at the PN-junction forces the electrons into the N-region and the holes into the P-region. The N-region is negative; the P-region is positive. There is a potential difference of about 0.6 volt between the two regions when the battery is exposed to direct sunlight. If a load is connected between the two terminals, the potential will cause electrical current to flow. Light energy has been converted directly into electrical energy by the solar cell.

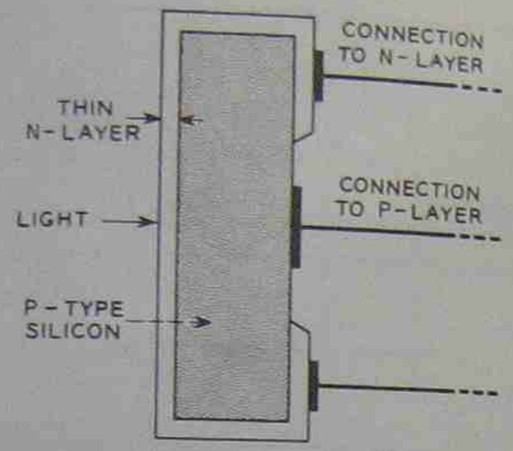


Fig. 24-11 Cross-section shows construction of the solar cell.

Figure 24-10 illustrates how an electric field is built up at the PN-junction. Drawing (A) shows the P-region and N-region separated by an imaginary slide. In (B), the slide is pulled out and electrons and holes diffuse across the junction. In (C), an electric field quickly builds up at the PN junction to prevent further flow.

If wires are connected to the N-region and the P-region, and a load is placed across the terminals, electrons will flow from the N-region to the P-region, figure 24-11.

Cost

Costs of producing electricity from solar cells started at $1000 per watt of power in the 1950s. Ten years ago the cost had been slashed to $20. Today's cost is $5-9, still a high price considering that electricity from conventional sources is 6¢ per kilowatt hour. However, a technique for producing solar cells in a ribbon form is reducing prices even further—down to 40¢ to $1 per kilowatt hour, figure 24-12.

The thin film solar cells are just one thousandth (0.0001") of an inch thick. The cells are silicon but their atomic structure is not in crystalline form. Their amorphic, random form allows them to be deposited on a thin film. These solar cells have an efficiency of 5% compared with 12% for a crystalline solar cell but the cost of production far outweighs the loss in efficiency.

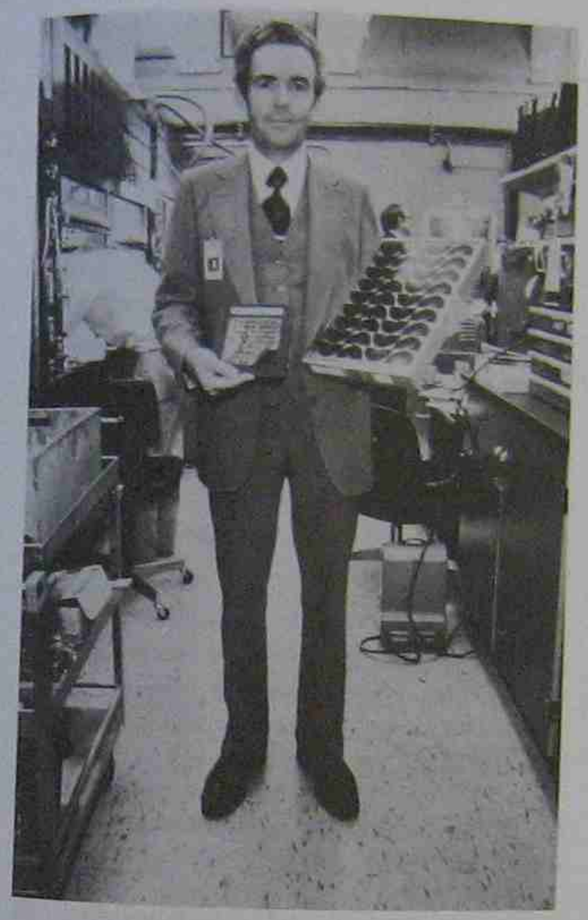


Fig. 24-12 A commercial solar cell array currently priced at $200 a square foot. The smaller model (left hand) portrays a comparable thin film cell which researchers hope can be made to sell for $2-3 per square foot. (Courtesy Standard Oil of California)

THERMOPHOTOVOLTAIC CONVERTERS

Thermophotovoltaic converters use heat (thermo) to develop an incandescent light source, producing thermal photons (photo) which are directed to a semiconducting material capable of inducing voltages across its terminals (voltaic). This new concept was introduced in 1961 by Pierre Aigrain during his lecture series at the Massachusetts Institute of Technology.

Figure 24-13 illustrates a thermophotovoltaic (TPV) converter. In this converter, the photons that excite the semiconducting material do not come from the sun as they do in the case of the solar battery. They come from a hot incandescent light source. The photons that are generated are directed toward the surface of the semiconducting converter by a parabolic mirror.

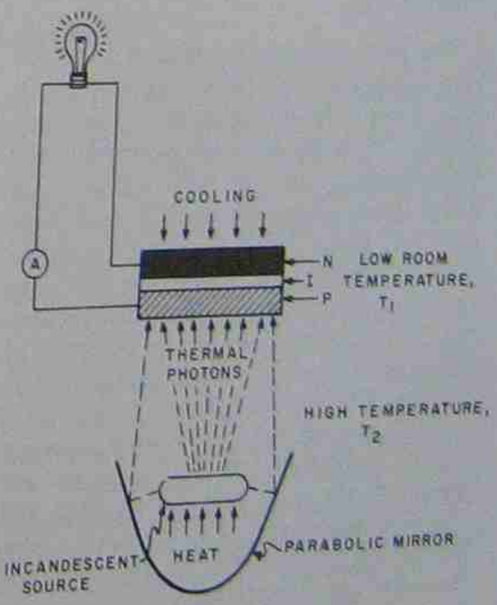


Fig. 24-13 Thermophotovoltaic converter

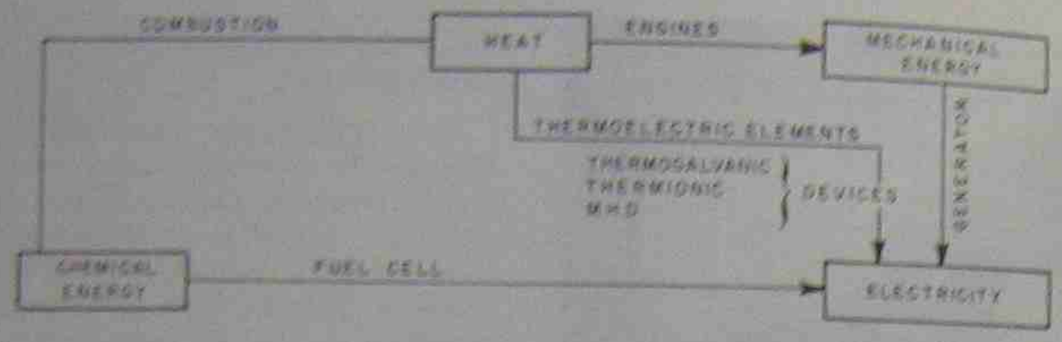


Fig. 24-14 Paths for conversion of chemical energy into electrical energy. Note that fuel cells bypass the heat conversion step.

Much exploration remains to be done with the TPV process, but it has several advantages. A practical efficiency of 30 to 35% is anticipated. Heat is converted to light through incandescence and, in turn, light is converted to electrical energy by a photocell at room temperature.

FUEL CELL

The fuel cell produces electrical energy directly from chemical energy, figure 24-14. To date, these cells are the most efficient nonnuclear devices for generating electrical power. Theoretically, they are 100% efficient, but actual gross efficiences of 80% have been recorded, figure 24-15. Electrical generation by heat engines can seldom top 40%. The Gemini spacecraft used fuel cells to produce the electrical power needed for operation of the space capsule's electronic and life-support systems. The nation's moon shot project, Apollo, also used fuel cells for these purposes.

The applications of fuel cells are not limited to the space program. In 1962 Allis Chalmers announced plans to market a fork-lift driven by fuel cells. In 1966 the Esso Research and Engineering Company demonstrated an experimental automated fuel cell battery. If inexpensive materials can be found to replace the expensive platinum catalysts used, such systems may eventually have wide applications as a portable power supply, figure 24-16.

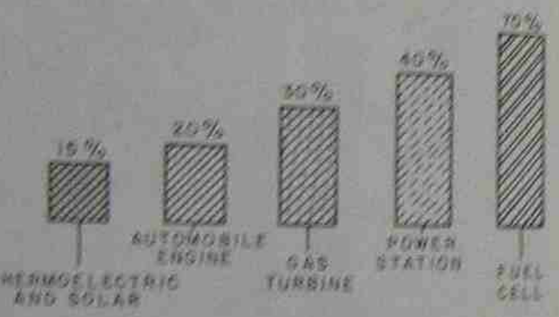


Fig. 24-15 Comparison of efficiencies of energy conversion systems. Note superiority of the fuel cell.

The fuel cell is an electrochemical device, like a storage battery, which converts chemical energy into electrical energy. But it is different in important ways. Where the storage battery has its fuel built in as expendable or rechargeable electrodes, the fuel cell has its fuel fed in from outside the cell. The electrodes of the fuel cell are not consumed as are the battery's.



Fig. 24-16 Fuel cell, delivering current for a power drill, operates on the low-cost liquid fuel, methanol. (Courtesy Esso Research and Engineering)

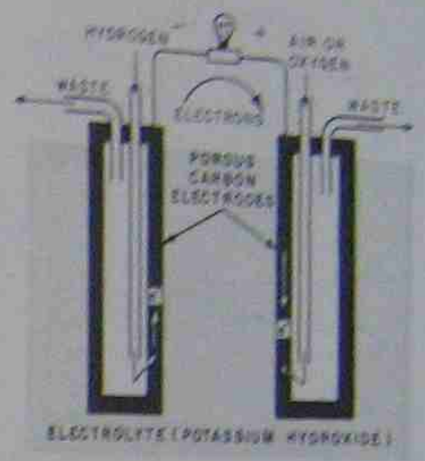


Fig. 24-17 Basic hydrogen-oxygen fuel cell

Fuel Cell Components

In addition to the fuel, the cell contains two electrodes, one positive and one negative, and an electrolyte which serves as the electrochemical connection between the electrodes. Catalysts promote the reaction.

The electrodes bring the reactants in contact with the electrolyte in a controlled way. They also serve as catalysts and carry the current generated by the reaction. Common electrode materials include silver, nickel, palladium, mercury, platinum, and carbon, figure 24-17. The *anode* is the electrode at which the fuel gives up electrodes for delivery to the external circuit. The *cathode* is the electrode that gives up electrons to the oxidizer.

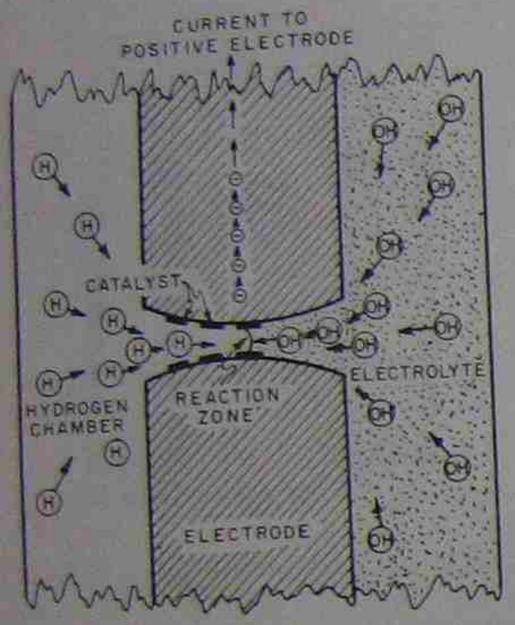
The electrolyte provides the means for ionic conduction. Some common electrolytes include potassium hydroxide, sea water, phosphates and zirconates.

No less than two fuels are needed for operation of the fuel cell. One is the oxidant or electron donor, and the other is the reductant, or electron acceptor. A few common oxidants are oxygen, air, chlorine and brine. Reductants include hydrogen, carbon monoxide, natural gas, methanol, and zinc.

Operation

The hydrogen-oxygen (hydrox) fuel cell is one of several types, and is used for space applications. Others are oxygen-concentration cells, redox cells, hydrocarbon cells, and ion-exchange cells. The basic principle on which the hydrox fuel cell operates is simple. When hydrogen and oxygen are combined to form water, they release electrical energy.

Figure 24-18 shows the cell and the basic chemical action. Two hollow porous carbon electrodes are immersed in a potassium hydroxide electrolyte. Hydrogen is pumped into one electrode and oxygen into the other. The hydrogen molecules containing two hydrogen atoms flow into the pores of the negative electrode. A catalyst splits them into two separate hydrogen atoms. The atoms drift to the reaction zone while ions from the potas-



g. 24-18 Reaction in pores of electrode between ydrogen and hydroxide produces electrons that ow toward positive electrode.

ium hydroxide electrolyte drift toward the ame zone. Here the hydroxyl ions combine o form water and release electrons.

The surplus electrons flow toward the ositive electrode. Here oxygen atoms are lowing into the pores of the electrode and combined with water molecules from the electrolyte. The incoming electrons combine with this combination to form ions which replace those being used on the negative electrode. The cycle is continuous.

Advantages and Uses

The advantages of fuel cells are numerous. They have high efficiencies of 70 to 90% because the thermal cycle necessary in the conventional conversion of chemical energy to electrical energy has been eliminated. Fuel cells have no moving parts, do not produce noxious fumes, and can be built in any size and capacity. They are rugged, require little maintenance, and are efficient in all sizes. An offshoot of the process in the hydrogen-oxygen cell is drinking water, which is utilized in such applications as manned space vehicles. Another important advantage is that when no load is connected to the cell, no energy is consumed.

For spacecraft use the two fuels, hydrogen and oxygen, are contained in high-pressure, low-temperature tanks which liquefy these gases, conserving valuable space and weight, figure 24-19. The gases are put through a heat exchanger which brings their temperature to about that of the cell. A fuel cell using methanol and air presents fewer fuel storage problems for land use and has greater promise of approaching a competitive energy cost. Methane is an inexpensive and readily available fuel.

The development of inexpensive materials and less complex systems are the goals for further research; there are also many problems which require such research. One problem is elimination of the water which results from the reaction and weakens the electrolyte in the hydrox-type cell. This very drawback on land is the main reason it is used in the space program. In the manned space application the astronauts will make good use of this water. Another problem is that gases of high purity are required. One attempt to avoid this is the redox cell, *red*uction and *ox*idation, figure 24-20. Although these and other problems remain to be overcome, the fuel cell holds promise as a significant power source.

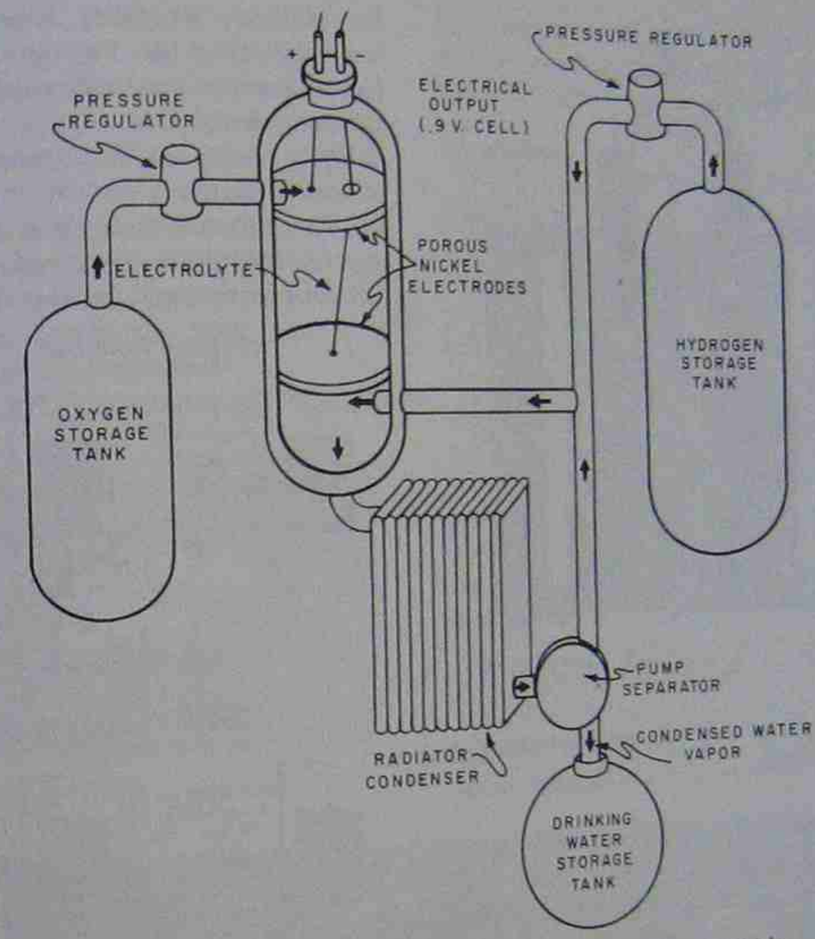


Fig. 24-19 Simplified representation of a fuel cell for manned space vehicles

THERMOELECTRICITY

The thermoelectric principle has been known for some 140 years. This principle, one that converts heat directly into electricity, was observed by T. J. Seebeck in 1821. Two dissimilar materials, such as two different wires, were joined together and heated. At the unheated terminals a small voltage was recorded. The voltages produced were so small that little practical use could be seen for the thermoelectric principle until recently when semiconducting materials were developed. Thermocouples made of semiconductive materials are vastly more efficient than earlier thermocouples.

A review of semiconductor principles will be helpful in understanding thermoelectricity.

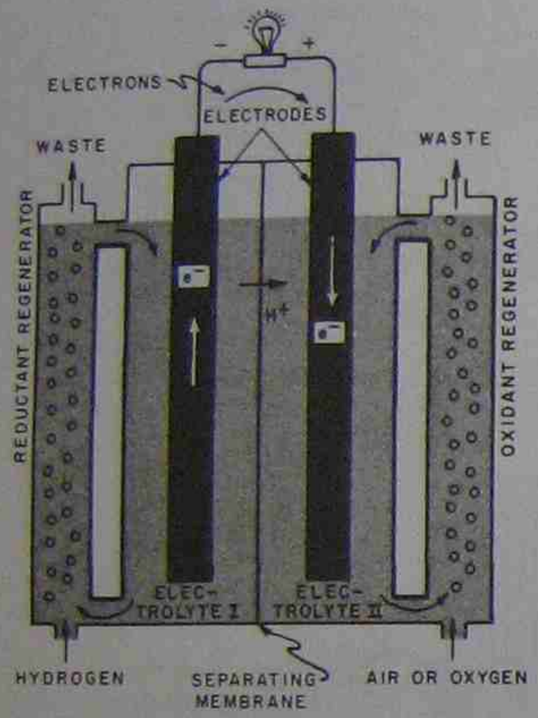
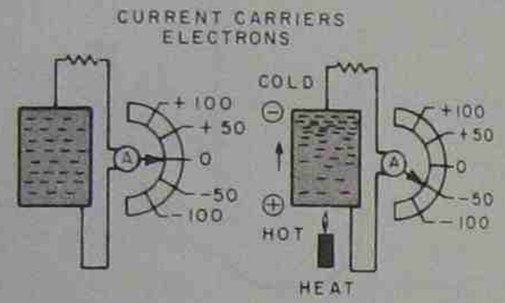


Fig. 24-20 Redox cell with membrane separating the two electrodes

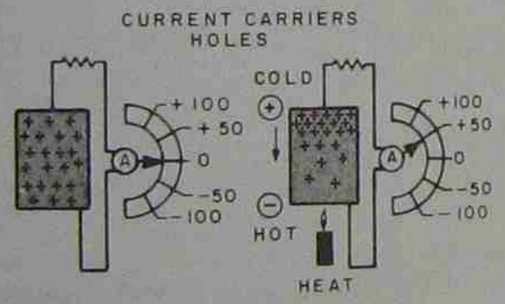
The semiconductor does not have many loose electrons that can become current as do metallic materials. The semiconducting material would, in fact, be an insulator if impurity atoms were not introduced into the material. If the impurity atom that is introduced has more than enough electrons to satisfy the valence-bond needs of the surrounding atoms, there is an electron surplus. A semiconductor of this type is called an N-type semiconductor.

If the impurity atoms introduced on the semiconducting material are basically short of electrons themselves and therefore do not have sufficient electrons to satisfy the valence-bond needs of the surrounding atoms, the material is full of positive holes. The holes can move within the lattice framework of the material, wandering around much the same as electrons do. But the hole is positive; hence these semiconductors are referred to as P-type semiconductors.

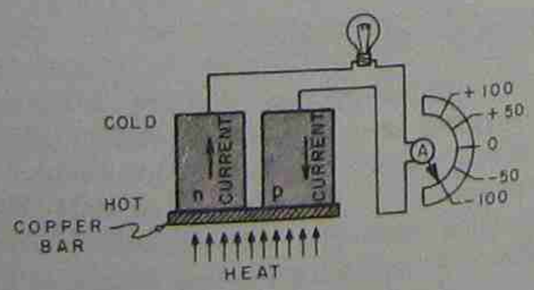
Figure 24-21 shows a simplified version of heat-to-electricity conversion in N-type and P-type semiconductors. When heat is applied to one end of the semiconductor (A), the electrons in that end increase their velocities



(A) N-Type Semiconductor



(B) P-Type Semiconductor



(C) Thermoelectric Generator

Fig. 24-21 Thermoelectric converter

and their kinetic energy. These electrons travel toward the cold end of the semiconductor and pile up. When the circuit is closed, these electrons will flow through the semiconductor and through the wire from negative to positive.

When a P-type semiconductor is used (B), the positive holes pile up at the cold end, and electrons flow from the cold toward the hot end of the semiconductor, from negative to positive through the wire.

A thermoelectric generator (C) connects

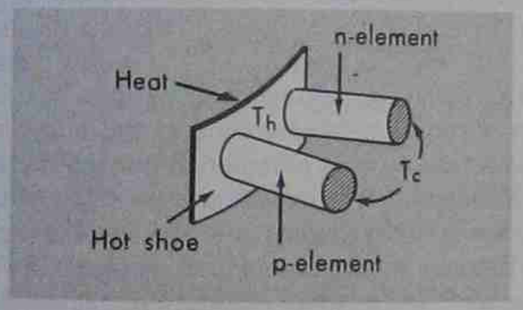


Fig. 24-22 Thermoelectric couple

both the types of semiconductors into an effective producer of electric power. It transforms heat directly into electrical energy.

Advantages

The whole operation of producing electricity from a heated thermocouple is still inefficient, in the range of one percent to five percent, whereas a steam power plant might have an efficiency of 35 to 40%. There are still distinct advantages to this direct conversion principle, however. There are no moving parts, so maintenance and lubrication are not a problem, figure 24-22. The device is silent. Any source of heat can be used to stimulate the flow of electrons and holes: gas and radioisotopes, for example. Thermoelectric devices can, therefore, operate for long periods of time unattended. It is on this point they find their greatest application; powering navigational buoys, remote weather stations in the polar regions, powering floating weather stations, and powering undersea navigational beacons, figure 24-23.

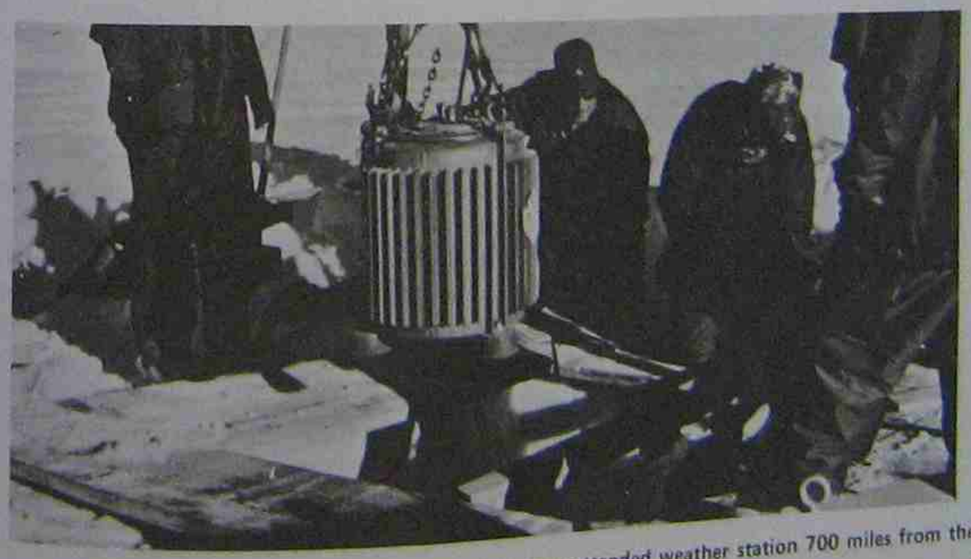


Fig. 24-23 A SNAP generator being installed in an unattended weather station 700 miles from the south pole (Courtesy Atomic Energy Commission)

In the space program, a thermoelectric generator of electricity has several advantages over solar batteries in that it can provide power when the satellite or space capsule is in a shadow and cannot use the sun. Also, when solar cells pass through radioactive belts, they tend to deteriorate. Compared to traditional batteries, the thermoelectric device has the advantage in both length of service and weight.

The thermoelectric converters that are used in the space programs of today have been largely developed under the SNAP program which was initiated by the Atomic Energy Commission in 1956. SNAP stands for Systems for Nuclear Auxiliary Power.

One of the basic concepts of the program is to apply the heat from decaying radioisotopes to the junctions of a thermoelectric mechanism to produce electricity. Another branch of the SNAP program is at work producing electricity by using small nuclear space reactors as a power source.

Radioisotopes and Thermocouples

An isotope of an element has the same number of electrons and protons as the element, but it has a different number of neutrons. Therefore, the chemistry of the isotope and the element is the same but their atomic weights are different. Of the many isotopes, some are unstable and decay, emitting three types of radiation: alpha, beta, and gamma rays. These unstable isotopes are called *radioisotopes*.

Radioisotopes can be used in several different ways. They may be directed at a material with the purpose of altering the material, such as destroying cancerous tissue with radiation treatment. They may be used by directing a fixed source at the object to detect the amount of radiation that is reflected or penetrates the object, such as using radioactive material to gauge a moving sheet of steel. They may be used in medical and agricultural research where small amounts of radioactive material can be introduced into and followed

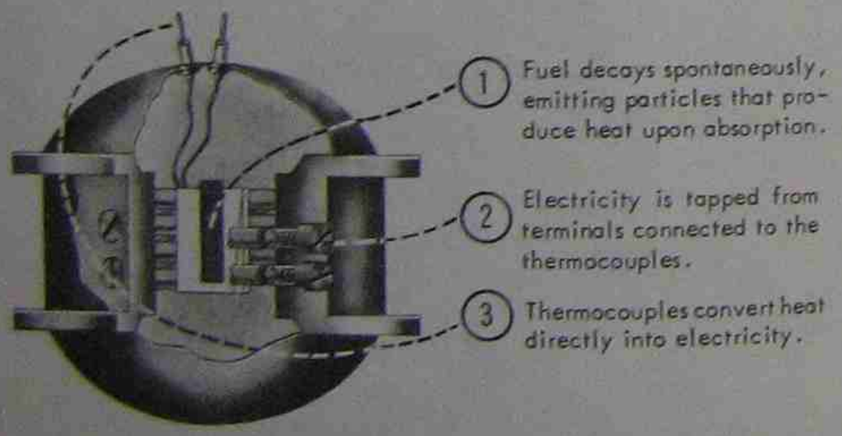


Fig. 24-24 Operation of thermoelectric generator powered by radio isotopes

DESIGNATION	USE	POWER (watts)	GENERATOR LIFE	ISOTOPE
SNAP-3	Demonstration Device	2.5	90 days	Polonium-210
SNAP-3A	Satellite Power	2.7	5 years	Plutonium-238
	Axel Heilberg Weather Station	5	2 years min.	Strontium-90
SNAP-7A	Navigational Buoy	10	2 years min.	Strontium-90
SNAP-7B	Fixed Navigational Light	60	2 years min.	Strontium-90
SNAP-7C	Weather Station	10	2 years min.	Strontium-90
SNAP-7D	Floating Weather Station	60	2 years min.	Strontium-90
SNAP-7E	Ocean-bottom Beacon	7.5	2 years min.	Strontium-90
SNAP-7F	Offshore Oil Rig	60	2 years min.	Strontium-90
SNAP-9A	Satellite Power	25	5 years	Plutonium-238
SNAP-11	Moon Probe	21-25	90 days	Curium-242
SNAP-13	Demonstration Device	12	90 days	Curium-242
SNAP-15A	Military Use	0.001	5 years	Plutonium-238
SNAP-17	Communication Satellite	25	5 years	Strontium-90
SNAP-19B	Nimbus-B Weather Satellite	30	5 years	Plutonium-238
SNAP-21	Deep Sea Use	10	5 years	Strontium-90
SNAP-23	Terrestrial Uses	60	5 years	Strontium-90
SNAP-27	Lunar Landings	60	5 years	Plutonium-238
SNAP-29	Various Missions	500	90 days	Polonium-210

Fig. 24-25

or traced through a system. The energy released in radioisotope decay can be used to produce thermal energy. SNAP devices produce thermal energy as the radiation is absorbed.

Scientists have successfully combined the semiconducting thermocouple and the radioisotope. The first of these devices was completed in 1959. It was the size of a grapefruit and capable of producing 2.5 watts of electricity for a 90-day period, figure 24-24. It used polonium-210 as the radioisotope fuel. Other SNAP devices of various power outputs and longevity have followed, figure 24-25.

The SNAP device is made up of an outer shell that protects the internal components. A radioactive shield is under the shell. If alpha-emitting fuels are used, there is little need for the shield, but if gamma radiation is present, a massive shield may be needed.

Thermoelectric converters or thermocouples that convert a portion of the decay into electricity, and the fuel capsule of radioactive material are located at the very center of the generator.

The radiation particles themselves do not escape from the device. All are trapped inside the fuel capsule where their vast kinetic energy is converted into heat energy. Of the heat energy that is produced, only 5 to 10% is used to produce electricity, the rest eventually escapes to the outer shell and to the media the device is operating in, figure 24-26.

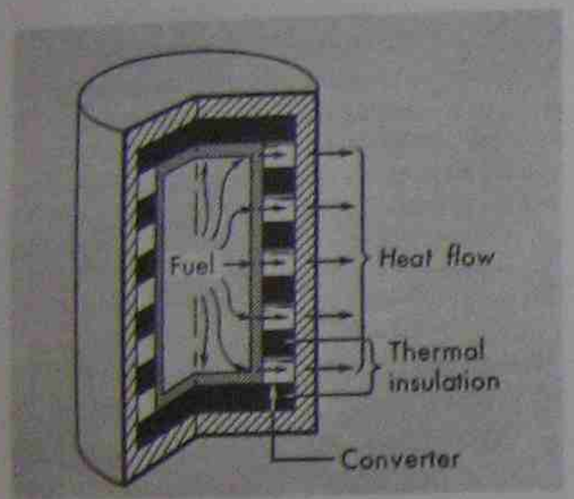


Fig. 24-26 Radioisotope generator showing unavoidable heat loss

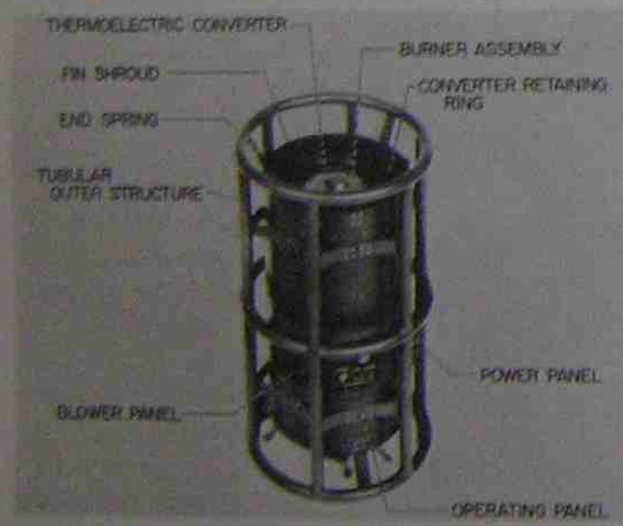


Fig. 24-27 A thermoelectric device that can operate on leaded gasoline, jet fuel, or diesel fuel

Other Heat Sources. Thermoelectric devices that employ more conventional heat sources have also recently come out of the laboratory and into production. These units employ propane or natural gas fuels fired through an enclosed burner. The primary advantage of hydrocarbon fuels versus radioisotope fuels is that of cost; radioisotope fuels are expensive, and hydrocarbon fuels can even compete with conventional batteries. Remote site power can be provided for $2 to $3 per kilowatt-hour using a gas-fired thermoelectric generator, while primary batteries may cost $10 to $18 per kilowatt-hour.

Like the SNAP devices, the gas-fired thermoelectric devices are excellent for remote, unattended service. Of course, periodic replenishment of the fuel is necessary. The Minnesota Mining and Manufacturing Company (3M) is currently producing commercial units that range in output from less than one watt to fifty watts, with larger wattage units being developed, figure 24-27.

THERMIONIC CONVERTERS

Thermionic converters are low-voltage, high-current generators. Their main uses have been in space vehicles. The idea of thermionic conversion, (the generation of electricity from heat) is based on Thomas Edison's discovery that electrons are emitted from a heated cathode. It is called the *Edison effect*. Boiling off electrons from the hot cathode to the cold anode results in an electrostatic charge of negative electrons forming near the cathode. This *space charge* repels other electrons and blocks their flow, figure 24-28. Depending on the methods used to overcome the space charge barrier, three main types of thermionic converters have been developed:

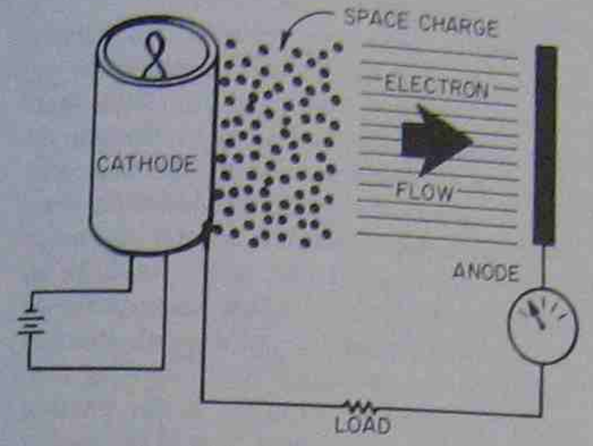


Fig. 24-28 Space-charge effect

- Vacuum close-spaced diode
- Magnetic triode
- Cesium plasma diode

Vacuum Close-Spaced Diode

This vacuum tube places the cathode and anode very close together to avoid the detrimental effect of the space charge, figure 24-29. Close-spaced diodes were first developed at MIT in 1956 and were called thermoelectron machines. They are heat engines which use the electron gas to deliver useful work as a result of passing through the electrostatic field.

The efficiency of these devices is from 12 to 14% and they weigh the least of all energy converters. However, the cathodes must operate at high temperatures, which shorten their life considerably and reduce efficiencies.

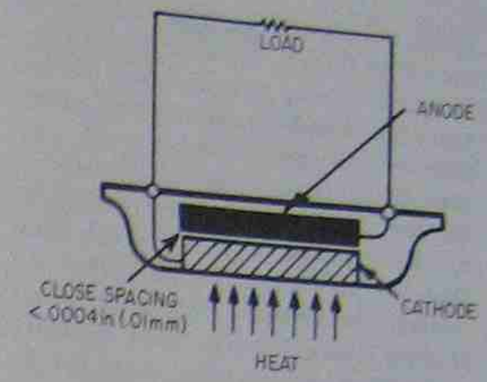


Fig. 24-29 Vacuum close-spaced diode

Magnetic Triode

This device reduces the space charge effect by using crossed electric and magnetic fields. A hot cathode and a cold anode are placed in the same plane and close together. Above them an accelerating anode is placed. A battery produces an electric field between the cathode and anode. An external magnetic field is superimposed by operating the entire device between the poles of a large magnet, figure 24-30.

The electron emitted from the hot cathode

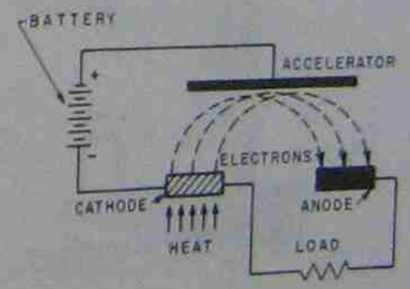


Fig. 24-30 Magnetic triode

speeds towards the accelerator. But the magnetic field deflects it toward the surface of the anode. During its acceleration, the electron gains kinetic energy from the electric field. When it falls back to the anode, it returns that energy to the field. The result is that the energies of the electrons arriving at the anode are the same as they were when they left the cathode. In theory then, the magnetic triode should produce more power than the close-spaced diode. However, due to a number of electron losses, this is not the case.

Cesium Plasma Diods

Use of an ionized gas is another way of counteracting the space charge. In diodes filled with cesium plasma, the positive ions neutralize the negative space charge and allow the electrons to flow toward the anode, figure 24-31. A single ion can effectively cancel several hundred electrons.

As in the vacuum close-spaced diode, the cathode must operate at exceedingly high temperatures which shorten its life. Other fabrication difficulties are involved with the corrosiveness of the cesium vapor. Efficiencies of 10 to 25% have been achieved.

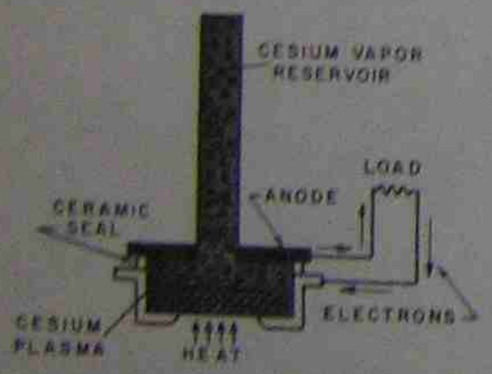


Fig. 24-31 Cesium plasma diode

Further Research

Intensive thermionic research is underway with the goal being the development of reliable converters for space use. These thermionic devices can be heated by the sun, by decaying radioisotopes, or by the heat of a fission reactor. If scientists could simply wrap the thermionic converter emitter around a reactor fuel element, the result would be an ideal combination. However, many problems are involved in developing materials that can withstand the extremely high operating temperatures, 3092°F (1700°C), in the physical construction of the device, and in the nuclear physics factors that must be considered. Much work remains to be done in the area of thermionic conversion devices before practical applications can be made.

THE NUCLEAR BATTERY

The nuclear battery is capable of directly converting the nuclear energy of a strong beta emitter, like strontium 90, directly into electricity. The device is simply a central rod that is coated with a beta-emitting radioisotope, the source of electrons. The rod is in a vacuum-sealed container and the beta particles (electrons) cross the vacuum gap to a metal sleeve that acts as a collector. The sleeve is connected to the load. Current flows from the sleeve, through the load, and back to the central rod, figure 24-32.

Space charge effects do not bother the nuclear electrons. They are leaving the radioisotopes with a million times more kinetic energy than electrons leaving a thermionic surface.

While nuclear batteries apply voltages of 10,000 to 100,000 volts, the electron flow is only a few millionths of an ampere.

A NUCLEAR BATTERY

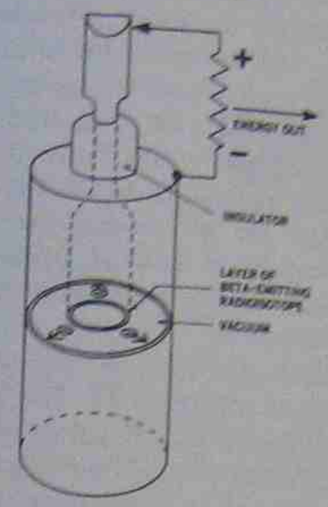


Fig. 24-32 A nuclear battery

MAGNETOHYDRODYNAMIC GENERATOR

The magnetohydrodynamic power generator makes use of the basic principles of electrical generation that were discovered by Faraday in the early nineteenth century. He discovered that moving an electrical conductor through a magnetic field, or vice versa, induces a voltage. Steam, water, and gas turbines are often used in this way, applying their energy to rotate a conductor through a magnetic field. In the magnetohydrodynamic (MHD) generator, a pressure-driven conductive gas replaces the copper wire of the armature that moves through the magnetic field of the normal generator, figure 24-33.

The idea of a gaseous conductor sounds

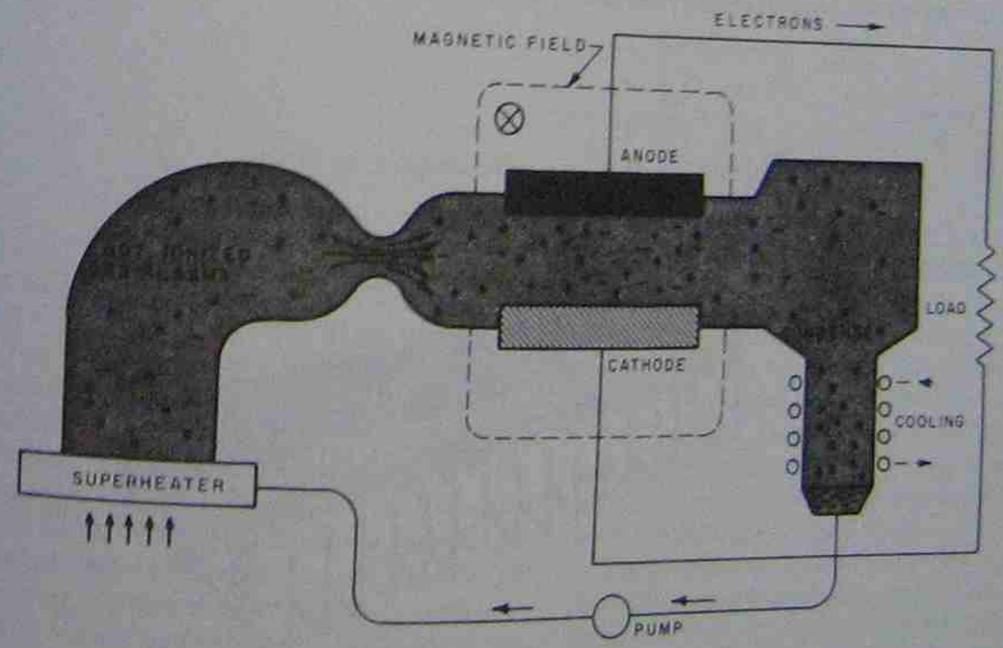


Fig. 24-33 Magnetohydrodynamic (MHD) generator

simple at first, but in order for a gas to be an effective conductor of electricity it must be ionized, and this can only be accomplished by intense heat. In the ionization process, electrons boil off and become free electrons, leaving the gas atom with a positive electrical charge; it is ionized. These free electrons drift in the ionized atoms, but many are free at any given time. Many free electrons are drawn to and picked up by the anode and delivered to the load.

The hot gaseous ionized fluid is referred to as *plasma*. Simply burning chemical fuel such as powdered coal, oil, or natural gas with air does not produce temperatures sufficient enough to promote the slight ionization that is necessary. To solve this problem a gas is seeded with a material that will ionize easily, such as potassium. When seeded with potassium, ionization will result at ordinary oxygen combustion temperatures of 2500–3000°K (2227–2727°C). To insure efficiency and to obtain the high temperatures needed, the air is often oxygen-enriched and preheated.

Temperatures of the magnitude required in an MHD generator are destructive to ordinary turbine generators, but in the MHD generator there are no moving parts that the gaseous stream is directed toward. In the actual production of electricity, there are no moving parts at all.

The combustor itself is very similar to a rocket engine, figure 24-34. The hot plasma exits from the nozzle into a duct of increasing diameter. A magnetic field surrounds this duct. The motion of a conductive plasma gas through this field induces voltage across the electrodes. In actual practice the electrodes are segmented, each segment being separately attached to the load to minimize the Hall

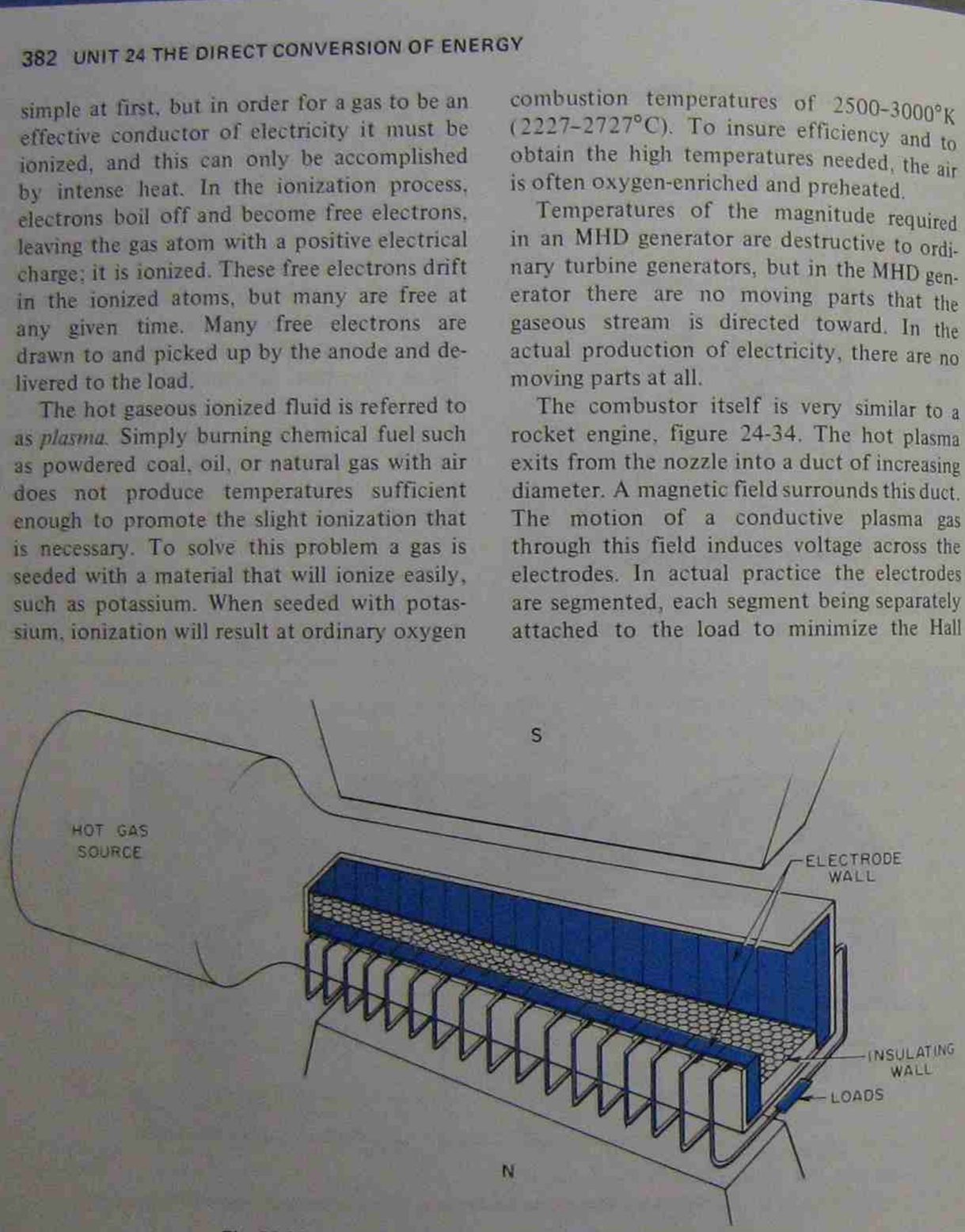


Fig. 24-34 Drawing of MHD generator, normal segmented hookup

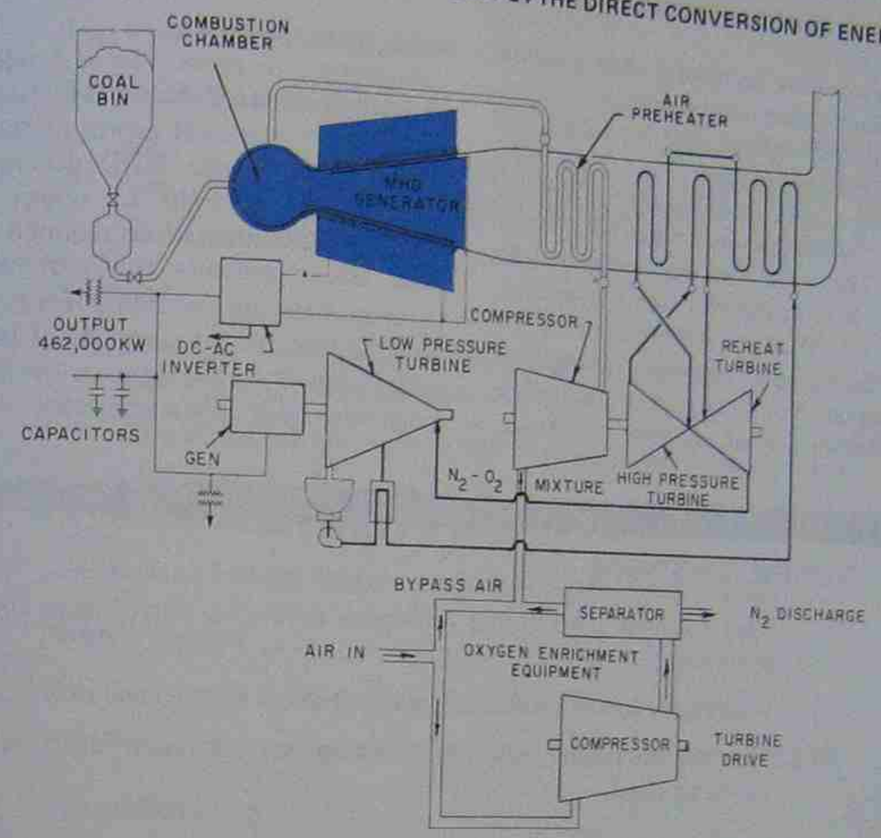


Fig. 24-35 Design for a coal-burning, open-cycle MHD power plant

effect. This is the tendency of the conductor to set up a magnetic field around itself, which cancels out the force of the field coil.

The MHD generator is ideally suited for producing large quantities of electricity at central power stations. When these units are installed they will incorporate several other principles and machines to attain efficiencies of an expected 50%, ten percent higher than conventional plants are now capable of achieving. To attain high efficiency, hot gases cannot simply be exhausted. If the hot plasma is exhausted, it would represent a tremendous loss. A portion of the heat is used in a regenerator to preheat the incoming air. Another portion of the hot gases is used in a steam cycle whose turbine turns both a compressor and a conventional generator. Even the seed material is reclaimed from the ash of the exhaust gases. This type of operation is referred to as an open cycle since the plasma gas is eventually exhausted from the mechanisms when as much energy as practical has been derived from it, figure 24-35.

The possible use of nuclear reactor power for MHD generators presents another area of promise. However, the temperatures attained are too low to cause ionization. Either of two routes can be taken to solve this limitation; reduce the temperature at which an MHD

generator operates, or build nuclear reactors that produce greater heat intensities.

Current finds indicate that future nuclear-powered MHD generators will be a closed-cycle design. The plasma, probably argon or helium, is heated by the reactor but does not interact with it. The ionized gas passes through the duct but is not exhausted from the system. It is drawn off at the discharge end of the duct, reheated and expanded through the nozzle again. Safety factors of radioactive contamination present problems for the design of these generators.

At present the prime area of developement of MHD generators is directed toward the generation of electrical power at the central power station. Large MHD generators can produce huge amounts of power at high efficiency. The intense heat required to ionize gases always presents the problem of developing materials and components that can take the heat for long periods of time. Concentrated work on MHD generators has shown much progress in only a few years.

REVIEW QUESTIONS

1. What common direct energy conversion device has served man for many years?
2. What energy form is produced by most all direct energy converters?
3. What are the general requirements for space exploration electronic power supplies?

Solar Cell

4. Explain how a power source such as coal can be traced to the sun.
5. Name three early devices for converting the sun's energy directly into electricity.
6. What group of men is responsible for the latest improvements in the solar battery?
7. What is the efficiency of present day solar batteries?
8. What applications have been found for the solar battery?
9. What is a semiconductor?
10. How can a semiconductor be made conductive?
11. What type of semiconducting material is used in the solar battery?
12. What is the arsenic doped region called?
13. What is the boron doped region called?

14. What is the PN-junction?

Thermophotovoltaic Converter

15. What is the source of the photons that excite the semiconducting material of the thermophotovoltaic converter?
16. Where and when was this converter introduced?

Fuel Cell

17. How does the efficiency of the fuel cell compare with all other non-nuclear energy conversion systems?
18. Does a fuel cell store the energy of a fuel or does it furnish power as it consumes a fuel?
19. What potential uses are seen for the fuel cell?
20. Has the fuel cell seen any practical application to date? Explain.

Nuclear Battery

21. Explain the basic operating principle of the nuclear battery.
22. Why are space charge effects of little consequence to a nuclear battery?

Thermoelectricity

23. Explain the basic principle of a thermocouple.
24. Why are semiconducting materials used in modern thermoelectric devices?
25. What characteristics of a thermoelectric device makes it suitable for use at remote, unattended locations?
26. How can radioisotope materials be used for thermoelectric devices?
27. What is the SNAP program?

Thermionic Converter

28. Explain the term space charge. What has it to do with the problems of thermionic converters?
29. Describe the basic principle upon which the vacuum close-spaced diode operates.
30. What is the major disadvantage of the vacuum close-spaced diode?

31. How does the magnetic triode solve the problem of space charge?
32. On what principle does the cesium plasma diode operate?

Magnetohydrodynamic Generator

33. Explain the principle on which the MHD generator operates.
34. What is plasma?
35. What is the difference between the open cycle principle and the closed cycle principle?
36. What difficulties are encountered in MHD generator design?

SECTION 8
ENERGY FROM THE EARTH—FOSSIL FUELS

Unit 25 Coal

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the formation of coal.
- Describe the several types of coal.
- Discuss coal mining, processing, and transportation.
- Discuss the environmental problems caused by coal mining and coal burning.
- Explain the concepts of coal liquification and coal gasification.

Coal is known as a fossil fuel. Its formation on the earth is the result of plants and animals that lived and died between one and 440 million years ago. When ignited it will burn and release heat energy. It is thought that the plants that now make up coal deposits grew in swampy areas of the earth. They died and accumulated over a period of time. The decaying plants first hardened into a material called peat. As time passed, sand and minerals formed into sedimentary rocks covering the peat and the increasing weight caused the peat to turn into coal.

Coal types vary according to how long they have been underground and how much pressure has been exerted on them. The harder the coal the higher the carbon content and the more efficient the burn. Lignite is the first stage of coal development; it is dark brown in color. The texture of wood is sometimes still distinct on its surface. Subbituminous coal is next in line followed by still

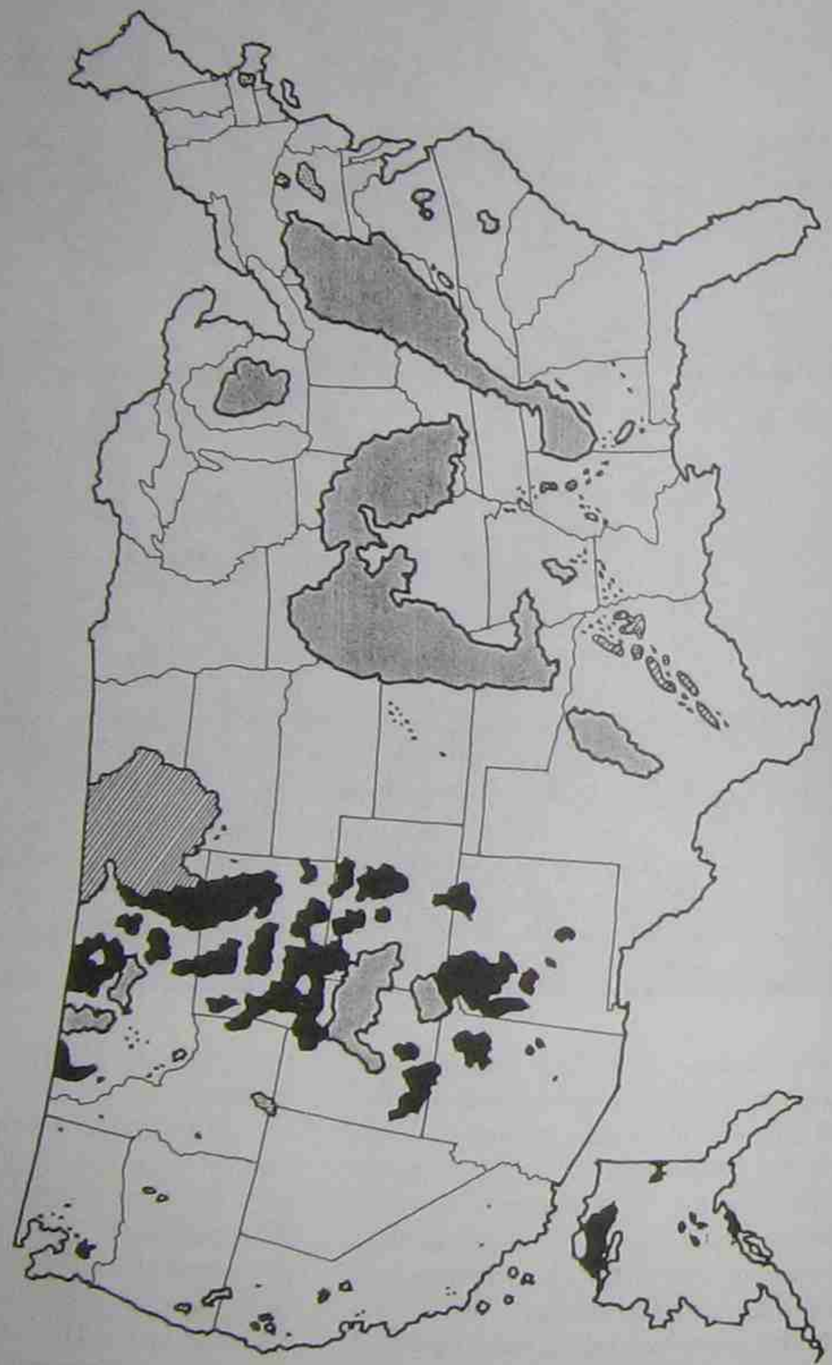


Fig. 25-1 U.S. coal deposits of lignite, subbituminous, bituminous, and anthracite (Courtesy of Standard Oil Company of Indiana)

harder bituminous coal. These two last are often called soft coal because they crumble easily. The hardest and oldest of coals is anthracite, figure 25-1.

In terms of their heating value measured in Btus (British thermal units–the amount of heat required to raise one pound of water one degree Fahrenheit), anthracite coal is the best, 13,000 Btus per pound. Bituminous coal has 10-13,000 Btus per pound; followed by subbituminous, 8,000 Btus per pound; and lignite, 6,000 Btus per pound. Bituminous coal is the most plentiful type of coal that is economically recoverable.

It is not known when man began to burn coal but it is recorded that the Chinese had a coal industry as early as 300 AD. In Europe, coal mining was underway in the 1200s. For most uses wood was the preferred fuel but by the 1600s wood was becoming so scarce that coal was the only alternative. England was the world's leading producer. Coal was often con-



Fig. 25-2 Machines at work in an underground mine (Courtesy of National Coal Association)

verted into coke for many industrial processes such as smelting metals. Coal was the fuel for the industrial revolution. It served as the fuel for steam engines that powered factories and the heat for industrial processes. Soon coal was also used in steam ships and railroad locomotives. Coal was king in industry, transportation and home heating for years, until the development of the petroleum industry.

MINING COAL

Coal layers are called seams or veins. They may be close to the earth's surface or buried very deep. Some seams are thin, perhaps an inch thick while others have been known to be 400 feet thick. Movements in the earth's crust have shifted some coal seams up so the layers can be seen in hillsides as outcroppings.

How deep the coal is located will determine how it is to be mined. Underground mines are for coal that is more than 120 feet in the ground. These mines are the most expensive and the most dangerous. Even though the pick and shovel days are over and machines now do the backbreaking work that men used to, underground mining is still rugged work and a dangerous occupation, figure 25-3. Safety regulations are strict but falling rock and explosions are an ever-present hazard. Underground shaft mines generally have at least two shafts, one to provide access for the miners and the other for hauling out the coal. Both shafts provide ventilation to the mine. If the shafts go straight down (the deepest mines) it is called a shaft mine. Slope mines enter the earth at an angle, often following a rock seam until they meet the coal seam. A drift mine will enter parallel to a coal seam that is usually outcropping on a hillside.

Strip mining (surface mining) is done when the coal is relatively near the surface of the earth—no deeper than 120 feet, figure 25-4. The overburden, composed of earth and rock



Fig. 25-3 Coal mining is a dangerous profession and the men and women who work the mines must be constantly alert. (Courtesy of National Coal Association)



Fig. 25-4 Surface mining of coal (Courtesy of Ashland Oil Inc., by American Petroleum Institute)



Fig. 25-5 Bucket wheel excavator used in surface mining (Courtesy of Environmental Protection Agency by American Petroleum Institute)

that is directly over the coal seam, must be removed. The land is cleared, then explosives are used to loosen the overburden. Power

shovels as high as a twenty-story build
move the overburden down to the coa
A bucket wheel excavator is especially
tive in mining to minimize the amou
reclamation necessary, figure 25-5. S
power shovels remove the coal seam, l
the coal into huge trucks which take th
to processing plants for cleaning, washin
grading.

In past years strip mining left acres o
as spoil banks—scarring the earth and re
ing it virtually useless. Today, surface m
is done in such a way that the land ca
reclaimed to make it attractive and us
much as it was before the coal was remo
figure 25-6.

The upper layer of the earth (top soi
removed and stored. After mining is compl



Fig. 25-6 Farming operations returned to [illegible]

the overburden is graded and returned to its original contours and then the life-giving top soil is returned and the land is fertilized and reseeded. Reclamation and mining are done at virtually the same time. Today, 60% of the coal mined is done by surface mining.

TRANSPORTATION OF COAL

Coal is shipped within the country by barge, rail, or truck. Barges are the most economical method of transportation but this shipping method is limited to delivery at coastal or river ports, figure 25-7. Rail transportation accounts for about two-thirds of coal shipments in the United States. Most coal trains are called *unit* trains in that every rail car in the train carries coal. For example, the entire



Fig. 25-7 Coal barges on the river (Courtesy of American Petroleum Institute)

shipment goes from the mine processing plant to an electrical utility several hundred miles away. In figure 25-8, an automated coal-handling system offloads coal from railroad cars at a generating station. This system includes a rotary railroad car dumper, a 1200-foot conveyor belt and a stacker-reclaimer. The stacker-reclaimer delivers the unloaded coal to storage areas on both sides of the conveyor at the rate of 3,000 tons per hour. Truck transportation is only economical for small shipments and short distances.



Fig. 25-8 Automated coal handling system at a power generating station can unload and store coal at the rate of 3,000 tons per hour (Courtesy of Wisconsin Power and Light Company)

COAL USAGE AND RESERVES

There are several important reasons why coal continues to be important as an energy source. In the first place, it is our most abundant fossil fuel. Studies hav
consumption continues at
there are enough coal reserve
to 400 years; there are 70
known reserves. Secondly, w
petroleum and natural gas ar
much more rapidly than coa
understandable why coal re
tant source of energy. Coal
the world's energy today and
is expected to rise in future ye

Only about one percent
duced is sold for retail uses
heating. What about the rest



Fig. 25-9 Coal-burning power plants produce electricity. (Courtesy of

percent of the coal goes to electric utilities where it is crushed and burned to heat water making steam to drive the steam turbines that power the electrical generators, figures 25–9 and 25–10. Eleven and one-half percent of coal production is converted into coke for smelting, while nine and one-half percent is consumed in general industrial use.

Coal is very competitive costwise with petroleum and natural gas but its impurities do present environmental problems. Sulfur is usually present in coal and is very undesirable. When sulfur is burned, a poisonous gas, sulfur dioxide, is produced. Special scrubbers in the utilities remove much of the sulfur dioxide before it reaches the outside air. Fly ash particles coming out of a smoke stack represent a hazard; these are controlled by filters, scrubbers, or electrostatic precipitators. Fly ash particles contain traces of lead, cadmium, and arsenic, and also block out sunlight. Acid rain and the greenhouse effect are to some extent caused by burning coal. Keeping the environment clean when using coal is expensive, however. It has been estimated that about forty percent of the cost of a new coal fired electric power plant goes to equipment and technology required to meet environmental protection requirements.



Fig. 25-10 Coal on a conveyor on the way to the crusher before it is burned at the power plant (Courtesy of National Coal Association)



Fig. 25-11 Research model of a coal gasification unit (Courtesy of Gulf Oil Corporation by American Petroleum Institute)

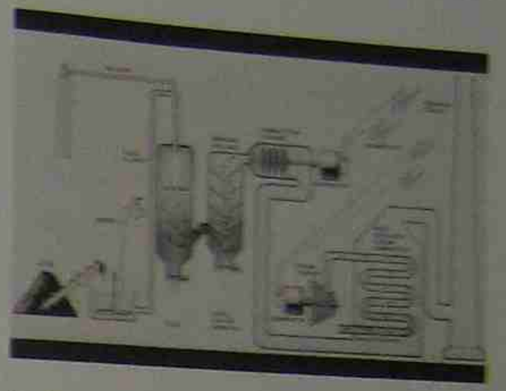


Fig. 25-12 Diagram of an electric power generator using coal gasification (Courtesy of Texaco, Inc., by American Petroleum Institute)

COAL GASIFICATION AND COAL LIQUIFICATION

Coal can be a versatile fuel—it does not have to be burned as a solid chunk or a powder. It is possible to change coal into a liquid that can be burned much the same as petroleum products or changed into a gas similar to natural gas.

Coal liquification is done by first crushing, drying, and grinding the coal. The coal is then combined with liquid to form a slurry that is heated and pressurized. When hydrogen is added the coal dissolves. Mineral matter and organic solids are removed as are gases. The result is a low-sulfur liquid fuel that can be burned in power plants designed to burn oil.

Coal gasification is designed to burn a small portion of the carbon in the coal, figure 25–11. Usually all of the carbon is burned or oxidized in normal burning. Coal gasification relies on carefully controlling the amount of oxygen admitted to the burning process and also controlling the temperature and time of burning, figure 25–12. The controlled oxidization of the coal results in the formation of hydrogen and carbon monoxide gases. In the presence of a catalyst, methane gas is then produced which is combustible.

Both processes are under intense development by the coal industry. The concepts are not new but the technologies to liquify and gasify coal are still developing. However, plants are being built and run successfully with the products of the two methods.

REVIEW QUESTIONS

1. What type of coal is the oldest and hardest?
2. How many Btus of energy does a pound of bituminous coal contain?
3. Explain how coal fueled the industrial revolution.

4. Briefly describe the two principal methods of mining coal.
5. Explain why reclamation of land is important in strip mining.
6. Discuss why coal usage is predicted to rise in years to come.
7. What industry uses the greatest amount of coal?
8. Briefly explain coal liquification.
9. Briefly explain coal gasification.

Unit 26 Petroleum

OBJECTIVES

After completing this unit, the student should be able to:

- Discuss the importance of oil as an energy source.
- Explain how petroleum was formed.
- Briefly discuss oil exploration and drilling.
- Outline the refinery process.
- Explain the importance of petrochemicals.
- Discuss the potential of oil shale.

Oil is the main energy source for our modern industrial society. Some 43% of the energy the United States uses each year comes from oil (petroleum). This can be broken down as:

- The 120 million automobiles registered in the country consume 54% of the oil products used.
- Residential and commercial use is 12%.
- Industry uses 25%.
- Electric utilities use 9% of the oil.

Our country uses about 17 million barrels (42 gallons per barrel) of oil each day; of this we import about 6.8 million barrels. We are very aware that oil is vital to our nation's well-being but, at the same time, we cannot fail to know that the earth's oil supply is limited, figure 26–1. This is why, as we enjoy the benefits of oil, we must be conservative and wise in its use. At present, the United States represents only 6% of the world's population yet we consume one third of the world's energy. Each person in our country consumes energy equal to 60 barrels of oil each year, figure 26–2.

Petroleum (crude oil) that comes from the earth is made of many types of hydrocarbon (hydrogen and carbon combinations) molecules jumbled together. It began forming millions of years ago. The most accepted theory of its formation is that oil is the result of organic material formed by prehistoric remains of plants and animals that decayed in the ancient seas of the earth. Layer upon layer of

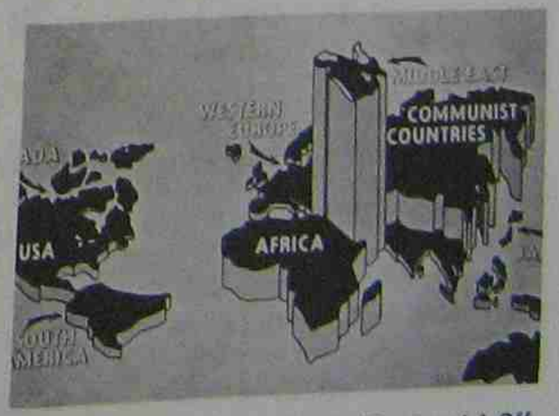


Fig. 26-1 Oil reserves of the world (Courtesy LA Offshore Oil Port, Inc., by American Petroleum Institute)

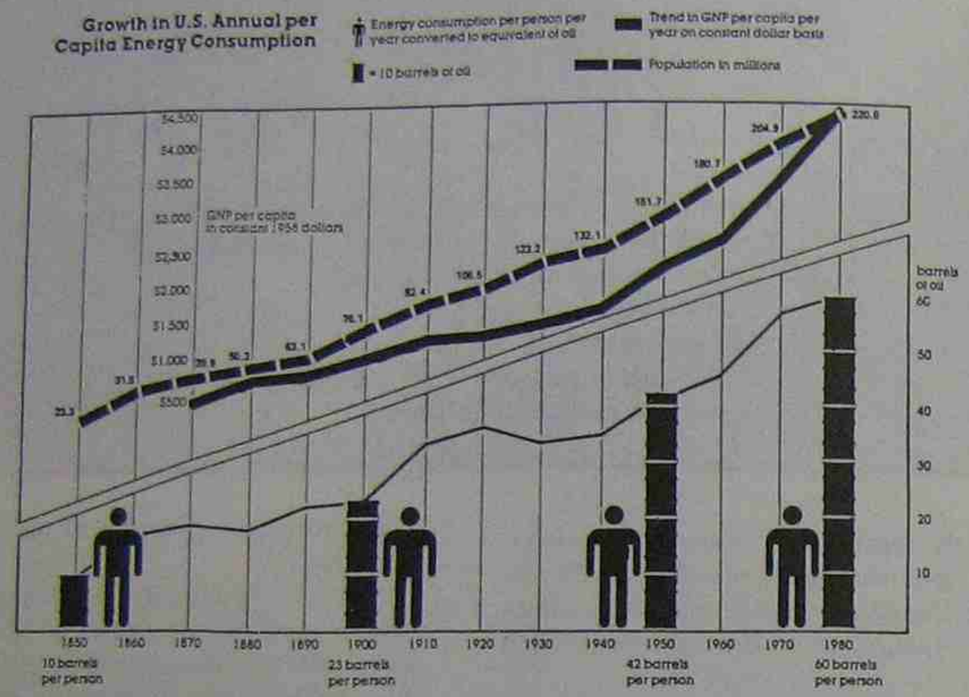


Fig. 26-2 Growth of energy consumption in the United States (Courtesy of Standard Oil Company of Indiana)

plant and animal matter accumulated along with mud and silt and pressure built up on the lower layers. With the increasing pressure came heat and the chemical, bacterial, and radioactive action which reformed the accumulated matter into the compounds of hydrogen and carbon that we refer to as petroleum.

Shifting layers of the earth's crust enabled some oil to drift to the surface where it could be easily collected, so it is very likely that petroleum has been known for centuries. As a matter of fact, it is known that oil was used in ancient Egypt and Greece. The Chinese even *drilled* successfully for oil in 300 BC. These early, limited uses of oil were for lighting, grease, and caulking ships.

In colonial times candles were the main source of illumination along with whale oil. Since whaling ships were well into the process of depleting the ocean's supply of whales, the search was soon on for other sources of illumination. It was already known that petroleum could serve this purpose but gathering oil from the few spots where it naturally broke through the earth's surface was limited, slow, and inefficient.

Edwin L. Drake, financed by a group of businessmen, began to drill for oil near an old oil spring in Titusville, Pennsylvania, figure 26-3. Drake wanted to recover petroleum in



Fig. 26-3 Titusville, Pennsylvania—site of the first commercial oil well (Courtesy of American Petroleum Institute)

large quantities so it could be refined into kerosene for illumination. In 1859, a dark green liquid rose to the top of the 69½ foot hole; Drake had struck oil! The oil rush was on; thousands of oil wells were being drilled by the emerging petroleum industry. Since the automobile was not yet on the scene the early refiners concentrated on kerosene for lighting. Oil fields were soon discovered and developed in Colorado, Texas, West Virginia, California, Ohio, Illinois, Oklahoma, Louisiana, and Kansas. Today, oil and/or natural gas are produced in 32 states, figure 26-4.

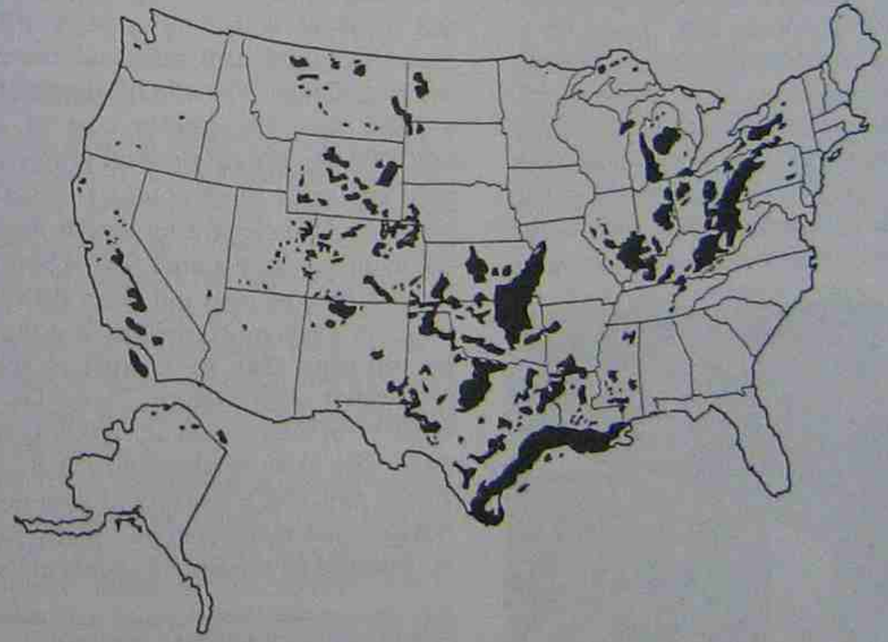


Fig. 26-4 Oil and gas fields in the United States (Courtesy of Standard Oil Company of Indiana)

OIL EXPLORATION

Most of the sedimentary basins of the earth where oil occurs are well known, but even this is no guarantee that every well that is drilled will have oil at the other end. A geophysicist continues the search aided by a magnetometer, gravimeter, and seismograph that more thoroughly map the underground structure of the earth. If the reports indicate a good chance for oil, test drilling is done and the rock formations are examined by geologists. Then, actual drilling of a well is done because it is the only way to be certain that oil is present. Even when a site looks very promising, only one in ten wells will strike oil and only one in fifty of these will strike oil that flows in quantities that produce enough petroleum to be commercially practical.

Alaska is the site of our latest petroleum and natural gas discoveries. Exploration, drilling, and transporting oil from the hostile arctic areas pose many costly problems but the quantities of oil resources are enormous, 42 billion barrels of oil and 181 trillion cubic feet of natural gas. The construction of the Trans-Alaska oil pipeline, figure 26–5, brings oil from the northern-most production areas



Fig. 26-5 The trans-Alaska pipeline (Courtesy American Petroleum Institute)

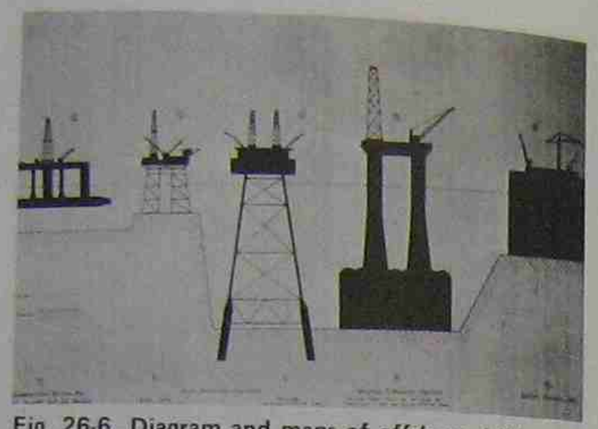


Fig. 26-6 Diagram and maps of offshore drilling rigs (Courtesy of American Petroleum Institute)

to shipping ports in southern Alaska where it is loaded onto tankers.

OIL DRILLING

Drilling for oil is a financially risky operation involving a drilling crew, a drilling rig, expensive rotary drill bits, and thousands of feet of drill pipe. The average depth of drilling is 5,000 feet; the average cost of a well is $380,000. As the rotary drill grinds away the rock and goes deeper into the earth, pipe must be added–length by length. Water, clay, and additives form a mud that is pumped into the drill hole to cool and clean the rotary bit. In recent years much drilling is done on drilling platforms that are located at sea on the continental shelf, figure 26–6. The average depth of offshore wells is 10,000 feet; the average cost of an offshore well is $2,545,000. Part of this cost is because drilling is carefully watched and monitored and many safeguards are installed to prevent accidents and oil spills.

TRANSPORTATION OF OIL

Transporting petroleum to the refineries is done by pipelines, barges, highway tank trucks, and railroad tank cars. Most domestic

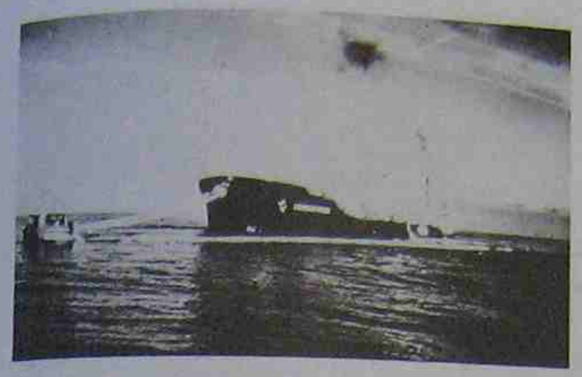


Fig. 26–7 Ocean oil tanker (Courtesy of LA Offshore Oil Port, Inc., by American Petroleum Institute)

oil is delivered to the refinery by pipeline. More than 218,000 miles of petroleum pipelines deliver petroleum and petroleum products throughout the United States. When oil is imported from overseas it arrives by ocean tanker, figure 26–7.

REFINING OIL

There are 300 oil refineries in the country today and each is a huge complex of pipes, columns, and steel structures. Nothing seems to be moving, but the refinery is operating 24 hours a day to convert the hydrocarbons that make up the crude oil into many products. Not all crude oil is heavy and black, some is amber, green, or brown in color; some oil may be almost like water while some is thick as molasses, figure 26–8.

In most cases, fractional distillation is the first process in refining, figure 26–9. Crude oil is heated to 725°F and then released into a vertical tower. Many of the various hydrocarbons vaporize under this temperature and begin to rise from the bottom of the tower toward the top. At different levels in the tower the hydrocarbon molecules cool and condense and are collected. As expected, the

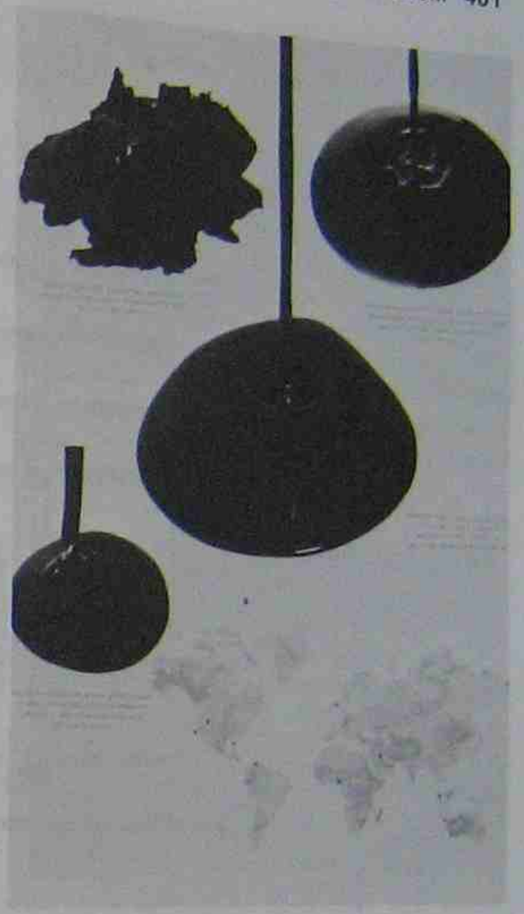


Fig. 26-8 Crude oil: samples of several types (Courtesy of Standard Oil of California by American Petroleum Institute)

heavy molecules condense near the bottom and the lighter molecules condense near the top. From the bottom up the crude is separated as follows–asphalt and heavy fuel, lubricating oil, fuel oils, kerosene, and gasoline. Other lighter gases that do not condense are carried off for further processing.

Fractional distillation by itself does not produce enough gasoline to meet the demand so other processes such as thermal cracking,

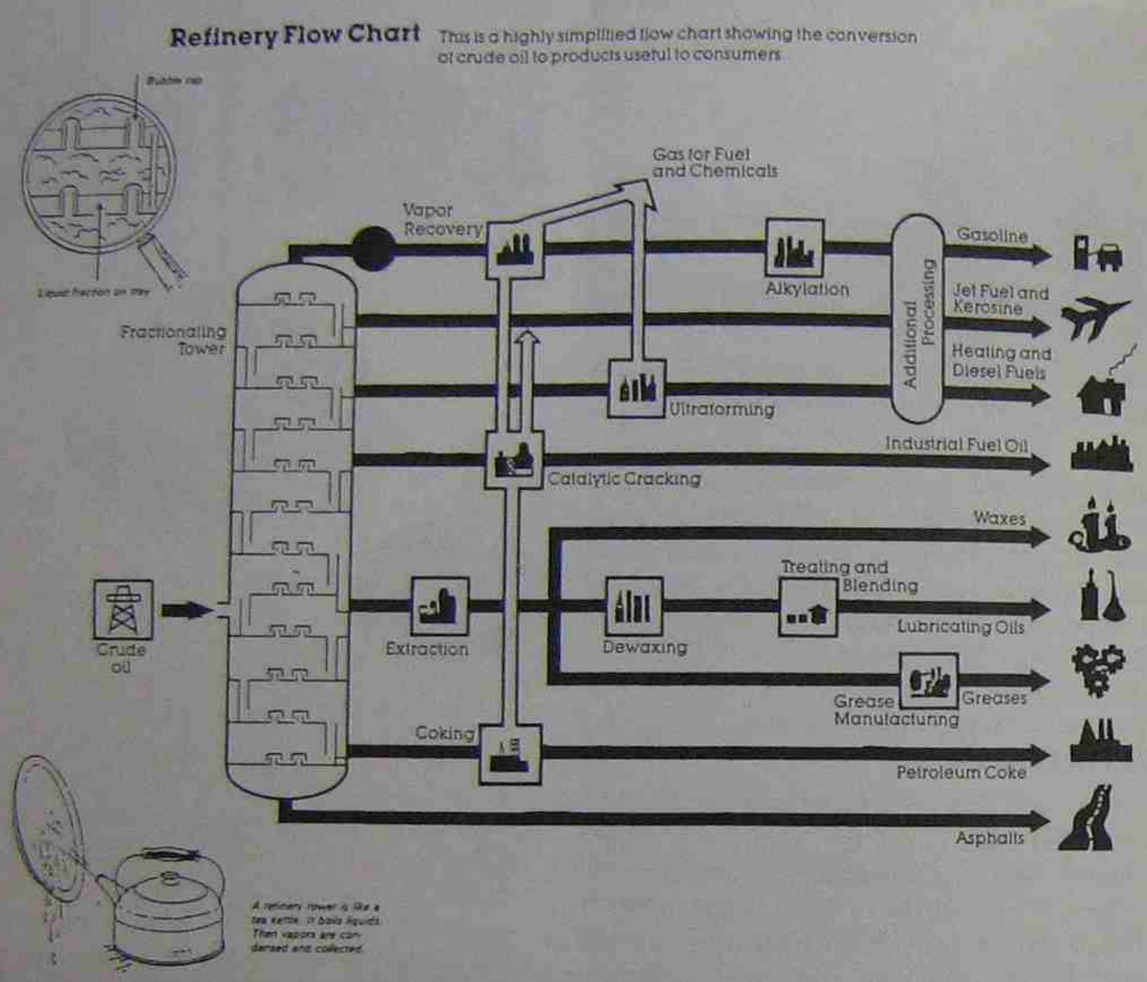


Fig. 26-9 Refinery flow chart (Courtesy of Standard Oil Company of Indiana)

catalytic cracking, and polymerization are used to reform the hydrocarbon molecules into gasoline molecules. Thermal cracking uses higher temperatures to break the bonds of the larger complex molecules of less volatile heating oils into gasoline. Catalytic cracking uses a catalyst to speed up the chemical changes in breaking up the heavier hydrocarbons into gasoline. Polymerization uses a catalyst to reform lighter molecules into liquids called polymers which are essential in high octane fuel. Using these processes refiners now obtain 19 gallons of gasoline from each 42 gallon barrel of crude oil.

PETROCHEMICALS

Petrochemical manufacturing has expanded the uses of petroleum beyond the wildest dreams of early oil pioneers, figure 26-10.

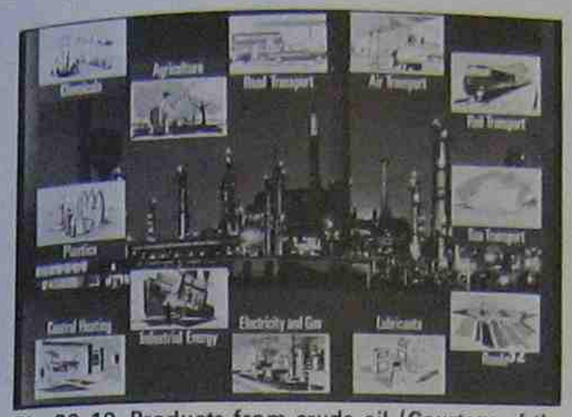


Fig. 26-10 Products from crude oil (Courtesy of the British Petroleum Co., Ltd., by American Petroleum Institute)

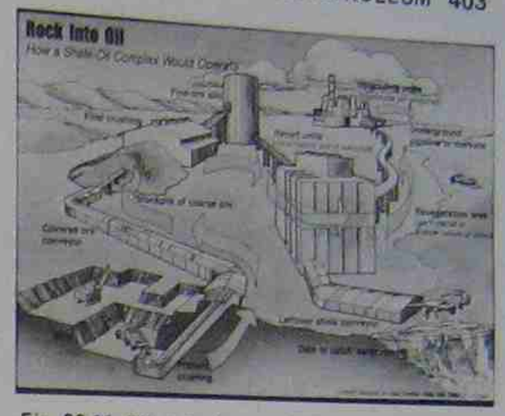


Fig. 26-11 Oil shale—how a shale oil complex would operate (Courtesy of U.S. News and World Report by American Petroleum Institute)

About 3,000 different chemicals are produced from petroleum and natural gas in some 600 petrochemical plants. Many of the chemicals produced are seen in consumer products such as polyethylene plastic. Petrochemicals also play a part in the creation of synthetic fibers, films, antifreeze, construction materials, plastics, synthetic rubber, pharmaceuticals, cleaning compounds, plastic bottles, detergents, hydraulic fluids, explosives, dyes, photographic chemicals, lacquer, saccharin, food preservatives, insulation, paints, foam cushions, fertilizers, and insecticides.

OIL SHALE

Oil shale represents great potential for expanding oil production. The hard shale rock is light grey to charcoal in color and contains kerogen, a hydrocarbon. Kerogen will break down to produce oil, gases, and residual carbon when it is heated. Processes are under development to economically recover petroleum products from oil shale, figure 26-11.

One process involves first mining the oil shale and then crushing it. The crushed oil shale is then heated in huge vessels or retorts where the kerogen is released and is further broken down into hydrocarbon gases and carbon residue. To produce 25-35 gallons of oil about 2,000 pounds of rock must be processed, figure 26-12.

Fig. 26-12 This amount of oil shale rock can fill twelve 55-gallon drums with oil when it is processed. (Courtesy of Standard Oil Company of California by American Petroleum Institute)

In another process, most of the action is done underground. After about one-third of the oil shale of a given area is removed the remaining two-thirds is loosened by explosives and then burned *in situ*, (in place). The oil shale burns at about 900°F and this heat causes the hydrocarbons to leave the

burn zone in vapor form which is condensed and pumped away for further processing.

Processes for oil shale recovery show promise for the future. The deposits of oil shale are tremendous, especially in Colorado, Utah, and Wyoming. These states represent an oil source equal to 90% of the proven oil reserves of the world.

REVIEW QUESTIONS

1. How much energy is consumed by each person in a year?
2. What is Edwin Drake credited with?
3. List several oil production states.
4. What are the chances that drilling will produce a commercially practical oil well?
5. What is a hydrocarbon?
6. What products come from fractional distillation?
7. Explain the purposes of thermal cracking, catalytic cracking, and polymerization.
8. List several products produced by the petrochemical industry.
9. Briefly describe what is involved in extracting oil from oil shale.

Unit 27 Natural Gas

OBJECTIVES After completing this unit, the student should be able to:

- Discuss the advantages of natural gas.
- Explain how natural gas is distributed throughout the country.
- Discuss sources that can supplement our natural gas supply.

Natural gas is also a fossil fuel. Similar to coal and oil, it was formed millions of years ago as organic matter decayed and was subjected to heat and pressure as layers of material built up. Usually it is found in underground faults and traps in porous rock. Exploration for natural gas is done in much the same way as it is for oil.

Natural gas is a hydrocarbon like petroleum. In fact it is found with crude oil about 30% of the time, figure 27-1. The main hydrocarbon in natural gas is methane which will burn readily to release heat energy. The advantages of natural gas are quickly apparent: (1) it can be transported easily through pipelines, (2) when it burns there is no ash or smoke, and (3) the flow can be stopped and started by valves. It is the ideal fuel for home heating and cooking. In the 1940s natural gas replaced coal for much of our home heating needs. It is also ideal for industrial uses.



Fig. 27-1 Natural gas processing plant located in a gas field (Courtesy Standard Oil Company of California by American Petroleum Institute)

Natural gas provides about 25% of the nation's energy; only oil provides a larger percentage of our energy than gas. Like oil, large amounts of capital are required for the production of natural gas. Even after all these expenditures, only one of ten wells drilled for gas is successful.

The states of Alaska, Kansas, Louisiana, New Mexico, Oklahoma, and Texas account for 90% of our gas production. A vast network of pipelines gathers the gas and transports it to points of use. Underground pipes—approximately 68,000 miles of pipe—gather the gas to bring it to wellheads. Before transmission the gas goes to processing plants where water vapor, impurities, and hydrocarbon liquids are removed.

Large-diameter transmission pipelines—almost 278,000 miles of them—carry the gas to almost every major area of the nation. Gas in these transmission lines is moved along by

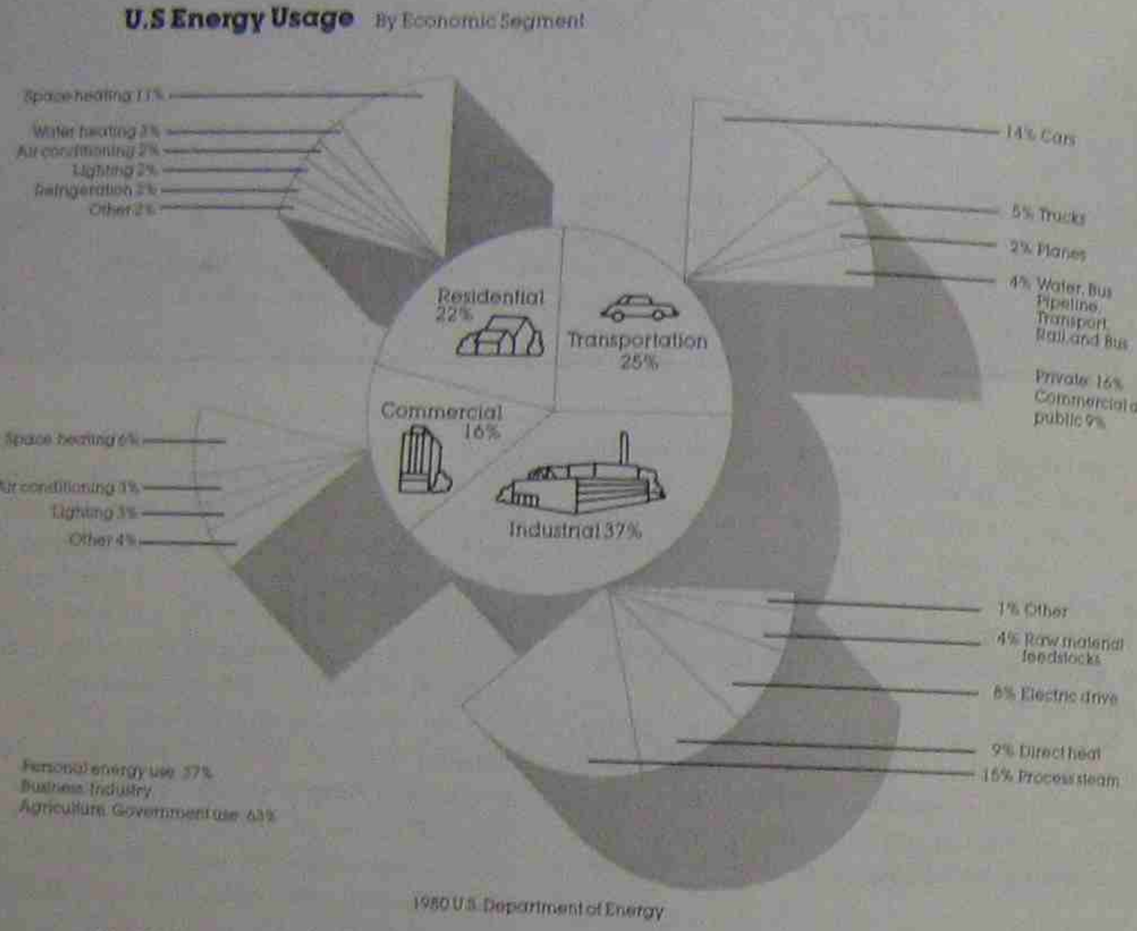


Fig. 27-2 United States energy usage (Courtesy of Standard Oil Company of Indiana)

pumping stations about 50 to 150 miles apart. In the transmission pipeline the gas is under a pressure of 1,000 pounds per square inch and moves along at 15 miles per hour. In the distribution lines, your local gas company will reduce the pressure to about 20 pounds per square inch; these gas mains are under the streets. When gas is brought into a home or other building, the pipe is called a service. These service lines carry only one-half pound of pressure.

Gas flows from a well constantly so distribution companies have huge underground storage reservoirs to store extra gas for cold winter usage when demand increases. Certain underground rock formations can also be used to store the natural gas.

Natural gas will continue to be important in the nation's overall energy supply, but present estimates are that gas can supply 25% of our energy needs for only the next forty years. These facts indicate that continued exploration and drilling will be required, conservation must be practiced, and new sources of substitute gases must be developed.

Sources that can supplement gas are coal gasification and biomass gases. Natural gas is also imported in increasing amounts by means of large ocean-going tankers which carry liquified natural gas. To liquify natural gas it is cooled to minus 260°F; the volume of 615 cubic feet of gas can be reduced to 1 cubic foot by this process. The insulated ships needed to carry the liquified gas increase the cost and complexity of obtaining gas for our use.

SUMMARY

It is important to remember that all forms of fossil fuels which took millions of years to form are on the verge of being used up in a matter of a few hundred years. Ultimately the answer to supplying our energy needs will be in new energy sources; in the meantime conservation of energy is essential. Examine the chart on energy usage, figure 27-2. There are many places where every person who uses energy can help to conserve it. We use energy in our homes, in the stores in which we shop, in the autos we drive, and in the products we buy.

REVIEW QUESTIONS

1. What is the main hydrocarbon in natural gas?
2. What percentage of the nation's energy is provided by natural gas?
3. What states produce most of our natural gas?
4. At what pressure does natural gas enter the home?
5. What is the purpose of liquifying natural gas?

SECTION 9
POWER TECHNOLOGY AND THE FUTURE

Unit 28 Occupational Opportunities in Power

OBJECTIVES

After completing this unit, the student should be able to:

- **Discuss the types of jobs related to power technology.**
- **Describe the training required for various job classifications.**

The scope of *Power Technology* is so wide that it touches the lives of everyone, figure 28-1. Every person is a consumer of power; it is part of our way of life. The automobile, electrical household appliances and machines, power lawn mowers, and recreational equipment are all woven very thoroughly into the American way of life. Everyone has a future in power, as a consumer if not as a vocation.

Understanding the concept of power technology can help to make a person a more intelligent consumer. It's easy, for instance, to understand that you heat your home with gas. It's quite another to know that at our present rate of consumption–in only 40 years–there will be *no more gas* unless certain things are done, and quickly. This understanding can increase everyone's appreciation of our resources too. Concepts of power and its relationship to the community can also help a person to enjoy life more.

OCCUPATIONS

But what about *occupations* in power technology? Is there a future for large numbers of people? What kind of skills, aptitudes, and talents are needed? These questions go back to the definition of power technology, energy

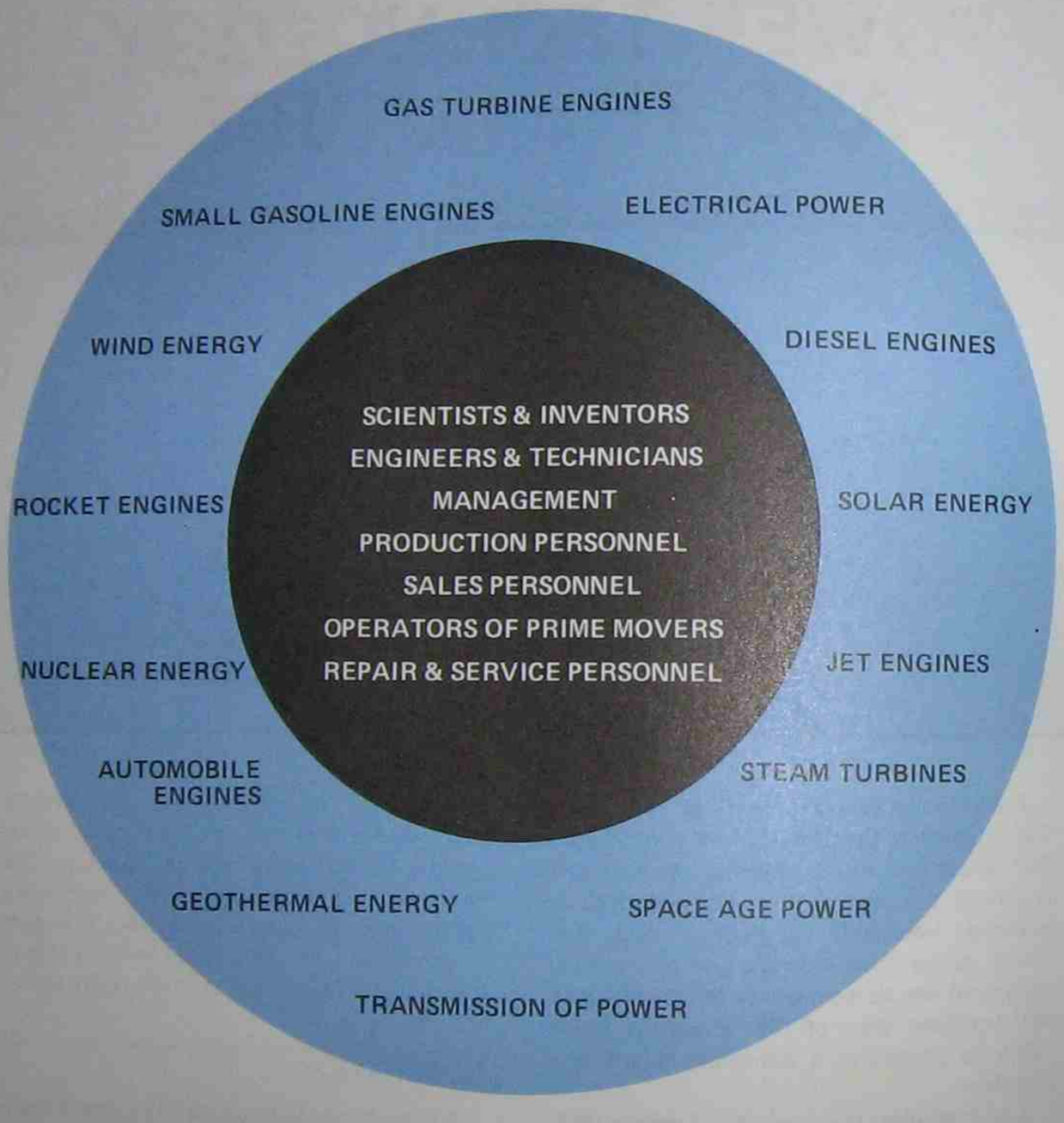


Fig. 28-1 A wide range of skills, talents, and interests lie within the field of power technology.

sources, and the machines that convert energy into useful work. The definition, in turn, leads to the units that lie within this book:

- Small gasoline engines
- Automobile engines
- Diesel engines
- Jet engines
- Rocket engines
- Gas turbine engines
- Electrical power
- Mechanical transmission of power
- Fluid transmission of power
- Steam turbines
- Alternative sources of energy
- Petroleum, coal, and natural gas energy
- Nuclear energy

The vastness of the field and the number of opportunities stagger the imagination. Millions of trained men and women are needed to meet the demands of our power-consuming society.

To the inexperienced, a career in power technology can have as narrow a meaning as a career as an auto technician. This is one phase of power technology that employs over 700,000 people. However, in its broad sense, the field of power technology also encompasses the electrical engineer and the nuclear physicist.

In every community, power fields employ many people, some in a very direct way, as service station managers or the employees of the public utility company. Other employed in power in a more indirect operating trucks, trains, buses, or aircr the community's transportation network

Every spoke on the power techn wheel requires persons with special talen terests, and skills:

- Scientists, researchers, and inve conceive ideas and principles, figure
- Engineers and technicians develo entific principles into practical ap tions, figure 28-3.
- Management organizes large-scal deavors in power, figure 28-4.
- Production personnel manufactur ever-lengthening list of prime m figure 28-5.
- Sales personnel understand powe fill the needs of business, industry individual consumers.
- Operators of prime movers includ professional airplane pilot, the ra engineer, the truck driver, and th tionary engineer of the power figure 28-6.
- Repair and service personnel hav skill needed to keep prime move erating efficiently and safely.

The entire list of industries producin for prime movers should also be listed they represent the sources of energy cons by prime movers: coal, natural gas, petro nuclear fuel, and exotic fuels for spac power.

Unit 29 Computers and Power Technology

OBJECTIVES After completing this unit, the student should be able to:

- Define a computer in terms of what it does.
- List the major developments in the evolution of the computer.
- List the generations of computers and list the major distinguishing feature(s) of computers in each generation.
- Explain the function of each of the five major parts of a microcomputer.
- Define RAM and ROM.
- Describe several applications of computers in manufacturing.
- Describe how computers are used in modern automobiles.

In our society power technology has touched every person to varying degrees. None of us can escape the effects of power and its applications to automobiles, the electricity we use in our homes, at work and for recreation, space exploration, and all of the other uses of energy by means of numerous machines and devices that bring power into all aspects of our lives.

Computers are also a part of our everyday life and they play a part in all of power technology. It is not unrealistic to say that we are all involved with computers today. We may not realize that we are using computers, but many of our late model automobiles, home appliances, and office equipment contain computers.

The purpose of this unit is to help the reader develop a sense of computer awareness. We must all learn to be at ease with the computer world—it will not go away, figure 29–1. We must realize that computers are here to help us, not just to test our intellectual capacity; computers are merely tools to aid the mind.

Simply stated, a computer is an electronic device or machine used to solve problems and to organize, process, and store information (data) at a very high speed. A computer does its work by following a program or prescribed set of instructions.

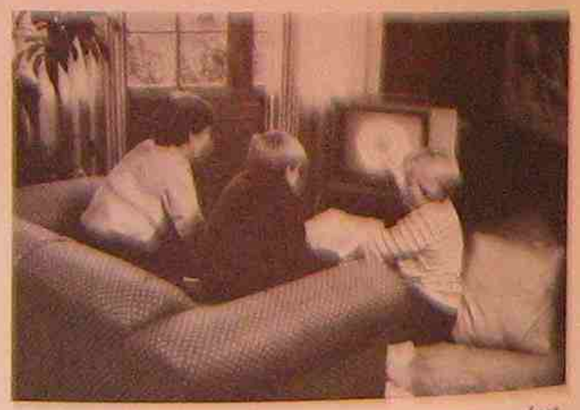


Fig. 29-1 Young people are usually more comfortable with computers than the older generation. (Courtesy Apple Computer, Inc.)

A computer does not work by itself; it cannot be instructed what to do until a person has carefully thought out what needs to be done. Understanding, knowledge, and logic are the characteristics of the human mind that are needed to program a computer to accomplish a given task. Since computers can manipulate vast amounts of information at a high speed, a direct connection can be made to the steam engine of the industrial revolution. The steam engine multiplied physical capacity and the computer multiplies mental capacity.

The steam engine was the key to the industrial revolution, but other machines were needed to take advantage of its power. These machines included the locomotive, steamship, spinning jenny, and lathe. The digital computer is the heart of the computer revolution, but it is also necessary to devise ways to apply the computer to various jobs. Programs must therefore be written for every application.

All levels of skills and talent are needed in our computer society. Scientists and engineers are needed to design the computers, other people are required to develop the programs that will allow the computer to do a given job. Knowledgeable and highly-trained people are needed to maintain and repair computer systems, and millions of people must be trained to operate computers in offices and factories. If you are going to be one of the millions who operate a computer, figure 29–2, you should be aware that you do not have to know how to construct or program a computer to operate one. You do not have to be an automotive engineer to operate an auto, but the more you know about how it operates, the more enjoyment and better performance you will be able to obtain from it. Computers can be approached in this same way.



Fig. 29-2 At school, in the home, and in the world of work, the computer is revolutionizing the way work is done. (Courtesy Apple Computer, Inc.)

COUNTING AND CALCULATING MACHINES IN HISTORY

The average person has not had many opportunities until recently to learn anything with regard to computer technology even though we have been increasingly a part of a computerized society. That is because although most important inventions have taken 50 to 100 years to become integrated into our society, this is not true with computers. The growth of computers has been phenomenal. Forty years ago there were none. Thirty years ago there were 250, twenty years ago there were 24,000, and today there are millions; tomorrow, there will be tens of millions.

Modern computing may be new, but the roots of computing extend far back into history. Many historians consider the abacus to be our first attempt at computing. The abacus was a counting board developed by the Babylonians about 5,000 years ago. A version developed by the Chinese consisted of wires

stretched in a framework with wooden counters that could slide on the wires. This simple counting device is still used in many parts of the world.

In 1642 Blaise Pascal, an accountant who wanted to be liberated from the tedious calculations that had to be performed by hand, created a mechanical device that was capable of addition and subtraction. In his machine the counting was done by means of a gear-driven mechanism.

Another pioneer was Joseph-Marie Jacquard who used a punch card system to control the automatic weaving of complicated textile patterns. His system was put into use in 1801.

Charles Babbage was a man ahead of his time. He devised the *difference engine*—a device that could calculate scientific and astronomic tables. Between 1812 and 1822 he built a working model of his machine, but manufacturing techniques had not developed the precision needed to make his machine practical. In 1834, he began work on an *analytical engine* which was designed to be a universal automatic calculator. His design contained the essentials of modern digital computers—input, memory, control, processing, and output. Unfortunately, Babbage died in 1871 before completing the machine.

In 1890 Herman Hollerith (who later founded IBM) developed his famous punch card machine. The machine was developed specifically to tabulate the 1890 census. It was an electromechanical system that *sorted* punch cards. All types of statistics could be entered on the cards by punching small holes at specific locations. The cards were then sorted by the machine into groups depending upon the information desired; a tabulator then totalled the cards. The system is considered to be the first data processor because the machine counted, collated, and analyzed information.

DEVELOPMENT OF THE MODERN COMPUTER

Modern computers are often grouped into generations. Each generation is identified by a major change from a previous generation by increased speed and accuracy.

First Generation Computers

The computers in the period from 1944 to 1951 could perform thousands of calculations per second. The first truly electronic computer was the ENIAC (Electronic, Numerator, Integrator, Analyzer, and Computer). The ENIAC was a highly classified military project for the United States Navy. It was designed to calculate firing tables for the large guns on naval ships. The computer was huge, consisting of 17,468 vacuum tubes, 70,000 resistors, 10,000 capacitors, 1,500 relays, and 6,000 manual switches. To contain these parts, forty panels were arranged in a horseshoe pattern. The unit weighed 30 tons and was 8 feet high and 80 feet long. To program the computer, thousands of switches had to be set by hand, and hundreds of cable connections had to be made. The tremendous heat of the vacuum tubes had to be kept under control with large air blowers.

UNIVAC was the first of the large computers to be made commercially available. The first unit was placed in operation at the Bureau of the Census.

The IBM 650 computer was the most popular of these first generation computers of the 1940s and early 1950s. Generally, these computers used vacuum tubes, were large, and required extensive air conditioning.

Second Generation Computers

These computers used transistors in place of vacuum tubes. Transistors performed the same function as tubes but were much smaller, required far less electric power, and were more reliable. Second generation computers were produced from 1959 to 1965, and were used in scientific and commercial applications.

Third Generation Computers

Computers continued to become smaller and faster. The component that was responsible for these changes was the integrated circuit (IC). An integrated circuit is a group of transistors, capacitors, resistors, and other parts that are made into a solid, inseparable piece which performs the functions of the individual components. Third generation computers using integrated circuits can perform a million calculations in a second, more than a thousand times faster than first generation computers.

Fourth Generation Computers

These computers reflect the current state of computer technology with commercial applications. In these computers *chips* contain the integrated circuits. A process called microminiaturization enables a thousand circuits to be created on one tiny silicon chip about the size of a fingernail. This technology has resulted in reduction in the size of computers and in an increase in speed. Another result is a major decrease in computer prices.

Within forty years the computer has become an affordable consumer item. It is for this reason that one of the most significant developments in fourth generation computers is the *personal computer*. Stores that sell computers are not only located in almost every city of any size, large computer manufacturers, the Apple Computer Company—for instance—has an automated plant that is capable of manufacturing one million of its Macintosh personal computers a year, figure 29-3.



Fig. 29-3 Apple Computer's automated manufacturing plant for the Macintosh computer (Courtesy Apple Computer, Inc.)

THE MICROCOMPUTER

A brief explanation of a typical personal computer—also know as a microcomputer—will be helpful in understanding what a computer can do and will introduce some common computer terminology.

Most microcomputers have five major parts: video screen, central processing unit, keyboard, disk drive, and printer. All of these items make up a group of devices commonly known as computer *hardware*.

The *video screen (monitor)* is a very familiar item to all. The computer monitor is similar to an ordinary television set. The monitor, however, cannot be removed from the computer for use as the family TV set. Most monitors do not have a volume control and they do not have a tuner for receiving TV sig-

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nals. Monitors have more lines of resolution than televisions to produce a crisper image. The monitor presents the information generated by the computer in visual form.

The *central processing unit* is the heart of the computer. All calculations and information processing take place in the central processing unit. In the modern microcomputer, the microprocessing chip is no larger than your thumbnail. A chip is a very small sliver of pure silicon. Many transistors and circuits are etched on the silicon using photographic processes. The end result is called an integrated circuit. The IC is so small that you can see the circuitry only through a microscope.

The *keyboard* is basically like an ordinary typewriter keyboard. The keyboard is used to put information into the computer instead of on a piece of paper. In many instances the information typed in will also be duplicated on the monitor.

The *disk drive* is about the size of a box of tissues. It is used to store and retrieve information by means of disks. The disks or diskettes, commonly called "floppy disks," are round, flexible circles of plastic with a coating of magnetic material similar to recording tape. The most common size for disks is 5¼ inches in diameter. These disks are referred to as *software*. The diskettes generally contain sets of instructions for the computer. These instructions are called programs. The program causes the computer to accomplish a certain job or task.

The *printer* can be thought of as a high technology typewriter. In many instances, it is necessary to have a copy of what is seen on the monitor. The image usually can be duplicated by using the printer. In computer language, a typed page is commonly referred to as "hard copy."

Information Capability of the Microcomputers

The key factor in classifying the size of a personal computer is the amount of information that it is capable of storing in its memory. There are two basic types of memory–RAM and ROM. RAM (Random Access Memory) chips make up the main memory of the computer. They store information while the computer is in use. Unless the data is transferred to a diskette, the information in RAM will be lost when the computer is turned off. On the other hand, ROM (Read Only Memory) is basically used to store the computer's internal instructions. These instructions are permanent and are not lost when the computer is turned off.

Computer storage capacity is usually expressed in RAM storage such as 16K, 48K or 128K (where K represents 1,000). What does this really mean? As an example, 16K means 16,000 bytes. A byte is roughly equivalent to one keystroke on the keyboard, whether this keystroke is a character or a space. A computer with 16K of memory is capable of holding approximately 3,200 words in its memory at any given time.

When a person operates a computer three things will typically happen. Information typed into a computer is considered to be INPUT. The computer acts on this information in a step called PROCESS. Finally, the result of input and process is usually seen on the monitor or is printed as hard copy and is referred to as OUTPUT.

COMPUTER APPLICATIONS

Wherever we look–at home, in business, in government, and in industry–we can see applications of computers, figure 29-4. In addition, new ideas for computer applications are being developed every day. Increasingly, we live in an information based society. Many of the most common computer applications include the accurate and rapid processing and storage of information. For example, a travel agent can quickly type a few commands into the computer and it will display airline flight information. A few more commands will allow the travel agent to reserve seats on your specified flight. The entire process takes only minutes and does not require letters or phone calls.

In some cases the speed and accuracy of computers is absolutely essential. For example, the calculations needed to control and direct the flight of a space craft can be done in microseconds. Time limitations would not permit such calculations to be done by hand or by slower machines.

In every application that now utilizes a computer, the computer is now doing the job because it is faster, more efficient, or more reliable than the old methods. Organizations that manage huge amounts of information have always been the largest users of computers.



Fig. 29-4 A microcomputer in the home permits the entire family to enjoy and learn from the numerous programs that are available. (Courtesy of Apple Computer, Inc.)

Government agencies keep track of mountainous amounts of information, insurance companies manage insurance policy records for millions of policy holders, utility companies use computers for billing their customers, financial institutions maintain records on all of their business and personal accounts, and large companies of all kinds use computers throughout their organizations. Figure 29-5 shows computers at the New York Stock Exchange where millions of shares are traded every day.



Fig. 29-5 Computers on the New York Stock Exchange have permitted trading to keep pace with the demands of stockholders. (Courtesy of the New York Stock Exchange)

Routine Applications of Computers

Computers can take care of the routine tasks of handling data, figure 29-6, but they also help business people analyze facts, figure 29-7. With a computer as a tool, the business people have more than experience, knowledge, and hunches to aid in decision making.

A short list of computer applications will show how widespread computer usage has become:

- Doctors–diagnosing diseases
- Police–checking vehicle registrations
- Stockbrokers–following the market
- Legislators–following the progress of legislation
- Lawyers–retrieving information on court decisions
- Railroads–keeping track of railroad cars
- Students–tutoring themselves
- Business–taking inventory
- Credit Bureaus–screening loan applications
- Realtors–locating homes to suit client needs
- Schools–keeping student records
- Weather forecasters–tracking storms
- Designers and engineers–developing new products

Computers are used to control and monitor many industrial processes and operations. A modern oil refinery is a good example of the use of computers to keep the various refining processes on track. The principle of feedback is used. Feedback allows one process to be adjusted to another process. For example, a thermostat turns on the furnace to maintain a given room temperature and then turns the furnace off again when the desired temperature is reached.

Feedback can also be seen in a business where information is fed through the organization as people and departments need to know the status of various situations if they are to accomplish a given task. As an example, when a retailer orders an item, the order affects an entire organization, including all departments in the factory, and the companies that supply the factory. Because computers can supply information quickly, the results of an order can be communicated to all concerned without delay. Inventories at the distributor and the factory can be checked and factory suppliers can be notified immediately to ship materials. With the aid of computers, the chain of events that may otherwise take weeks is done in moments. The result is faster service and a reduction of expensive inventory stockpiles.

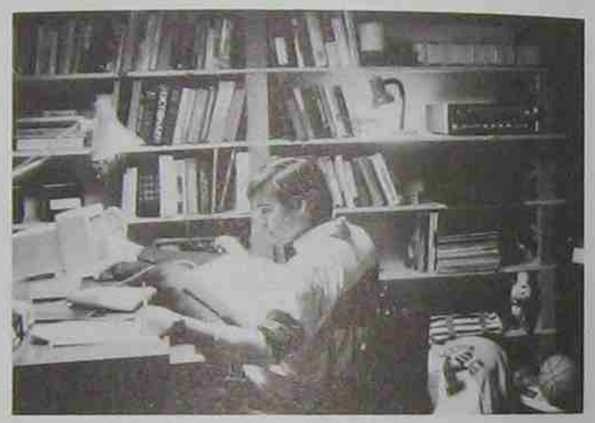

Fig. 29-6 Computers are a valuable tool for many students in high school and college. (Courtesy of Apple Computer, Inc.)



Fig. 29-7 The computer analyzes large amounts of data to help business people make decisions affecting the business. (Courtesy of AT & T Information Systems)

CAD, CAE, AND CAM

Increasingly, today's manufacturing industries are using computers. Three areas are commonly recognized–Computer Aided Design (CAD), Computed Aided Engineering (CAE), and Computer Aided Manufacturing (CAM).

In Computer Aided Design, figure 29-8, the drafting board and T square are replaced by a computer video screen. Using the computer, the designer can present parts on the screen where they can be studied. The parts



Fig. 29-8 Computer aided design of a new automobile model (Courtesy of Ford Motor Company)

are represented in computer graphics and they can be rotated, analyzed, and enlarged for better viewing. Alternative designs can also be considered. The designer is using computer graphics to help him see and understand the geometry of the part and its surfaces better than he could by presenting the part on a drafting board. Using CAD, designs or design changes can be made on the spot.

Computer Aided Engineering (CAE) is used to evaluate a part before prototypes are made or production is started. The computer helps to evaluate the function and performance of the part. When it is verified that the part meets the prescribed standards the design can be transferred to manufacturing.

Computer Aided Manufacturing (CAM) refers to the use of computers to run the machines needed for production. Computers are used for testing and monitoring quality. Robotics and numerically controlled machines are also a part of CAM.

The functions of CAD, CAE, and CAM are not separate, but rather overlap and interact. Experts in the field are finding new ways to use computers in industry every day.

CIM and Robotics

Manufacturing plants are moving rapidly in the direction of Computer Integrated Manufacturing (CIM). In this type of operation, the center is a large computer which contains the data base or all of the company's basic information. Many computer terminals are placed throughout the office and the factory itself. Design engineers use information on parts specifications that are located in the data base. Computer aided design allows the part to be designed quickly to specifications. The design now moves to the manufacturing engineering section where programs are developed for the numerically controlled machining centers. In the center of a cluster of machines is a robot that loads the part to be machined and then removes the completed parts from the machining center. Most parts move by conveyors or in computer controlled carts. Fewer workers are found in such a factory, but at almost every level of employment some knowledge of computers is required.

The science of robots is called robotics. Robotics promises to play an ever increasing role in manufacturing as industry strives to improve quality, cut production costs, and meet foreign competition. This is why manufacturers continue to use more and more robots in their operations. Often they perform jobs that are considered to be dangerous or uncomfortable for humans, such as welding, forging, or spray painting. Robots also are used to move parts from one place to another and, increasingly, they are used to perform exacting operations that are beyond human ability. The motion of the robots is not only directed by a computer program, but many robots can be reprogrammed easily to accomplish different jobs.

COMPUTERS IN AUTOMOBILES

Computer technology is increasingly a part of all modern automobiles. In many ways the use of computers in automobiles has been aided by both emission control requirements and the desire for increased gasoline mileage. Most automobiles manufactured in the United States now use microcomputers to monitor and control engine performance. The result is more efficient engine operation.

The typical computer is connected to sensors that are mounted on various engine components. The sensors monitor conditions and send information to the computer which then examines the data and sends signals to other engine components to correct or maintain proper operation. The primary job of the system is to provide precise control of the mixture of fuel and air through the carburetor or fuel injection system. For maximum efficiency of the catalytic converter and for best fuel economy, the air-fuel ration must be between 14.4:1 and 14.8:1. Several of the sensors associated with the system are: the coolant sensor mounted on the engine block, the catalytic converter temperature sensor mounted in the catalytic converter, the manifold pressure sensor, the throttle position sensor, and the oxygen sensor located in the exhaust manifold. Data fed to the computer from the sensors is analyzed. If the fuel mixture is too rich or too lean, signals are sent to a solenoid that controls the amount of gasoline mixing with the air.

The use of the computer, oxygen sensor, and low cost electronics has made it possible for manufacturers to use more electronic fuel injection systems to replace carburetors. The computer receives information about engine temperature, speed, load, and the oxygen content of the exhaust gases. This information is used to calculate the exact amount of gasoline needed for best combustion. A pulse of current is sent to the fuel injector to trigger the solenoid coil. As a result, the correct amount of fuel is delivered by the injector. The longer the pulse sent by the computer, the more fuel is delivered.

Two electronic fuel injection systems are commonly used. The multipoint or port system has a separate injector for each cylinder. The throttle body system has one or two injectors in a casting that bolts to the intake manifold. Its appearance is similar to the traditional carburetor. Both systems are very successful, but the multipoint system generally provides slightly better performance. The throttle body system is more economical.

In addition to the critical role of improving engine efficiency and controlling emission, computer and electronic systems perform many other functions. One of these functions is to monitor critical items such as engine temperature, fluid levels, and brake light operation. If a malfunction occurs appropriate lights go on or, in some cases, voice warnings are given.

Trip computers are found on several luxury automobiles. They can provide information on how much fuel has been used, how far you can travel on the remaining amount of fuel, estimated time of arrival, average speed traveled, fuel economy, and inside and outside temperatures.

Volkswagen has an upshift indicator light that goes on when the driver should shift to the next higher gear. Indications of engine speed and intake vacuum are sent to a computer. When the computer determines that the same power could be delivered more effectively at a higher gear the light goes on to indicate that it is time to shift.

Antiskid braking is a significant new safety feature. The danger of locking the brakes and loosing control while trying to stop on slippery roads has been a major safety concern. Within a few years this feature will be common on automobiles manufactured in the United States. Sensors at each of the four wheels relay information to the computer concerning the deceleration rate of each wheel during braking. If the computer determines that the rotation of the wheel is slowing too fast for the speed of the automobile, or if the wheel has locked, a signal is sent to decrease the

hydraulic pressure at the brake. As a result, the wheel begins to rotate faster. While the driver's foot is on the brake pedal, the computer will control the slowing of all four wheels–applying pressure and releasing it rapidly to prevent the wheels from locking and putting the auto through a skid.

Electronic transmission control may become common before many years have passed. In addition to regulating the transmission by hydraulic pressure, these systems will use information from sensors on speeds within the transmission, the engine load, and the type of driving being done. A computer will determine the best gear for the given situation.

Computers are also in common use now in automotive repair shops to diagnose problems with various systems within the automobile, figure 29-9. Such computer analysis can help reduce troubleshooting time and repair costs. Computers are also used to monitor parts usage and inventories.



Fig. 29-9 Computer controlled diagnosis of automotive systems can benefit the consumer with reduced repair time and costs. (Courtesy of Apple Computer, Inc.)

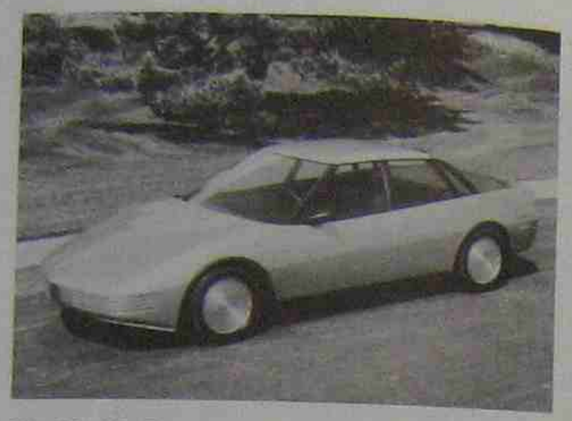

Fig. 29-10 Aero 2000, the automobile of the future, contains many high technology features. (Courtesy of General Motors Corporation)

Designers are including computers to a greater extent in future automobile models. For example, the General Motors Aero 2000 experimental subcompact auto, figure 29-10, has a sophisticated computer-controlled electronic system. Power windows and the heating/air-conditioning system are programmed to respond to spoken commands. Other features include a satellite navigation system, a video camera that provides a 180° view of the rear to replace mirrors, radar to assist in timely braking, and a complete electronic diagnostic system to monitor engine performance.

COMPUTER PROGRAM AREAS

Applications for microcomputers are unlimited today for business, educational and personal uses. Thousands of written programs or software are available. Several common program areas are listed with examples of each.

- ACCOUNTING PROGRAMS: accomplish business/accounting functions such as a general ledger, accounts payable and receivable, and payroll.
- BUSINESS GRAPHICS PROGRAMS: make it possible to produce bar graphs, line graphs, and technical illustrations.
- COMMUNICATIONS PROGRAMS: allow the operator to exchange data with other companies and to access on-line information data bases.
- DATA BASE PROGRAMS: help the user to store, find, and keep track of information.
- OFFICE MANAGEMENT PROGRAMS: keep track of appointments, phone numbers, various office forms, and other common office functions.
- SPECIFIC APPLICATION PROGRAMS: designed for special users such as architects, engineers, electronic designers, medical offices, and law offices.
- SPREADSHEET PROGRAMS: designed to help answer the "what if" questions; they project results in response to changes in variables.
- TRAINING PROGRAMS: designed to teach users how to operate computers, how to type, how to program, or how to do almost anything.
- WORD PROCESSING PROGRAMS: designed to make writing easy; they are used for correspondence, reports, memorandums, and for writing books.
- EDUCATIONAL PROGRAMS: help a person learn math, reading, writing skills and many other subjects.
- PERSONAL AND HOME FINANCE PROGRAMS: help an individual manage money matters such as checkbooks, financial and investment planning, and various home accounting needs.

THE COMPUTER INDUSTRY

Computer companies are part of the high technology industry. These companies deal with process systems, telecommunications, computer assisted design, computer aided manufacturing, robotics, fiber optics, information processing, electronic mail, and many other products and services.

High technology companies tend to be relatively small and able to react quickly to market demands. These companies generally locate where highly trained personnel are readily available, such as near universities which promote research and also provide training programs that are in step with advancing technology.

Many leaders in high technology industries are relatively young–under 30. Changes are taking place rapidly and there is room for those with the necessary skills.

To be sure, not everyone will work in the computer and high technology industries. However, everyone is now and will continue to be affected by these industries. Completing this unit on computers should not be the end of your computer studies, but only the beginning.

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REVIEW QUESTIONS

1. Write a simple definition of a computer.
2. Explain the various occupational levels needed in the computer society.
3. Does a computer operator need to know how to program a computer? Explain.
4. Trace the rapid growth in the numbers of computers in the country.
5. Discuss the abacus and its history.
6. List several early pioneers who worked with computer principles and machines.
7. State a significant characteristic of each of the four generations of computers.
8. What is an integrated circuit? A chip?
9. List the five major parts of a microcomputer and write a statement about each.
10. Explain the term "software."
11. Explain why the government has always been a major user of computers.
12. List five occupations and how they might use computers.
13. Explain the term "feedback."
14. Briefly explain CAD, CAE, and CAM.
15. Explain why computers are used in various automobile systems. List several systems which now include computers.

Unit 30 Power Technology and the Environment

OBJECTIVES After completing this unit, the student should be able to:

- Explain how the use of power contributes to pollution.
- List the major sources of pollution.
- Discuss the role of government in controlling pollution.
- Explain the need for recycling.

Throughout the centuries civilizations have regarded this planet earth as a challenge. They met the challenge almost as if the earth was the enemy. They have been thorough and sometimes ruthless in the way they have cut the trees, mined the minerals, and killed the wildlife. And remember, all this was done in the name of *progress*.

The earth has been considered something limitless, figure 30-1. It was assumed that people could go on taking forever, using what they wanted and discarding what did not suit them as waste. These *civilized* people have proved themselves to be nature's most untidy and careless animal, even though they possess as intelligence superior to any other creature.

Even in today's enlightened scientific age, most persons share to some degree these careless, shortsighted views about the earth. Our environment and our world are threatened by a huge appetite for manufactured goods. Can our environmental problems be solved? Solutions require sacrifice and a change in our life style.

It is important that students of power technology understand the problem and do their part in the overall solution, figures 30-2 and 30-3. Power has much to do with our present high degree of civilization. However, energy is being used on an ever increasing scale. In 1945 there was a total of 31 million automobiles in the United States. Today there

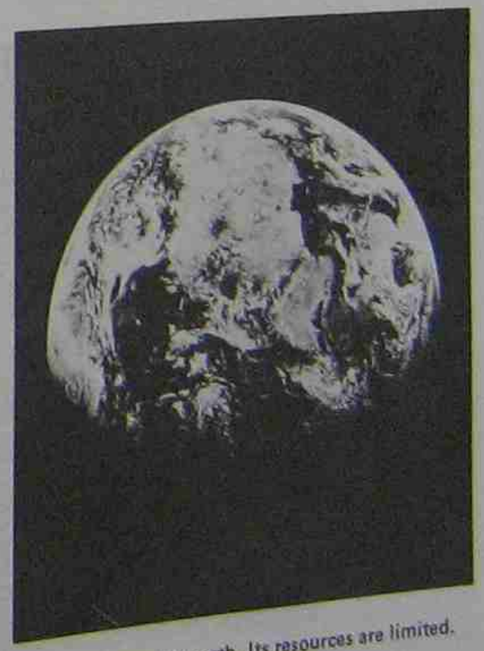


Fig. 30-1 Spaceship earth. Its resources are limited.



Fig. 30-2 Solar energy is a clean solution to heating. (Courtesy of Electric Power Research Institute)



Fig. 30-3 Electric-powered vehicles would help reduce pollution. (Courtesy of Electric Power Research Institute)

are more than 100 million automobiles on our highways. Our electrical consumption has doubled every decade for the last 50 years. Only in recent years has it become obvious that a huge price is being paid for all this power: mineral depletion, scarred landscape, and polluted air.

The scope of the problem is a vast one with many interrelated parts. It is important to define three important terms.

- **Environment** is the sum total of the things, conditions, and influences that affect the development of life.
- **Pollution** is the waste that makes the environment unclean or foul. Pollution can affect health, safety, and even technology itself. Pollution also offends moral and aesthetic sensibilities, decreasing the quality of life.
- **Ecology** is a branch of biology that concerns itself with the relationship of organisms and their environment. Ecology is the study of the *interdependence* of all forms of life.

THE GOVERNMENT AND POLLUTION

Conservationists have tried through the years to inform the citizens of a rapidly approaching environmental crises. They experienced moderate success in arousing the public and in securing the passage of legislation aimed at environmental problems. The late Rachel Carson's book, *Silent Spring*, which was published in 1962, did much to stimulate widespread interest in the environment. Later in the decade, oil spills fouled beaches and destroyed marine life, and smog endangered the health of people living in urban areas. These events finally awakened the public to the fact that the environment was indeed being threatened.

The federal government expressed concern with the passage of the Air Pollution Control Act in 1955 which funded air pollution research. The Clean Air Act of 1963 poured millions of dollars into solving pollution problems. It shifted the emphasis to developing, establishing, and improving pollution prevention and control programs.

In 1965 the Motor Vehicle Air Pollution Control Act provided for establishment of emission standards for new motor vehicles. In 1968 the auto industry began to meet federal emission standards, which have become increasingly stringent in recent years.

Federal involvement in all forms of pollution continued to grow. In 1970 a master agency called the Environmental Protection Agency (EPA) was formed. The EPA has authority over municipalities, states, and industries in pollution control of air, water, radiation hazards, solid wastes, and pesticides.

The Council on Environmental Quality, CEQ, and the National Oceanic and Atmospheric Agency, (NOAA), were established in 1970. The CEQ is assigned the task of supervising the government itself. This agency checks out all projects, plans, and proposals that may affect the environment. The NOAA is designed to be a superior scientific agency. It determines how badly air and water are already polluted and suggests what can be done about it. In addition, the NOAA determines existing resources in the sea and air. It also explores ways to shape the weather.

AIR POLLUTION

The major sources of air pollution are transportation, in which the main culprit is the automobile; industrial and residential heating plants; refuse burning; pollution from industrial processes; and utilities, especially coal-burning electrical power generation sta-

tions. These sources of pollution are highly concentrated in urban areas where 70% of the population lives.

People are quick to single out the billowing industrial stacks—the other guy, so to speak—as the prime polluter, but the fact is that the individual should turn around and look at the effects of his own pollution. These include furnaces, incinerators (Note: It is best to mention here that the majority of states have outlawed backyard incinerators. If your state has not, they should be considered a major source of pollution by an individual.), power mowers, and automobiles, which are the largest single source of air pollution.

Several types of air pollutants have been identified. Carbon monoxide is the colorless, odorless, and tasteless killer in auto exhaust. Other pollutants include sulfur oxides, carbon dioxide, lead, nitrogen oxides, assorted hydrocarbons, ash, mists of oil, aerosols, metallic oxides, and various soots. At this point researchers are just beginning their list of harmful air pollutants.

Property damage caused by pollution has a price tag of ten billion dollars per year. Photochemical smog is partially produced by the reactions of nitrogen oxides with oxygen in the sunlight. It is agreed that smog produces damage in the human body, but specific research results are lacking. It can be said, however, that pollutants do aggravate all types of respiratory conditions. Millions of people have experienced the effects of smog: stinging eyes, irritated nasal passages, and breathing difficulties. Breathing polluted air over a lifetime may well be costing far more than is now realized.

SOLUTIONS TO AIR POLLUTION

Air pollution is being reduced, figure 30-4. The big stacks of industry are being equipped with electrostatic precipitators, centrifugal collectors, filters, baffles, and water scrubbers to reduce pollution hazards. These devices are expensive, but industries are moving rapidly to control the emissions from their stacks. Nuclear-powered electrical plants are the cleanest power source, but even nuclear reactors pose environmental threats from radiation and thermal pollution.



Fig. 30-4 Scientists collecting samples of rain water to be tested for pollution. (Courtesy of Electric Power Research Institute)

The individual can help reduce air pollution. The cumulative power demands of the public are reflected at the power station as it consumes mountainous stockpiles of coal. Instead of loading the home with labor-saving devices to the point where it takes on the appearance of a miniature factory, the family should do more under their own power. Burning a cleaner fuel for residential heating also reduces pollution.

Choosing a Residential Heating Fuel

Natural gas is quite clean, but it is also in short supply. The most plentiful fuel is coal, but the cheapest coal is high in sulfur content. Taking the sulfur out of coal before burning it—though possible—is an expensive process. Much of the fuel oil that is priced competitively with coal is also high in sulfur content. Home heating oil has most of the sulfur removed, but it costs about twice as much as the heavier oils.

POLLUTION FROM AUTOMOBILES

Many environmentalists favor deemphasizing the auto and its place in today's lifestyle. In other words, they advocate a return to mass transit systems. They even want to prohibit automobiles from the most congested area of a city. The millions of autos in a metropolis pollute the air, take acres of parking space, require fantastic highway complexes, and are generally inefficient in moving people. Ranked in order of efficiency of people moving, the bus, train, bicycle, and even walking are all ahead of the automobile.

No doubt there is a renewed interest in mass transit, but there is little evidence that people are about to willingly give up the family car. It is so woven into our economy and our lives that some people feel that life without the car is as unpalatable as life with polluted air. Hence, the automobile must be cleaned up. Spurred on by the pollution reduction standards of the Environmental Protection Agency, automobile manufacturers are doing just that.

Automobile pollution comes from three principal sources: vapors from the crankcase, fuel vaporization from the gas tank and carburetor, and combustion by-products from the tailpipe. The solutions to automobile pollution are discussed in detail in Unit 9.

RECYCLING

Society cannot afford to continually discard the by-products of living. This practice not only depletes resources but, literally buries us in garbage. Recycling of the earth's resources must someday become the rule rather than the exception, figure 30-5. While recycling is common with things such as scrap iron, copper, brass, aluminum, and paper, the field of recycling is still new. Generally, industrial wastes are located, collected, separated, and controlled or recycled, but the costs are high for industry. The collective refuse from a community is not nearly so easy to separate and control or recycle. Up to now it has been dumped in the ocean or on the land, buried in landfills, or burned in incinerators. A totally closed system must be developed where the wastes that cannot be recycled are controlled, yet do not pollute the environment or damage the ecological balance of the earth.

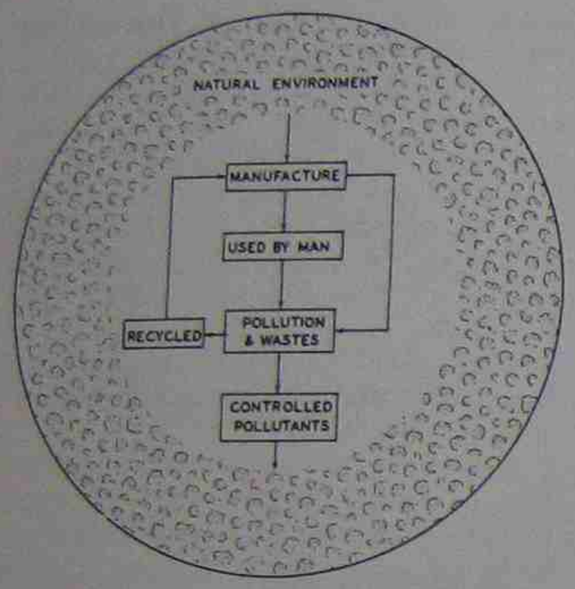


Fig. 30-5 Our natural environment can be saved with a system that recycles resources and controls pollutants.

SUMMARY

Most air pollutants come from transportation; engines and turbines on autos, trucks, trains, ships, and aircraft; and the production of electric power at coal-burning power stations. But identifying and controlling emissions from these sources is not enough. What about the scars on the earth left by the coal strip mines, the millions of wrecked and abandoned automobiles, the chemical pollution in lakes and waterways?

The noise pollution of the city and industrial site has a relationship to power usage. Power has played a part in the production of thousands of nonbiodegradable plastics that will litter the landscape for years to come. The psychology of our prepackaged, throw-away society creates mountains of refuse. Pollution in all forms has a relationship to power usage.

Attitudes have a lot to do with success or failure. The attitudes of individuals, communities, and nations are important. The old attitudes of conquering nature and taking all types of resources must be replaced with attitudes of conserving, obeying the laws of nature, and learning to live on the earth without destroying it, figure 30-6.



Fig. 30-6 Industry can live in harmony with agriculture and nature. (Courtesy American Petroleum Institute)

REVIEW QUESTIONS

1. Explain how the use of power has contributed to pollution.
2. Define the following terms:
   environment pollution ecology
3. What is the function of the Environmental Protection Agency?
4. Name five major sources of air pollution.
5. List five air pollutants.
6. Explain why rapid transit systems pollute less than automobiles.
7. What are the three sources of pollution from the automobile?
8. List three features of auto design that reduce pollution.

Appendix A Troubleshooting, Tune-up, and Reconditioning

Troubleshooting is the intelligent, step-by-step process of locating engine trouble. The troubleshooter examines and/or tests the engine to determine the cause of its disorder. To engage in this process, a person must thoroughly understand the how and why of engine operation. Troubleshooting is more a mental activity than a physical one.

The troubleshooter first establishes the engine's symptoms. The most common causes for these symptoms are then checked. If the solution is not found, another possible cause for the engine's problem is explored. The possible cause for engine failure must quickly be narrowed down because there are many afflictions that can creep into an ailing engine.

An experienced mechanic troubleshoots quickly and with little apparent effort. Years of experience and a thorough understanding of engine operation allow the mechanic to work with such competence.

Engine owners can do their own troubleshooting when they understand engine operating principles. Many owner's manuals contain a troubleshooting chart that is of great assistance. With the aid of an engine troubleshooting chart, the engine owner or operator can locate and correct many engine difficulties without calling in a professional mechanic.

Troubleshooting requires a knowledge of engine operation as well as some common sense. For example, if the engine does not start, there are two possible reasons: either (1) fuel is not getting into the combustion chamber, or (2) fuel is being provided but it is not being ignited. Therefore, the trouble is either in the fuel system or the ignition system. Lubrication or cooling systems have little influence on the ability of the engine to start so these systems are not inspected.

The troubleshooter starts with the simplest and most frequent causes of trouble. In inspecting the fuel system, the first step is to check for fuel in the tank. If this is not the cause of the trouble, the fuel shutoff valve is then checked. The inspection continues in a logical manner until the trouble is found. It would be a mistake to completely disassemble the carburetor or magneto as the first step in troubleshooting.

Look at the troubleshooting charts (figures A-1 to A-3) and discover how many of the common engine troubles can be corrected by an owner who has the tools on hand.

ENGINE TUNE-UP

Engine tune-up does not involve major engine repair work. Rather, it is a process of cleaning and adjusting the engine so that it gives top performance. A tune-up can be done by an experienced engine owner or it can be done by a mechanic. Before beginning tune-up THINK SAFETY. Study the following safety rules.

GENERAL SAFETY RULES FOR TUNE-UP AND RECONDITIONING

- Do not run an engine in a closed building without proper ventilation.

FAULT	POSSIBLE CAUSE
Poor Compression	1. Loose spark plug 2. Damaged spark plug seat 3. Cracked cylinder crankcase 4. Loose or missing crankcase bolts 5. Compression loss in the crankcase 6. Broken or worn piston rings 7. Broken or worn piston lands 8. Scored piston 9. Scored cylinder
Weak Or No Spark (Ignition System)	Spark plug 1. Fouled 2. Wrong gap 3. Cracked or dirty insulation Breaker points 4. Dirty or greasy 5. Burned or pitted 6. Wrong gap 7. Poor alignment 8. Breaker block worn Wiring 9. Loose terminals 10. Broken wires 11. Frayed insulation 12. Connector pulled from lead Lamination 13. Wrong air gap Switch 14. Grounding out or in "OFF" position Condenser 15. Defective Coil 16. Defective Magnet 17. Weak

Fig. A-1 Troubleshooting chart

- Exhaust fumes contain carbon monoxide which is poisonous and can be fatal.
- Do not touch the cylinder head, cylinder block, or exhaust system on an engine that is running or one that has just been stopped. The parts may be hot enough to cause a severe burn.
- Do not add fuel to a hot engine or an engine that is running. Gasoline spilled on the engine could burn.
- Do not operate an engine without all safety guards in place. Take care that your clothing, hands, feet, and hair do not get caught in any moving parts.
- Do not touch any electrical wires or electric components on a running engine. A faulty part or unguarded terminal represents an electrical shock hazard that could cause injury or death.
- If the engine has a battery system that must be disconnected, disconnect the negative or ground cable first. When reconnecting the battery, reconnect power (positive) cable first. Be careful not to spill any battery acid as it can cause serious burns. However, if a spill occurs, it can be neutralized using baking soda.

A typical tune-up procedure includes the following steps. The mechanic's repair manual for the particular engine should be at hand.

1. Inspect the air cleaner then clean and reassemble it. Is the cleaner damaged in any way? Is the filter element too clogged for cleaning? If so, replace the cleaner and/or element. Clean the unit according to the manufacturer's instructions.
2. Clean the gas tank, fuel lines, and any fuel filters or screens.

Problem	No Fuel	Improper Fuel	Dirt In Fuel Line	Dirty Air Screen	Incorrect Oil Level	Engine Over-Loaded	Dirty Filter Element	Faulty Spark Plug
Will not start	X		X			X	X	X
Hard starting	X	X	X	X		X		X
Stops suddenly	X		X	X	X	X	X	
Lacks power		X	X	X		X	X	X
Operates erratically		X	X	X		X	X	X
Knocks or pings		X		X		X		X
Skips or misfires		X	X	X			X	X
Backfires			X			X	X	X
Overheats			X	X	X	X	X	
High fuel consumption							X	X

Fig. A-2 Troubleshooting chart for the engine owner

Engine Will Not Crank

Hydrostatic drive not in neutral.
Battery discharged or defective.
PTO drive engaged.
Defective safety switch.
Defective starter.
Defective solenoid.
Loose electrical connections.
Defective key switch.

Engine Cranks But Will Not Start

Empty fuel tank.
Restricted fuel tank vent.
Fuel shut-off valve closed.
Clogged or restricted fuel line.
Breaker points worn or pitted.
Defective spark plugs.
Battery not fully charged.
Loose electrical connections.
Faulty condenser.
Defective ignition coil.
Dirt in fuel system.

Engine Starts Hard

Defective spark plugs.
Breaker points worn or pitted.
Loose wires or connections.
Restricted fuel tank vent.
Clogged or restricted fuel line.
Broken choke or throttle cable.
Dirt or water in fuel system.
Carburetor not properly adjusted.
Wrong valve clearance.
Head gasket leaking.
Low compression.

Engine Starts But Fails To Keep Running

Restricted fuel tank vent.
Carburetor not properly adjusted.
Broken choke cable.
Dirt or water in fuel system.
Breaker points not properly adjusted.
Loose wires or connections.
Defective head gasket.
Faulty condenser.

Engine Runs But Misses

Breaker points not properly adjusted.
Defective spark plugs.
Loose wires or connections.
Carburetor float leaking or not properly adjusted.
Dirt or water in fuel system.
Wrong valve clearance.
Faulty coil.
Air intake or shrouding plugged.

Engine Misses Under Load

Defective spark plugs.
Carburetor not properly adjusted.
Incorrect spark plugs.
Breaker points not properly adjusted.
Ignition out of time.
Dirt or water in fuel system.

Engine Will Not Idle

Idle speed too slow.
Idle mixture needle not properly adjusted.
Dirt or water in fuel system.
Restricted fuel tank filler cap.
Defective spark plugs.
Wrong valve clearance.
Low engine compression.

Engine Loses Power

Crankcase low on oil.
Air intake or shrouding plugged.
Excessive engine load.
Restricted air filter.
Dirt or water in fuel system.
Carburetor not properly adjusted.
Defective spark plugs.
Too much oil in crankcase.
Low engine compression.
Worn cylinder bore.

Engine Overheats

Air intake or shrouding plugged.
Carburetor not properly adjusted.
Too much oil in crankcase.
Crankcase low on oil.
Excessive engine load.

Engine Knocks

Engine out of time.
Excessive engine load.
Crankcase low on oil.

Engine Uses Excessive Amount of Oil

Clogged breather assembly.
Breather not assembled properly.
Worn or broken piston rings.
Worn cylinder bores.
Wrong size piston rings.
Worn valve stems and/or valve guides.
Incorrect oil viscosity.

Fig. A-3 Troubleshooting chart for the mechanic

3. Check the compression. This can be done by slowly turning the engine over by hand. As the piston nears top dead center, considerable resistance should be felt. As top dead center is passed, the piston should snap back down the cylinder. A more thorough test can be made with a compression gauge, figure A-4. The manufacturer's repair manual should be consulted for normal and minimum acceptable compression pressure.

   NOTE: Many engines have an automatic compression release mechanism which holds the intake valve slightly open for cranking the engine during starting. This allows the operator to start the engine with less pull. However, the automatic compression release makes checking the compression difficult.

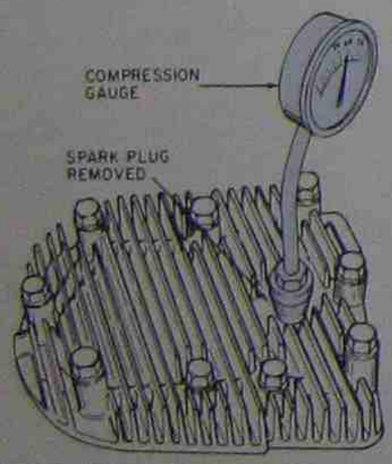


Fig. A-4 Checking compression with a gauge

4. Check the spark plug: clean, regap, or replace it. Remove the spark plug and attach a grounded spark plug tester to the spark plug, figure A-5. Reattach the spark plug cable and clamp the tester to the engine block. Turn the engine over. If a good spark jumps at the plug electrodes the plug is good, figure A-6. This is not an absolute test but is a good indication. If the plug is questionable, replace it.

5. Check the operation of the governor, figure A-7. Be certain the governor linkages do not bind at any point.

6. Check the magneto. On most engines, the flywheel must be removed for access to the magneto parts. Use a flywheel or gear puller if available, figure A-8. Otherwise, pop the flywheel loose by removing the flywheel nut and delivering a sharp hammer blow to a lead block held against the end of the crankshaft.

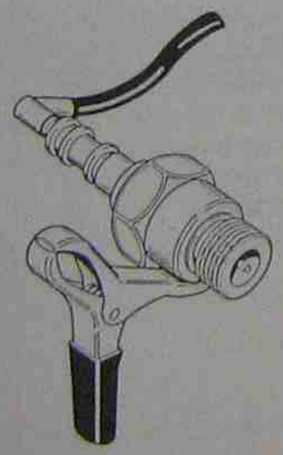


Fig. A-5 Checking for spark (Courtesy of Tecumseh Products Company)

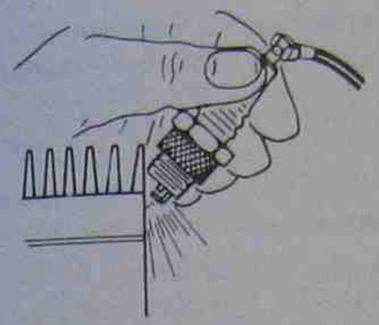


Fig. A-6 Checking spark plug

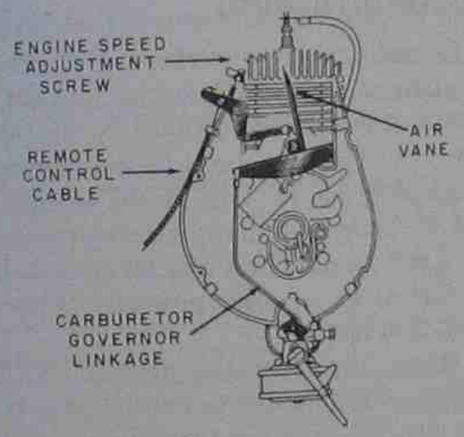


Fig. A-7 Air vane governor parts

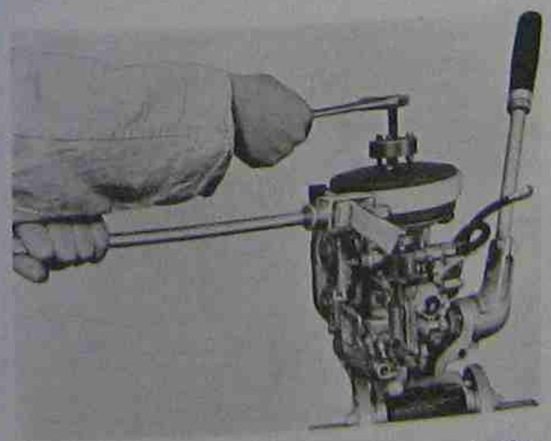


Fig. A-8 Removing a flywheel using a special puller

Another method is to back off the flywheel nut until it is about 1/3 off the crankshaft and then strike it sharply. Do not hammer on the end of the crankshaft as this can damage the threads, figure A-9.

Adjust the breaker point gap and check the condenser and breaker point terminals for tightness, figure A-10. Breaker points are set for 0.020 inch in most cases although the correct setting may vary according to the manufacturer. Turn the engine over until the breaker points reach their maximum opening, then check with a flat feeler gauge or wire gauge. Adjust the points if the setting is incorrect. Breaker points must line up, figure A-11. Points can be cleaned if necessary. If the points are pitted or do not line up, they should be replaced, figure A-12.

7. Fill the crankcase with clean oil of the correct type. (four-stroke cycle engines)



Fig. A-9 Removing the flywheel with a soft hammer

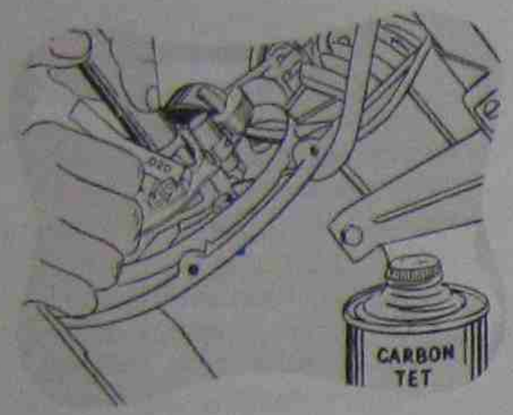


Fig. A-10 Clean and check breaker points.

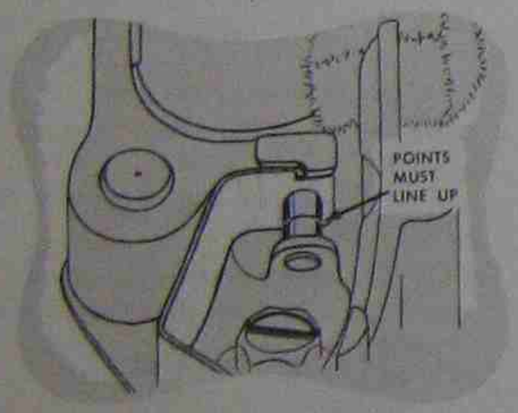


Fig. A-11 Breaker points must line up.

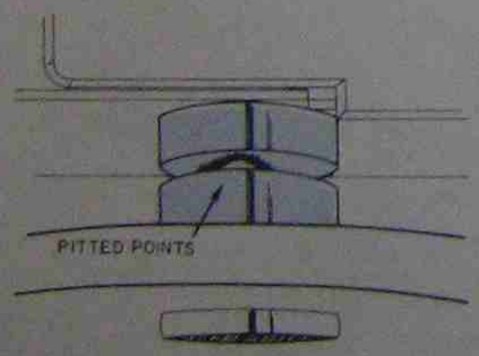


Fig. A-12 Pitted breaker points should be replaced.

8. Fill the gasoline tank with regular gasoline. (four-stroke cycle engines)

   Fill the gasoline tank with the correct mixture of gasoline and oil. (two-stroke cycle engines)

9. Start the engine.

10. Adjust the carburetor for peak performance. See carburetor parts shown in figure A-13.

RECONDITIONING

Reconditioning or overhauling an engine is generally the job for the mechanic – one who has the tools and know-how to do the job correctly. However, much reconditioning and overhauling can be done by the amateur who has the basic tools and the correct approach. Care and precision are very important. Every part must be in place correctly, with none missing or left over.

Before beginning the disassembly of an engine, provide a spot to put the parts as they are removed. One good method is to lay out a large sheet of paper. As the parts are placed

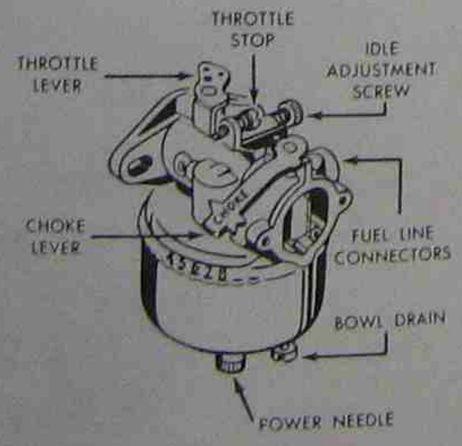


Fig. A-13 Carburetor parts

on the paper, label them so they will not be lost. It is often difficult to remember just where a part came from when forty or fifty pieces are laid out; also, it may be several days before the engine is reassembled.

A mechanic's handbook or service manual is essential for top-quality overhaul work. These books can sometimes be obtained directly from the engine manufacturer or borrowed from a mechanic. In only a few instances is this type of book supplied with the new engine. The service manual is quite detailed, fully explaining each step of overhaul or reconditioning. Allowances, clearances, torque data and other specifications are also given, figure A-14. Without the use of the service manual there is too much guesswork involved. The amateur mechanic should have the service manual for the engine before any repair work is started.

Tools and Equipment

Unless the engine owner is a skilled mechanic and has an adequately equipped repair shop, the owner cannot perform all types of engine repair and overhaul. Most owners

CLINTON ENGINES TORQUE DATA – INCH POUNDS
"Red Horse"

		1600 A1600 A1690	1800 1890	2500 A2500	B2500 B2590 2790
Bearing Plate P.T.O.	Min.	160	160	160	160
	Max.	180	180	180	180
Back Plate to Block	Min.	70	70	70	70
	Max.	80	80	80	80

CLINTON ENGINES SERVICE CLEARANCES
"Red Horse"

		1600	A1600	A1690	1800	1890	2500	B2500	B2590	A2500	2790
Piston Skirt Clearance	Min.	.007	.007	.007	.007	.007	.0085	.0085	.0085	.005	.005
	Max.	.009	.009	.009	.009	.009	.0085	.0085	.0085	.007	.007
	Rework	.010	.010	.010	.010	.010	.010	.010	.010	.0085	.0085
Ring End Gap	Min.	.007	.007	.007	.007	.007	.010	.010	.010	.010	.010
	Max.	.017	.017	.017	.017	.017	.020	.020	.020	.020	.020
	Rework	.025	.025	.025	.025	.025	.028	.028	.028	.028	.028

CLINTON ENGINES TOLERANCES AND SPECIFICATIONS
"Red Horse"

	1600	A1600	A1690	1800	1890	2500	B2500	B2590	A2500	2790
Cylinder - Bore	2.8125 2.8135	2.8125 2.5135	2.8125 2.8135	2.9995 3.0005	2.9995 3.0005	3.1245 3.1255	3.1245 3.1255	3.1245 3.1255	3.1245 3.1255	3.1245 3.1255
Skirt - Diameter	2.8045 2.8055	2.8045 2.8055	2.8045 2.8055	2.9915 2.9925	2.9915 2.9925	3.117 3.118	3.117 3.118	3.117 3.118	3.1185 3.1195	3.1185 3.1195

Fig. A-14 Torque data, clearances, tolerances, and specifications as excerpted from a service manual

TORQUE SETTINGS – GENERAL

Tightening Torque Into Cast Iron or Steel

Size	Grade 2	Grade 5	Grade 8
8-32	20 in-lb	25 in-lb	
10-24	32 in-lb	40 in-lb	
10-32	32 in-lb	32 in-lb	
1/4-20	70 in-lb	115 in-lb	165 in-lb
1/4-28	85 in-lb	140 in-lb	200 in-lb
5/16-18	150 in-lb	250 in-lb	350 in-lb
5/16-24	165 in-lb	270 in-lb	30 ft-lb
3/8-16	260 in-lb	35 ft-lb	50 ft-lb
3/8-24	300 in-lb	40 ft-lb	60 ft-lb
7/16-14	35 ft-lb	55 ft-lb	80 ft-lb
7/16-20	45 ft-lb	75 ft-lb	105 ft-lb
1/2-13	50 ft-lb	80 ft-lb	115 ft-lb
1/2-20	70 ft-lb	105 ft-lb	165 ft-lb
9/16-12	75 ft-lb	125 ft-lb	175 ft-lb
9/16-18	100 ft-lb	165 ft-lb	230 ft-lb
5/8-11	110 ft-lb	180 ft-lb	260 ft-lb
5/8-18	140 ft-lb	230 ft-lb	330 ft-lb
3/4-10	150 ft-lb	245 ft-lb	350 ft-lb
3/4-16	200 ft-lb	325 ft-lb	470 ft-lb

Tightening Torque Into Aluminum

Size	Grade 2	Grade 5
8-32	20 in-lb	20 in-lb
10-24	32 in-lb	32 in-lb
1/4-20	70 in-lb	70 in-lb
5/16-18	150 in-lb	150 in-lb

CONVERSIONS

in-lb X 0.083 = ft-lb
ft-lb X 12 = in-lb
ft-lb X 0.1383 = kgm
ft-lb X 1.3558 = N m

Fig. A-15 General torque settings for bolts

would not find it practical to purchase the equipment necessary to do all types of overhaul and repair. Professional repairers may have invested from five hundred to several thousand dollars in tools and equipment. Equipment may consist of: magneto testers, valve seat resurfacers, air compressors, steam cleaners, special sharpeners, grinders, lapping stands, special factory tools, general repair tools, repair parts, and others.

A small investment in tools allows a person to perform many repair jobs. Most home workshops have some of the basic tools that are necessary. Several specialized tools can be added, figure A-16. A tentative list of necessary tools include the following:

- Screwdriver (various sizes)
- Combination wrenches (set)
- Adjustable wrench
- Socket set
- Torque wrench
- Deep well spark plug socket
- Needle nose pliers
- Feeler gauge/wire gauge
- Spark gap gauge
- Piston ring compressor
- Piston ring expander
- Valve spring compressor



Fig. A-16 Some of the special tools needed for engine overhaul

Additional tools:

- Flywheel puller
- Compression gauge
- Tachometer
- Valve grinder – hand operated
- Arbor press

Basic Steps

Reconditioning or overhaul of an engine involves four basic steps: disassembly, inspection of parts, repair or replacement of worn or broken parts, and reassembly. In actual practice, a service manual would be followed for these steps. However, the following disassembly procedure is a general guide for a four-stroke cycle engine. Before disassembly, however, check for compression, spark, and crankshaft end-play. These items cannot be checked once the engine is disassembled.

1. Disconnect the spark plug lead and remove the spark plug.
2. Drain the fuel system – tank, lines, carburetor.
3. Drain the oil from the crankcase.
4. Remove the air cleaner.
5. Remove the carburetor.
6. Remove the metal air shrouding, gas tank, and recoil starter.
7. Remove the flywheel.
8. Remove the breaker assembly and push rod.
9. Remove the magneto plate assembly.
10. Remove the breather plate assembly (valve spring cover). Check the valve clearance.
11. Remove the cylinder head. Check for warpage.
12. Remove the valves.
13. Remove the base.
14. Remove the piston assembly.
15. Remove the crankshaft.
16. Remove the camshaft and tappets.
17. Remove the mechanical governor.

As general information, the disassembly, inspection, repair, and reassembly for each engine part are discussed in this unit.

FLYWHEEL

Removal of the flywheel is necessary to gain access to the ignition system parts. If a special flywheel puller designed for the specific engine is available, use it. Otherwise use a flywheel puller. Be sure the flywheel nut or any threaded starter mechanism is removed before trying to pull the flywheel. Opposing pressure against the flywheel and the end of the crankshaft will break the contact of the tapered hole and the tapered shaft. Care should be taken with aluminum flywheels since excessive force can cause them to break.

If a flywheel puller is not available, the flywheel can be removed by first removing the flywheel nut and then striking the end of the crankshaft with a plastic, lead, or other soft-face hammer. A sharp blow on the shaft while exerting some outward pull on the flywheel will separate the flywheel from the shaft. Take care not to damage the end of the crankshaft, especially the threads. Engines that rotate clockwise have right-handed threads on the crankshaft and engines that

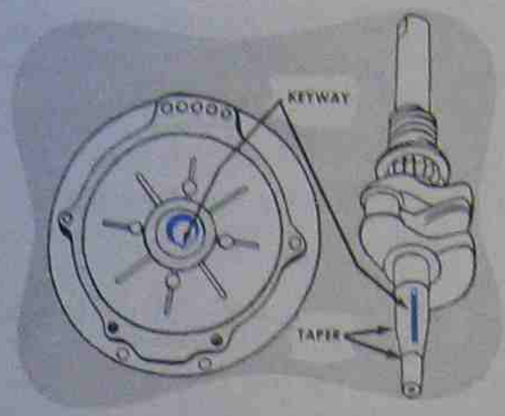


Fig. A-17 Keyway on tapered end of the crankshaft and the flywheel

rotate counterclockwise have left-handed threads.

The magnets in the flywheel can be damaged if the flywheel is dropped or if the magnets are hammered. Excessive heat causes the magnets to lose magnetism.

The key that aligns the crankshaft and flywheel is small; care should be taken not to lose it. If the key is damaged or worn, it should be replaced since poor alignment can affect engine timing. When reassembling the flywheel onto the crankshaft, carefully fit the key into the keyway, figure A-17. Also, be sure that no washers are forgotten when the flywheel is reinstalled.

MAGNETO PARTS

The magneto parts (high-voltage coil, breaker points, condenser) may need to be removed for checking or replacement. The coil may be visually inspected for cracks and gouges in insulation, evidence of overheating, and the condition of the leads where they go into the coil. If an ignition coil tester is available, the coil can be checked for firing, leakage, secondary continuity, and primary continuity. This checking should be done using the procedure recommended by the manufacturers.

Breaker points that are corroded, pitted or dirty, provide a poor electrical contact. This lowers the magneto's ability to produce the proper voltage in the primary windings. Also, when the breaker points open, less voltage is induced because a clean, quick break is not produced. Breaker points that are in poor condition can seriously reduce the voltage available to the spark plug.

The setting of the breaker points (usually 0.020 inch) affects the engine timing. If the points are set for too small an opening, the spark is retarded. The spark is late because the cam must rotate further before the points open. Too wide an opening causes the spark to be advanced. Both conditions cause an engine to lose power. The two points should meet each other flat with their surfaces in full contact with each other. Points have a chrome or silvery appearance when new, and become gray as they are used.

The condenser can be visually inspected for dents, terminal lead damage and broken mounting clips. A condenser tester is used to check the condenser for capacity, leakage and series resistance, figure A-18. The test procedure suggested by the test equipment manufacturer should be followed.

Manufacturers often recommend replacing the condenser when the points are replaced even though the condenser is still reliable and in good condition. If one of the breaker points is a part of the condenser, the entire condenser must be replaced.

When the magneto is reassembled, the laminated iron core must be as close to the flywheel and its magnets as possible without

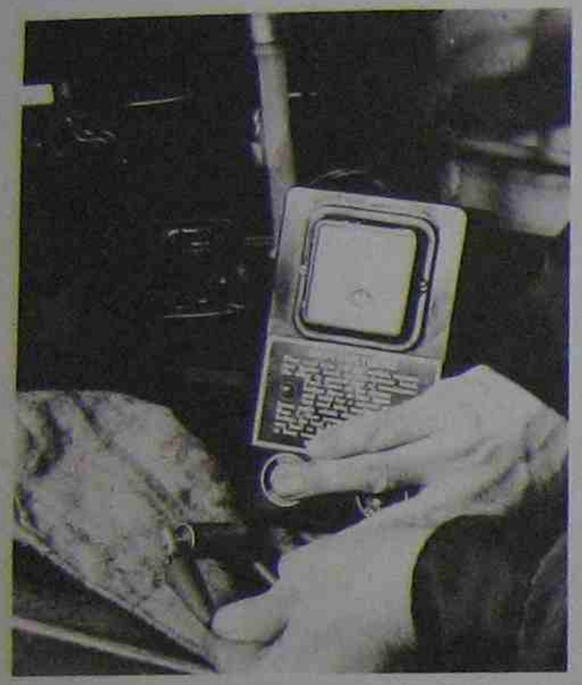


Fig. A-18 Checking a condenser

touching or rubbing as the flywheel revolves. The closer the magnet is to the core (or pole shoes) the stronger the magnetic influence of the flywheel magnets. A space of about 0.007 inch to 0.012 inch is usually suggested, about the thickness of a postal card.

ENGINE TIMING

Engine timing refers to the magneto timing to the piston – the position of the piston just as the breaker points start to open. Timing is set at the factory but it is possible for timing to cause engine trouble. If the breaker points open too late in the cycle, power is lost. If the breaker points open too early in the cycle, detonation can result. Improper engine timing can be caused by the

- crankshaft and camshaft gears being installed one tooth off
- spark advance mechanism being stuck
- breaker points incorrectly set
- magneto assembly plate loose or slipped
- rotor incorrectly positioned.

These causes of trouble depend on the engine and the type of magneto.

The position of the piston for timing a magneto varies from engine to engine. The piston can be at top dead center (TDC) or slightly before the top dead center (BTDC). Check engine specifications for this information.

One common method of checking timing is to locate TDC. This is the point where the piston does not seem to move as the flywheel is rotated. A dial indicator can be used for greater accuracy. With TDC located, place a reference mark on the flywheel and the magneto assembly plate, figure A-19. Now remove the flywheel. Rotate the crankshaft until the breaker points barely open (0.001 inch). Carefully replace the

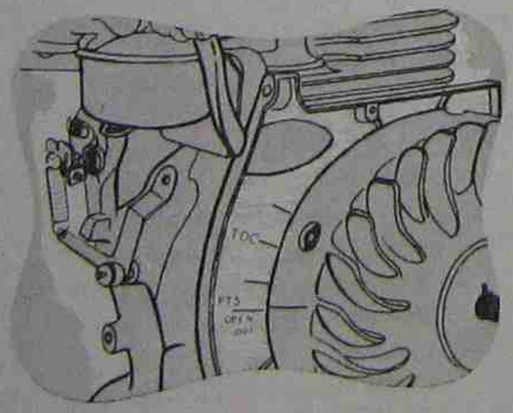


Fig. A-19 Timing marks

flywheel. Put another mark on the magneto plate aligned with the flywheel reference mark. The difference between the marks on the magneto plate is the magneto timing to the piston. This can be figured in degrees by dividing the number of flywheel vanes into 360 degrees. (Twenty vanes; each vane 18 degrees.) The correct number of degrees of firing before top dead center is found in the engine specifications.

If the engine has a magnetic rotor magneto, the rotor and armature must be timed to the piston, figure A-20. Timing is correctly set when the engine leaves the factory. However, if the armature has been removed or the

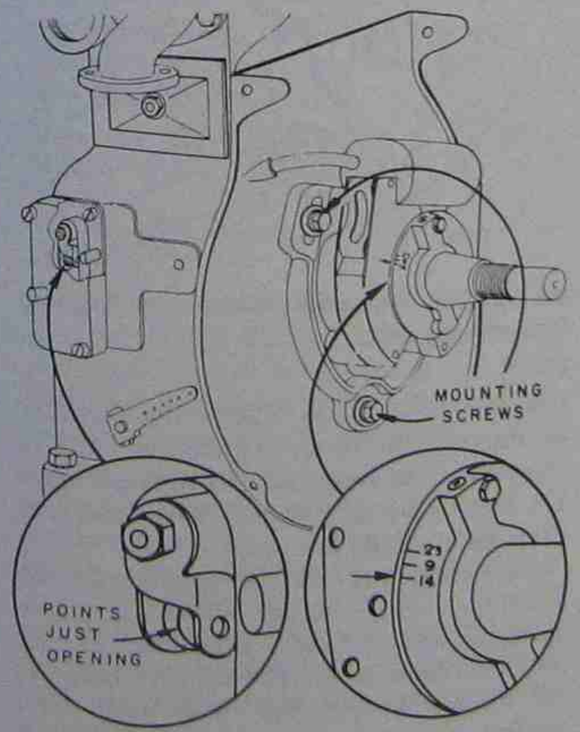


Fig. A-20 Timing the rotor and armature to the piston. The numbers represent model numbers.

crankshaft or cam gear replaced, it is necessary to retime the rotor. Breaker points are first set correctly (0.020 inch). The rotor is on the shaft correctly and tightened. The armature is mounted but mounting screws are not tight. Turn the crankshaft until the breaker points just start to open. (Place a piece of tissue paper between the points to detect when the points let go.) Now turn the armature slightly until the timing marks on the rotor and the armature line up.

Provisions are made on many engines to check the timing of the engine when the engine is running. This timing is done with a timing light, figure A-21. Follow the instructions given for the particular timing light and engine. The timing light flashes each time the breaker points open. Reference marks on the engine must be located – one on a stationary part of the engine and one on the flywheel. The timing light is directed at the flywheel. If the two marks line up, timing is correct. If the marks do not line up, the breaker plate must be loosened and shifted to a position where the marks do line up.

Two-cycle engine timing is quite similar.

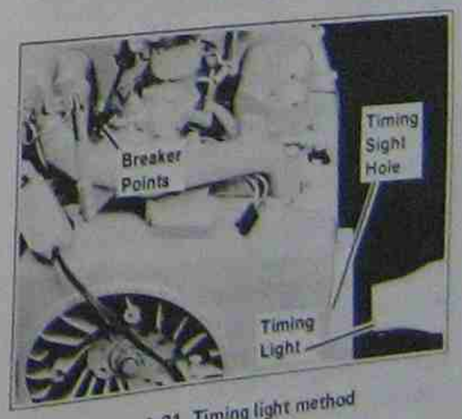


Fig. A-21 Timing light method

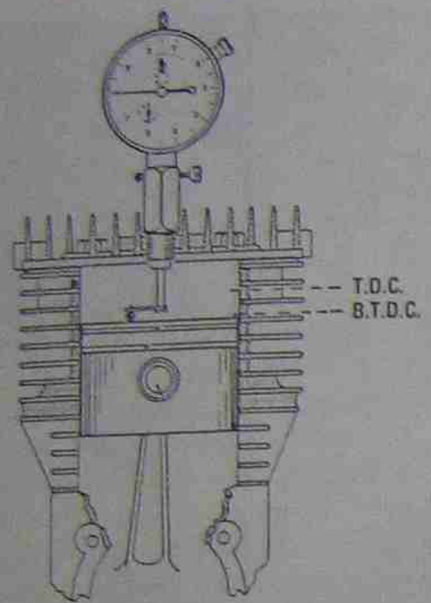


Fig. A-22 Two-cycle engine timing (Courtesy of Tecumseh Products Company)

figure A-22. One common procedure is to remove the spark plug and locate top dead center using a dial indicator. With TDC located, back the piston down the cylinder the correct distance (check manufacturer's specifications for the measurement before TDC). Now the breaker points should just begin to open. If timing is incorrect, loosen the stator plate setscrew and rotate the stator plate slightly until the points just begin to open. Retighten the stator plate setscrew. See figure A-23 for an example of two-cycle timing.

CYLINDER HEAD

The cylinder head must be removed if work is to be done on the piston, piston rings, connecting rod, or valves. It must also be removed if the combustion chamber is to be cleaned. The head bolts or nuts should be

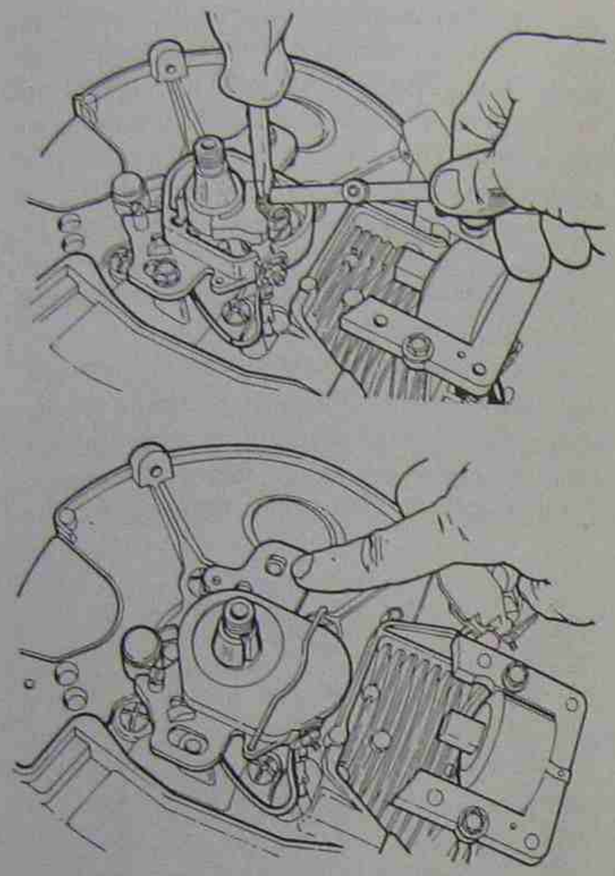


Fig. A-23 Two-cycle timing (Courtesy of Tecumseh Products Company)

removed and set aside. The head gasket may be stuck to the head, cylinder, or both. In many cases the gasket is badly damaged while the head is being removed. If the gasket is damaged, it should be discarded.

Carbon deposits should be carefully scraped from the cylinder head and all old gasket material scraped away from the contact surfaces, figure A-24. The cylinder head can be checked for warpage by laying it on a *surface plate* (a large block of metal with a perfectly flat surface), figure A-25. If the cylinder head is warped, it should be replaced.



Fig. A-24 Cleaning cylinder heads

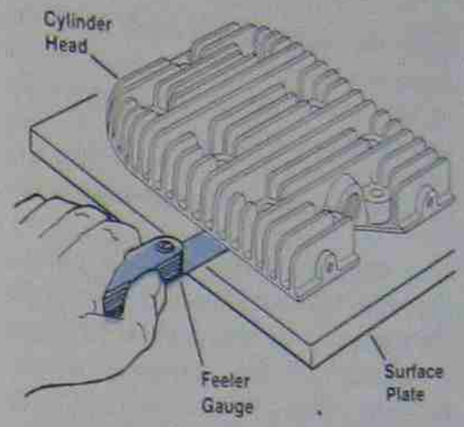


Fig. A-25 Checking cylinder head flatness

A new head gasket should be used upon reassembly. The cylinder head bolts or nuts should be tightened in the correct sequence. To be certain of the correct degree of tightness, a torque wrench should be used (generally 14 to 18 ft-lb), figure A-26.



Fig. A-26 Tightening the cylinder head bolts with a torque wrench

VALVES

Valve problems are fairly common and can be quite serious. Faulty valves affect engine power and cause hard starting. A poorly seated valve is one of the possible causes for poor compression. If it is reasonably certain that the piston rings are in good shape and well-oiled and the head gasket is air tight and a compression test indicates leakage, the leakage is probably caused by a valve problem. A quick test is to remove the spark plug and hold a finger over the spark plug hole while turning over the engine. Compression should blow the finger away from the hole with noticeable force.

With the cylinder head removed the valves can be visually inspected. Look for problems such as carbon fouling, burned valves, valve corrosion, or valve sticking.

Carbon Fouling. Carbon deposits may have built up to the point where the valves do not fully seat. Also, carbon particles that have broken loose may be under the valve seat.

Burned Valves. Burned valves are often caused by improper tappet clearance, figure

A-27. The valve may seat nicely when the engine is cold. However, when the parts heat up they expand and the valve cannot fully seat. Being constantly exposed to the hot gases of combustion, the valve may burn and the valve seating becomes progressively worse.

Valve Corrosion. Valve corrosion can be seen when the valve is removed, figure A-28. The top of the valve stem (neck) is worn away or thinned out. The problem is usually caused by having too lean a fuel mixture or by condensation. Condensation can form during storage or when the engine is frequently stopped before it reaches its normal operating temperature.



Fig. A-27 Burned valve



Fig. A-28 Valve corrosion

Valve Sticking. A stuck valve means that the valve stem and valve guide have built up deposits of carbon and gum, figure A-29. The deposits build up more rapidly in hot weather and under heavy engine loads. An engine that runs hot due to clogged radiating fins or a clogged air inlet screen builds up valve stem deposits faster than normal. Old gasoline often causes a rapid buildup of gum deposits. When the engine is cold, the valves may not stick; as the engine warms up the deposits expand and the valves stick. To correct the problem, the valve guides must be reamed out and the valves cleaned or replaced. Exhaust valves take more punishment than intake valves and are more subject to valve problems.

Engine owners may be able to do some valve work themselves. However, a large amount of work or a complete renewal of the valve system should be done by a mechanic who has the tools and necessary experience.



Fig. A-29 Gum deposits cause valve sticking

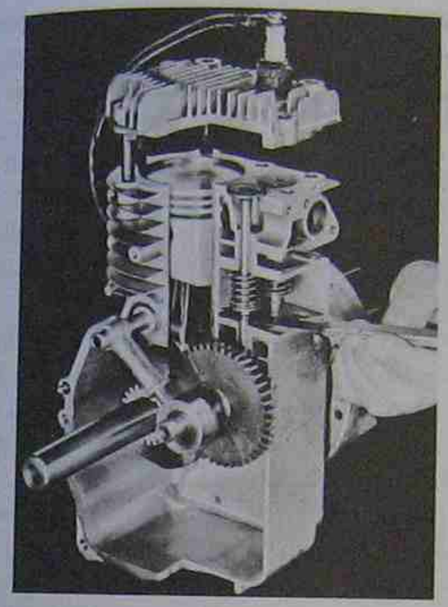


Fig. A-30 Checking tappet clearance

A complete valve job may include:

- Installing new valves
- Installing new valve guides
- Installing new valve seats
- Installing new valve springs
- Grinding valve seats
- Lapping valves
- Setting valve clearances

One of the first check points is the valve *clearance* (space between tappet and end of valve). This clearance is checked with a feeler gauge, figure A-30. On most small engines the clearance can be enlarged by grinding a small amount from the end of the valve. If the clearance is already too large, the valve must be replaced. Some small engines have adjustable tappet clearances.

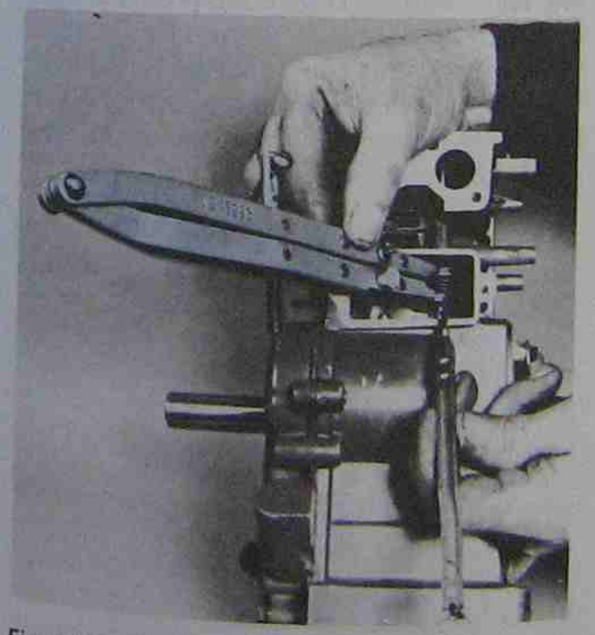


Fig. A-31 Using a valve spring compressor to remove the valve springs

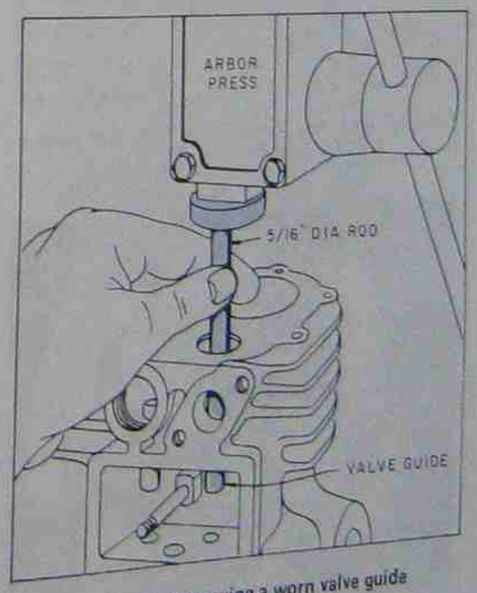


Fig. A-32 Removing a worn valve guide

To remove the valves, first compress the valve spring; then slip off or slip out the valve spring retainers, sometimes called keepers. Pull the valve out of the engine. The valve spring and associated parts will also come out, figure A-31.

With the valve out, the valve stem, face, and head can be closely inspected and cleaned. The valve guide and valve seat can also be inspected.

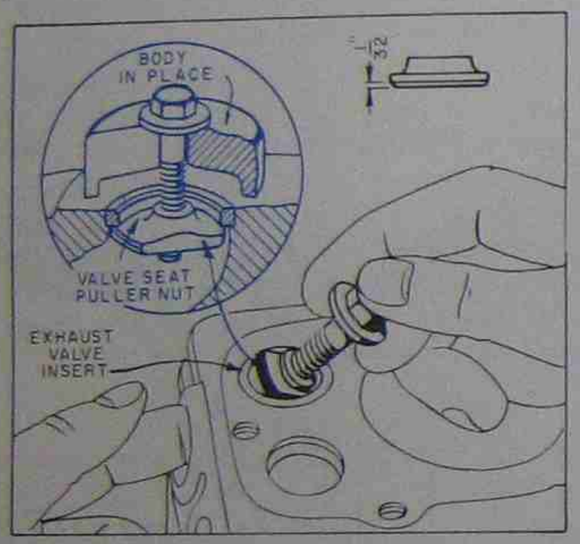


Fig. A-33 Removing the exhaust valve seat with a special puller



Fig. A-34 Valve grinder

Many engines have replaceable valve guides. If these are worn or other wise damaged, they must be pressed out using an arbor press or carefully driven out with a special punch, figure A-32. Also, the exhaust valve seat is removable on many engines. If the seat is beyond regrinding, remove it and reinstall a new valve seat. A special valve seat extracting tool is used for this job, figure A-33.

If the valve and/or valve seats need regrinding, this can be done with special valve grinding equipment, figure A-34. However, in some cases hand valve grinders can be used, figure A-35.

If either or both of these parts have been replaced or reground, the parts must be lapped to provide the perfect seal necessary for valve operation, figure A-36. When lapping, use a small amount of lapping compound. Rotate the valve against the seat a few times until the compound produces a dull finish on the valve face. Do not lap the valves too heavily. When the valves are replaced, oil the stems and be sure the exhaust valve goes in the exhaust side and that the intake valve goes in the intake side.

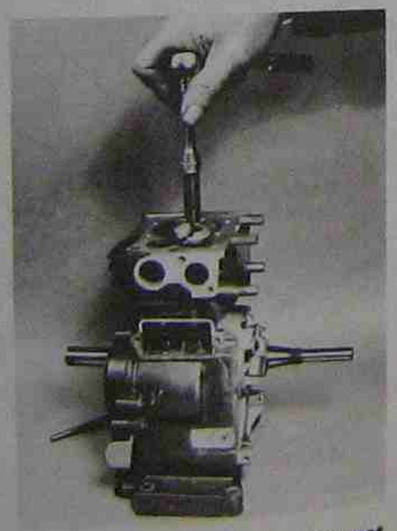


Fig. A-35 Reconditioning a valve seat

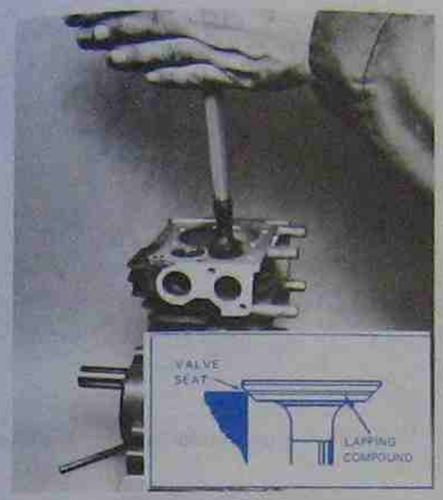


Fig. A-36 Lapping valves

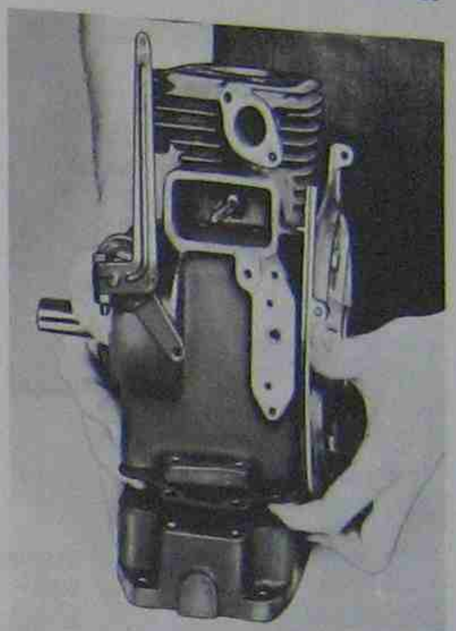


Fig. A-37 Engine base, gasket, engine

PISTON AND ROD ASSEMBLY

In order to gain access to the piston and connecting rod assembly, the connecting rod bolts must be reached. On many engines the mechanic must first remove the engine from the base or sump, figure A-37. This is done by loosening the bolts and breaking the seal. In most cases, a new gasket should be installed upon reassembly to prevent oil leakage. On engines that do not have a separate base, the bearing plate on the power takeoff side will need to be removed.

To remove the piston rod assembly, remove the connecting rod cap from around the crankshaft. Look for the boss marks that indicate how the end of the connecting rod and the rod cap go together. They must be reassembled in the same position. Push up on the bottom of the connecting rod and push the piston rod assembly up and out of the cylinder, figure A-38. If there has been carbon buildup in the cylinder above the point of ring travel, the carbon should be scraped clean before the piston is removed.

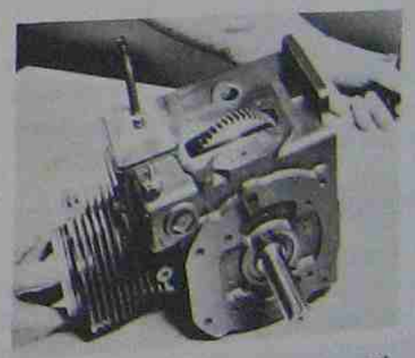


Fig. A-38 Connecting rod and piston removal

Mark the piston so it can be reinstalled the same way it came out.

CYLINDER

The cylinder should be checked for score marks. Scoring or wear scratches in the area of ring travel cause increased oil consumption and reduced engine power. Also the cylinder

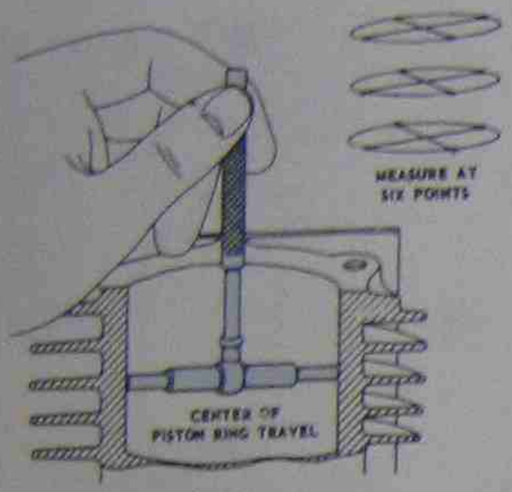


Fig. A-39 Check cylinder bore

should be checked for distortion or warpage and size with a cylinder gauge, figure A-39.

If the cylinder appears to be in good condition, it can be deglazed with a finish hone to prepare the cylinder for new rings, figure A-40. However, a cylinder in poor condition may have to be rebored to a larger size which will also require a new and oversize piston for the cylinder. Some manufacturers do not recommend honing or deglazing.

PISTON

The piston should be checked for scuffing, scoring and scratches. Scoring marks are relatively deep marks that are caused by overheating and the metal fusing against the cylinder and wiping away metal. Lack of lubrication is usually the cause. Scuffing marks are not as deep. Scratches may be caused by abrasive materials entering the engine through the oil supply or air cleaner, figure A-41.

The size of the piston itself can be checked with a micrometer. Generally it is 0.005 inch to 0.010 inch smaller than the cylinder. If the piston is too small, the piston skirts may slap the cylinder as it moves up and down.

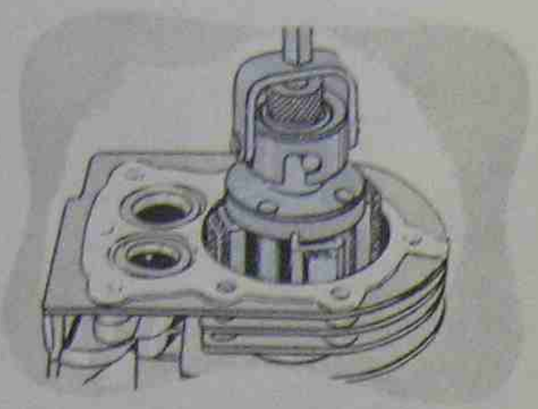


Fig. A-40 Deglazing a cylinder with a finish hone

PISTON PIN

The piston pin can be removed by dislodging the retainer rings from their grooves. Needle nose pliers work quite well for this operation. The piston pin is usually quite tight in the piston so it must be driven out with a soft punch and hammer. Reassemble the piston pin and connecting rod in the same positions.

PISTON RINGS

If the piston size and condition have checked out all right, the piston rings should be checked next. Check the side groove clearance with a feeler gauge, with the rings still on the piston, figure A-42. The correct side groove clearance is found in the engine overhaul specifications. Remove the piston rings from the piston with a piston ring expander, figure A-43. Once the rings are removed, start at the top and look at the end of each ring to see how it was installed. Many rings will have a bevel or notch that must face up or down. Carefully put the ring in the cylinder, square it with the piston, and check the end gap with a feeler gauge, figure A-44. Too little end gap can cause the ring to freeze



Stuck, Broken Rings



Abrasive Scratched Rings



Scored Piston and Rings

Fig. A-41 Piston damage



Fig. A-42 Checking the ring grooves with a feeler gauge

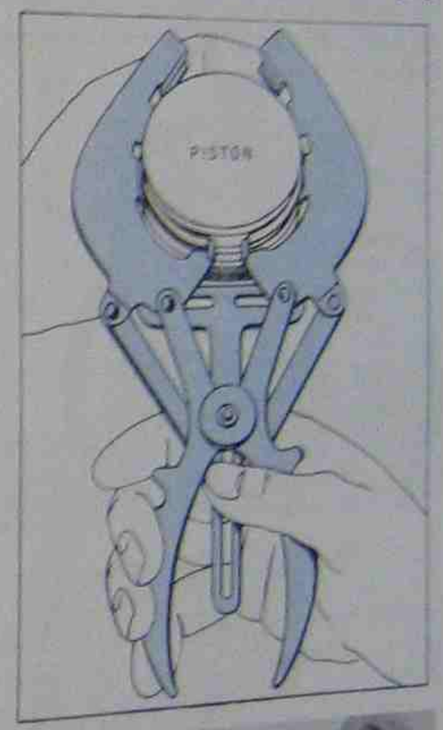


Fig. A-43 Piston ring tools



Fig. A-44 Checking the ring gap with a feeler gauge (end gap)



Fig. A-45 Piston ring compressor

or snap when it becomes hot and expands. Too much end gap may allow blow-by and a resulting loss of power. Piston ring grooves should be cleaned to remove any carbon accumulations. New piston rings are usually installed during engine overhaul.

Use a piston ring compressor to reinstall the piston assembly, figure A-45. Remember to place the piston in the cylinder the same way it came out. Also, put the connecting rod cap on the same way it came off, finding the match marks, figure A-46. A torque wrench

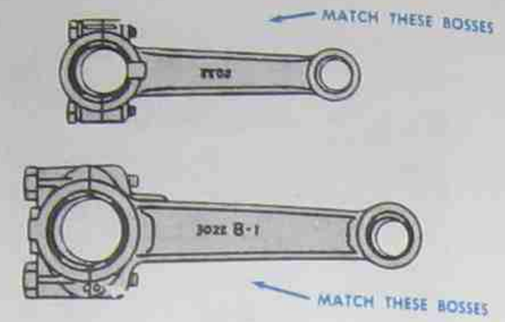


Fig. A-46 Match boss marks when reassembling the connecting rod and connecting rod cap.

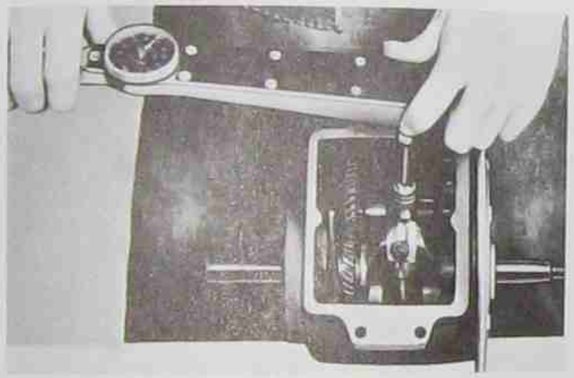


Fig. A-47 Torque wrench used to correctly tighten connecting rod cap

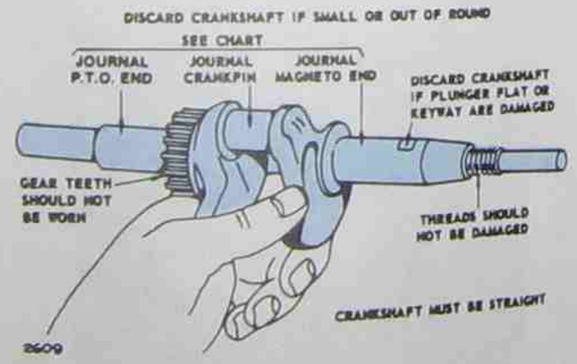


Fig. A-48 Crankshaft check points

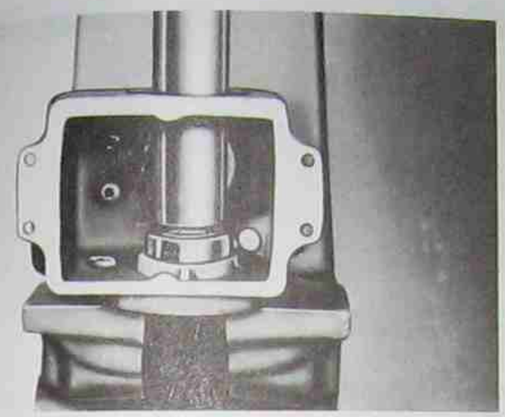


Fig. A-49 Pressing in the main ball bearing

should be used to tighten the connecting rod cap bolts according to the manufacturer's specifications, figure A-47.

CRANKSHAFT

The crankshaft should be removed and checked for scoring and any metallic pickup. The journals and crankpin should be checked with a micrometer for roundness. The gear and keyway should be checked for wear. Also, check the crankshaft for straightness, figure A-48. In some cases, the main ball bearings may come out with the crankshaft. Upon reinstallation, the bearings may have to be pressed into place. An arbor press is good for this job, figure A-49.

CAMSHAFT AND LIFTERS

The camshaft and valve lifters can also be removed for inspection and repair. The camshaft pin should be driven out with a drift punch from the power takeoff side of the engine. Upon reassembly of the camshaft and crankshaft be certain to line up the timing marks, figures A-50 and A-51.

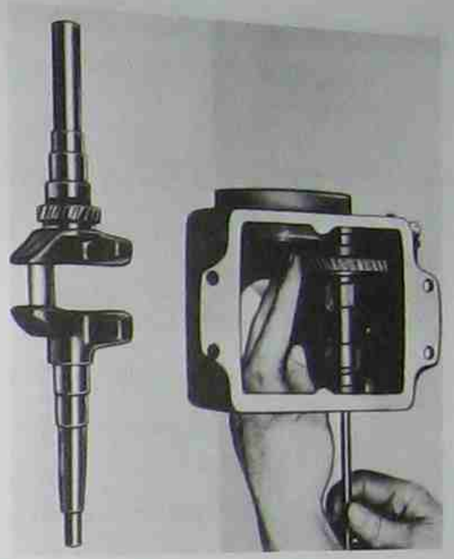


Fig. A-50 Reinstalling the camshaft

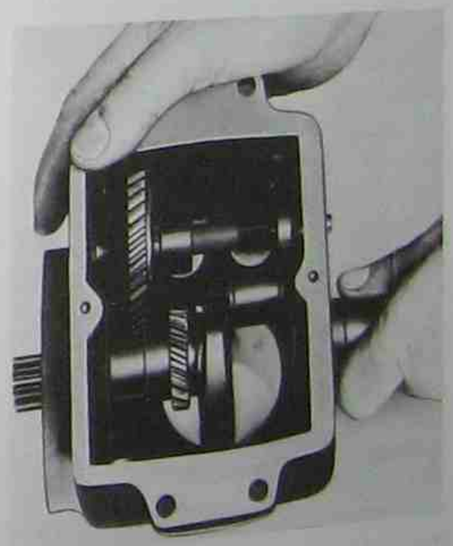


Fig. A-51 Reinstalling the crankshaft

REVIEW QUESTIONS

1. Define troubleshooting.
2. Of what value is a troubleshooting chart?
3. Can troubleshooting be done by an individual engine owner or operator?
4. Define engine tune-up.
5. What does engine reconditioning or overhaul involve?
6. Can any reconditioning or overhaul be accomplished by the amateur mechanic?
7. Why is the careful layout of parts important during disassembly?
8. Why is a mechanic's handbook or service manual essential for the reconditioning of an engine?
9. Explain engine timing.
10. What might a complete valve job include?

Appendix B Horsepower and Buying Considerations

Horsepower (hp) is the yardstick of the engine's power, its capacity to do work. James Watt, the inventor of the steam engine, devised the unit. He assumed that the average horse could raise 33,000 pounds one foot in one minute. An engine that can lift 33,000 pounds one foot in one minute is a one-horsepower engine. The engine can lift 8250 pounds four feet in one minute, and still be delivering 1 horsepower.

As discussed in unit 1, the formula for horsepower is:

$$\text{Horsepower} = \frac{\text{Work}}{\text{Time (in minutes)} \times 33{,}000}$$

Remember that work is the energy required to move a weight through a distance. For example, lifting one pound, one foot, is one foot-pound of work. Lifting 50 pounds, two feet, is 100 foot-pounds of work. The element of time is not a factor.

In horsepower the time factor is added. For example, a boat with an outboard motor might cross a river in ten minutes. An identical boat with a larger motor might make the crossing in five minutes. The same amount of work has been accomplished by each engine but the larger horsepower engine did the work faster.

There are a variety of terms related to horsepower, such as brake horsepower, frictional horsepower, indicated horsepower, SAE or taxable horsepower, rated horsepower, developed horsepower, maximum horsepower, continuous horsepower, corrected horsepower, observed horsepower, and others. Several of these are discussed in the following paragraphs.

Brake horsepower is usually used by manufacturers to advertise their engine's power. Brake horsepower is measured either with a prony brake or with a dynamometer. The *prony brake* consists basically of a flywheel pully, adjustable brake band, lever, and scale measuring device. With the engine operating, the brake band is tightened on the flywheel and the pressure or torque is transmitted to the scale. The readings on the scale and other data are used to calculate the horsepower.

The *dynamometer* is a device that measures power produced by an internal combustion engine. The electric dynamometer contains a dynamo. As the engine drives the dynamo the current output can be carefully recorded. The more powerful the engine, the more current is produced. This current is correlated to horsepower.

Frictional horsepower is the power that is used to overcome the friction in the engine itself. The parts themselves absorb a certain amount of power. Losses included are mainly due to the friction of the piston moving in the cylinder but also included are losses due to oil and coolant pumps, valves, fans, ignition parts, and other accessories. These losses can amount to 10 percent of the brake horsepower.

Indicated horsepower is the power that is actually produced by the burning gases within the engine. It does not take into account the power that is absorbed by or used to move the engine parts. It is the sum of the brake horsepower plus the power used to drive the engine (frictional horsepower).

SAE or taxable horsepower is the horsepower used to compute the license fee for automobiles in some states.

$$\text{SAE hp} = \frac{D^2 \times \text{No. of Cylinders}}{2.5}$$

D = Diameter of bore in inches

$$\text{Example: } \frac{(3.5 \times 3.5) \times 6}{2.5} = 29.4 \text{ hp}$$

FACTORS AFFECTING HORSEPOWER

Many factors affect the horsepower of an engine. Some of these factors are discussed in the following paragraphs.

Engine torque is a factor that relates to horsepower. *Torque* is the twisting force of the engine's crankshaft. Torque can be compared to the force a person uses to tighten a nut. At first a small amount of torque is used, but more and more torque is applied as the nut tightens. Even when the nut stops turning, the person still may be applying torque. Motion is not necessary to have torque. Torque is measured in foot-pounds or inch-pounds. On an engine, the maximum torque is developed at speeds below the maximum engine speed. At top speeds, frictional horsepower is greater and volumetric efficiency is less.

Volumetric efficiency relates to horsepower also. It refers to the engine's ability to breathe or take in a full charge of fuel mixture in the short time allowed for intake. Engine design largely determines the volumetric efficiency of the engine. At high speeds the volumetric efficiency drops off. It can be increased with superchargers and turbochargers that force or blow air into the intake manifold. Also, volumetric efficiency can be increased by using multiple-barrel carburetors (two-barrel and four-barrel) with the extra barrels opening up at high speed when the demand for air is greater.

Compression ratio is another factor that affects horsepower. This is the relationship of the volume of the cylinder when the piston is at the bottom of its stroke compared to the volume of the cylinder (and combustion chamber) when the piston is at top dead center. For small gasoline engines it may be 6:1; for automobile engines, the compression ratio may be 8:1 or higher. The higher the compression ratio, the greater the horsepower delivered when the fuel mixture is ignited.

Piston displacement is the volume of air the pistons displace from the bottom of their stroke to top dead center. Piston displacement also relates to horsepower. Generally, the greater the piston displacement the greater the horsepower. Most engines deliver 1/2 to 7/8 horsepower per cubic inch displacement. High performance engines develop about 1 horsepower per cubic inch displacement. Supercharged engines can deliver much more than 1 horsepower per cubic inch displacement. Displacement equals *area of bore* × *stroke* × *number of cylinders*, and is expressed in cubic inches.

Estimating Horsepower

The following formula can be used to estimate the maximum horsepower of a four-stroke cycle engine.

$$\text{Horsepower} = \frac{D^2 \times N \times S \times \text{rpm}}{11{,}000}$$

D^2 (Bore in Inches)

N (Number of Cylinders)

S (Stroke in Inches)

11,000 (Experimental Constant)

For a two-cycle engine, the formula can be used with 9000 as the experimental constant.



Fig. B-1 Manufacturers of high-quality engines maintain elaborate testing laboratories.

BUYING CONSIDERATIONS

The person who is shopping for a gasoline engine will have no trouble finding an engine for the job. There are many manufacturers of small gasoline engines who produce engines in a variety of horsepower that are designed and engineered to satisfy every need. It is not uncommon to find a manufacturer's basic model with variations to adapt the engine for many different jobs. Manufacturers of high-quality engines conduct many tests on their engines to assure quality performance, figures B-1 to B-3. Several points to consider in buying an engine are: cost, reputation of manufacturer, availability of repair parts, power requirements, engine warranties.

Cost. Beware of bargains. A good bargain can be found now and then but the general rule, "You get what you pay for," is a good one. This does not mean that the most expensive engine is the best buy. The engine must be the right one for the intended usage. For cutting the grass once a week, an economical, dependable engine should be enough. However, if the engine will be exposed to continuous heavy usage it would be wise to buy a heavy-duty engine, one made to operate for a long period of time without failure. The additional cost is worthwhile in this case.

Reputation of the Manufacturer. Be certain the manufacturer's past record in the field justifies faith in the new engines. Talk with engine dealers and individual owners of engines. Their opinions and experience can help in making the best selection.

Availability of Repair Parts. If an engine breaks down and requires a new part, will it be readily available? Can the part be found at a local dealer or will it be necessary to send to



Fig. B-2 Cold room freezing test insures dependable operation in cold weather.

a factory that may be many miles away? Delays caused by breakdowns can be costly as well as annoying. The availability of service and repair parts is an important consideration.

Power Requirements. Be certain the engine is big enough for the job. Constant overloading or constant operating at full throttle shortens engine life. A dealer can assist in finding the correct power plant for the job.

Manufacturers today produce engines that operate on either the four-cycle or the two-cycle principle; both have their place and both are entirely successful. Some engines are water cooled, some are air cooled; some have simple splash lubrication, some have pump lubrication; some have fuel pumps, and some do not. In fact, no two engines look exactly alike or operate exactly alike.

Engine Warranties. Most engine manufacturers give a warranty to the purchaser of



Fig. B-3 Endurance tests of engines insure their dependability.

a new engine. A common warranty is good for ninety days. If during the ninety days after purchase any parts fail due to defective material or workmanship, the manufacturer will repair or replace the defective part.

In most cases the part or engine must be returned to the factory or to an authorized distributor. Most manufacturers require the owner to pay shipping charges to the factory. In some cases, the owner must also pay any labor costs involved in the repair.

If the engine has been damaged through misuse, negligence, or accident, most warranties are void. A few manufacturers require that the engine be registered shortly after purchase; if the engine is not registered, the warranty is not valid. Generally, engine components such as magnetos, carburetors, starters, etc. are only covered by the terms of their individual manufacturer.

REVIEW QUESTIONS

1. If an engine can lift 150,000 pounds a distance of one foot in three minutes, what is its horsepower?
2. In general, can larger horsepower engines do work faster than smaller horsepower engines?
3. What type of horsepower rating do most manufacturers use in advertising their engines?
4. What is a dynamometer?
5. In what way is SAE horsepower used?
6. Estimate the horsepower of a two-stroke cycle having a bore of 2 inches, one cylinder, a stroke of 1 1/2 inches, and operating at 3600 revolutions per minute.
7. What is engine torque?
8. What is volumetric efficiency?
9. What is the relationship between compression ratio and horsepower?
10. What is the relationship between piston displacement and horsepower?
11. List four important considerations for a person to think about before purchasing an engine.

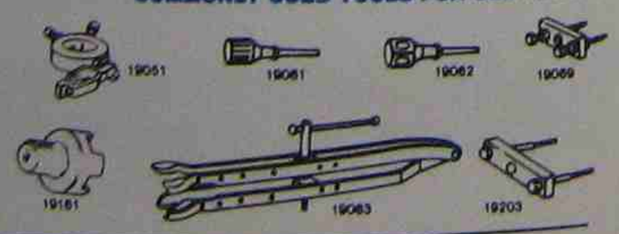
Appendix C

1. Spark plug gap: .030 All Models
2. Condenser capacity: .18 to .24 MFD. All Models
3. Contact point gap: .020 All Models

	BASIC MODEL SERIES	IDLE SPEED	ARMATURE AIR GAP TWO LEG	ARMATURE AIR GAP THREE LEG	VALVE CLEARANCE INTAKE	VALVE CLEARANCE EXHAUST	VALVE GUIDE REJECT GAGE	TORQUE SPECIFICATIONS FLYWHEEL NUT FT. LBS.	TORQUE SPECIFICATIONS CYLINDER HEAD IN. LBS.	TORQUE SPECIFICATIONS CONN. ROD IN. LBS.
ALUMINUM	6B, 60000	1750	.006 .010	.012 .016	.005 .007	.009 .011	19122	55	140	100
	8B, 80000, 81000, 82000	1750	.006 .010	.012 .016	.005 .007	.009 .011	19122	55	140	100
	92000, 94000	1750	.006 .010		.005 .007	.009 .011	19122	55	140	100
	100000	1750	.010 .014	.012 .016	.005 .007	.009 .011	19122	60	140	100
	110000	1750	.006 .010		.005 .007	.009 .011	19122	55	140	100
	130000	1750	.010 .014		.005 .007	.009 .011	19122	60	140	100
	140000	1750	.010 .014	.016 .019	.005 .007	.009 .011	19151	65	165	165
	170000, 171700•	1750 **	.010 .014		.005 .007	.009 .011	19151	65	165	165
	190000, 191700•	1750 **	.010 .014		.005 .007	.009 .011	19151	65	165	165
	220000, 250000	1750 **	.010 .014		.005 .007	.009 .011	19151	65	165	190
CAST IRON	5, 6, N	1750		.012 .016	.007 .009	.014 .016	19122	55	140	100
	8	1750		.012 .016	.007 .009	.014 .016	19122	55	140	100
	9	1200			.007 .009	.014 .016	19151	60	140	140
	14	1200			.007 .009	.014 .016	19151	65	165	190
	19, 190000, 200000•	1200 **	.010 .014	.022 .026	.007 .009	.014 .016	19151	115	190	190
	23, 230000	1200 **	.010 .014	.022 .026	.007 .009	.017 .019	19151	145	190	190
	243000	1200 **	.010 .014		.007 .009	.017 .019	19151	145	190	190
	300000	1200 **	.010 .014		.007 .009	.017 .019	19151	145	190	190
	320000	1200 **	.010 .014		.007 .009	.017 .019	19151	145	190	190

COMMONLY USED TOOLS FOR SERVICING

19051 Spark Tester, all models
19061 Carburetor jet screwdriver, all models
19062 Carburetor jet screwdriver, all models
19063 Valve spring compressor, all models
† 19161 Starter clutch wrench, use with ½" drive torque wrench
19203 Flywheel Puller, 170000 thru 320000 Aluminum Models & Cast Iron Models



4. Top governed speed: See Briggs & Stratton Service Bulletin No. 467 or Engine Replacement Data
5. Crankshaft End Play: .002-.008 All Models

CRANKSHAFT REJECT SIZE MAG. JOURNAL	CRANKPIN	P.T.O. JOURNAL	MAIN BEARING REJECT GAGE	CYLINDER BORE STD. ▲
.8726	.8697	.8726	19166	2.375* 2.374
.8726	.9963	.8726	19166	2.375 2.374
.8726	.9963	.8726	19166	2.5625 2.5615
.8726	.9963	.9976	19166 Mag. 19178 PTO	2.500 2.499
.8726	.9963	.8726	19166	2.7812 2.7802
.8726	.9963	.9976	19166 Mag. 19178 PTO	2.5625 2.5615
.9975	1.090	1.1790	19178	2.750 2.749
.9975 1.1790•	1.090	1.1790	19178	3.000 2.999
.9975 1.1790•	1.122	1.1790	19178	3.000 2.999
1.3760	1.2470	1.3760		3.4375 3.4365
.8726	.7433	.8726	19166	2.000 1.999
.8726	.7433	.8726	19166	2.250 2.249
.9832	.8726	.9832	19117	2.250 2.249
1.1790	.9964	1.1790	19117	2.625 2.624
1.1800	.9964 1.1219•	1.1790	19117	3.000 2.999
1.3769	1.1844	1.3759	19117	3.000 2.999
Ball	1.3094	Ball	Ball	3.0625 3.0615
Ball	1.3094	Ball	Ball	3.4375 3.4365
Ball	1.3094	Ball	Ball	3.5625 3.5615

INITIAL CARBURETOR ADJUSTMENT ALL MODELS	TURNS OPEN FROM SEAT	
CARBURETOR TYPE	NEEDLE VALVE	IDLE VALVE
Pulsa-Jet Vacu-Jet	1⅛	
Two Piece Flo-Jet	1⅛	1
One Piece Flo-Jet	2¼	1⅛
One Piece Flo-Jet (6, 7, 8, 10 & 11 H.P. Vertical Crankshaft)	1⅛	1¼
One Piece Flo-Jet (11 H.P. Horizontal Crankshaft)	1⅛	1

CYLINDER RESIZING

▲ Resize if .003 or more wear or .0015 out of round on C.I. cylinder engines. .0025 out of round on aluminum alloy engines.

Resize to .010, .020 or .030 over Standard.

*Model 6B series and early Models 60000 and 61000 series engines have cylinder bore of 2.3125 - 2.3115.

RING GAP REJECT SIZES

MODEL	COMP. RINGS	OIL RING
Alum. Cylinder Models	.035"	.045"
C.I. Cylinder Models	.030"	.035"

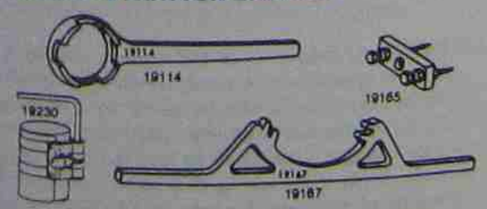
GOVERNED IDLE

For Adjustment Procedures, see Service & Repair Instructions 270962, Section 5, for Single Cylinder Models and Repair Instructions MS-7000 or 271172, Section 5, for Twin Cylinder Models.

■ With Valve Springs Installed.

• Synchro-Balance.

BRIGGS & STRATTON ENGINES



Flywheel puller, all models thru 130000	19069
Piston ring compressor, all models	19230
Starter clutch wrench, all rewind starter models	19114
Flywheel Puller, 140000, 170000, 190000 & 250000 Models	19165
Flywheel holder, all models 6B thru 130000	19167

See Section 13 for Complete List of Tools

Fig. C-1 Engine specifications for all popular Briggs and Stratton engine models. A good service and repair manual contains specifications such as these for their engines.

GENERAL INFORMATION
Check-up

CHECK - UP

Most complaints concerning engine operation can be classified as one or a combination of the following:

1. Will not start
2. Hard starting
3. Kicks back when starting
4. Lack of power
5. Vibration
6. Erratic operation
7. Overheating
8. High oil consumption

When the cause of malfunction is not readily apparent, perform a check of the Compression, Ignition and Carburetion Systems. This check-up, performed in a systematic manner, can usually be done in a matter of minutes. It is the quickest and surest method of determining the cause of failure. This check-up will point up possible cause of future failures, which can be corrected at the time. The basic check-up procedure is the same for all engine models, while any variation, by model will be shown under the subject heading.

NOTE: What appears to be an engine malfunction may be a fault of the powered equipment rather than the engine. If equipment is suspect, see Equipment, affecting engine operation.

Check Compression

Spin flywheel in reverse rotation (counterclockwise) to obtain accurate compression check. The flywheel should rebound sharply, indicating satisfactory compression.

If compression is poor, look for –

1. Loose spark plug
2. Loose cylinder head bolts
3. Blown head gasket
4. Burnt valves and/or seats
5. Insufficient tappet clearance
6. Warped cylinder head
7. Warped valve stems
8. Worn bore and/or rings
9. Broken connecting rod

Check Ignition

Remove the spark plug. Spin the flywheel rapidly with one end of the ignition cable clipped to the 19051 tester and with the other end of the tester grounded on the cylinder head. If spark jumps the .166" tester gap, you may assume the ignition system is functioning satisfactorily. Try a new spark plug.

If spark does not occur look for –

1. Incorrect armature air gap
2. Worn bearings and/or shaft on flywheel side
3. Sheared flywheel key
4. Incorrect breaker point gap
5. Dirty or burned breaker points
6. Breaker plunger stuck or worn
7. Shorted ground wire (when so equipped)
8. Shorted stop switch (when so equipped)
9. Condenser failure
10. Armature failure
11. Improperly operating interlock system

NOTE: If engine runs but misses during operation, a quick check to determine if ignition is or is not at fault can be made by inserting the 19051 tester between the ignition cable and the spark plug. A spark miss will be readily apparent. While conducting this test on Magna-Matic equipped engines, Models 9, 14, 19 and 23, set the tester gap at .060".

Fig. C-2 General check-up procedures (troubleshooting) suggested for Briggs and Stratton engines

Check Carburetion

Before making a carburetion check, be sure the fuel tank has an ample supply of fresh, clean gasoline. On gravity feed (Flo-Jet) models, see that the shut-off valve is open and fuel flows freely through the fuel line. On all models, inspect and adjust the needle valves. Check to see that the choke closes completely. If engine will not start, remove and inspect the spark plug. If plug is wet, look for –

1. Overchoking
2. Excessively rich fuel mixture
3. Water in fuel
4. Inlet valve stuck open (Flo-Jet carburetor)

If plug is dry, look for –

1. Leaking carburetor mounting gaskets
2. Gummy or dirty screen or check valve (Pulsa-Jet and Vacu-Jet carburetors)
3. Inlet valve stuck shut (Flo-Jet carburetors)
4. Inoperative pump (Pulsa-Jet carburetors)

A simple check to determine if the fuel is getting to the combustion chamber through the carburetor is to remove the spark plug and pour a small quantity of gasoline through the spark plug hole. Replace the plug. If the engine fires a few times and then quits, look for the same condition as for a dry plug.

Equipment - Effecting Engine Operation

Frequently, what appears to be a problem with engine operations, such as hard starting, vibration, etc., may be the fault of the equipment powered rather than the engine itself. Since many varied types of equipment are powered by Briggs and Stratton engines, it is not possible to list all of the various conditions that may exist. Listed are the most common effects of equipment problems, and what to look for as the most common cause.

Hard Starting, Kickback, or Will Not Start

1. Loose blade – Blade must be tight to shaft or adaptor.
2. Loose belt – a loose belt like a loose blade can cause a back-lash effect, which will counteract engine cranking effort.
3. Starting under load – See if the unit is disengaged when engine is started; or if engaged, does not have a heavy starting load.
4. Check remote Choke-A-Matic control assembly for proper adjustment.
5. Check interlock system for shorted wires, loose or corroded connections, or defective modules or switches.

Vibration

1. Cutter blade bent or out of balance – Remove and balance
2. Crankshaft bent – Replace
3. Worn blade coupling – Replace if coupling allows blade to shift, causing unbalance.
4. Mounting bolts loose – Tighten
5. Mounting deck or plate cracked – Repair or replace.

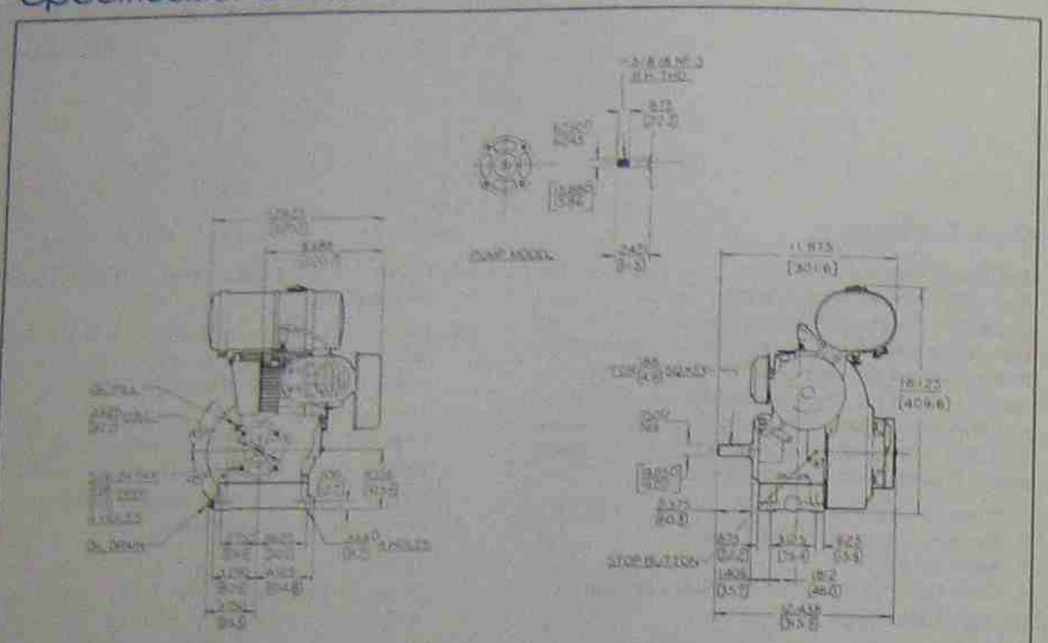
Power Loss

1. Bind or drag in unit – If possible, disengage engine and operate unit manually to feel for any binding action.
2. Grass cuttings build-up under deck.
3. No lubrication in transmission or gear box.
4. Excessive drive belt tension may cause seizure.

Noise

1. Cutter blade coupling or pulley – an oversize or worn coupling can result in knocking, usually under acceleration. Check for fit, or tightness.
2. No lubricant in transmission or gear box.

Specifications/model **K91**



SPECIFICATION DATA

ENGINE TYPE: 4-cycle, gasoline, one cylinder, cast iron, air-cooled, L-head, horizontal shaft.

Model		K91
RATING (4000 RPM):	horsepower	4
	kilowatts	2.98
BORE:	inches	2.56
	millimetres	65.0
STROKE:	inches	2.00
	millimetres	50.8
DISPLACEMENT:	cubic inches	8.86
	cubic centimetres	145.2
WEIGHT:*	pounds	43
	kilograms	19.5

(* Retractable start version)

MODEL VARIATIONS: Engines are available in the following variations: No suffix — rope start; T — retractable start; S — electric start; P — pump; R — gear reduction. Example: K91 indicates rope start version; K91T indicates retractable start version.

LUBRICATION: Splash. Dipper is integral with connecting rod. Capacity: 1.50 pints; .7 litres.

CRANKSHAFT: Heat-treated forged steel casting with integral counterweights; rotation counter-clockwise when viewed from PTO end.

PISTON: Cam-ground, permanent mold aluminum alloy.

BEARINGS: Anti-friction ball bearings at both ends of crankshaft.

GOVERNOR: Precision oil-bathed internal flyweight type with provisions for external adjustment.

VALVES: High carbon steel intake valve. Aluminum-coated austenitic steel exhaust valve and replaceable, hard exhaust valve seat insert.

CARBURETOR: Float feed type. Provision for remote choke hook-up.

FUEL TANK: Capacity: .67 U.S. gallons; 2.5 litres. Tank has fuel shut-off valve with integral screen.

FUEL: Regular grade gasoline, leaded or unleaded, with octane number as follows: 86 pump octane minimum in U.S., 90 research method octane minimum in Canada and all other countries.

AIR CLEANER: Replaceable dry type, high efficiency, pleated paper element.

STARTING: Retractable, rope, or motor-generator.

IGNITION: Magneto with easily adjustable external breaker points. Stop button mounted on breaker point cover. High tension lead boot facilitates all-weather starts. Electric start model includes battery ignition and 10-amp battery charging motor-generator.

Fig. C-3 Specification sheet for Kohler Model K91. Specification sheets like these help the engineer, designer, and buyer select the type of engine suitable for a particular application or job

DISASSEMBLY and REASSEMBLY PROCEDURES

With the disassembly operations, instructions on reassembly are also given, as often it will not be necessary to disassemble the entire engine. If it is desired to disassemble the entire engine, the reassembly instructions can be looked up under the headings of the various parts.

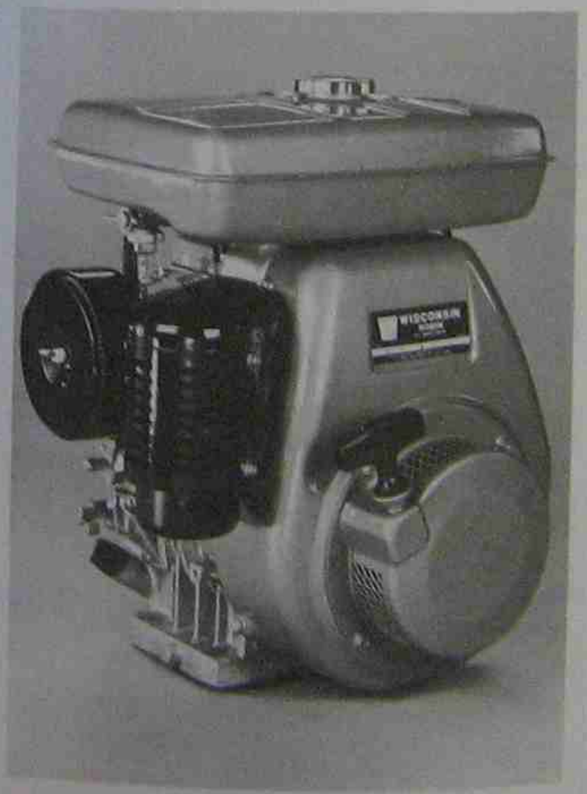
Tighten the capscrews of the cylinder head, gear cover, connecting rod, flywheel and spark plug to the specified torque readings indicated in the related paragraphs of reassembly. Use caution in tightening all other screws and nuts so as not to strip threads or break flanges.

RECOIL STARTER

1. Remove four mounting screws and take off recoil starter assembly.
2. *In reassembly;* check condition of rope for possible replacement. Repair per the *Repair Instructions* beginning on *Page 20*.

FLYWHEEL SHROUD

1. Disconnect coil primary wire from stop button wire.
2. Take off flywheel shroud from cylinder-case and cylinder head.
3. Remove baffle from cylinder block.



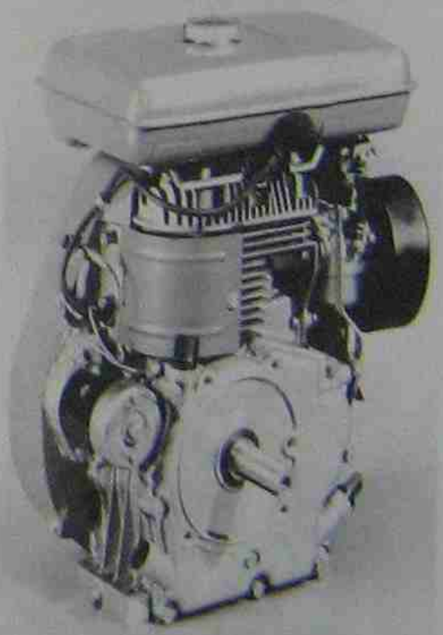


Fig. C-4 Disassembly and reassembly procedures for a Wisconsin ROBIN engine Model W1-145. This is an excellent example of the type of detailed information that a good repair manual will provide the mechanic

FUEL TANK

1. Disconnect fuel line at carburetor. Be **responsible** to be advisable to use a new fuel line.
2. Remove fuel tank from cylinder head.
3. Remove cover from cylinder head.

AIR CLEANER

1. Remove air cleaner cover, element and retainer.
2. Disconnect breather tube from inspection cover.
3. Take out two lock washers and remove air cleaner body and gasket from carburetor studs.
4. **In reassembly** wash element per Air Cleaner Instructions on Page 4. Mount new gasket and assemble back cover, element and cover per Fig. 1. Connect breather line.

GOVERNOR LEVER and CARBURETOR

1. Disconnect governor spring from lever to speed control assembly.
2. Remove governor lever from shaft, and disconnect rod and spring from lever to carburetor.
3. Remove carburetor, insulating plate and gaskets from studs in cylinder side.
4. If necessary, the speed control assembly can be removed from cylinder head by taking off flange bolt.
5. **In reassembly** see "Governor Adjustment", Page 6.

MUFFLER

Take off the two hex nuts and remove muffler and gasket from cylinder side.

STARTING PULLEY and FLYWHEEL (magneto)

1. Flywheel **Nut** should remain on to the flywheel nut and give the wrench a sharp blow with a soft hammer. Remove nut, spring washer and pulley.
2. As illustrated in Fig. 16, attach puller to flywheel — two screws hold clockwise until flywheel becomes loose enough to be removed.

   Puller is not available. Screw flywheel nut flush with end of crankshaft to protect shaft threads from being damaged. Place the end of a large screwdriver between the crankcase and flywheel in line with the keyway. Then, while the end of the flywheel nut with a hardwood hammer and at the same time wedge outward with the screwdriver.
3. The ignition coil along with attached high tension cable can then be removed by taking out two mounting screws.
4. Take off point cover and remove contact breaker and condenser.
5. **In reassembly** refer to "Breaker Point Adjustment" and "Timing" instructions.
6. Securely tighten flywheel nut after timing is finished, but first be sure woodruff key is in position on shaft. Do not drive flywheel on to taper of crankshaft and **do not** overtighten flywheel nut. Simply turn nut until lock washer collapses. Then, tighten by placing wrench on nut and giving handle of wrench 1 or 2 sharp blows with a soft hammer. If torque wrench is available, tighten **nut** to 47 ft. lbs. (6 to 6.5 kgms).

CYLINDER HEAD and SPARK PLUG

1. Remove spark plug from cylinder head.
2. Loosen mounting screws and remove cylinder head along with gasket.
3. Clean carbon from combustion chamber and dirt from between the cooling fins. Check the cylinder head mounting face for distortion. If **warpage** is evident, replace head.
4. **In reassembly** use new cylinder head gasket and spark plug. Torque head screws 14 to 17 ft. lbs. (1.9 to 2.3 kgm).

   Leave spark plug out temporarily, for ease in turning engine over for remainder of assembly and for timing adjustments. When mounting spark plug, tighten it 7 to 10.8 ft. lbs. (1.0 to 1.5 kgm).

INTAKE and EXHAUST VALVES, Figs. 11, 12, 13

1. Remove the valve inspection cover, breather plate and gaskets from cylinder case.
2. Position valve spring retainer so that notch on outer diameter is toward the outside of the valve compartment.



Fig. 16

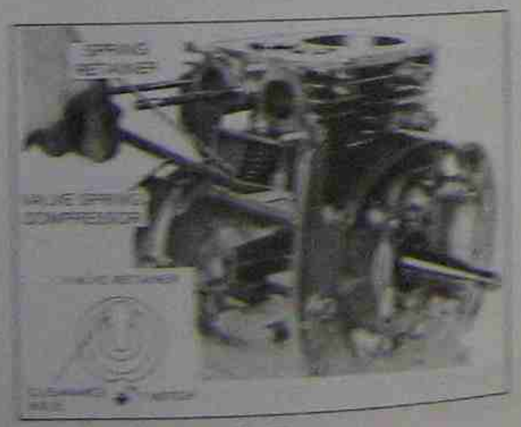


Fig. 17

Place **compressor** tool "EXTENSION" under spring retainer and compress valve spring. At the same time, draw retainer outward toward notch so that **clearance hole** in retainer allows for valve to be pulled out from top of cylinder block.

Caution: Do not **damage** gasket surface of upper chamber with the compressor tool.

3. Clean carbon and gum deposits from the valves, **ports** and guides.
4. **In reassembly** replace valves that are badly burned, pitted or warped. With retainer notch facing outward, place retainer under valve spring with clearance hole over valve stem. While compressing valve spring with compressor tool, force retainer outward so that it locks in place on valve stem. See Fig. 11.

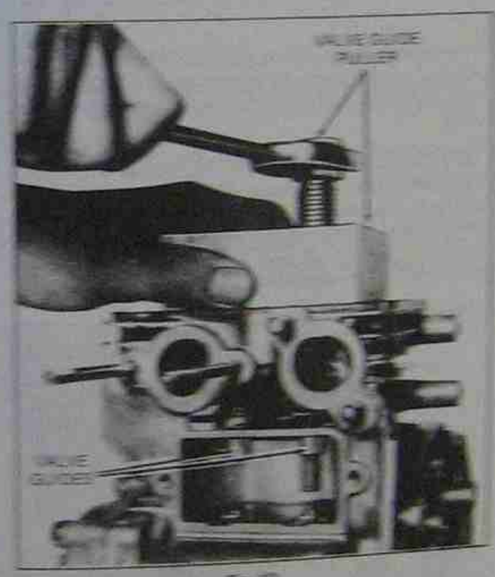
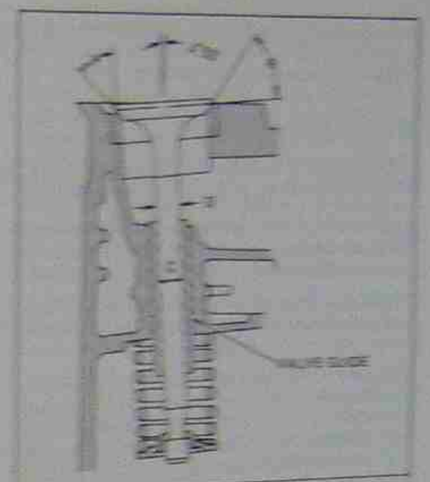


Fig. 10

5. **Valve guides** should be replaced when valve stem clearance becomes excessive. Use valve guide puller tool "EXTENSION" as illustrated in Fig. 10. Drive valve guides out and press new guides in, using the same puller tool. Refer to Fig. 12 for clearance specifications and proper assembly.
6. After replacing valves and valve guides, lay valves in place and a machine ring will show accurately contact face of the valve. Clean valve, and wash valve face slightly with a light solution of soap and water. Wipe cylinder walls with clean cloth to remove metal and lapping oil. Do not reassemble valve springs and caps until valve face has been checked. See "Tappet Adjustment".

TAPPET ADJUSTMENT, Fig. 14

With tappet in its lowest position, hold valve down and insert feeler gauge between valve and tappet stem. The clearance for both intake and exhaust, with engine cold, 0.002 to 0.005 inch (0.05 to 0.13mm).



A - Valve Face Angle		45°
B - Seat Angle		45°
C - Guide Inside Diameter		0.2559 to 0.2566 inch (6.50 to 6.520 mm)
D - Valve Stem Diameter	Intake	0.2540 to 0.2546 inch (6.452 to 6.470 mm)
	Exhaust	0.2535 to 0.2537 inch (6.422 to 6.446 mm)
Maximum Allowable Clearance Between D and C		0.016 inch (0.3 mm)

Fig. 11

If the clearance is less than it should be, grind the end of valve stem a very little at a time and measure. Stem must be ground square and flat.

If clearance is too large, replace the valve and, or stem.



Fig. 12

After obtaining correct clearance, assemble valve springs and retainers. Check operation of valves by turning crankshaft over — remeasure tappet clearance.

GEAR COVER, Fig's. 15, 16 and 17

Place a rag under engine to absorb excess oil, and remove gear cover mounting screws. Use a soft hammer and evenly tap around outer surface of gear cover until it breaks free from crankcase face. Carefully remove cover so as not to damage oil seal. Dowel pins will remain in crankcase flange.

Inspect adjusting shim, oil seal, governor cross shaft, gear and thrust sleeve. If any of these parts are damaged or worn — they should be replaced.

Governor Gear-Flyweight Assembly: can be removed by straddling the handles of a pliers under the gear hub and across the gear cover face. Then, press down on the jaw end of the pliers and gear-thrust sleeve will loosen from shaft. ***In Reassembly***, place spacing washer on shaft. Insert sleeve between flyweights, mount complete assembly to shaft and press down until unit ***snaps*** in place. ***NOTE: Thrust sleeve cannot be assembled or removed when gear assembly is mounted to shaft.***

Crankshaft End Play is regulated by a selected thickness of adjusting shim. The ***end play*** should be ***0*** to ***0.008 inch*** (0 to 0.2mm) ***engine cold***.

The ***adjusting shim*** is located between the crankshaft gear and main bearing, and replacement is seldom necessary unless the crankshaft or gear cover are replaced.

To determine what thickness ***adjusting shim*** to use for regulating the end play, refer to *Fig. 15* and the following instructions:

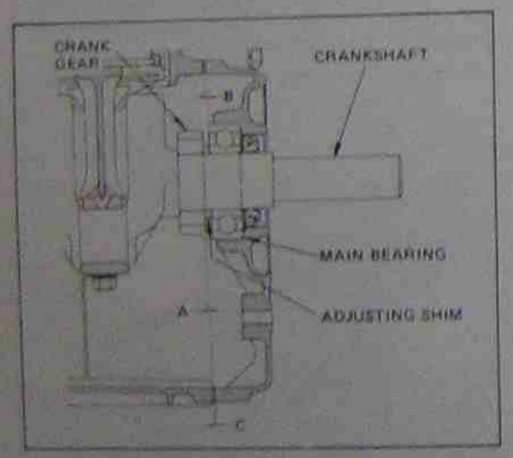


Fig. 15

1. With the gear cover removed, tap end of crankshaft slightly to insure that shaft is shouldered against main bearing at flywheel end.
2. Use a Depth Micrometer and measure the distance between the machined surface of crankcase face and end of crank gear (dim. ***A***).
3. Measure the distance between the machined face of gear cover and outer face of main bearing (dim. ***B***).
4. The compressed thickness of gear cover gasket is ***0.0086 inch*** (0.22mm) dim. ***C***.
5. From the following chart, select an ***adjusting shim*** that is ***0*** to ***0.008 inch*** (0 to 0.2mm) ***less*** that the total length, ***A + B + C***.

Adjusting Shim Thickness	Part Number
.0215 to .0257 inch (.546 to .654 mm)	EY0230250110
.0267 to .0343 inch (.728 to .872 mm)	EY0230250120
.0362 to .0425 inch (.920 to 1.080 mm)	EY0230250130

In reassembly of gear cover, apply oil to bearing surfaces, gear train and tappets. Also lubricate lips of oil seal and add a light film of oil on gear cover face to hold gasket in place.

Mount adjusting shim to crankshaft at crank gear face.

When assembling gear cover, as illustrated in *Fig. 16*, be sure that governor gear-flyweight assembly is in place, and that thrust sleeve aligns with governor cross shaft. If available, use an oil seal sleeve mounted on to the crankshaft, to prevent damage to the oil seal lips.

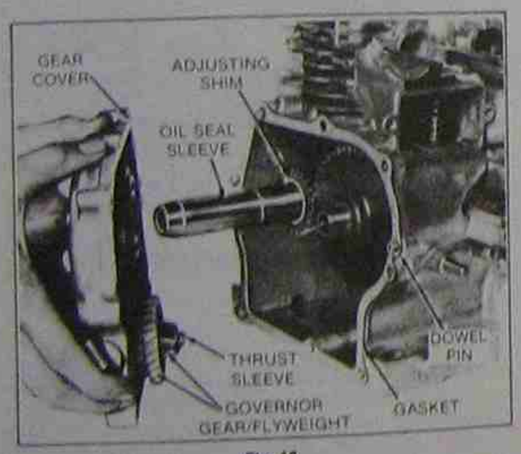


Fig. 16

Caution: ***Be sure timing marks on crankshaft and camshaft gear, Fig. 18, remain correctly mated when end of camshaft is fitted into bearing hole of gear cover, and that governor gear engages camshaft and gear.***

Tap gear cover in place with a soft hammer, remove oil seal sleeve and tighten gear cover capscrews to ***5.8*** to ***7.2 ft. lbs. torque*** (0.8 to 1.0 Kgm).

Check End Play after gear cover and flywheel are in place. If the proper thickness of adjusting shim was selected as explained in *'Crankshaft End Play'* paragraphs and *Fig. 15*, then a satisfactory end play of ***0*** to ***0.008 inch*** (0 to 0.2mm) should have been obtained. However, on installations where end play is critical, and to confirm the actual amount of end play, adhere to the following instructions and *Fig. 17*.

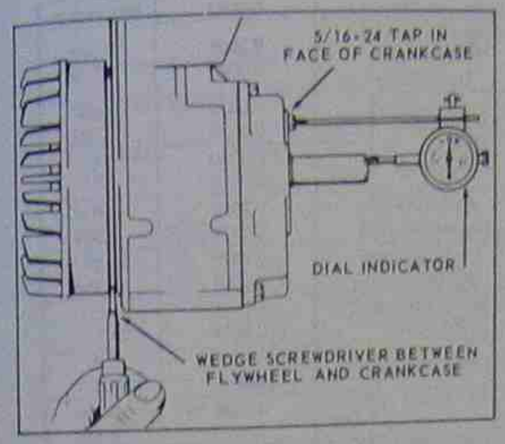


Fig. 17

1. Tap end of crankshaft with a soft hammer so that crankshaft will shoulder against main bearing at flywheel end.
2. Tap crankshaft in the opposite direction (from flywheel end) to seat adjusting shim against main bearing at take-off end.
3. Attach a Dial Indicator to one of the 5/16-24 tapped holes on the face of the crankcase, and set the dial at 0.
4. Wedge a screwdriver between the flywheel and crankcase. The movement of the flywheel away from the engine block will register as end play on the Indicator dial.

If ***end play is more*** than the limits of ***0*** to ***0.008 inch*** (0 to 0.2mm) use the reading from the Indicator dial as a guide in selecting what thickness of adjusting shim to use. If there is ***no end play***, revert to *Gear Cover* paragraphs on Page 12 and follow procedures for adjusting ***crankshaft end play*** and determine exactly what adjusting shim thickness is required.

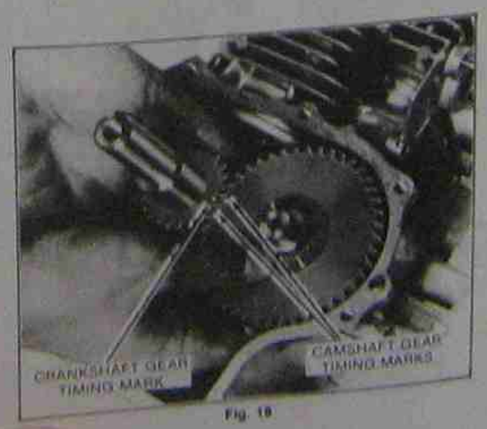


Fig. 18

CAMSHAFT, TAPPETS and TIMING MARKS, Fig. 18

1. To prevent tappets from falling out and becoming damaged when camshaft is removed, turn crankcase over on its side as shown in *Fig. 18*. Push tappets inward to clear cam lobes, and remove camshaft.
2. Withdraw tappets and mark them for identification with the hole that they were removed from.
3. ***In reassembly***, put tappets back in their corresponding guide hole. This will eliminate annecessary valve stem grinding for obtaining correct tappet clearance.
4. Lubricate bearing surfaces of camshaft, push valve tappets to their uppermost position and mount camshaft assembly to crankcase.
5. ***Timing marks*** on camshaft gear and crankshaft gear must match up. Mount camshaft so that the ***marked tooth on crankshaft gear*** is between the ***two marked teeth*** of the ***camshaft gear***, *Fig. 18*. If valve timing is off, engine will not function properly or may not run at all.

CONNECTING ROD and PISTON, Fig's. 19 thru 24

1. Straighten out the bent tabs of lock plate and remove bolts from connecting rod.
2. Take off lock plate, oil dipper and connecting rod cap.
3. Scrape off all carbon deposits that might interfere with removal of piston from upper end of cylinder.
4. Turn crankshaft until piston is at top, then push connecting rod and piston assembly upward and out thru top of cylinder.
5. Remove piston from connecting rod by taking out one of the snap rings and then removing the piston pin. ***A new snap ring should be used in reassembly.***

6. Reassembly

a. Piston Rings

As illustrated in *Fig. 19*, use a Ring Expander tool to prevent ring from becoming distorted or broken when installing onto piston.

If an expander tool is not available, install rings by placing the open end of the ring on first land of

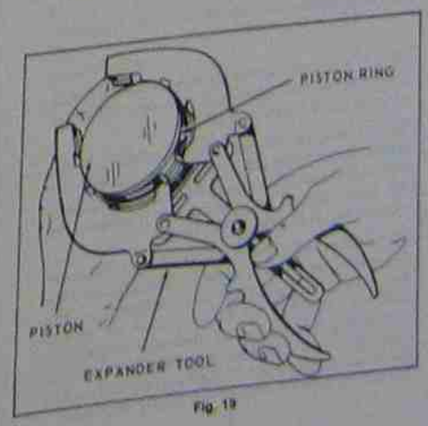


Fig. 19

piston. Spread ring only far enough to slip over piston and into correct groove, being careful not to distort ring.

With or without expander tool, assemble bottom ring first and work upward, installing top ring last.

Mount scraper ring with scraper edge down, otherwise oil pumping and excessive oil consumption will result. Refer to *Fig. 20* for correct placement of rings.

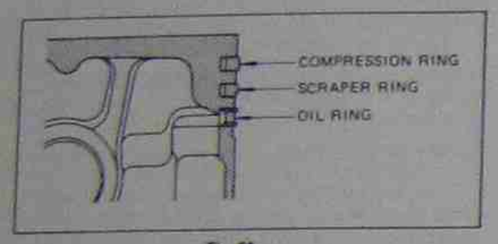


Fig. 20

b. *Piston, Cylinder and Connecting Rod*

Measure the diameter of the piston in the center of the thrust faces at the bottom of the piston skirt, as illustrated in *Fig. 21*.

Measure the cylinder bore and inspect for out-of-round and taper. If cylinder is scored or worn more than .005" (0.125mm) over standard size, it should be rebored and fitted with an oversize piston and rings.



Fig. 21

Refer to chart, *Fig. 22*, for clearance between piston and cylinder. Size, clearance and wear limits are given in more detail on *Page 17*.

When installing the piston in the cylinder, oil the piston, rings, wrist pin, rod bearings and cylinder wall before assembly. Stagger the piston ring gaps 90° apart around the piston. Use a piston ring compressor as illustrated in *Fig. 23*.

Turn crankshaft to bottom of stroke and tap piston down until rod contacts crank pin. Mount connecting rod cap so that the ***cast rib*** between face of rod and bolt boss matches up with the cast rib on the connecting rod. *See Fig. 24*. Assemble ***oil dipper*** to cap. The dipper should be ***toward the flywheel*** end of the connecting rod cap. If engine is operated on a ***tilt toward the take-off end***, reverse dipper mounting.

		Inches	Millimeters
Piston to Cylinder at Piston Skirt Thrust Face		0.0008 0.0023	0.020 0.059
Connecting Rod to Crank Pin	Dia.	0.0015 0.0025	0.037 0.063
	Side	0.0039 0.0118	0.1 0.3
Piston Pin to Connecting Rod		0.0004 0.0012	0.010 0.029
D - Crankshaft Pin Diameter		0.9429 0.9434	23.950 23.963
W - Crankshaft Pin Width		0.9055 0.9094	23.0 23.1
Piston Ring Gap		0.008 0.016	0.2 0.4
Piston Rings - Side Clearance In Grooves	Top	0.0035 0.0053	0.090 0.135
	2nd	0.0024 0.0041	0.060 0.105
	Oil	0.0004 0.0025	0.010 0.065
Piston Pin to Piston		0.00035 tight to 0.00039 loose	0.009 0.010

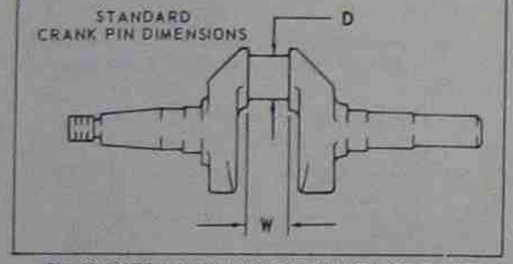


Fig. 22 PISTON, RING AND ROD CLEARANCE CHART

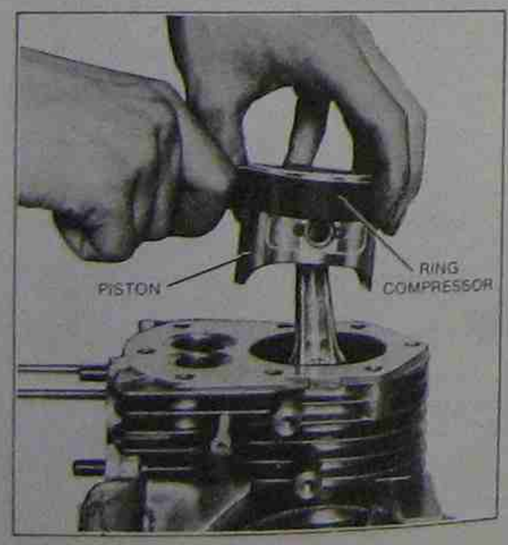


Fig. 23

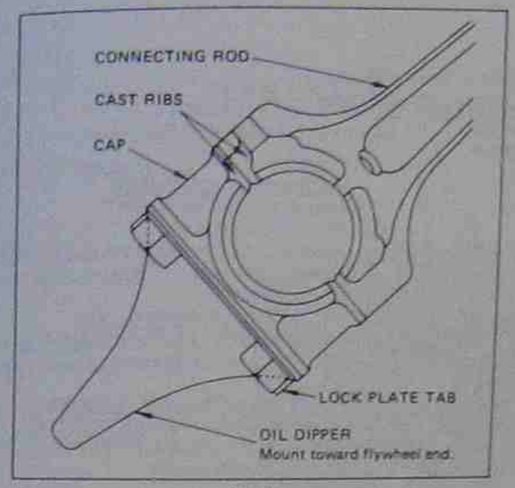


Fig. 24

Install a new rod bolt lock plate. Mount connecting rod bolts and tighten to the following torque specifications — ***6.5 to 8.3 ft. lbs.*** (0.90 to 1.15 Kgm).

Check for free movement of connecting rod by turning crankshaft over slowly. If satisfactory, bend tabs on lock plate against hex head flat of connecting rod bolts.

CRANKSHAFT, Fig. 25

1. Remove flywheel woodruff key.
2. Pull crankshaft out from open end of crankcase and take care not to damage the oil seal. If necessary, loosen shaft by tapping lightly at flywheel end with a soft hammer.
3. ***In reassembly***, inspect crankcase oil seal and main bearing for possible replacement. Mount crankshaft with extreme care so as not to damage lips of oil seal. Use an oil seal sleeve if available.
4. ***End Play*** is regulated by means of an ***adjusting shim*** at the gear end of the crankshaft. This should be set immediately before mounting gear cover as explained in *'Crankshaft End Play'* paragraphs on *Page 12*.

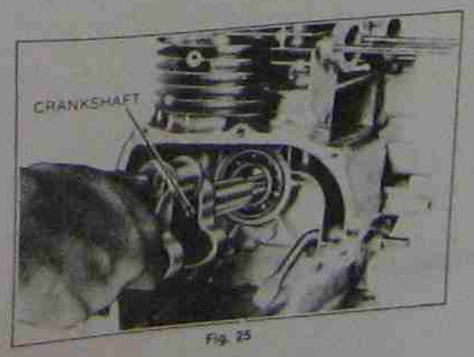


Fig. 25

ENGINE REASSEMBLY

Rebuild the engine in reverse order, and by following the reassembly instructions which are included with the disassembly procedures.

After complete reassembly, turn the engine over by means of the starting pulley to check for any abnormal conditions and loose fitting parts. Then, review and proceed with the following:

1. Crankshaft end play — *Page 12*.
2. Check ignition spark — *Page 4*.
3. Timing — *Page 5*.
4. Governor adjustment — *Page 6*.
5. Carburetor adjustments — *Page 20*.
6. Fill crankcase with correct grade of oil — *Page 4*.
7. Fill fuel tank with a well known brand of *'Regular Grade'* gasoline.
8. Test engine per the following instructions.

TESTING REBUILT ENGINE

An engine that has been completely overhauled by having the cylinder rebored and fitted with a new piston, rings, valves and connecting rod should be thoroughly ***'RUN-IN'*** before being put back into service. Good bearing surfaces and running clearances between the various parts can only be established by operating the engine under reduced speed and loads for a short period of time.

Load		Speed	Time
No Load		2500 r.p.m.	10 minutes
No Load		3000 r.p.m.	10 minutes
No Load		3600 r.p.m.	10 minutes
1.35 hp.	1.01 kw.	3600 r.p.m.	30 minutes
2.7 hp.	2.01 kw.	3600 r.p.m.	60 minutes

While engine is being tested — check for oil leaks. Make final carburetor adjustments and regulate the engine operating speed.

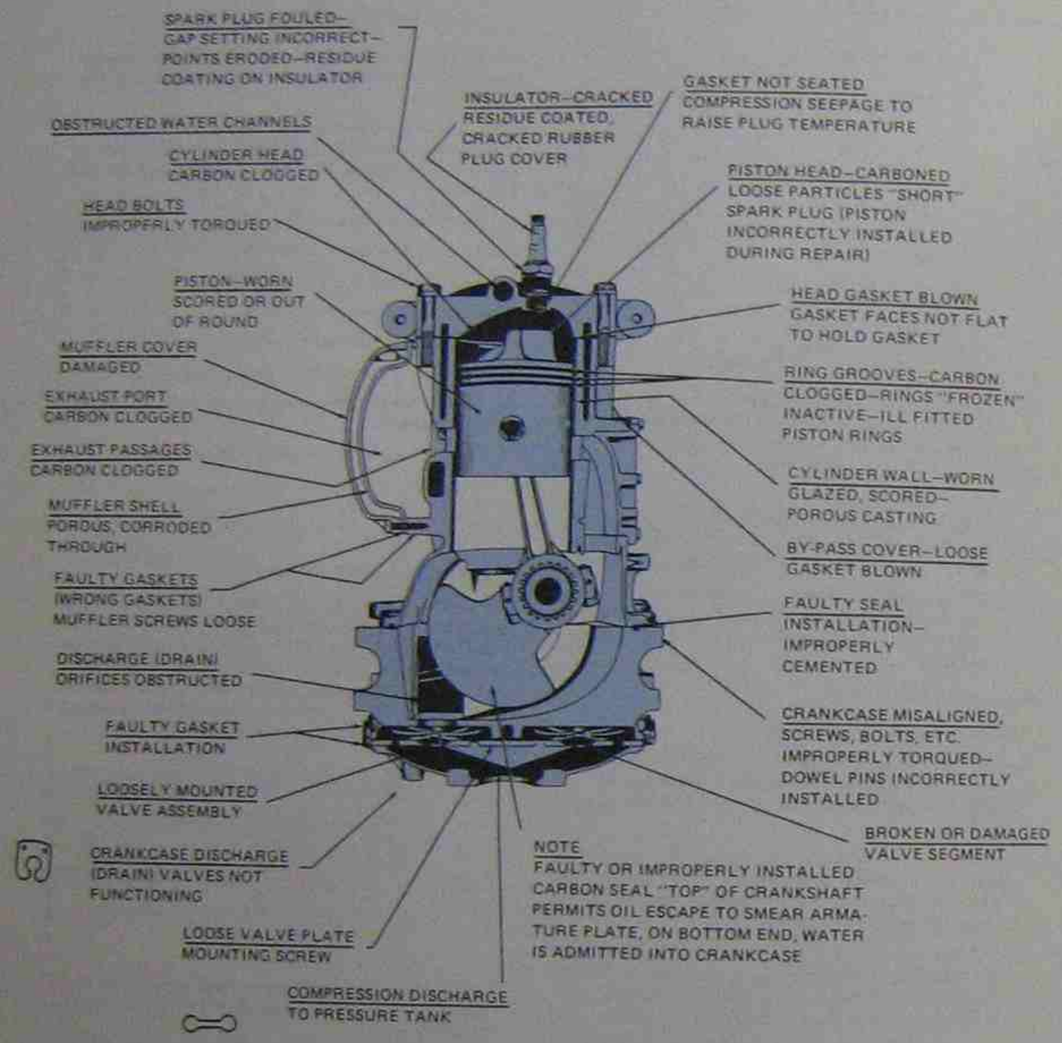


Fig. C-5 Power head diagnosis chart

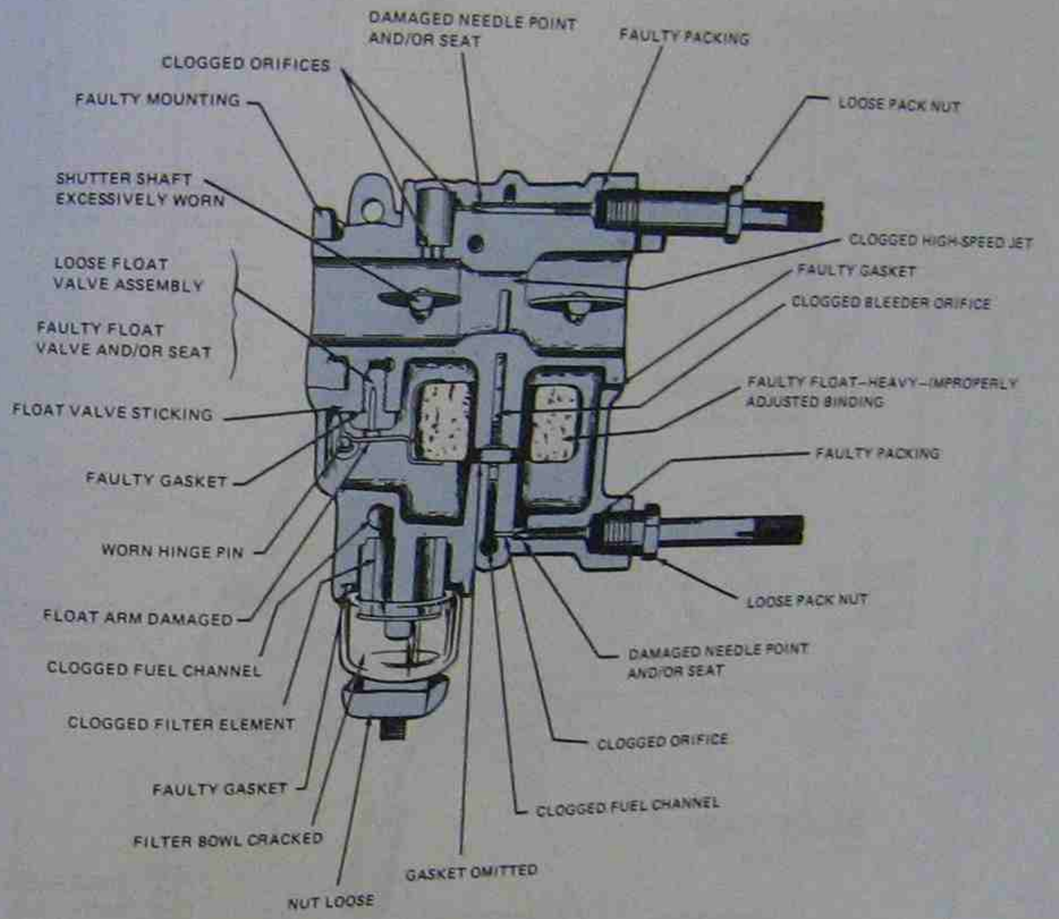


Fig. C-6 Carburetion diagnosis chart

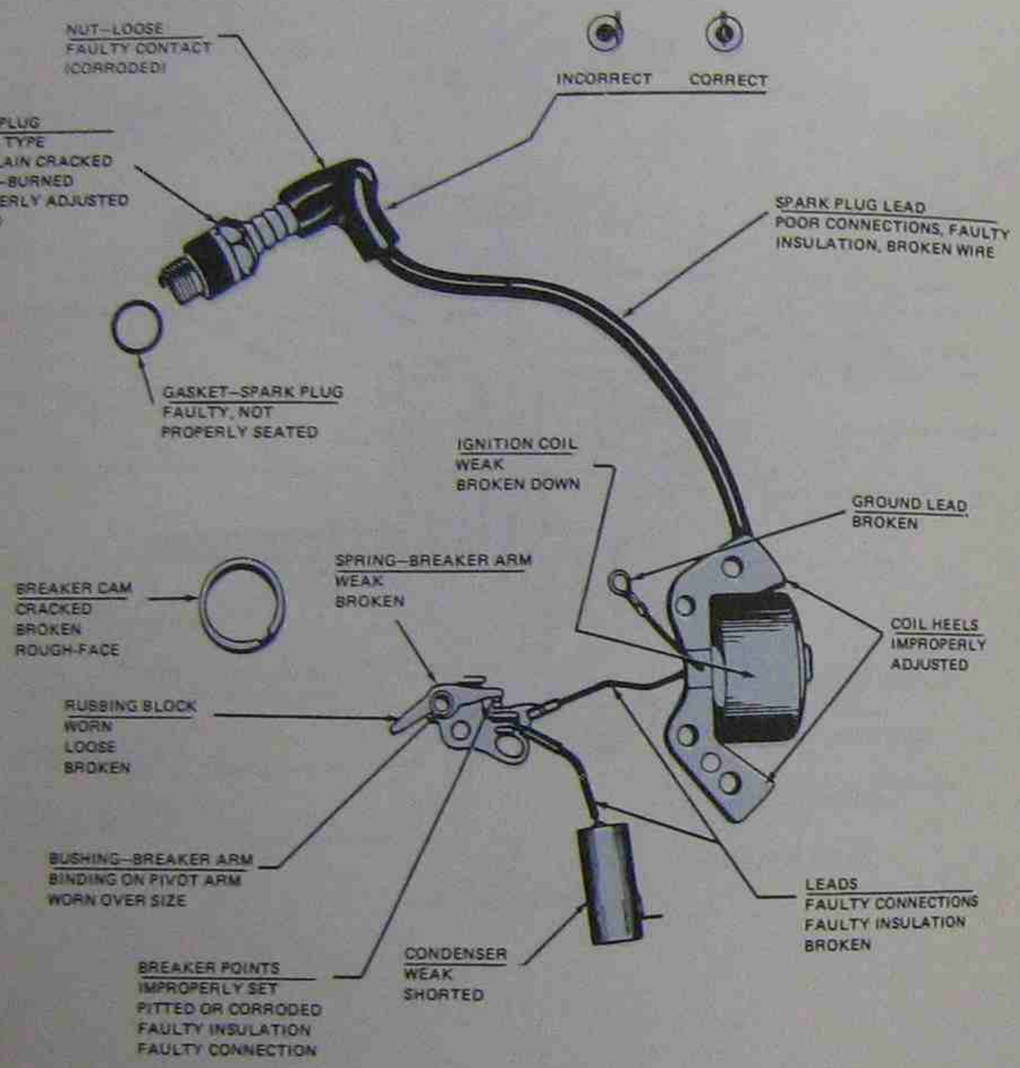
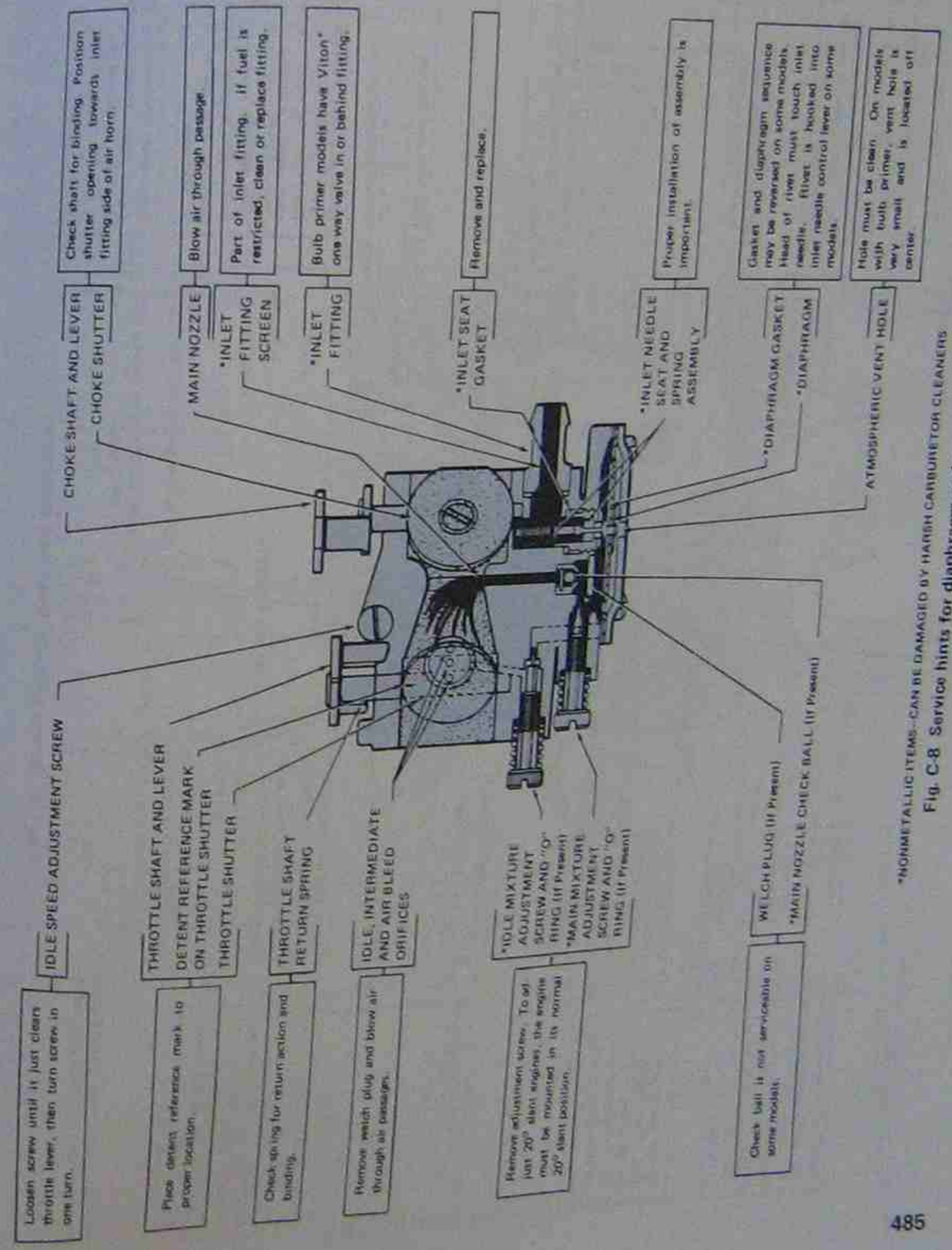


Fig. C-7 Magneto diagnosis chart



*NONMETALLIC ITEMS—CAN BE DAMAGED BY HARSH CARBURETOR CLEANERS

Fig. C-8 Service hints for diaphragm carburetors

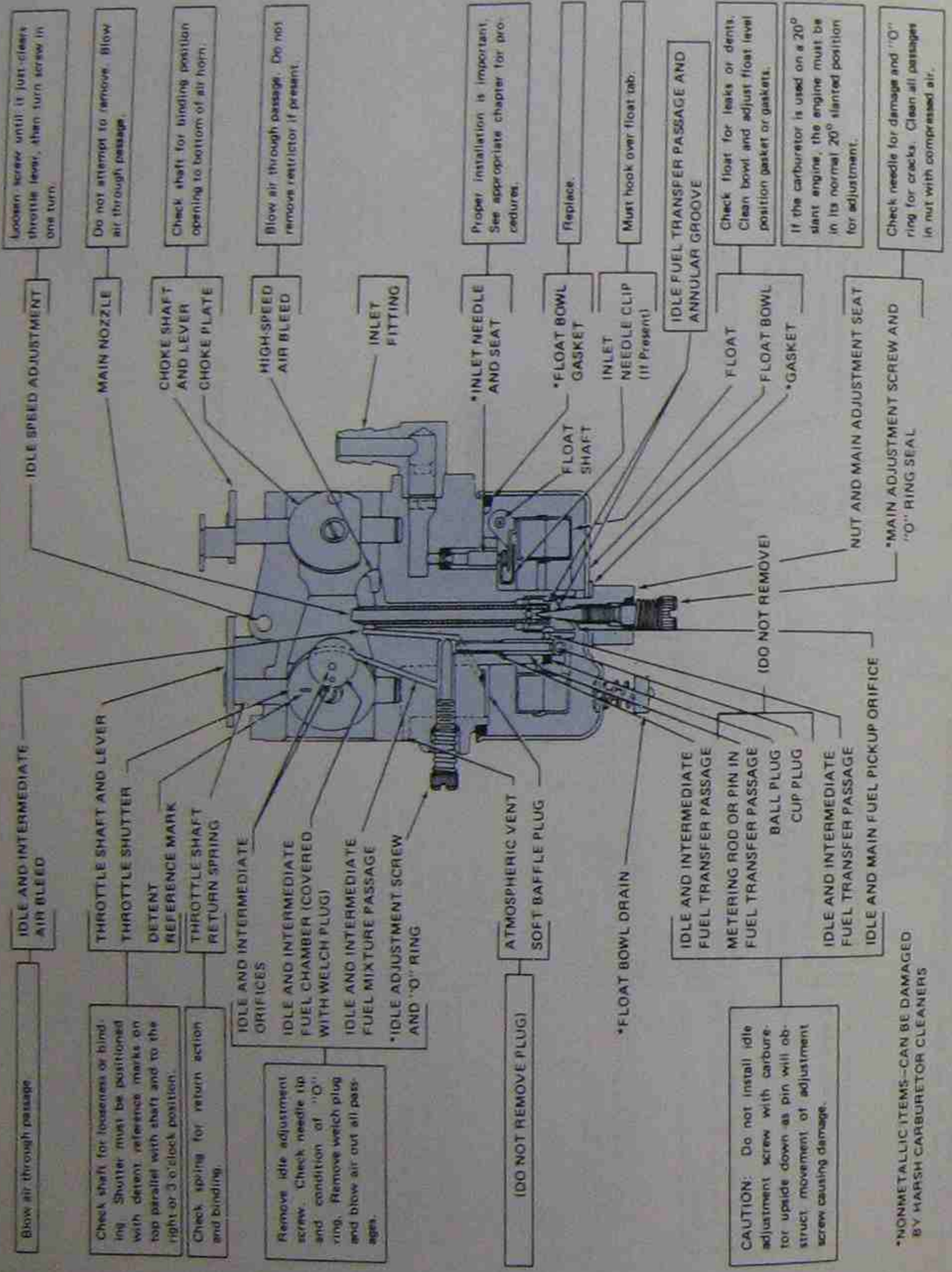


Fig. C-9 Service hints for float-feed carburetors

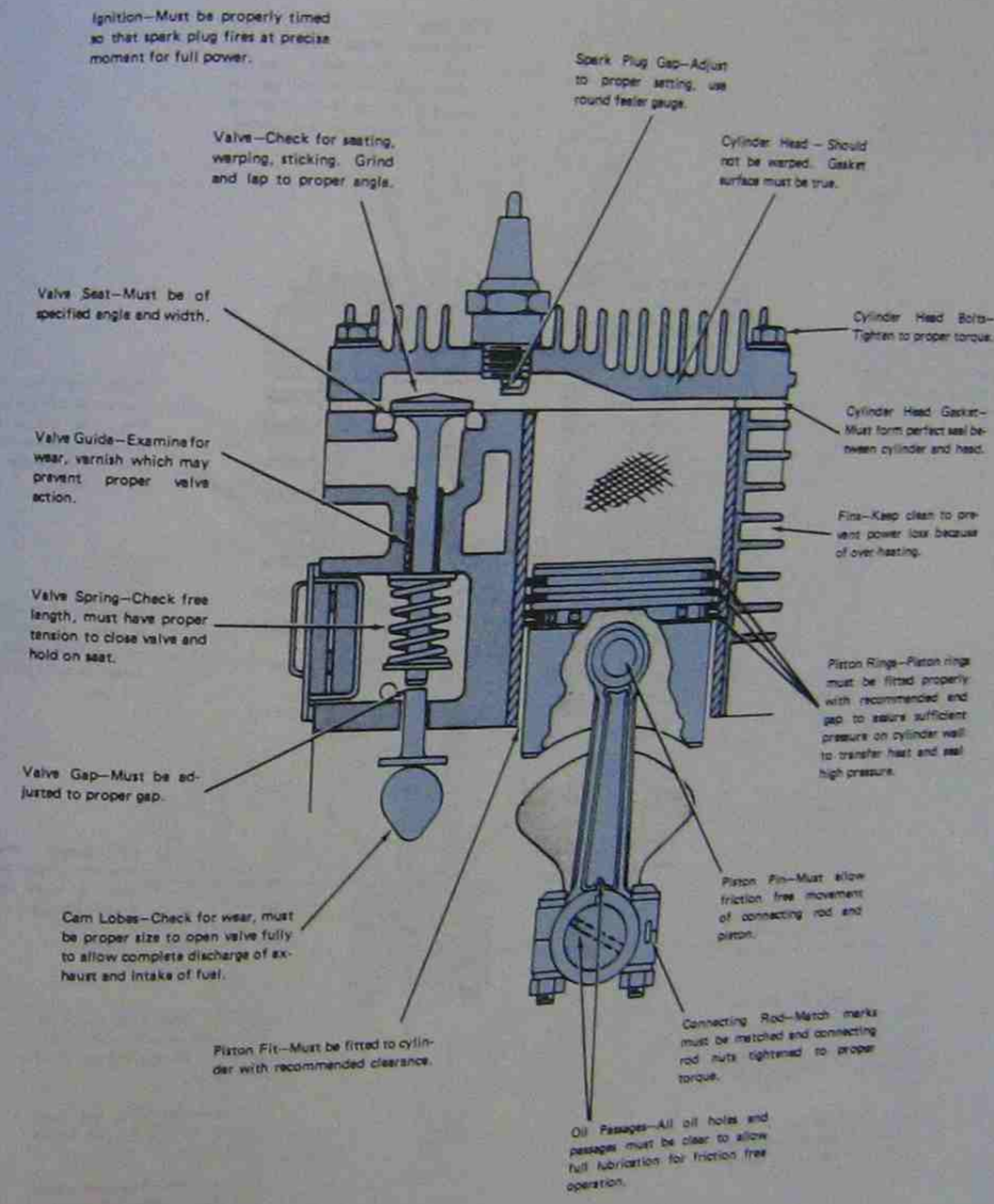


Fig. C-10 Points to check for engine power

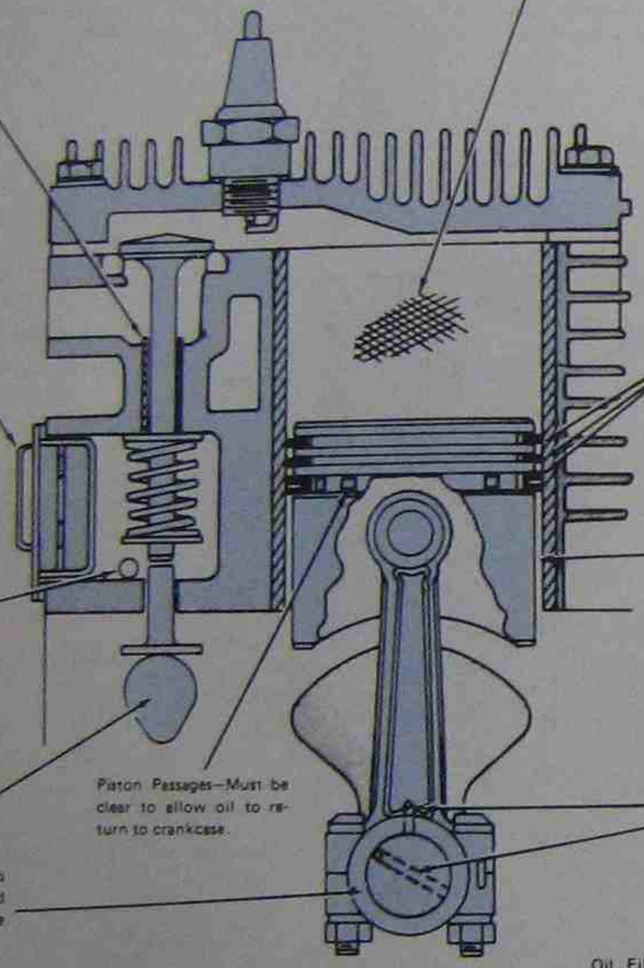


Fig. C-11 Points to check for engine oil control

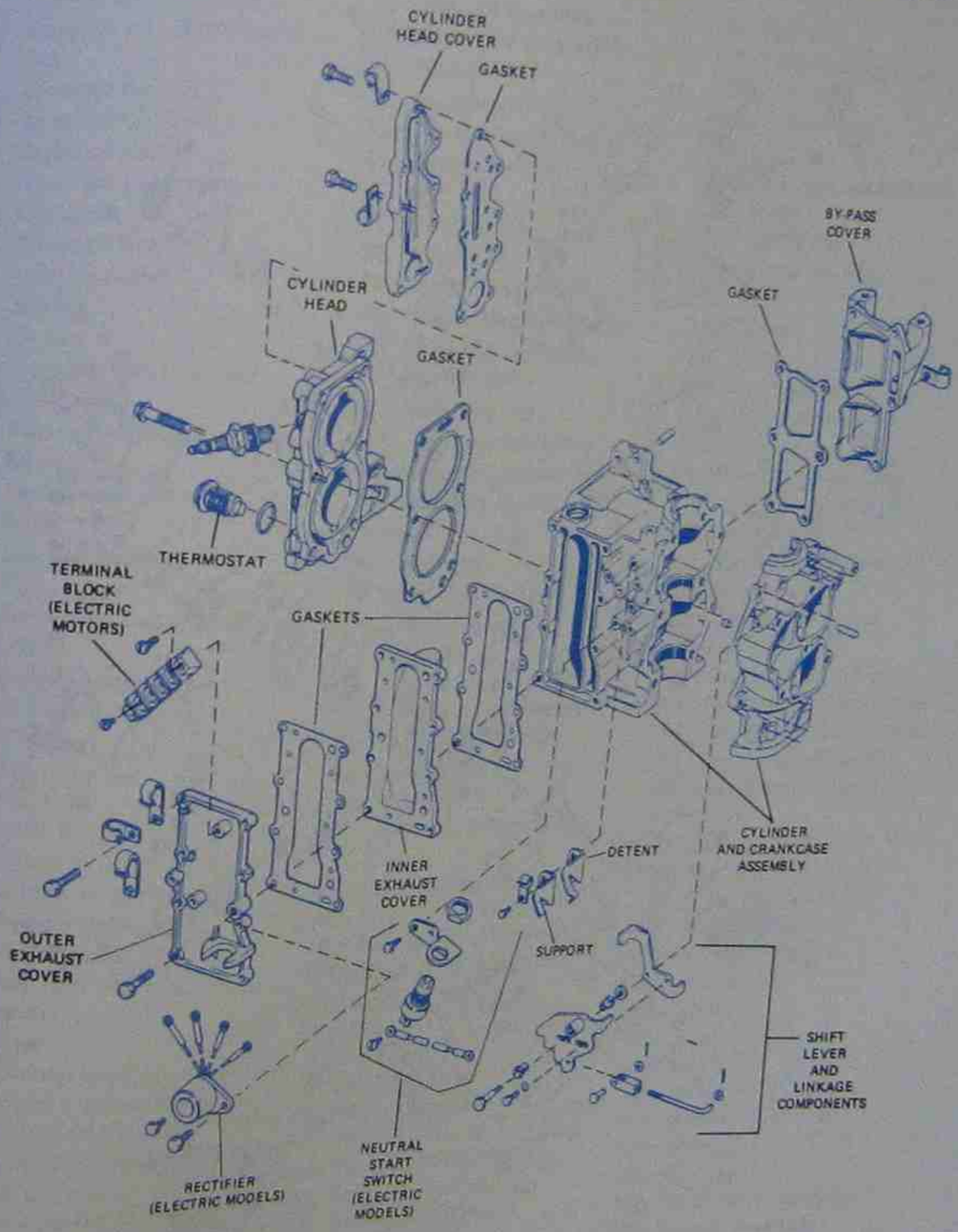


Fig. C-12 Power head – exploded view

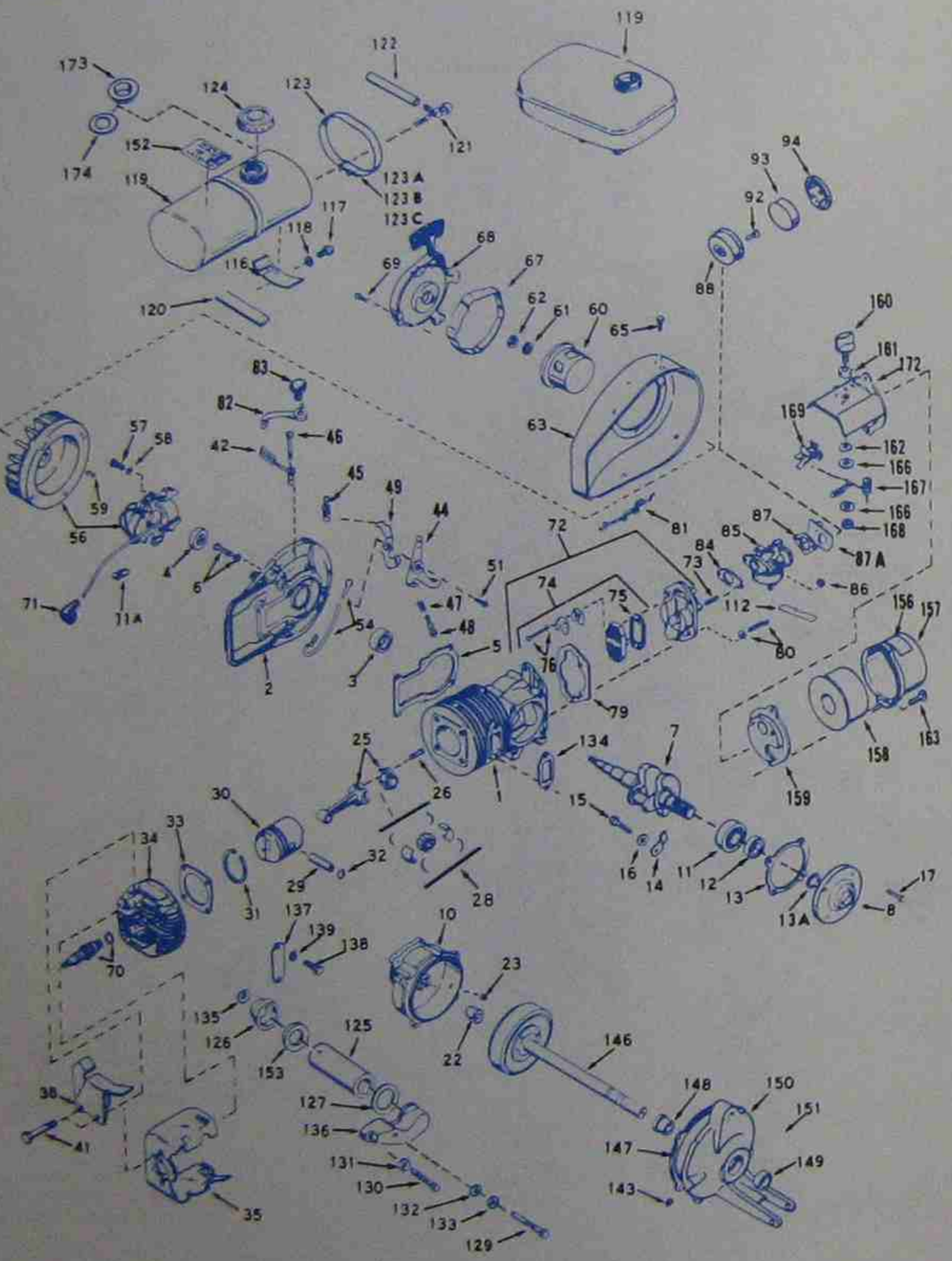
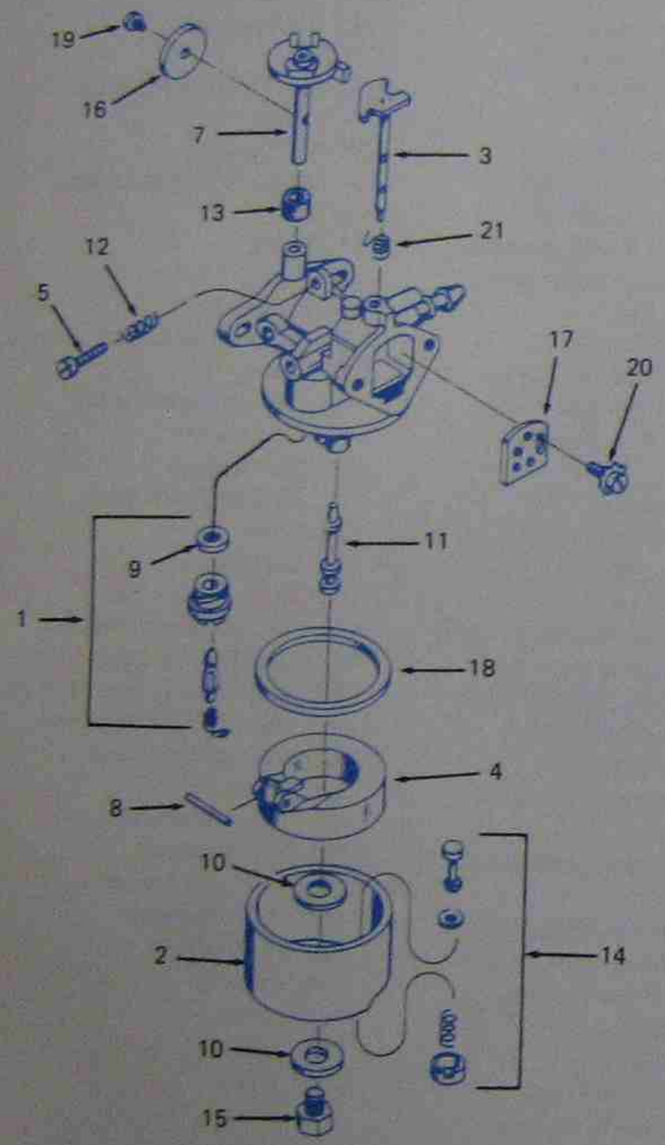


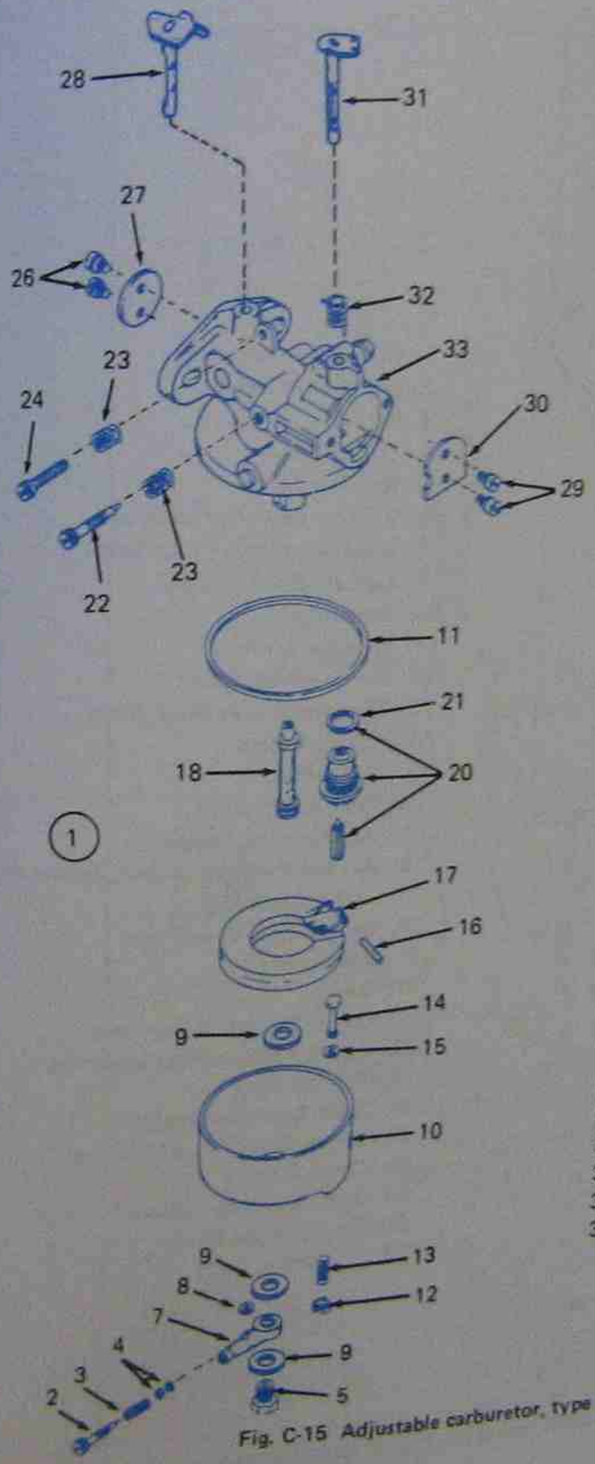
Fig. C-13 Horizontal engine, exploded view

1. Cylinder and Crankcase
2. Backplate with Bearing and Seal
3. Backplate Bearing
4. Backplate Oil Seal
5. Backplate Gasket
6. Screw and Lockwasher
7. Crankshaft
8. Crankcase Head
10. Crankcase Head
11. Bearing
12. Oil Seal
13. Crankcase Head Gasket
13A. Ring, Snap
14. Bearing Retainer Clip
15. Screw
16. Lockwasher
17. Screw
22. Gearcase Bushing
23. Plug
25. Connecting Rod Assembly
26. Screw
28. Bearing Assembly, 28 Rollers, 2 Liners, 4 Guides
29. Piston Pin
30. Piston
31. Piston Ring
32. Piston Pin Retaining Ring
33. Cylinder Head Gasket
34. Cylinder Head
35. Air Deflector
38. Fuel Tank Mounting Bracket
41. Screw
42. Governor Vane Assembly
44. Control Lever Assembly
45. Governor Vane Spring
46. Screw, Governor Vane
47. Spring, Control
48. Screw, Speed Control
49. Lever, Governor Spring
51. Screw, Control Lever Mounting
54. Stop Switch Wire
56. Magneto Assembly
57. Screw and Lockwasher
58. Washer
59. Flywheel Key
60. Rewind Starter Hub
61. Washer, Belleville
62. Nut
63. Fan Housing
65. Screw
67. Starter Screen
68. Rewind Starter Assembly
69. Screw and Lockwasher
70. Spark Plug
71. Spark Plug Cap
71A. Terminal, Spark Plug
72. Carburetor Adapter and Reed Plate Assembly
73. Stud
74. Reed Plate
75. Reed Plate Gasket
76. Screw, Reed Plate Mounting
79. Adapter Mounting Gasket
80. Screw and Lockwasher
81. Choke Link Assembly
82. Governor Link
83. Push Rivet
84. Carburetor Mounting Gasket
85. Carburetor Assembly
86. Nut
87. Plate Mounting Gasket
87A. Bracket, Throttle Wire
88. Air Filter Housing
92. Screw
93. Air Filter
94. Air Filter Cover
112. Decal, Choke, and Shutoff
116. Tank Mounting Bracket
117. Screw
118. Lockwasher (Washer)
119. Fuel Tank Assembly
120. Pad, Fuel Tank Mounting
121. Shutoff Valve Assembly
122. Fuel Line
123. Tank Mounting Strap
123A. Screw
123B. Lockwasher
123C. Nut
124. Fuel Tank Cap Assembly
125. Muffler
126. Muffler Cap
127. Muffler Mounting Gasket
128. Bolt
129. Screw
130. Screw
131. Lockwasher
132. Muffler Head Gasket
133. Washer
134. Exhaust Flange Gasket
135. Lockwasher
136. Muffler Head
137. Exhaust Flange Cover
138. Screw
139. Lockwasher
143. Plug
146. Gear and Shaft Assembly
147. Gear Reducer Cover Gasket
148. Gear Reducer Cover Bearing
149. Gear Reducer Cover Seal
150. Gear Reducer Cover
151. Screw
152. Decal, Name, Mix
153. Muffler Gasket
156. Decal, Air Cleaner
157. Air Filter Body
158. Air Filter
159. Bracket
160. Knob
161. Spacer
162. Washer
163. Screw
166. Washer
167. Spring
168. Nut
169. Stop Switch Assembly
172. Bracket Assembly
173. Baffle Assembly
174. Gasket, Fuel Tank Cap



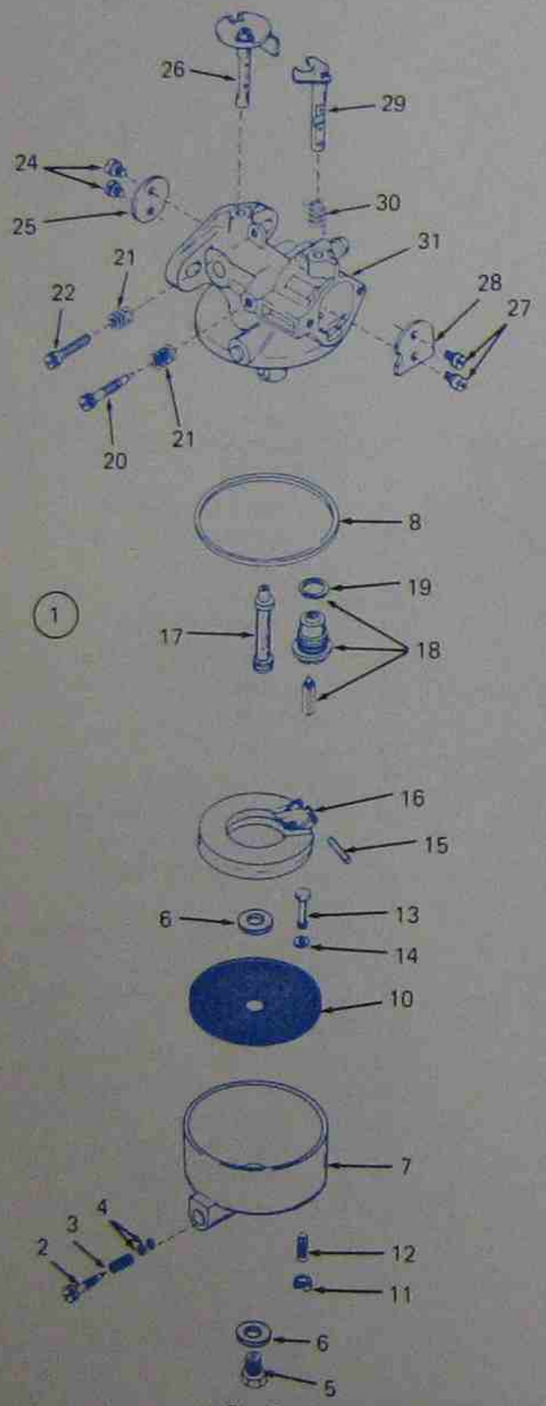
1. Matched, Float Valve Seat, Spring and Gasket Assembly
2. Bowl Assembly—Float Bowl
3. Shaft Assembly—Choke
4. Float Assembly
5. Screw—Throttle Adjustment
7. Shaft Assembly—Throttle
8. Shaft—Float
9. Gasket—Float Valve Seat
10. Gasket—Nut to Bowl
11. Main Metering Nozzle
12. Spring Throttle Adjustment
13. Seal—Throttle Shaft
14. Bowl Drain Assembly
15. Retainer Screw
16. Throttle Plate
17. Choke Plate
18. Gasket—Bowl to Body
19. Screw
20. Screw
21. Spring—Choke Return

Fig. C-14 Fixed-jet carburetor, exploded view



1. Carburetor Assembly
2. High-Speed Needle
3. Spring
4. "O" Rings
5. Retainer—Bowl
7. High-Speed Needle Housing
8. Rubber Gasket
9. Gasket—Bowl Nut to Bowl
10. Bowl Assembly—Float Bowl
11. Gasket—Body to Bowl
12. Retainer Screw
13. Spring—Drain Bowl
14. Stem Assembly—Drain Bowl
15. Rubber Gasket
16. Shaft—Float
17. Float Assembly
18. Main Metering Nozzle
20. Matched Float Valve, Seat, Spring and Gasket Assembly
21. Gasket—Seal Valve Float
22. Needle—Idle
23. Spring—Throttle Adjustment Screw
24. Screw—Idle Speed
26. Screw—Throttle Plate Mounting
27. Throttle Plate
28. Shaft Assembly—Throttle
29. Screw—Choke Plate Mounting
30. Choke Plate
31. Shaft Assembly—Choke
32. Choke Return Spring
33. Carburetor Body

Fig. C-15 Adjustable carburetor, type 1, exploded view



1. Carburetor Assembly
2. High-Speed Needle
3. Spring
4. "O" Rings
5. Retainer Screw
6. Gasket—Bowl Nut to Bowl
7. Bowl Assembly—Float Bowl
8. Gasket—Body to Bowl
10. Screen
11. Retainer Screw
12. Spring—Drain Bowl
13. Stem Assembly—Drain Bowl
14. Rubber Gasket
15. Shaft—Float
16. Float Assembly
17. Main Metering Nozzle
18. Matched Float Valve Seat, Spring and Gasket Assembly
19. Gasket—Seal Valve Float
20. Needle, Idle
21. Spring
22. Screw, Throttle Adjustment
24. Screw—Throttle Plate Mounting
25. Throttle Plate
26. Shaft Assembly Throttle
27. Screw—Choke Plate Mounting
28. Choke Plate
29. Shaft Assembly—Choke
30. Spring Choke Return
31. Carburetor Body

Fig. C-16 Adjustable carburetor, type 2, exploded view

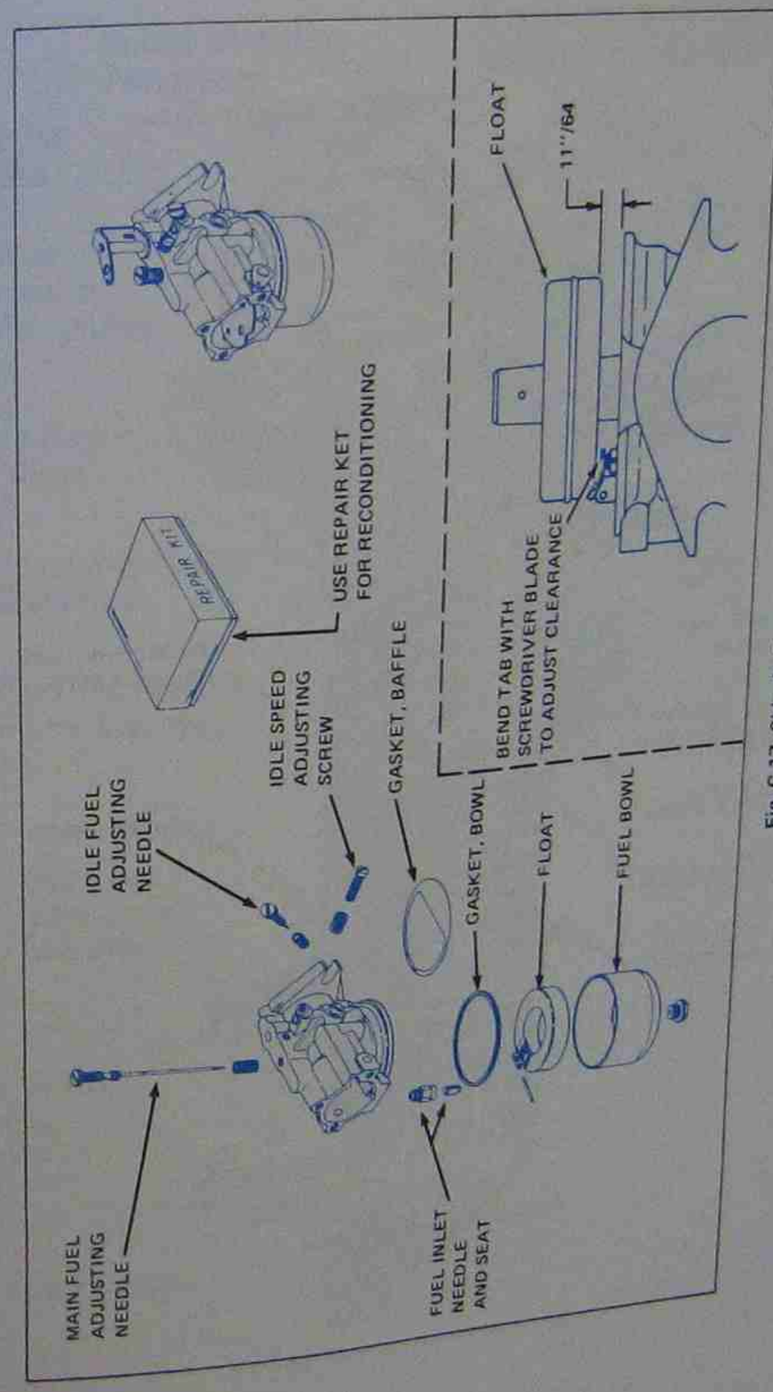


Fig. C-17 Side-draft carburetor

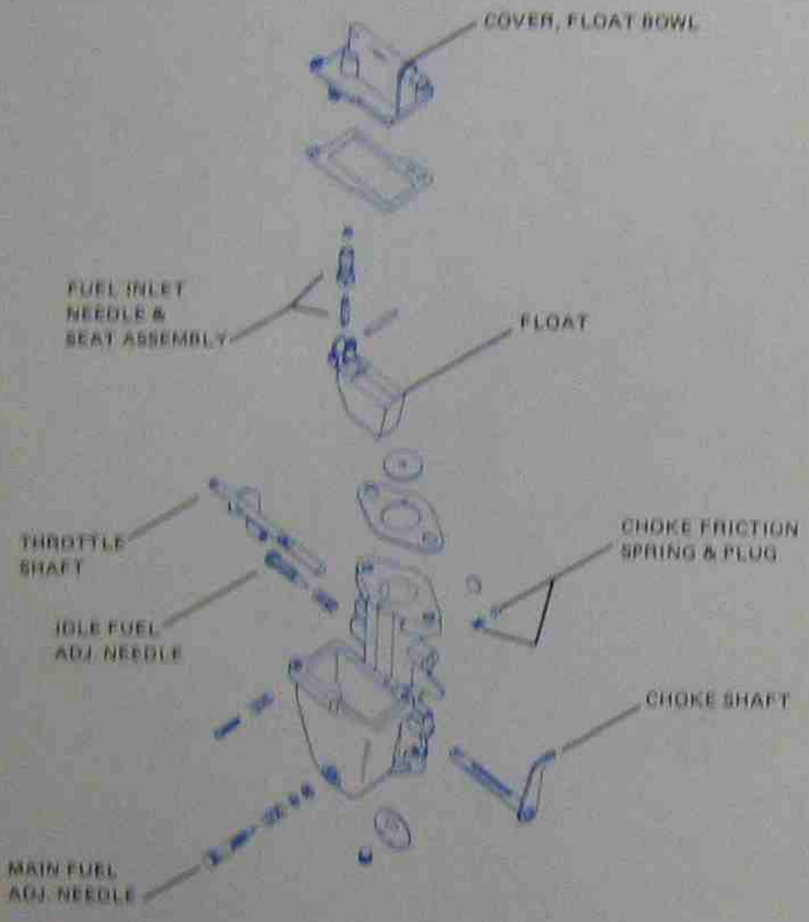


Fig. C-18 Up-draft carburetor

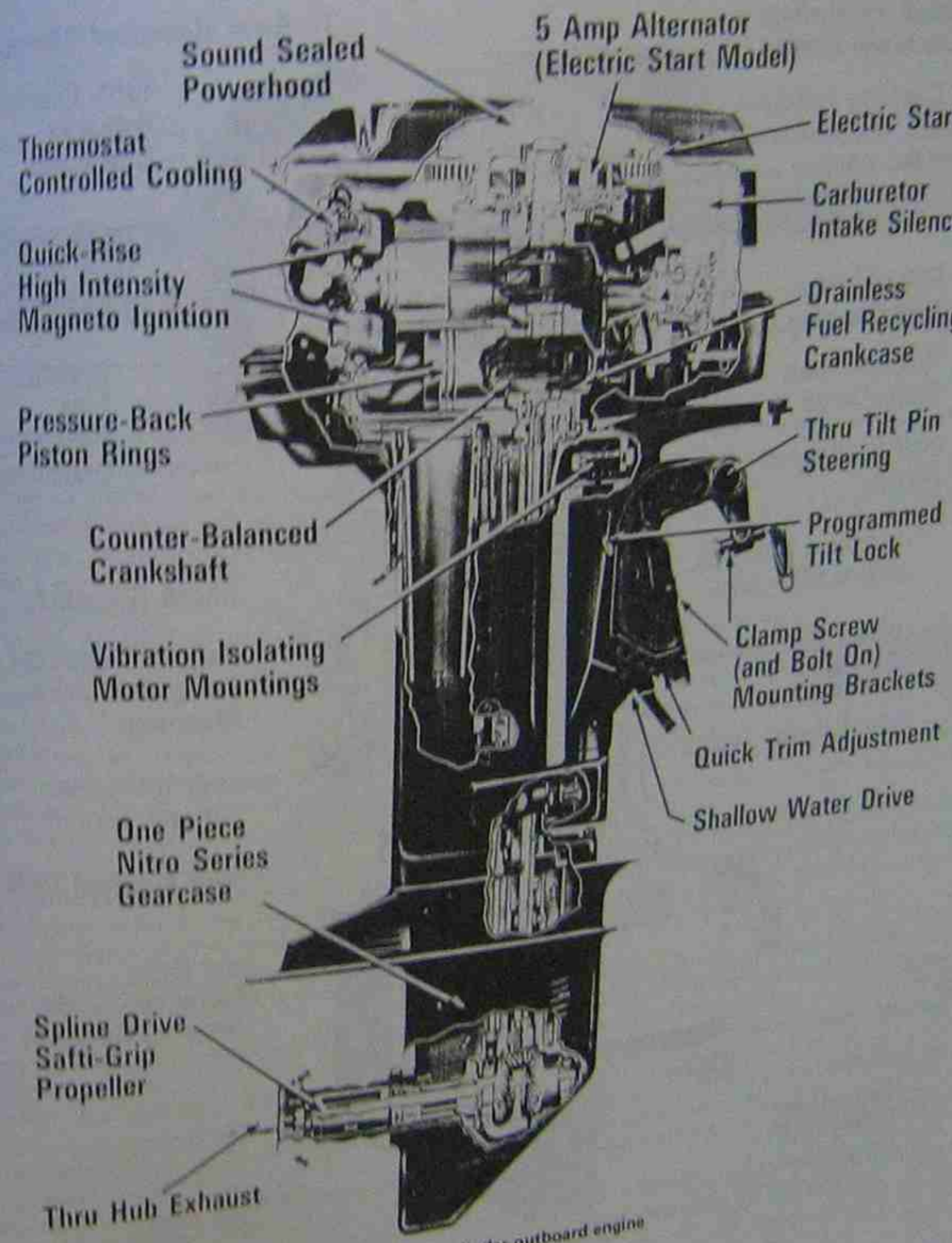


Fig. C-19 Two-cylinder outboard engine

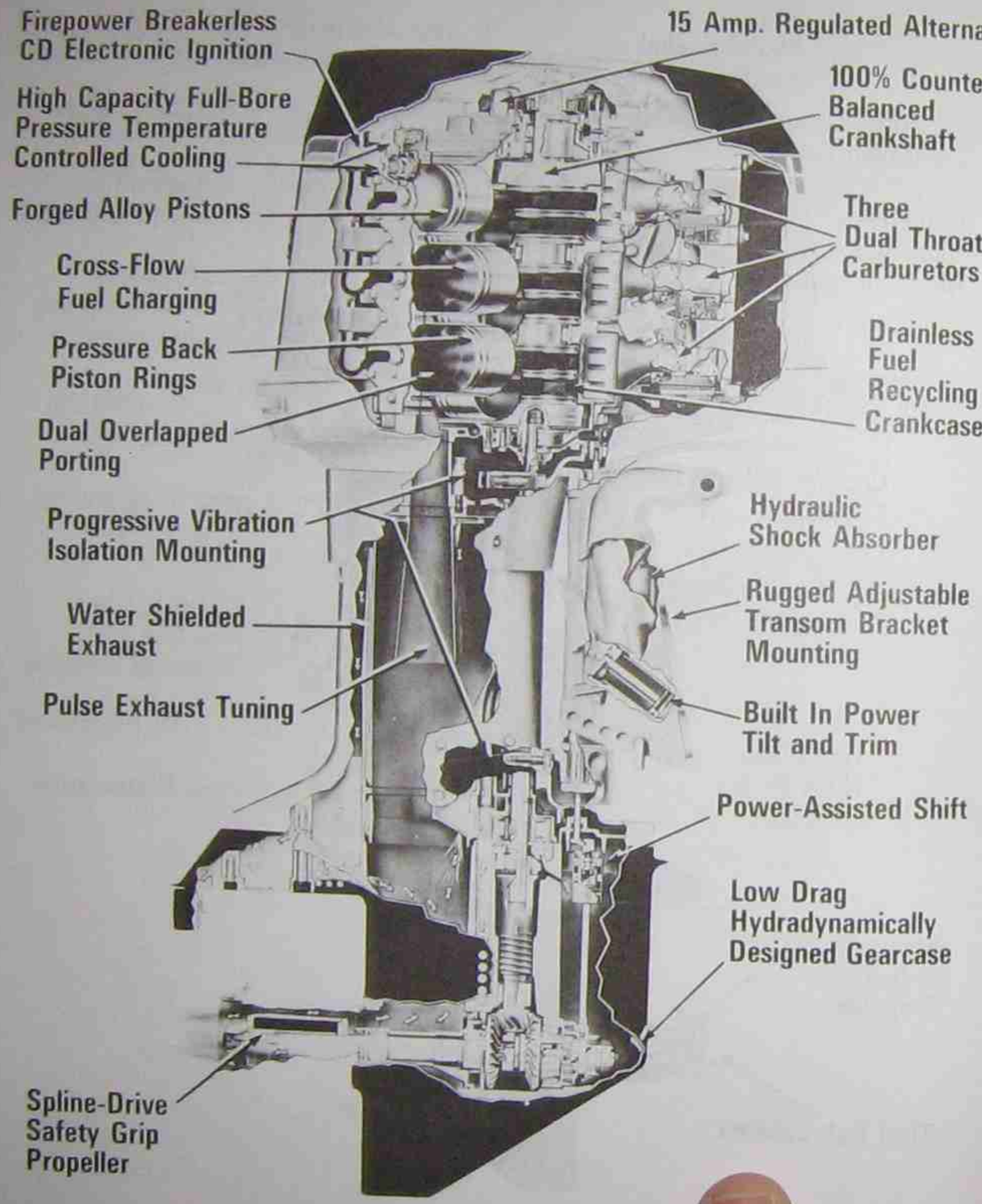


Fig. C-20 Six-cycle outboard engine

Glossary

Additives. Substances added to oils to improve their ability to function properly.

Alternating current. Electrical current that changes its direction back and forth regularly in a cycle (AC).

Alternator. An electrical device that produces AC electricity with stationary coils of wire and a rotating magnet.

Ammeter. An electrical instrument for measuring current flow in a circuit.

Ampere. The electrical measurement of the rate of current flow in a conductor.

Anthracite. The hardest type of coal which also contains the most heat energy.

Antifriction bearing. A bearing that substitutes rolling friction for sliding friction such as a roller bearing or ball bearing.

API. American Petroleum Institute

Atmospheric pressure. The weight of the atmosphere above the earth: 14.7 psi at sea level.

Atom. The smallest particle of an element that still retains the properties of that element.

Backfire. Unwanted ignition of fuel mixture in the intake manifold.

Battery. A number of primary cells grouped together to store chemical electrical energy.

BDC. Bottom dead center or the lowest point of the piston's travel.

Bearing. A supportive part in which a shaft revolves or moves.

Biomass. All organic matter which can be used as a fuel directly or be converted into a fuel.

Bituminous coal. The most plentiful type of coal that is economically recoverable. It is softer than anthracite but harder than subbituminous coal.

Blow-by. Refers to combustion gases that pass between the cylinder wall and the piston and rings and enters the crankcase.

Bore. The diameter of a cylinder.

Brake horsepower. The measurement of the engine's horsepower taken at the flywheel.

Breaker points. An electrical switch used to interrupt the current flow in the primary coil of an ignition coil in an ignition system. The opening of the points triggers the spark.

Breeder reactor. A nuclear reactor that is capable of producing more fissionable material than it consumes.

British thermal unit (BTU). The unit of measurement of heat energy. The amount of heat required to raise the temperature of one pound of water 1°F.

Calorie. The metric unit of measurement for heat. The amount of heat required to raise the temperature of one gram of water 1°C.

Camshaft. A shaft with lobes that convert rotary motion into linear motion for opening valves.

Carbon monoxide. A poisonous gas produced by the burning of carbon-type fuels.

Carbonaceous. Referring to all hydrocarbon-type fuels.

Carburetor. A device for mixing fuel and air in the correct proportions for burning in an engine.

Carburetor icing. The formation of frost on the throttle plate under certain humidity and temperature conditions.

Catalyst. A substance that speeds up a chemical reaction without entering into the reaction.

Catalytic converter. An emission control device in the engine's exhaust system that removes hydrocarbons and carbon monoxide.

Centrifugal force. The force that tends to throw objects away from the center of rotation.

Choke. A device for controlling the amount of air that can enter the carburetor. It is used mainly to provide a rich mixture for starting and warmup.

Clutch. A device for engaging and disengaging the engine from the transmission.

Coal gasification. A method of producing methane gas from coal by burning it with a controlled amount of oxygen.

Coal liquification. The process of converting coal into a liquid fuel that can be burned much the same as heating oil.

Combustion chamber. The small volume formed by the cylinder head, the top of the cylinder and the top of the piston, where combustion of fuel takes place.

Compression ignition. The principle of operation of a diesel engine.

Compression ratio. The ratio of maximum volume to minimum volume in the cylinder caused by the piston's motion.

Compression stroke. The stroke of the piston in which the trapped fuel mixture is squeezed into a small space just before combustion.

Condenser. An electrical device for storing electrical energy. It prevents arcing at the breaker points. Also, a device for converting a gas into a liquid.

Connecting rod. The part that connects the crankshaft with the piston pin and piston.

Coolant. The liquid circulated through the engine's cooling system.

Crankcase. The main body of the engine which holds the crankshaft and many other engine parts.

Crankcase breather. A part that vents the crankcase to the atmosphere to prevent pressure building.

Crankshaft. The main shaft of the engine to which the connecting rods are attached. The crankshaft converts reciprocating motion into rotary motion.

Critical. When the process of fission is proceeding at a controlled rate.

Crude oil. Oil in its unrefined state—just as it comes from the ground.

Cylinder. A round hole bored into the engine block to accept the piston.

Cylinder block. Commonly called the 'block;' the largest single part of the engine which contains the cylinders.

Cylinder head. The top of the cylinder, usually bolted down tightly but sometimes cast as a part of the cylinder.

Detergent. Used in reference to oils, these are additives that keep the dirt, soot, and other minute particles in suspension.

Detonation. Sometimes called knock; occurs when two flame fronts in the combustion chamber meet, exploding the fuel mixture between them.

Diesel engine. An engine that uses the heat of compression to ignite the fuel. Diesel fuel is used; no spark plug is necessary. It is named after its inventor Rudolph Diesel.

Differential. An arrangement of gears with the rear axle which permits one wheel to turn faster than the other when corners are turned.

Direct current. Electrical current that flows in only one direction, such as current from a storage battery (DC).

Dynamometer. A device used to determine the horsepower developed by an engine.

Ecology. That branch of biology that concerns itself with the relationship of organisms to their environment.

Electron. A very small part of an atom. It is negatively charged and orbits around the nucleus.

Emissions. Term commonly applied to the harmful portions of the exhaust gases of an engine.

Energy. The ability to do work. Heat energy is measured in BTUs (British Thermal Units) or joules (metric).

Environment. The sum total of the things, conditions and influences that affect the development of life.

EPA. Environmental Protection Agency.

ERDA. Energy Research and Development Administration.

Ethanol. Made by the distillation of grain or plants to produce ethyl alcohol (grain alcohol) a combustible liquid.

Exhaust stroke. The stroke of the piston in which the exhaust gases are removed from the cylinder.

External combustion engine. An engine that burns fuel in a fire box under a boiler outside the engine, to boil water and produce steam to drive the engine.

Fluid power. The use of a fluid—either liquid or gas—to operate a mechanism. hydraulics and pneumatics.

Flywheel. A relatively large wheel that stores energy and stores it by momentum.

Fossil fuels. Fuels that have been formed in the earth over million of years—petroleum, coal and natural gas. Originally deposited as dead plants and organisms, they were changed into hydrocarbon molecules by the action of heat, pressure, and chemical changes.

Fouling. Term used to denote damage done to spark plugs.

Four-stroke cycle. An engine that completes its operating cycle in four strokes of the piston and two revolutions of the crankshaft.

Fractional distillation. A basic refinery process in which many of the hydrocarbons that make up crude oil vaporize when heated and then condense at various levels in a cooling tower.

Friction. The resistance to motion between two parts in contact with each other.

Fuel cell. A device that converts chemical energy directly into electricity. A reaction between hydrogen and oxygen is used.

Fuel injection. Refers to engines, either gasoline or diesel, which inject the fuel into the cylinder after the air is compressed.

Fuel pump. A device that is operated by the motion of a diaphragm to deliver fuel from the tank to the carburetor.

Fuel system. The entire contents of an internal combustion engine. Includes fuel tank, fuel line, fuel pump, and carburetor.

Gas turbine. An internal-combustion engine in which hot gases are directed against vanes mounted on a rotary shaft.

Gasket. A thin, relatively soft material made of rubber, fiber, metal, or cork, used to form an air-tight seal.

Gasohol. A blended fuel containing 9 parts gasoline to 1 part ethanol (ethyl alcohol).

Generator. A device for converting mechanical energy into electrical energy.

Geothermal energy. Energy released from the magma (molten core of the earth). This energy is usually seen in certain parts of the earth where the heat is close to the surface and underground water comes in contact with the hot rocks to produce steam.

Governor. A device used to control or regulate engine speed.

Ground. An electrical term for a large conductive body that acts electrically neutral to accept a flow of electrons.

Heat engine. An engine that converts the heat of a burning fuel into mechanical energy.

High voltage coil. A coil containing a primary and a secondary coil. Its transformer action steps up low voltages to high voltages which can jump the spark gap in the spark plug. Sometimes it is called the ignition coil.

Horsepower. Unit of measurement for the rate of doing work. Lifting 33,000 pounds 1 foot in 1 minute is 1 horsepower.

Hydraulics. A fluid transmission system that uses a liquid within a dynamic system as the transmission medium.

Hydrocarbon. A compound consisting of molecules of hydrogen and carbon. Petroleum is a hydrocarbon.

Hydroelectric. Electricity produced by water-driven

turbines which in turn drive a generator. Water for driving the turbines is collected behind dams.

Industrial revolution. The period in history beginning in the mid 1800s when the rapid growth of industry and transportation took place using the steam engine as its main power source.

Intake stroke. The stroke of the piston in which the fuel mixture is brought into the cylinder.

Internal combustion engine. An engine that burns fuel inside the engine itself.

Jet propulsion. An engine that uses Newton's principle; for every action there is an equal but opposite reaction. Rapidly escaping gases from one end of the engine produce thrust at the other end of the engine.

Journal. The part of an axle or shaft that makes contact with the bearing.

Key. A device for locking two parts together, such as the crankshaft and the flywheel. Also called a shear pin.

Kinetic energy. The energy of motion.

Lignite. A type of soft coal with a relatively low heat value.

Magnet. A hard steel alloy in which a magnetic field is permanently maintained due to its molecular arrangement.

Magneto. An electrical device that converts magnetism into high voltage for the spark plug of the ignition system. It is self-contained and uses only the energy of a moving magnetic field.

Manifold. A pipe that has several openings to connect cylinders with a single inlet or outlet—intake manifold or exhaust manifold.

Methane. A combustible gas produced by the decomposition of organic matter.

Methanol. Made by the destructive distillation of wood or plants to produce methyl alcohol (wood alcohol) a combustible liquid.

Metric. The decimal system of weights and measures with units such as meters, liters, and grams.

Molecule. The smallest portion of a chemical compound that still has the properties of the compound.

NASA. National Aeronautics and Space Administration.

Natural gas. A gaseous hydrocarbon fuel found in underground formations. Its principle ingredient is methane, a combustible gas.

Needle valve. A tapered end of a threaded shaft that fits into a tapered hole. Used to regulate the amount of gasoline that can flow out of the hole.

Nuclear battery. An electrical device that produces electricity from radioactive materials.

Nuclear energy. Energy released when the nucleus of an atom is split (nuclear fission). Uranium is the only natural element that can be split.

Nuclear fission. Splitting the nucleus of an atom to release energy.

Nuclear fusion. The coming together of the nuclei of light elements. When they collide and merge energy is released.

Nuclear reactor. A device in which a chain reaction of nuclear fission can be sustained and controlled. Heat produced from the reactor is used to produce electricity.

Octane number. A measurement of a fuel's ability to resist detonation or knocking; its anti-knock quality.

Ohm. The electrical measurement for the resistance to electrical current flow in a conductor.

Oil shale. A shale rock that contains the hydrocarbon kerogen.

Orbit. The path of a satellite around the earth during its periodic revolution.

Overdrive. An arrangement of gears in the transmission in which the output shaft is going faster than the engine (input shaft).

Parallel circuit. An electrical circuit in which there is more than one path for electrical current to flow.

Petrochemicals. A wide variety of chemical products made from petroleum.

Petroleum. A fossil fuel formed in the earth. It is made up of many types of hydrocarbon molecules. Commonly called crude oil.

Photosynthesis. The process by which plants grow—converting the energy of the sun, carbon dioxide, and water into plant tissue.

Piston. A cylindrical part that is fastened to the connecting rod and moves up and down in the cylinder.

Piston displacement. The volume that the piston displaces between TDC and BDC. Displacement is measured in cubic inches, cubic centimeters, or liters.

Piston pin or wrist pin. A sturdy, finely machined steel pin used to connect the piston and the connecting rod.

Piston rings. Cast iron bands which fit into grooves machined into the piston to provide a tight seal between the piston and cylinder walls.

Pneumatics. That branch of fluid power that deals with the use of gases, usually compressed air or nitrogen, to transmit power from one place to another.

Pollution. The waste that makes the environment unclean or foul.

Ports. Openings or holes usually in the cylinder wall.

Potential energy. The energy a body has due to its position, condition, or chemical state.

Power. The rate of doing work or the rate of energy conversion, usually measured in horsepower or watts.

Power stroke. The stroke of the piston in which the pressures of combustion force the piston down the cylinder.

Power technology. A study of energy sources and the machines and devices that are used to convert and apply energy.

Propellant. The fuel and oxidizer that are carried on board a rocket. They may be blended together—a monopropellant; or they may be contained in separate tanks—a bipropellant.

Reciprocation. Motion that is back and forth, such as the motion of a piston in a cylinder.

Reconditioning. The process of repairing or replacing worn parts of an engine to return it to peak performance.

Reed valves. Thin, springy sheet of metal that can be opened by air pressure to admit a fuel mixture. Sometimes called leaf valves.

Rocket engine. An engine that carries its own fuel supply and oxidizer. The operating principle is based on the reaction principle, as is the jet engine.

SAE. Society of Automotive Engineers.

Satellite. A manufactured object orbiting the earth.

Scavenging. To clean out, such as to clean the exhaust out of the cylinder. Usually, air is used.

Semiconductors. Materials that do not have the clear properties of insulators or conductors, but become electrically conductive when they are heated, exposed to light energy, or doped with an additive.

Series circuit. An electrical circuit in which there is only one path for electric current to flow.

Solar cell. A device that converts the energy of the sun directly into electrical energy.

Solar energy. Energy from the sun. Almost all energy sources trace their origin to the sun.

Solar heating. The use of solar energy to heat interior spaces. The system may be active, using solar panels, pumps and/or fans, and heat storage media. The system may be passive by simply storing the heat energy of the day in large collectors such as masonry construction or water tanks. The heat energy is then released naturally at night.

Solid-state ignition. An ignition system that has no moving parts. Its parts are transistors, diodes, and a silicon-controlled rectifier.

Space shuttle. A space craft that is capable of orbiting the earth in space and then returning safely to earth where it is prepared for successive flights.

Spark advance. A device used to cause the spark to occur earlier in the engine's operating cycle. Spark advance is needed most at high speeds.

Spark plug. A part that fits into the cylinder head and extends into the combustion chamber. Its two electrodes are separated by an air gap. When voltage arcs across the gap, the fuel mixture is ignited.

Steam engine. An external combustion engine in which the fuel burned heats water. The water is converted into steam which moves the piston.

Steam turbine. An external combustion engine in

which the fuel burned heats water. The water is converted into steam which is directed against the turbine blades, rotating them.

Stroke. Movement of the piston in a cylinder from top to bottom or from bottom to top.

Supercharger. A blower device that forces air into the cylinders. It permits more fuel to be burned and increases engine power.

Surface mining. A mining technique used for coal and other minerals that is used when the ore is relatively near the earth's surface. Also called strip mining.

Tachometer. A device for measuring the revolutions per minute of a shaft such as a crankshaft.

Tappets. Located between the valve stem and the cams. They transmit the motion of the cam to the valve. They are often referred to as valve lifters.

TDC. Top dead center or the upper limit of the piston's travel.

Throttle. The part of the carburetor that controls the amount of fuel mixture that can enter the engine, thereby controlling the engine's speed.

Thrust. Driving force which pushes a jet or rocket engine forward.

Torque. Effort applied toward twisting or turning.

Transaxle. A transmission device that combines the transmission and axle in one housing.

Transformer. An electrical device with coils of wire that will change voltage and amperage from one circuit to another by induction.

Transmission. A system of gears that can be placed in various combinations that can change the output speed. When speed is increased, torque is reduced.

Troubleshooting. The intelligent, step-by-step process for locating engine troubles. The process is based on knowledge of engine operations and uses observation and tests.

Tuneup. The process of cleaning, adjusting, and testing an engine so it will achieve peak performance.

Turbocharging. A device used to force or blow air into the cylinder of a gasoline engine. It is driven by the engine's exhaust gases.

Turbofan. A jet engine, similar to a turboprop engine, in which large ducted fans replace the propeller.

Turbojet engine. A jet engine that uses the principle of jet propulsion.

Turboprop engine. Essentially a turbojet engine in which the turbine drives the propeller to produce most of the engine's thrust.

Two-stroke cycle. An engine that completes its operating cycle in two strokes of the piston and one revolution of the crankshaft.

Valves. Devices for opening and sealing off a hole, port, or aperture.

Vapor lock. A condition in which the fuel vaporizes in the fuel line restricting its flow to the carburetor. Vapor lock is most likely to occur at high altitudes on hot days.

Venturi. The constricted part of the carburetor where the incoming air speeds up and air pressures are reduced.

Viscosity. The tendency of oil or any liquid to resist flowing. The rate at which a liquid flows.

Volatility. The ability of a liquid to vaporize.

Volt. The electrical measurement for electromotive force which will cause current to flow within a conductor.

Volumetric efficiency. The ability of an engine to take in a full charge of fuel mixture and to discharge the exhaust gases efficiently.

Warranty. A written agreement covering the responsibility of the manufacturer and the owner for the engine's performance during a certain length of time.

Wind turbine. A device that harnesses wind energy—similar to a wind mill—and converts it into electrical energy by driving a generator.

Work. Applying a force to cause motion. Measured in foot-pounds or joules.

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Delmar Publishers Inc.
ISBN 0-8273-2446-4