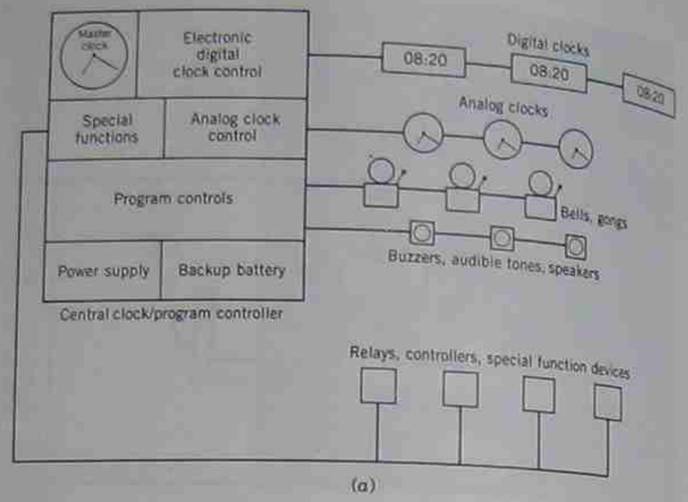

(a)

Fig. 22.10 (a) *The central clock and program device uses its electronic time base to control clocks of all types, time-based audible signals, and event controllers such as relays and switches.*

(b)

Fig. 22.10 (b) *Typical microprocessor-based master time clock and program device. This unit, which measures 14 × 12 × 5 in. deep, provides time correction signals to synchronous wired clocks of the digital or analog type and can be adapted to control minute impulse clocks. Programming of four output circuits can be daily or weekly, and can accommodate daylight savings, holidays, and leap-year update with a total program capacity in excess of 600 events. Programming is done locally or via a modem, from a remote computer. This type of device is applicable to any facility requiring a clock and/or program system in addition to its primary application in schools. (Courtesy of Midwest Time Control Inc.)*

being activated immediately on application of pressure. This arrangement (usable only where fire codes permit) allows sufficient time for the facility's staff to investigate the attempted exit before the door will open, and is applicable only where exit control is an overriding consideration. As mentioned in Section 13.20*b*, stair and exit door exit locks can be arranged to be centrally released from the fire control center.

22.14 School Clock and Program Systems

The clock system and the program system were at one time separate and distinct, sharing only the timekeeping facilities provided by the master clock. Now that electromechanical programming devices are effectively obsolete, the two systems are actually one, but the traditional two-system name remains. Referring to Fig. 22.10, we see that the heart of the system is the time base (electronic clock). This is precisely the same device that provides timing for all programmable switches and controllers. In a clock and program device it controls clock signals, audible devices, and if desired, other switching functions.

The clock system may use analog clocks (with hands) or digital units. The former are usually locally powered, and a correction signal is periodically transmitted via dedicated wiring from the master clock at the controller. This same controller continuously transmits a binary-coded signal to digital "slave" clocks, which can be either of the self-illuminated LED (light-emitted diode) type or of the LCD (liquid-crystal display) type. LCD units are easily visible only in high ambient illumination and when viewed directly (not at an acute angle). LED units are best applied in areas of low ambient illuminance. Conventional largeface clocks are easily visible in all ambient light situations.

The programming function of the controller serves to delineate audibly the various time periods into which the school day and week are divided. A single-circuit unit is utilized in the instance of an institution that operates entirely on one schedule, such as an elementary school on a morning period–lunch–afternoon period regimen. For a school employing different schedules for its various parts, the controller can provide multiple program schedules on different circuits, depending on its design. Controllers are user programmable and are normally provided with a local, master clock, crystal control to assure accurate timekeeping regardless of line frequency variation, backup power source to maintain user programming and master clock local display, and various conveniences such as daylight saving time correction, security arrangements, even timers, and so on. If desired, the clock and program controllers can also be used for mechanical system control, by the simple expedient of adding relays and switching devices, as shown in Fig. 22.10.

The audible devices in a program system may be bells, gongs, buzzers, horns, or a tone reproduced on a classroom loudspeaker. This last system has the following advantages:

1. Clear audibility in each classroom, with adjustable volume to accommodate both quiet and noisy areas.
2. No possibility of confusion between program tone and other signals such as fire alarm gongs.
3. Multiple use of the speaker unit, for classroom sound as well as program tone.
4. Complete flexibility of programming that is not possible with hall gongs. This is particularly desirable in schools with special programs for special groups of students.

Fig. 22.11 *Administrative telephone units of a modern school telephone/intercom system. The system, which is entirely solid state and requires no operator or switchboard, provides complete internal communications plus internal connection for selected administrative units, selective paging, and emergency call signals. Class-change signals on classroom intercom system speakers are also possible using time signals via interconnection with the school's master clock system. (Photo courtesy of Rauland-Borg.)*

22.15 School Intercom Systems

Various types of intercom systems are available depending on the needs of the school building involved. In small schools, a simple wired intercom system connecting the various offices is usually sufficient. This is supplemented by outside telephones in the administrative offices and a functional paging system that is normally part of the school's sound system arrangement. With larger buildings and correspondingly larger numbers of extensions and multiple-function demands, more sophisticated equipment is required. The unit illustrated in Fig. 22.11 is typical of modern school intercom equipment, and is actually a private telephone system of considerable flexibility. Such a system is generally interfaced with the school sound system, and provides these functions:

1. Intercom between staff members and offices.
2. Direct communication with classrooms, including selective and all-call capability.

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3. Zone, group call, and conference call functions.
4. Interconnection with the outside phone system.
5. Class-change signals via interface with master clock system.
6. School intercomputer communication via modems.

Fig. 22.12 (a) *Compact program/intercom control center. This unit, which measures 20.5 × 11 × 8.5 in. H has separate power amplifiers for intercom and program material. It distributes program material or provides intercom with 25 loudspeaker locations, and has additional capabilities, such as emergency/all-call paging, tone calling, time signal, night bell, and telephone paging. Program material derives from separate external sources. (Courtesy of Bogen Communications Inc.)*

These systems use direct pushbutton dialing and programming, thus eliminating the necessity for switchboards and operators. All stations are coded with three-digit codes, and all switching is solid state, minimizing maintenance problems. Such systems are adequate for all but the largest institutions.

22.16 School Sound Systems

An integrated sound-paging-radio system designed for school use offers several modes of operation and considerable flexibility. Its function is to provide a means for distributing recorded (records, tapes), broadcast (AM/FM), or live sound to preselected areas of the school. Thus, a simple system might provide a record player and single microphone input, and a single channel to all the speakers in the school, whereas a complex system can be arranged to operate with three simultaneous input signals distributed to six different areas of the school (see Fig. 22.12).

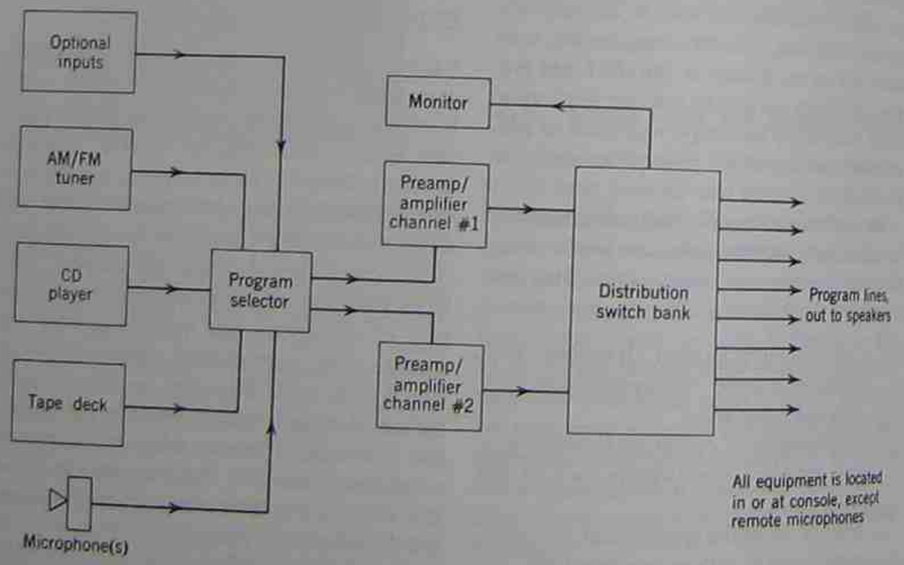

Fig. 22.12 (b) *Block diagram of a two-channel sound system. Optional facilities that can be added to the console are tape deck, private telephone communications, and equipment for rebroadcast of signals between areas. Intercom and master clock and program can also be incorporated.*

A conventional system consists of a desk-size control console containing most of the input units, amplifiers, and switching devices and connections to the remote loudspeakers. The input units may comprise one or more AM/FM tuners, turntables, CD player, tape deck, and microphones. One microphone is normally located at the console with others in the principal's office, auditorium, school office, or other selected location. If desired, mike outlets can be spotted around the school and a spare mike and stand supplied that can be plugged in at any of these points.

Loudspeakers, located in classrooms, gymnasium, auditorium, cafeteria, and outdoors receive the amplified signal through the switching mechanisms located in the console. It is the function of these switches to deliver the program material to the various loudspeaker circuits, which are also called program lines. Thus, using a system with multiple amplifiers, music can be piped to the cafeteria, an important radio program to senior classrooms and teachers' lounge, and instructions to an outdoor gym class or team practice. An all-call feature also allows announcements to reach all speakers in the system simultaneously. The intercom system discussed above can be interconnected with the sound system to allow conversation between classrooms and the console or other points. A small system can be contained in a compact desktop console (see Fig. 22.12*a*). A large system frequently requires a console. A console is usually built in a desk arrangement, and it is advisable to provide sufficient space for it and for the person who operates it. Often an alcove of 30 to 50 ft^2 is reserved for it and a library of recordings.

Loudspeakers may be in flush or surface baffles, at the discretion of the designer. Gymnasium, cafeteria, and auditorium units are normally flush-mounted in the ceiling. For large areas such as these it is well to provide a volume control, enclosed in a recessed wall box with a locking cover. A common variation of the above-described system uses separate subsystems for the cafeteria, auditorium, ball field, or other areas utilizing sound equipment frequently. These smaller systems have their own input, amplification, and control devices but utilize speakers in common with the central console. Normally, the console has an override feature that allows it to override local systems.

For a discussion of high-quality sound systems required for recital halls in music schools and the like, refer to Sections 26.27 to 26.29.

22.17 School Electronic Teaching Equipment

This area, as so many others that utilize computers, is growing and changing so rapidly that almost anything written on it is immediately out of date. We will therefore simply outline the present and projected near-future uses of electronic teaching equipment.

(a) Passive-Mode Usage. In this category we can include all recorded material, in whatever form, which is available to the student via some form of information retrieval technique. This would include printed, audio, and video material, in conventional and electronic library forms.

(b) Interactive Mode. Here students use a computer teaching terminal interactively to study at their own pace on a one-to-one basis, with the computer acting as tutor. Modern teaching programs sense the students' weak points (as do good teachers) and emphasize them in teaching. The building designer must be aware of the rapid developments in this field at all educational levels, including elementary school, in order to make adequate electric power, cable raceway, lighting, and HVAC provisions.

OFFICE BUILDING SYSTEMS

22.18 General

Under this category we include systems found in all office, professional, and sales-type buildings. Such buildings house tenants with varying schedules and requirements. This must be considered in the design of the signal systems for such buildings.

Fig. 22.13 Watchman's tour station. Here the clock and recording tape are inside. The station is operated by simply inserting a key as shown and giving it a quarter-turn. (Courtesy of Detex Corp.)

Although in many of the medium-sized and large buildings control, alarm, and security functions are combined in multiuse apparatus and consoles, which we will discuss, the basis systems are essentially separate despite shared-use equipment. We discuss them individually to demonstrate function and equipment, and combined to show economies and modern practice.

22.19 Office Building Security Systems

Although automatic surveillance systems *are* applicable to office and mercantile occupancies, they are more frequently found in industrial facilities and are discussed under that heading. Office buildings normally utilize some type of manual watchman's tour system so that surveillance of unoccupied areas is conducted on some regular basis.

The simplest type is nonelectric and comprises a number of small cabinets, each containing a key, placed at intervals around the interior and exterior of the building. The watchman uses these keys to operate a special clock that he carries about, thus recording the exact time at which he "clocked in" at any specific location. Alternatively, the clock is wall mounted and the guard carries only a key (see Fig. 22.13). A computerized version of this system is available which simplifies station check-in, automatically records guard visit data, and provides hard-copy printout.

Guard tour systems are also available that permit constant supervision and are particularly effective where more than one person is on duty. Such systems show on a panel the location and progress of the watchman, by means of lights that glow when the device at each location is operated. Since part of the effectiveness of these systems lies in the timing of the tour, a system can be arranged to sound an alarm if a particular station is not operated within a specific time period. Telephone jacks spaced at points along the guard's route allow him to communicate with the supervising office or other point, without interrupting the scheduled tour. For protection of areas housing extremely valuable items or documents, an intrusion alarm system may be employed.

22.20 Office Building Communications Systems

This planning item is composed of three parts, which are frequently melded into a single network:

1. Intraoffice voice communication, or intercom (see Fig. 22.14).
2. Interoffice and intraoffice data communication using telephone and communication cabling.
3. Outside-the-building communication via phone company lines.
4. Paging function. This item is discussed in Section 22.25 under industrial facilities.

Today, in most locations, the user has the choice of purchasing or leasing as much of the system as he desires. In other words, the communication system including cables, instruments, switching equipment, and so on can either be all privately owned, all supplied by the local telephone company, or almost any division desired. However, except for a small interoffice intercom, duplication is eliminated. That is, the same instruments and switching equipment are used for both intercom and outside connection.

Fig. 22.14 This desktop multifunction intercom unit is usable in either handset or hands-free mode. In addition to standard intercom functions, each handset, which is connected to its central exchange with a four-conductor cable, can be used for such additional facilities as automatic redial, call conferencing, searching, all-call, group call, all transfer, call registration (store incoming call numbers), privacy mode, special meaning tones, and networking possibility. In addition, the unit can be used for voice and "beeper" paging. Exchanges, which can handle up to 4000 stations, are microcomputer-controlled solid-state assemblies which vary in physical size according to the number of stations served. A typical large exchange might measure 60 in. W × 24 in. H × 20 in. D. (Courtesy of Dukane Corp., Communications Systems.)

What to buy, rent, or lease constitutes an economic decision, since the required functions are satisfied by either private or telephone company equipment.

The item of data handling is highly specialized and was discussed in Section 15.18 with respect to the responsibility of the building architect and designers.

22.21 Office Building Communications Planning

Planning for the telephone and other communications equipment in an office building is of prime importance because of the large amounts and critical locations of required space. Therefore it must be done simultaneously with other space planning. Exact requirements for office space are generally unknown at design time and, even if they were known, planning would have to account for changes in space usage as well as increased communications and data transmission services. For this reason, all planning is based on square foot areas. Planning is essentially for spaces only, from incoming service to final instrument, since cabling and equipment are furnished and installed either by a private telephone equipment supplier or by the telephone company.

The planning information that follows is applicable to office buildings with average telephone and data transmission loads. Buildings whose tenants include brokerage houses, insurance companies, headquarters of multibranch operations, and other heavy telephone and data transmission users may need more space. On the other hand, advances in technology, including the use of fiber optic cables, act to reduce equipment size and space requirements. As a result, the best course of action is to design for current requirements, with a reasonable estimate for the future based on advice from experts in the field.

Space is required for:

1. Service entrance including terminal space, cabinet, or room.
2. Riser spaces, shafts, conduits, and cabinets.
3. Apparatus closets for equipment.
4. Satellite locations for interconnections.
5. Equipment rooms for specific-use equipment.
6. Distribution system including conduits, boxes and underfloor duct, and raceway systems.

(a) Service Entrance. Adjacent to the service conduit a spare sleeve placed in the foundation wall and sealed will provide for future ser-

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vice expansion. Inside the building the telephone cable is terminated in a wall box, cabinet, or terminal room depending on the cable size. For buildings up to about 70,000 ft² of rentable area (depending on the type of anticipated tenant use), wall-mounted terminal cabinets are normally sufficient. In any case, the area should be dry, and it requires light, ventilation, one or more 120-V outlets on a separate circuit, and a good ground connection. In special cases more power is required.

Surface-type wall installations comprise simply a sheet of ¾-in. marine plywood on to which the phone company mounts its cabinet. Flush installations in finished areas require a cabinet with ¾-in. plywood back.

(b) Riser Shafts. These can accept the cables extending beyond the terminal room and carry them vertically through the building. Connection between terminal space and risers is preferably in conduit.

The riser shafts provide means for the cables to extend vertically and to terminate at each floor. Ideally, the risers comprise a series of vertically aligned closets connected by 3½- or 4-in. sleeves set in the floors and extending 1 in. above the floor. It is preferable to separate communications closets from electrical power closets. Where multiple risers are used, shafts should be interconnected by several 2-in. conduits to allow for interconnection of systems.

(c) Riser Closets. Here, cables from the riser system are interconnected to switching and power equipment, as well as to the cables that radiate from the closet to station locations throughout the floor. These closets may also be called *zone closets* or *apparatus closets*, particularly if they function with an underfloor raceway system. Walls of the closet should be lined with plywood at least ¾-in. thick to support the weight of switching and connection panels, power equipment, terminals, connecting blocks, and other hardware. Each riser (apparatus) closet must be provided with a switched ceiling light, and a separate 20-A, 120-V circuit with two duplex receptacles. A source of emergency power is desirable to avoid curtailment of telephone service during outages.

(d) Satellite Closets. Unlike riser (apparatus) closets, satellite closets do not contain switching and power equipment. Their primary use is to provide cable-connecting and -terminating facilities in large complex facilities, where riser closet space is insufficient.

(e) Equipment Rooms. Where extensive crossconnection is required or where tenants utilize PBX (private switchboard) equipment, the required equipment is placed in equipment rooms. These spaces, which are actually small closets or alcoves, should contain a 20- to 30-A, 2P, 120/208-V circuit, a 20-A, 120-V outlet, a grounding point, good lighting, and, obviously, sufficient equipment space. Space requirements vary with each installation and are obtainable from the equipment supplier. Ventilation is essential, as is absorptive acoustic material on the ceiling and at least one wall. Connections between these spaces and other communication equipment closets should be via floor or ceiling ducts or multiple 3½-in. conduits.

(f) Horizontal Distribution. Cabling from riser, satellite, apparatus, and equipment closets to individual outlets and instruments can be underfloor (Sections 15.24 to 15.28), in ceilings and plenum spaces (Section 15.30), under carpet (Section 15.29), or in surface raceways (Section 15.23). Because of the large raceway volumes required, conduit is infrequently used. When using underfloor raceways a header capacity of 2 in.² per workstation is reasonable, based on one multiline telephone and one video display unit per station.

(g) Fiber Optic Cables. In installations with very heavy data transmission loads, in those using video systems, and/or in applications for which the high-security, low-noise, and broad-bandwidth characteristics of optic fiber cables are desirable, they are used in lieu of copper cabling. Space requirements and connection accessories are obtainable from manufacturers. Since cables are often supplied with factory-applied terminations, raceways must be of the large capacity full access type.

22.22 Office Building Supervisory Control Center

As the modern office building's mechanical and electrical systems increased in complexity, the need arose for a central point of supervision, control, and data collection from which to survey and control an entire building's functioning. From such a point the water, air conditioning, heating, ventilating, electrical, and other systems could be controlled manually and automatically with much greater accuracy than if no such central control point were available. Data on temperatures, pressures, flow, current, voltage, and all of the many parameters of mechanical systems could be made instantly available, so that operational decisions could be made more accurately. Also, all systems could be monitored here, and all alarms instantly acted upon, automatically or manually.

Such control centers, generally called *supervisory control and data centers*, are now installed as a matter of course in office buildings. They are equipped with microprocessors or computers that process the huge amount of data received to arrive at operational decisions intended to optimize system performance. As such, they result in a considerable savings in operating costs, in addition to the work force savings generated by their remote monitoring and control functions. These units normally perform these functions:

1. Remote monitoring, recording, logging.
2. Remote start–stop.
3. Remote controls, resets, changes.
4. Alarm functions.

The system for which the supervisory control center is the control, calculation, data logging, and building systems connection point is called a *building automation system* (BAS). The format and functioning of a generalized version of a BAS is discussed in Appendix J, to which the reader is referred.

Architecturally, the BAS supervisory control center requires good lighting and ventilation, extensive raceway space, but little area. Because systems are tailored to the building, no guidelines can be stated for space requirements.

INDUSTRIAL BUILDING SYSTEMS

22.23 General

All industrial facilities ranging from the taxpayer loft, housing a small hand assembly plant, to the immense steel manufacturing plant, require a variety of signal and alarm equipment. Although, as in the case of commercial structures, a detailed analysis of the equipment is out of place here, it behooves the building designer to know generally the function, operation, and availability of this type of equipment.

Fire alarm systems for industrial buildings are discussed in Section 13.21. Audible alarms in industrial facilities for any of the building security systems must be selected with the usually high ambient noise level in mind. See Figs. 22.15 and 22.16 for recommendations.

22.24 Industrial Building Security Systems

Among the most important signal functions in this type of facility is protection. Although they may use a common control console, these systems are varied and perform separate functions.

(a) Door and Exit Controls. Outside doors and doors to restricted areas are supervised by electrified security hardware that triggers an alarm when a door is opened without authorization. The alarm mechanism may be concealed, or openly displayed, to act as a deterrent (see Fig. 22.9). Annunciation can be provided by a separate panel or tied into a central alarm panel.

(b) Personnel Entry Control. Several levels of security are available and can be applied in accordance with security needs. Beyond a simple lock, the first level at an unmanned portal is a card reader that grants entry to the card holder. The breaches at this level, however, are numerous. With the assistance of the card holder, more than one person can enter during a single portal opening (tailgating), or the card can be transferred to an outsider after the authorized person enters (passback). Finally, cards can be

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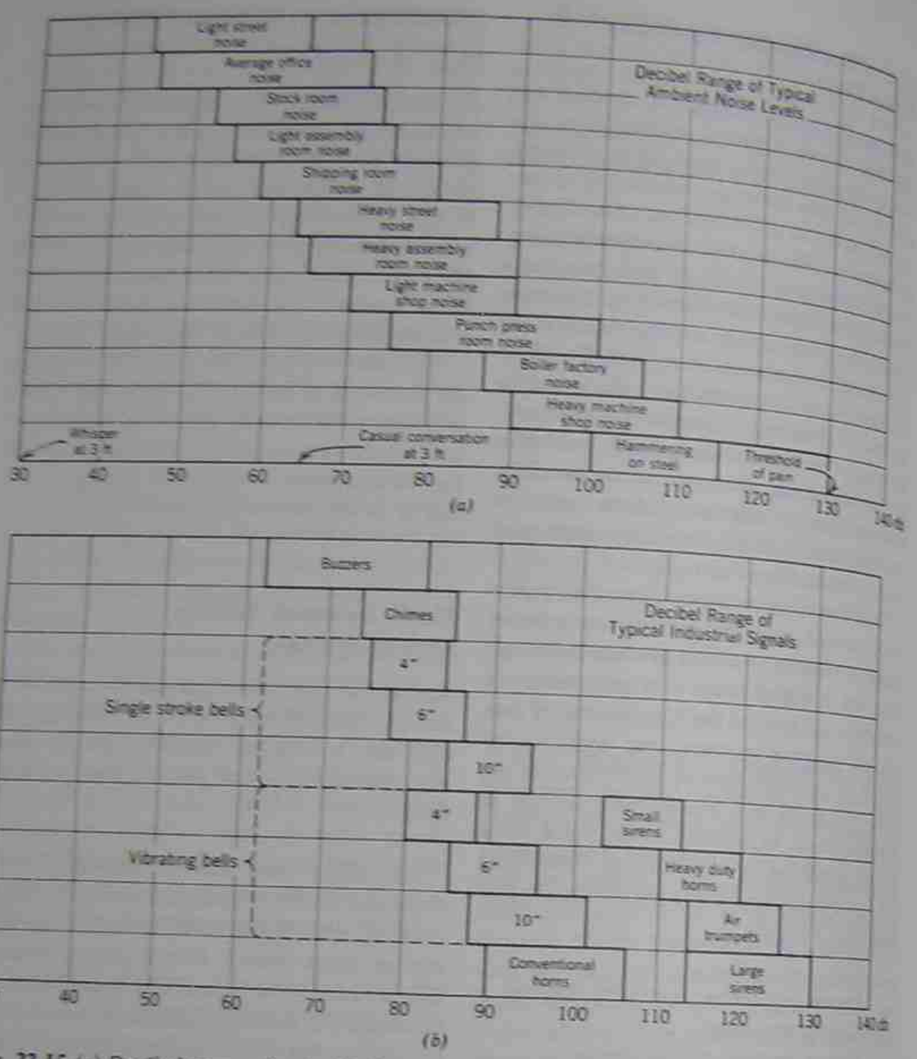

Fig. 22.15 (a) *Decibel range of typical industrial noise levels.* (b) *Decibel rating of typical industrial signals may be compared with ambient noise levels* (a) *to facilitate selection.*

found, forged, or stolen. The next level requires the encoding of a number simultaneously with presentation of a card, thus barring entry to holders of found or stolen cards. Beyond this level there are many techniques, including use of a computer to track card location so that a card already inside the building cannot be re-used without exiting, thus eliminating passback. Also, portals can be arranged so that tailgating is extremely difficult.

When entry security levels are high, personal identification techniques that cannot be forged are usable. Among them are voice prints, hand geometry, and retinal scans (see Fig. 22.17). Finally, an access control procedure involving a control card, visual identification, and visual tracking of the entry procedure through a controlled, physically limiting access portal can be used where a high risk of unauthorized entry justifies it (see Fig. 22.18).

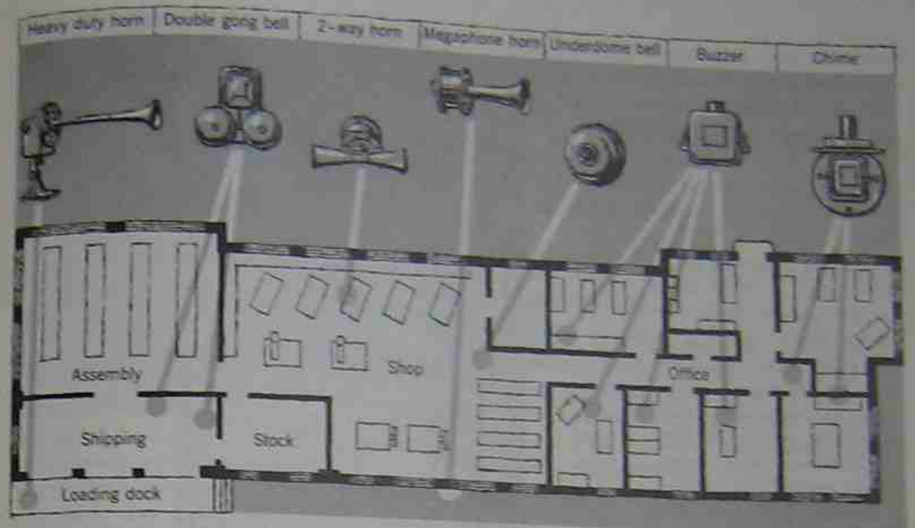

Fig. 22.16 *Plan of a small industrial facility, showing suggested locations of typical signals.*

Fig. 22.17 *This foolproof identification procedure relies on the fact that no two persons have identical retinal eye patterns. The illustrated device, usually placed at an unmanned controlled access portal, scans the entrant's retina, compares it to the previously recorded pattern, and then either permits or denies entry. (Photo courtesy of Eyedentify Inc.)*

(c) Watchman's Tour Equipment. When tour equipment is used, it is frequently of the combination-alarm type. This type of station allows guards to call in, alerts them to waiting calls, permits a general alarm to be turned in by key operation, and is usable as a manual fire alarm station. The station may be coded or non-coded as desired. The tour is normally timed so that any delay automatically sends an alarm and summons help.

(d) Intrusion Security Systems. A combination of the systems described in Section 22.2 is normally employed. Perimeter systems are normally arranged to sound an audible alarm and to energize all security lighting.

All the alarms above, plus others not discussed, can be connected to a central monitoring console. If the console is unattended, it is normally auxiliarized, so as to alert security personnel. Usually, however, the alarm signal is transmitted to a central security station—normally a constantly attended guard post. In all cases, a permanent printed record of every alarm should be made. See Appendix J for a diagram of centralized security control in a multibuilding facility.

Fig. 22.18 A person desiring entry at this high-security portal inserts her identification card and is viewed by a camera in the entrance device. At a remote location, images of the subject and her ID card are displayed on a screen (inset), while ID data from a memory bank are displayed simultaneously for comparison. Actual physical entry through the turnstile is controlled electrically and monitored by an overhead camera. (Photos courtesy of Visual Methods, Inc.)

22.25 Industrial Building Paging Systems

All the time saving and efficiency potential that results from the proper use of the various signal and communication equipment available can be lost if there is no recipient for the information transmitted. Furthermore, sometimes a decision must be reached quickly to avoid costly delay, reruns, and so on. These factors combine to make rapid and accurate paging an extremely important function in a manufacturing operation, particularly of the larger variety.

Paging systems fall into two general categories and several subcategories: they are either visual, audible, or both, and are either common or selective. The simplest visual and audiovisual types comprise flashing lights, which may be combined with buzzers or bells, either or both of which are generally coded. Such systems are nonselective in that they impinge on the senses of all the building occupants—an obvious disadvantage. Furthermore, they must override ambient noise levels, which may be high (see Figs. 22.15 and 22.16).

More sophisticated systems utilize a small pocket device that is carried by each person likely to be paged—maintenance personnel, plant engineers, executives, and so on. By means of either direct radio transmission or of electric fields induced by induction loops installed throughout the building, an individual pocket device can be alerted by a beep. In some systems, the alerted person then listens to the message directly. On others, it is necessary for a person, once having been paged, to go to a phone and call in to a central paging desk to receive the message. Others utilize small hand-held, two-way radio transmitters with paging, to enable conversation between the page originator and the recipient.

In older paging systems it was usual to have a dedicated paging console and in some cases even a separate paging operator. Modern systems generally incorporate the paging function into one of the facility's systems: telephone, intercom (see Fig. 22.14), or sound and music. Paging calls can originate at the paging control

Fig. 22.19 Voice paging equipment, designed to interconnect with a telephone system so that paging calls can be placed at any phone and distributed over the facility's loudspeaker system. Modular electronic construction permits addition of special paging features such as zone paging, talk-back via speakers (two-way communication), priority access, all call, and others. The illustrated wall-mounting cabinet, which measures approximately 24 in. W × 24 in. H and weighs 66 lb, contains all of the electronic equipment required, including an audio power amplifier. (Courtesy of Dukane Corp., Communications Systems.)

console, at an intercom station, or at an internal or external phone and can be placed by anyone entering the appropriate access code (see Fig. 22.19). Voice paging via speakers requires audio equipment only; paging via pocket pagers or belt-beepers requires radio frequency transmitters and antenna systems as well.

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SIGNAL EQUIPMENT

PART VIII
TRANSPORTATION

No facilities in a multistory structure are taken for granted more consistently than elevators and escalators, which are relied on to move people quickly and safely under all conditions, including emergencies. This movement should be quiet, trouble free, and economical. Furthermore, since vertical transportation accounts for 10 to 15% of a construction budget, somewhat less of the building area, and somewhat more of the operating cost, and is a determining factor in building shape, core layout, and lobby design, we see that elevator and escalator selection is a major task for the architectural designer.

Chapter 23, Passenger Elevators, introduces the subject with a description of the components of such facilities, including traction equipment, cars, safety devices, and systems of control and supervision. Special topics such as codes and standards, and requirements for the handicapped are also covered. The discussion then turns to actual selection of units. Criteria are established for elevator performance, including interval, waiting time, handling capacity, average trip time, and round-trip time. Extensive car performance data (curves) are presented, which can be used with the other criteria to select the size, number, and speed of elevators to fulfill the requirements. The discussion continues with principles of elevator zoning. The chapter concludes with an analysis of spatial requirements for elevators, including shafts, lobbies, and core arrangement. Throughout, application of principles and data is demonstrated through the use of examples.

Chapter 24, Special Topics, addresses important passenger elevator considerations other than elevator selection. These include power and energy requirements, with emphasis on energy conservation, fire-emergency operation, emergency power requirements, and passenger security. The next part of the chapter is devoted to special cases: freight elevators, hydraulic elevators, nonvertical designs, residential elevators, and chair lifts, with discussion of equipment, capacities, selection, and economy, and comparison (where applicable) to conventional design. The chapter concludes with a section on material-handling devices: dumbwaiters, horizontal and vertical conveyors, pneumatic systems, container delivery systems, and automated self-propelled vehicles. This section answers the need to plan for material handling in commercial and institutional buildings rather than treating the subject as an afterthought, with resultant inefficiency, overloading of freight facilities, and misappropriation of passenger elevators.

Chapter 25, Moving Stairways and Walks, treats these subjects with a discussion similar to the coverage of passenger elevators. Descriptions of equipment components, capacities, sizes, speeds, and methods of selection are followed by special topics including lighting, fire protection, power and energy requirements, and budget estimating. Information on inclined walks (ramps) is also presented, as is a section on shuttle-type people movers, which also affect building design.

23

VERTICAL TRANSPORTATION: PASSENGER ELEVATORS

GENERAL INFORMATION

23.1 Introduction

Among the many decisions that must be reached by the designer of a multistory building, probably none is more important than the selection of the vertical transportation equipment, that is, the passenger, service, and freight elevators and the escalators. Not only do these items represent a major building expense, being in the case of a 25-story office building as much as 10% of the construction cost, but also the quality of elevator service is an important factor in a tenant's choice of space in competing buildings.

Although the final decision as to the type of equipment rests with the architect, the factors affecting it are so numerous that it behooves the building designer to consult with an elevator expert. Such consultation service is readily available from consultants in the field and to an extent from the major elevator and escalator manufacturers. It is the function of this chapter to familiarize the architect and engineer with the nature and application of vertical transportation equipment, to enable them to make preliminary design decisions before turning to the consultants.

23.2 Passenger Elevators

Our discussion is principally concerned with the general-purpose traction elevator. Hydraulic elevators are covered in Section 24.10.

Ideal performance of an elevator installation provides minimum waiting time for a car at any floor level, comfortable acceleration, rapid transportation, smooth and rapid retardation, accurate automatic leveling at landings, and rapid loading and unloading at all stops. Furthermore, the system must provide quick and quiet power operation of doors, good visual floor and travel direction indication both in the cars and at landings, easily operated car and landing call buttons (or other devices), smooth, quiet, and safe operation of all mechanical equipment for all conditions of loading, comfortable lighting, reliable emergency and security equipment, and generally pleasant car atmosphere.

In addition to the passenger-oriented service considerations above, the elevators have architectural aspects as well. The cars and shaftway doors must be treated in a manner consonant with the architectural unity of the building. More important, though, the shaftways are major space elements whose integration into the building is a prime factor in composition.

23.3 Codes and Standards

Perhaps more than any other item of construction, elevators are governed by strict installation codes. The "bible" of the industry is the American National Standards Institute (ANSI/ASME) code A 17.1, *Safety Code for Elevators, Dumbwaiters, Escalators and Moving Walks*, an up-to-date copy of which should be an integral part of every architect's and engineer's working library. This code has legal force in most parts of the United States. In addition, Standards 17.3 and 17.4 cover existing elevators and escalators, and emergency evacuation of elevators, respectively. As with other items, some states and municipalities have their own elevator codes (Massachusetts, Wisconsin, Pennsylvania, New York City, Seattle, Boston, among others) that are generally based on, and more stringent than, the ANSI code.

In addition to the elevator code, other construction and installation codes have an influence on elevator work. Thus NFPA No. 101, *Life Safety Code*, states certain fire safety requirements, NFPA No. 70 (the National Electric Code) governs some of the electrical aspects of elevator construction, and state and local laws add a multitude of requirements and restrictions bearing on fire safety, emergency power, security regulations, and special accommodations for handicapped persons. Provisions for the handicapped are covered by ANSI A 117.1 (Barrier-free), a special industry code, and in most locations by local law. As with most large industries, the elevator industry is self-regulating and standardized. The National Elevator Industry, Inc. publishes standard elevator layouts for traction and hydraulic installations, as well as its own elevator standard for the handicapped, "Suggested Minimum Passenger Requirements for the Handicapped" (NEII, 185 Bridge Plaza North, Ft. Lee, NJ 07024). Elevator consultants and elevator companies are normally knowledgeable as to all the codes and standards in force, but this does not relieve the architect-engineer of legal responsibility for the installation. Therefore, we strongly recommend that in the preliminary planning stage all pertinent regulations concerning vertical transportation be acquired and studied.

ELEVATOR EQUIPMENT

23.4 Arrangement of Principal Parts

The car, cables, elevator machine, control equipment, counterweights, hoistway, rails, penthouse, and pit make up the principal parts in any traction elevator installation. An idea of the functioning and orientation of these units of equipment can be obtained from an inspection of Fig. 23.1. Specific installations will vary somewhat; in newer systems microprocessor logic modules are frequently used in lieu of the older electromechanical, relay-operated control panels, and solid-state equipment may be used in lieu of a motor-generator (m-g) set. On the whole, however, the basic functional components remain the same for all installations.

The cars, with their equipment for safety, convenience, comfort, and finish, are the only items with which the average passenger is familiar. Indeed, some of the building's prestige depends on proper design of the car. Essentially, the cab is a cage of some fire-resistant material supported on a structural frame, to the top member of which the lifting cables are fastened. By means of guide shoes on the side members, the car is guided in its vertical travel in the shaft. The car is provided with safety doors, operating-control equipment, floor-level indicators, illumination, emergency exits, and ventilation. It is designed for long life, quiet operation, and low maintenance.

The cables (ropes) that are connected to the cross-head (top beam of the elevator) and carry the weight of the car and its live load are made of groups of traction steel wires especially designed for this application. Four to eight cables, depending on car speed and capacity, are placed in parallel. Although multiple ropes are used primarily to increase traction area on the sheaves, they also increase the elevator safety factor, since each rope is normally capable of supporting the entire load. The minimum factor of safety varies from 7.6 to 12 for passenger elevators and 6.6 to 11 for freight elevators. The cables from the top of the car pass over a motor-driven cylindrical sheave at the traction machine (grooved for the cables) and then downward to the counterweight.

The counterweight is made up of cut steel plates stacked in a frame that is attached to the opposite ends of the cables to which the car is fastened. It is guided in its travel up and down the shaft by two guide rails typically installed on the back wall of the shaft. (Obviously the counterweight travels in the reverse direction to the car.) See Fig. 23.1.

The weight of the counterweight is equal to the weight of the empty car plus 40% of the live load. It has several purposes: to provide adequate traction at the sheave for car lifting, to reduce the size of the traction machine, and to reduce power demand and energy cost. Approximately 75% of the energy expended in lifting a load is returned to the system by regeneration when the load is lowered. (Regeneration is the process in which the traction motor becomes a

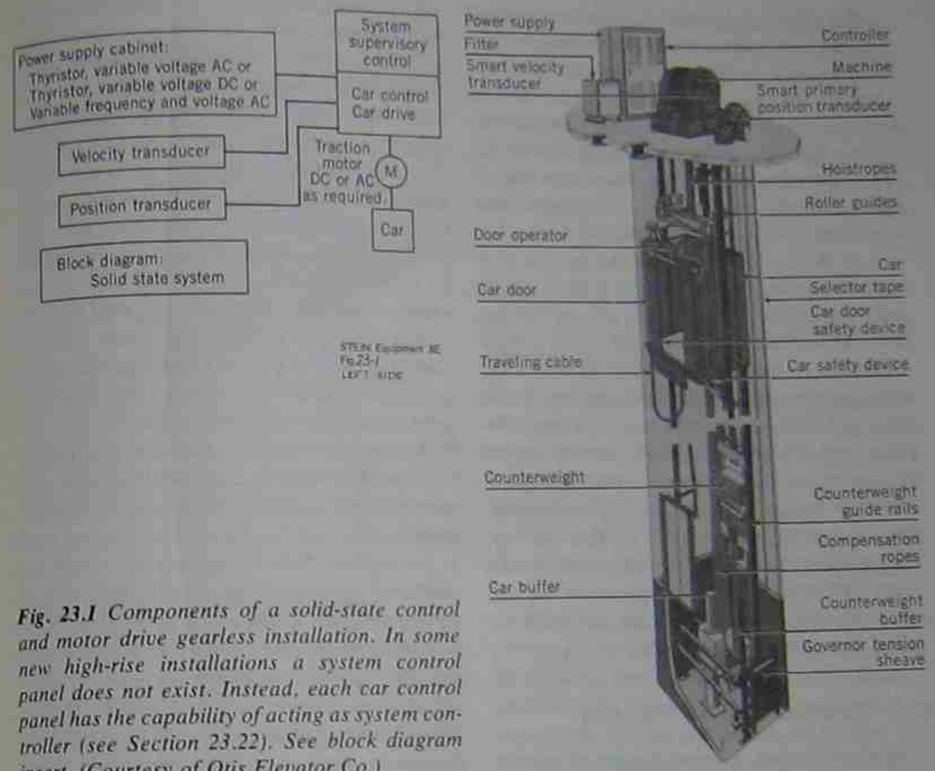

Fig. 23.1 Components of a solid-state control and motor drive gearless installation. In some new high-rise installations a system control panel does not exist. Instead, each car control panel has the capability of acting as system controller (see Section 23.22). See block diagram insert. (Courtesy of Otis Elevator Co.)

generator when the car is lowered, and pumps power back into the electrical system.) The "lost" energy appears as heat, primarily in the machine room. See Section 24.2 for a discussion of system energy requirements.

To compensate for hoist rope weight, which in high-rise elevators becomes an important factor, cables are attached to the bottom of the car and the counterweight, thus equalizing loads regardless of the cab position. These cables can be seen in Fig. 23.1.

The elevator machine turns the sheave and lifts or lowers the car. It consists of a heavy structural frame on which are mounted the sheave and driving motor, the gears (if any), the brakes, the magnetic safety brake, and certain other auxiliaries. In most existing installations the elevator-driving (traction) motor receives its energy from a separate m-g set, which is in operation during the period that the particular elevator is available for handling traffic. This m-g set is properly considered a part of the elevator machine, although it may be located some distance from it. In new installations, solid-state power and control equipment replaces the m-g set, as discussed in Section 23.17. The governor that limits the car to safe speeds is mounted on or near the elevator machine.

The control equipment is usually divided into three groups:

1. *Drive control* is concerned with the velocity, acceleration, position determination, and leveling of the car.
2. *Operating control* covers the area of car door operation and functioning of car signals, including floor call buttons and all indicating devices.
3. *Supervisory control* is concerned with group operation of multiple-car installations.

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The actual physical devices in these control systems were electromechanical in the past but are principally solid state in new installations. The indicating and control devices that are seen and used by the elevator user, including car and hallway buttons, lanterns, and audible devices, are all coordinated into the overall operational control scheme, which produces rapid, safe, and comfortable vertical transportation.

The shaft, or hoistway, is the vertical passageway for the car and counterweights. On its sidewalls are the car guide rails and certain mechanical and electrical auxiliaries of the control apparatus. At the bottom of the shaft are the car and counterweight buffers. At the top is the structural platform on which the elevator machine rests. The elevator machine room (which may be on one or two levels) is usually directly above the hoistway. It contains the traction motor, the m-g set or solid-state control that supplies energy to the elevator machine, the control board, and other control equipment. All machinery and control equipment are designed for quiet, vibration-free operation.

23.5 Gearless Traction Machines

A gearless traction machine consists of a d-c or a-c motor, the shaft of which is directly connected to the brake wheel and driving sheave. The elevator hoist ropes are placed around this sheave. The absence of gears means that the motor must run at the same relatively low speed as the driving sheave. Since it is not economically practical to build motors for operation at very low speeds, this type of machine is utilized for medium- and high-speed elevators, that is, 500 fpm and above. The motors range from 20 to 375 hp. Gearless machines are generally utilized for passenger service, with usual car capacities of 2000 to 4000 lb, although specials of up to 10,000 lb, such as at the World Trade Center, have been built. Below 500 fpm, geared machines are used. In the range of 500 to 700 fpm, a 2 : 1 roping arrangement (see Section 23.7) is generally used. This reduces motor size and increases sheave speed, thus reducing the cost. Above 800 fpm, motor speed is high enough for 1 : 1 roping to be applied economically. At this writing maximum car speeds are 1600 fpm, although 2000-fpm systems and faster have already been developed and will undoubtedly be an important factor in the development of ever taller, practical, workable buildings.

The gearless traction machine is generally considered superior to the geared machine. It is more efficient, quieter in operation, requires less maintenance, and has longer life. The decision as to whether these advantages are worth the additional cost involved is made only after a careful analysis. Generally, a gearless machine is chosen where rise is more than 250 ft and smooth, high-speed operation is desired. In the intermediate range of rise and speeds, that is, 150 to 250 ft height and 400 to 500 fpm, excellent equipment, both geared and gearless, is available. The choice depends on performance characteristics and cost.

Because virtually every major elevator company operates internationally, and because outside the United States, elevator size and speed are specified in kilograms and meters per second, it is useful to have approximate conversion factors in mind. Since 1 kg is 2.2 lb and 1 m/s is 196.86 fpm, the factors of 2 and 200 will give approximate American equivalents. Thus:

Weight		Speed	
Standard Metric (kg)	Approximate U.S. (lb)	Standard Metric (m/s)	Approximate U.S. (fpm)
1000	200	1	200
1250	2500–3000	1.5	300
1600	3500	2	400
2000	4000	2.5	500
		4	800
		6	1200

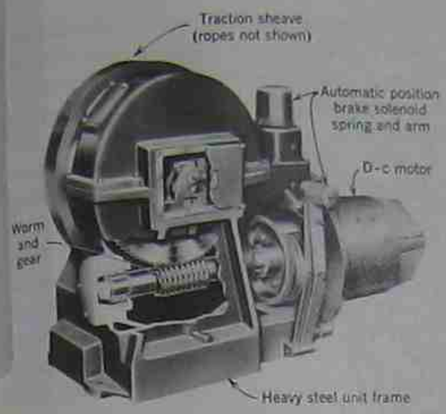

Fig. 23.2 Cutaway of a typical d-c geared traction machine. Note the grooves for multiple ropes in the traction sheave. (Photo courtesy of Schindler Elevator Corp.)

23.6 Geared Traction Machines

The geared traction machine (Fig. 23.2) employs a worm and gear interposed between the driving motor and the hoisting sheave. The driving motor can therefore be a smaller, cheaper high-speed unit rather than the large low-speed unit that a gearless installation would require.

The motor used in a geared installation, as in gearless, depends on the type of drive system, and may be either d-c or a-c. The characteristics of the various drive systems and their applicability is discussed in detail in Sections 23.12 to 23.17. Geared machines are used for car speeds up to 450 fpm and a maximum rise of about 300 ft. With an appropriate drive and control system a geared traction machine can give the same high-quality, accurate, smooth ride as is available from a gearless installation.

23.7 Arrangement of Elevator Machines, Sheaves, and Ropes

The simplest method of arranging vertical travel of a car is to pass a rope over a sheave and counterbalance the weight of the car by a counterweight. Then, by rotating the sheave, the car will move up or down and require very little energy to do it. This is essentially the scheme that is used on a majority of high-speed passenger elevators, as illustrated in Fig. 23.3*a*.

When the four or more supporting ropes merely pass over the sheave *T* and connect directly to the counterweights, the lifting power is exerted by the sheave through the traction of the ropes in the parallel grooves on the sheave. This system is referred to as the single-wrap traction elevator machine. The function of sheave *S* is merely that of a guide pulley; it is called the deflector sheave.

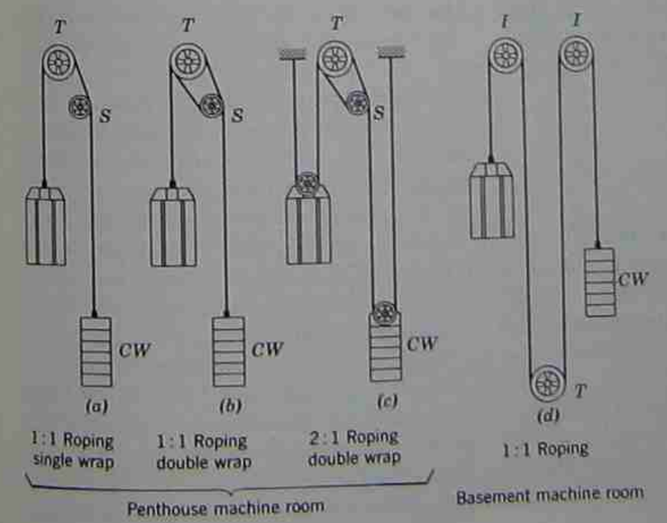

Fig. 23.3 Elevator roping and sheave arrangement. T, traction sheave; S, secondary sheave; I, idler sheave; CW, counterweight.

In Fig. 23.3*b* the ropes from the car are first wrapped over the traction sheave *T*, then around the secondary or idler sheave *S*, once more around sheave *T*, and back over *S* to the counterweights. This arrangement is characteristic of the one-to-one, double-wrap traction machine. It provides greater traction than the single-wrap machine and is used in many automatic high-speed installations.

A 1 : 1 roping arrangement (Fig. 23.3*a*, *b*, and *d*) gives no mechanical advantage; that is, the drive must supply sufficient power to move the unbalanced load. The 2 : 1 roping (Fig. 23.3*c*) has a mechanical advantage of 2, which results in a high-speed, low-power, and, therefore, low-cost traction machine. This arrangement is used for a wide variety of installations varying from medium-speed (500–700 fpm) gearless passenger elevators to low-speed, heavy-duty freight units.

In types *a*, *b*, and *c* in Fig. 23.3, the elevator machines are located at the top of the hoistway. When the elevator machines are placed in the basement, a very different arrangement of cables and sheaves must be utilized to secure the same results (see Fig. 23.3*d*). Much more rope is required in such an arrangement, and consequently the problems of rope maintenance are increased. These systems, however, obviate the necessity for a tall penthouse; and where this is desirable for architectural or other reasons, a basement machine is used. This arrangement uses geared traction equipment, with speeds up to 400 fpm. All the illustrated ropings are applicable to the full range of car capacities up to 4000 lb.

23.8 Safety Devices

The main brake of an elevator is mounted directly on the shaft of the elevator machine (see Fig. 23.2). The elevator is first slowed by dynamic braking of the motor, and the brake then operates to clamp the brake drum, thus holding the car still at the floor.

A dual safety system, designed to stop an elevator car automatically before the car's speed becomes excessive, is normally used. The device that acts first is a centrifugal governor, which is independent of the other elevator machinery, and at normal speeds has no effect on the operation of the elevator. In the event of a limited overspeed, the governor will cut off the power to the d-c motor and set the brake. This usually stops the car, but should the speed still increase, the governor actuates the two safety rail clamps, which are mounted at the bottom of the car, one on each side. These devices clamp the guide rails by wedging action, bringing the car to a smooth stop (see Fig. 23.4). Solid-state controllers can be arranged with sensing devices (transducers) which detect car overspeed, thereby eliminating the need for a mechanical governor or tachometer. The action on power control and brake activation is essentially the same.

Oil or spring buffers are usually placed in the elevator pit. Their purpose is not to stop a falling car but to bring it to a partially cushioned stop if it should overtravel the lower terminal. Electrical final-limit switches are located a few feet below and above the safe travel limits of the elevator car. If the car overtravels (down or up), these switches de-energize the traction motor and set the main brake. Safety arrangements under emergency condition of fire or power failure are discussed in Section 24.4.

23.9 Elevator Doors

The choice of car and hoistway door affects the speed and quality of elevator service considerably. Doors for passenger elevators are power operated and are synchronized with the leveling controls so that the doors are fully opened by the time a cab comes to a complete stop at the landing. The closing time, however, varies with the type of door and size of opening. For safety reasons, the kinetic energy of an automatic door is limited to 7 ft-lb, and its closing pressure to 30 lb. To provide fastest closing within this energy limitation, a center-opening door is used. Also, to reduce passenger transfer time and avoid discomfort, a clear opening of 3 ft, 6 in. (106.7 cm) is used in most commercial installations, which permits simultaneous loading and unloading without undue passenger contact. [Some consultants feel that simultaneous passenger transfer is practical only with a 48-in. clear opening; see Strakosch (1983).] See Fig. 23.5. When an opening narrower than 36 in. is used, loading will be delayed until unloading is complete; therefore, speed and quality of service will be markedly reduced. Such small doors are applied only in residential or small, light-traffic buildings. The available types are shown in Fig. 23.6.

A two-speed door design is used where space conditions dictate or where a wide opening is required. The two-speed nomenclature reflects the fact that the two halves of the door must travel at different speeds to complete their travel simultaneously (see Fig. 23.6*c*).

Installations can be equipped with an electronic sensing device that detects passengers in a wide area on the landing in front of the car door, rather than only directly in the door path. Such detection, often accompanied by an audible signal, causes the car door to remain open for a predetermined length of time, or a closing door to reverse. These devices are particularly useful in installations where passengers cannot approach the entrance or cannot enter the car quickly, for example, riders with baggage or holding children, people in wheelchairs, and employees moving bulky objects such as beds or carts in hospitals or wheeled objects in office and industrial facilities.

All automatic elevators, whether equipped with detection beams or not, are required by ANSI to have a safety edge device on the car doors that will cause the car and hoistway doors, which operate in synchronism, to reopen when the safety edge meets any obstruction.

23.10 Cabs and Signals

Possibly the only area in which the architect has a free hand in selection of equipment is in the decor of the cabs and the styling of hallway and cab signals. A normal elevator specification is a functional one that describes the intended oper-

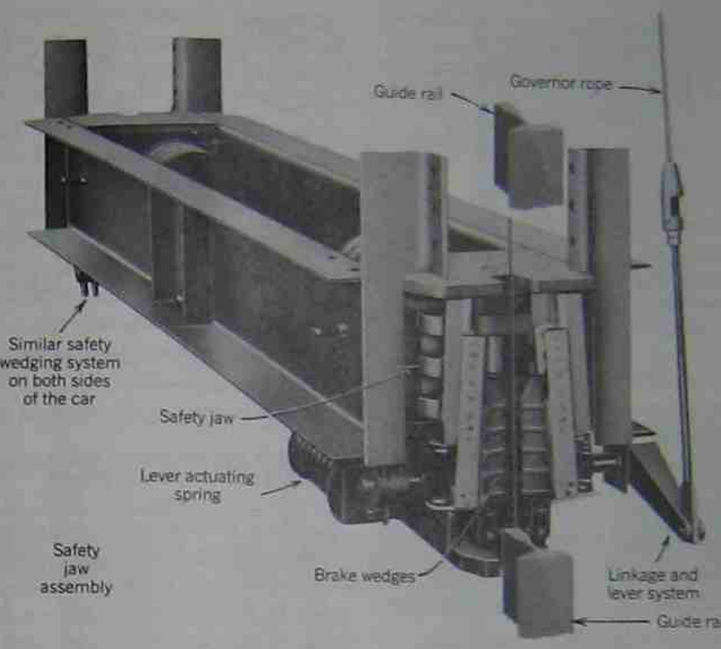

Fig. 23.4 Elevator safety devices. The governor trips, clamping the governor rope and releasing the safety jaws, which exert a constant retarding force on the car rails, thus bringing the car to a gradual and safe stop. (Photo courtesy of Schindler Elevator Corp.)

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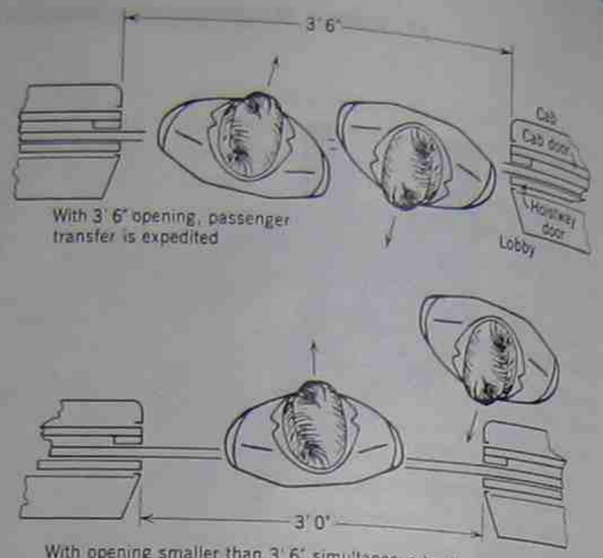

Fig. 23.5 *Transfer of passengers with door openings of different widths. With openings smaller than 3 ft 6 in. (42 in.), simultaneous loading and unloading is difficult and transfer time is lengthened. With a 42-in. opening, large people or people with bulky outerwear may brush against each other in passing. For complete isolation of passengers, a 48-in. opening may be necessary.*

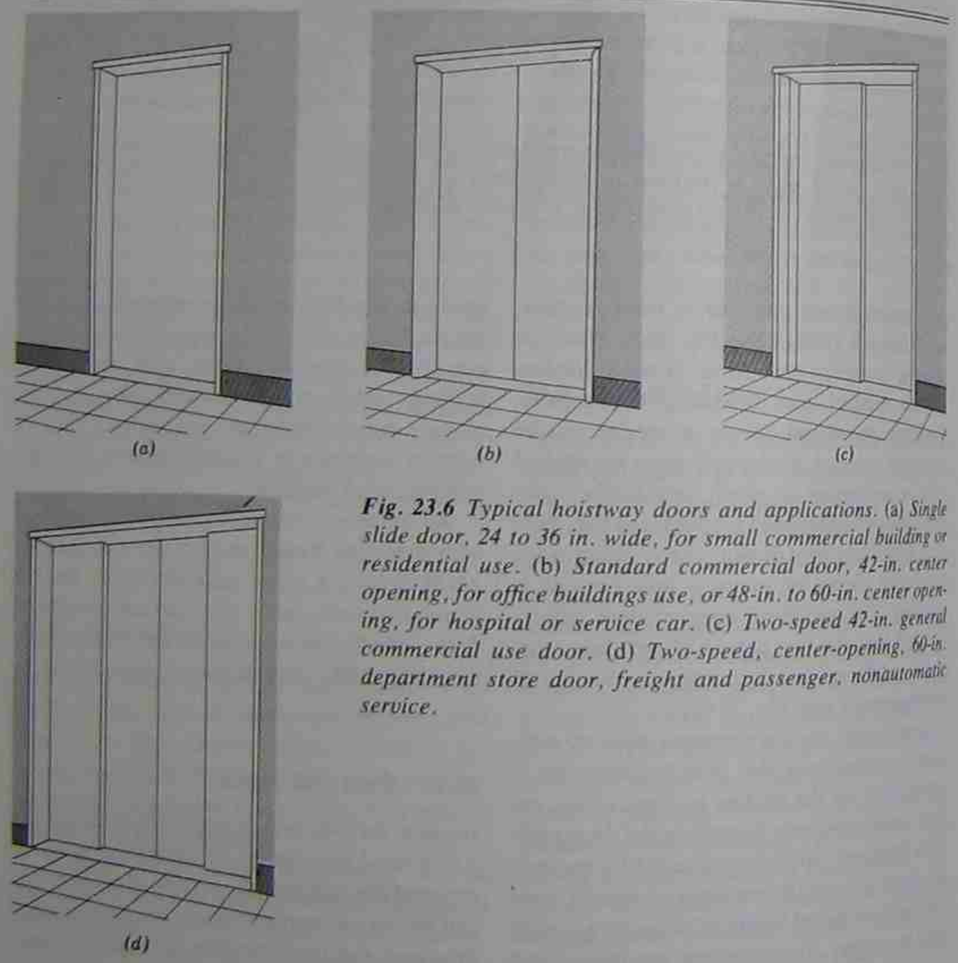

Fig. 23.6 *Typical hoistway doors and applications.* (a) *Single slide door, 24 to 36 in. wide, for small commercial building or residential use.* (b) *Standard commercial door, 42-in. center opening, for office buildings use, or 48-in. to 60-in. center opening, for hospital or service car.* (c) *Two-speed 42-in. general commercial use door.* (d) *Two-speed, center-opening, 60-in. department store door, freight and passenger, nonautomatic service.*

ation of the equipment and normally includes an amount to cover optional decor of the cabs. The type and functioning of signal equipment is also specified, but finish and styling are optional. Cab interiors may be finished in wood paneling, plastic (Micarta or Formica), stainless steel, or almost any material desired. Floors may be tile, wood, or carpeting as selected. Illumination may be from ceiling fixtures, coves, or completely illuminated luminous ceiling, of standard or special design. For each bank of elevators, it is wise to furnish at least one set of wall mats, to protect wall finishes when cars are being used to move tenant furniture. This is especially important where no separate service car has been provided.

Car and hallway signals and lanterns should be designed to fulfill their basic functions, take proper consideration of the needs of the handicapped, and be consonant with the decor of the cabs and the corridors. (For a discussion of cab control panel, see Section 23.26.) The hall buttons should indicate desired direction of travel and by visual means confirm that a call has been placed. The hall lantern located at each car entrance must visually indicate the direction of travel of an arriving elevator and preferably its present location. An audible signal should signal its imminent arrival. The latter feature allows waiting passengers to move to the next arriving car in a bank and thereby speeds service. Hall stations can be equipped with special switches for fire, priority, and limited access service, as required (see Fig. 23.7).

Within the cab, indication of travel direction and present location can be accomplished either with separate fixtures or by indicators built into the car panel. Several manufacturers now market voice synthesizers built into the car panel that announce the floor, direction of travel, and any other desired message such as safety or emergency messages.

23.11 Requirements for the Handicapped

Although the recommendations of the NEII special standard "Suggested Minimum Passenger Elevator Requirements for the Handicapped" are not mandatory except where local building

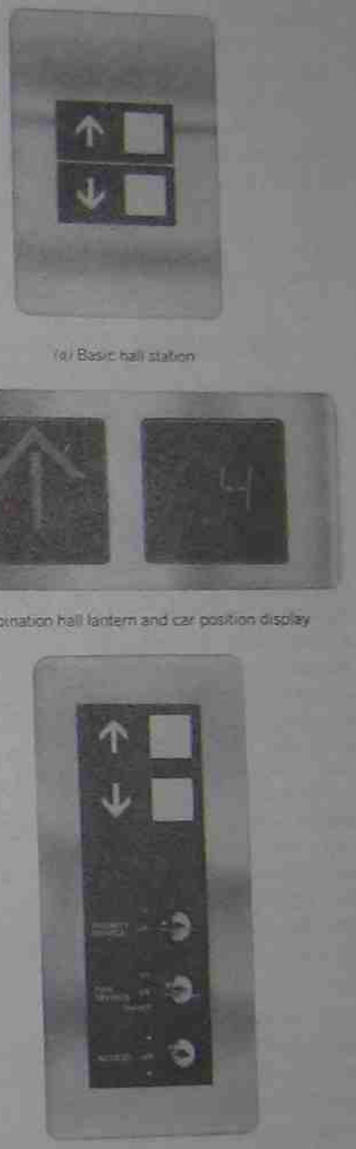

Fig. 23.7 *Typical hall fixtures. Buttons* (a) *must show direction and have visual indication. Lantern* (b) *must show travel direction, audibly announce imminent car arrival, and preferably also show present car location. Special hall stations* (c) *may incorporate priority, emergency, and security features. (Photos courtesy of Otis Elevator Co.)*

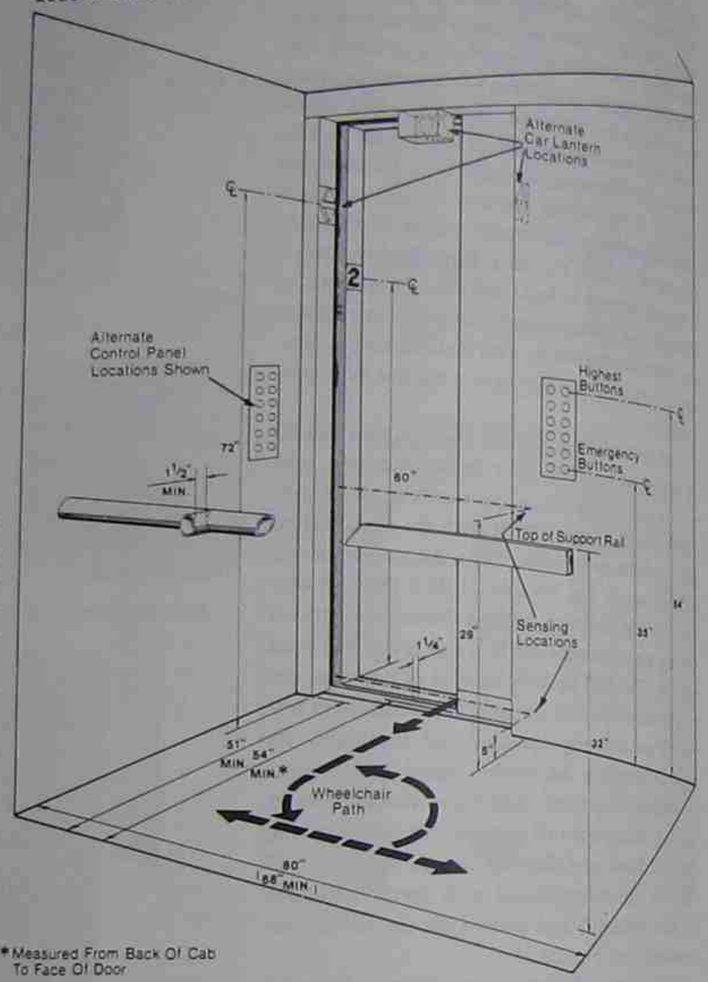

Fig. 23.8 Composite sketch embodying NEII recommendations for 2000- and 2500-lb elevator car sizes, arrangements, and appointments to accommodate the handicapped. (Reproduced with permission of National Elevator Industry, Inc., 185 Bridge Plaza North, Fort Lee, NJ 07024. Copyrighted July 1985, Elevator Requirements for the Handicapped, 4th ed.)

codes make them so, it is certainly advisable to adopt them in consonance with the modern concept of barrier-free buildings.

The basic physical limitations addressed are those of ambulation and sight. Thus to ease access for passengers in wheelchairs (or with walking aids), the standard requires excellent car leveling, 42-in. minimum clear door opening, delayed door closing, detection beams that will reopen the door *without contact* on sensing a passenger, inside car dimensions that will permit turning a wheelchair, buttons and emergency controls within easy reach, and appropriate car furnishings. For those with sight impairment, the NEII standard calls for audible signals in addition to easily seen and recognized visual ones, both in the car and at landings, to indicate call registration, car approach, car landing, direction of travel, floor, car position, and so on. In this connection, a voice synthesizer is of invaluable assistance. Additionally, Braille plates adjacent to car floor buttons and large, easily recognizable symbols adjacent to passenger-controlled emergency controls are to be used.

Many of these ideas will also make life easier for passengers with full faculties. A note of caution, is in order, however. Delayed door closing may increase travel time appreciably. In buildings with traffic peaks, it may be necessary to designate one or more specific elevators for use by the handicapped during these periods. Figure 23.8 is a composite sketch showing the application of some of these recommendations.

In addition to the NEII standard's requirements, peripheral facilities should meet the requirements of ANSI standard A117.1 (latest issue) *Buildings and Facilities—Providing Accessibility and Usability for Physically Handicapped People*.

ELEVATOR CAR CONTROL

23.12 Drive Control

Elevator drive control, or motion control, comprises the arrangement of hardware and in most modern installations, software, which effects the controlled motion of a car. The car's acceleration, velocity, braking, leveling, and all aspects of power control, including regenerative braking, are subsumed under this heading. The other aspect of car control is usually known as operating control, and deals with the operation of the car doors and the integration of car buttons, lanterns, and other passenger-operated devices into the overall control and indicating system. Elevator *car* control is separate and distinct from the control system that governs the functioning of a group of cars acting as a unit building system. That control arrangement is generally designated as the supervisory system, and is discussed separately below. It retains its separate identity as a supervisory system, albeit a relatively simple one, even in the case of a single-car system.

Elevator car acceleration and deceleration are accomplished by controlling the speed of the motor that drives the elevator traction machine. This speed control can be accomplished in a number of ways, all of which are in use in elevator installations. They are:

1. Rheostatic control of a single-speed a-c traction motor.
2. Rheostatic control of a two-speed a-c traction motor.
3. Thyristor control of an asynchronous (squirrel cage) a-c traction motor.
4. Thyristor control of a d-c traction motor.
5. Motor-generator set control of a d-c traction motor (Ward–Leonard system).
6. Variable-voltage, variable-frequency control of an asynchronous a-c traction motor.

We will describe each system briefly and note its applicability, advantages, and disadvantages.

23.13 Rheostatic a-c Motor Control

See Fig. 23.9*a*. Speed control is accomplished by introducing resistance into the motor circuit. This results in a relatively rough ride with poor leveling. Rise is limited to 150 ft and speed to 200 fpm (1 m/s). Use of a two-speed motor improves the ride and leveling by using the motor's low-speed winding for landing the car, but the ride quality is still not smooth. Other disadvantages of this arrangement are high starting currents, which cause line disturbances and require heavy feeders, and poor operating efficiency. The system is used where economic considerations are paramount and where a hydraulic unit is impractical.

23.14 Thyristor Control, a-c and d-c

(a) A-c. See Fig. 23.9*b*. The development of high power transistors in the last decade made possible and practical accurate speed control of inexpensive a-c squirrel-cage motors by the simple expedient of supplying the motor carefully regulated variable voltage. The resultant speed control is smooth and stepless, making it applicable to passenger elevator installations. However, the high motor slip caused by the constant frequency of the variable-voltage a-c supply causes large thermal losses with resultant low operating efficiency. Too, the "chopper" which is used to accomplish the necessary voltage control introduces undesirable harmonics into the power system in considerable quantity. These adversely affect all of the electrical systems components and can cause equipment overheating and overload (see Section 17.19). Furthermore, these same harmonics appear as line

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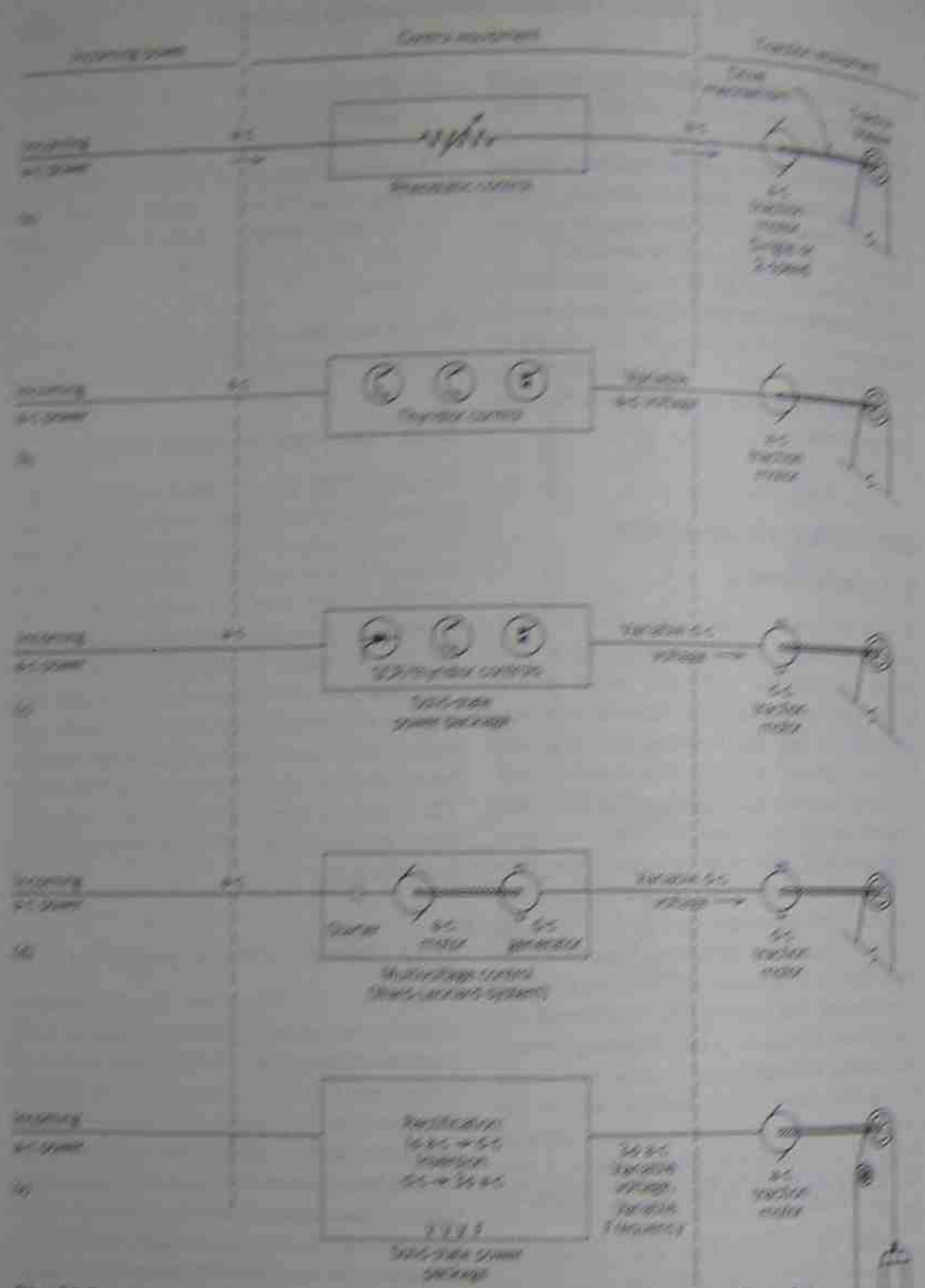

Fig. 23.9 Arrangement of electric speed-control equipment for elevator drives. (a) Rheostatic control is the simplest variety and is used in slow-speed, low-rise economy installations. (b) Thyristor-produced variable-voltage a-c is used in medium-quality, midrise, medium-speed geared installations. (c) Solid-state silicon-controlled rectifier (SCR) thyristor control produces variable-voltage d-c and finds application in good-quality new and retrofit medium- and high-speed installations. (d) The traditional Ward–Leonard system, which produces finely controlled, variable-voltage d-c. This is the system in use today in the vast majority of existing high-quality installations. (e) Variable-frequency a-c is energy efficient, highly accurate, and applicable to all types of installations.

"noise," which can also adversely affect computer and data communications. Finally, the system's low power factor increases line losses and necessitates increased feeder sizes. Despite excellent control electronics, the ride and leveling are not of the highest quality. This option is applicable to low and midrise residential and commercial passenger service, using geared machines, where economic factors offset the disadvantages. Maximum rise is approximately 250 ft and maximum car speed is 350 fpm (1.7 m/s).

(b) D-c. See Fig. 23.9*b*. A large improvement in ride quality can be had by utilizing the d-c version of thyristor control to supply variable voltage to a d-c traction motor. This arrangement provides the high-quality ride and leveling characteristic of d-c drives and removes the rise and speed limitations of its a-c equivalent, but not the system's low power factor, heavy line harmonics, and high machine room thermal losses. Line harmonics can be sharply reduced by the use of power line filters, which are supplied as a matter of course in good-quality installations. This control system is widely used today, with both geared and gearless traction machines as applicable, for installations of all rises and car speeds. Its extremely smooth ride makes it one of the three systems of choice in high-quality, center-city prestige buildings. The other two systems used for such installations are a Ward–Leonard variable-voltage d-c system and the relatively new variable-voltage, variable-frequency a-c system.

23.15 Variable-Voltage d-c Motor Control

See Fig. 23.9*d*. Before the development of electronic motor control, the only practical method of obtaining the precise motor speed control necessary for smooth stopless elevator operation was to impress a variable d-c voltage on a d-c traction motor. The variable d-c voltage required to drive the d-c traction machine was traditionally obtained from an auxiliary m-g set comprising an a-c motor and a d-c generator. This arrangement is known as a *Ward–Leonard system* or as a *unit multivoltage (UMV) drive*. Although this arrangement has disadvantages, it is the classic high-quality elevator drive arrangement and is found in the vast majority of existing high-quality geared and gearless installations. The disadvantages of this system—low overall efficiency, expensive machines, high thermal losses in machine rooms, high maintenance costs for three rotating machines, and high noise levels—are all accepted in the price of a system that operates faultlessly, with supreme accuracy at all speeds, for long periods of time given proper maintenance. As noted above, it is today still one of the three principal drive control systems being used in new installations.

In modernization work, buildings with existing Ward–Leonard systems are frequently converted to solid-state d-c thyristor control. This change maintains the excellent ride characteristics of variable-voltage d-c traction machine installations while improving system performance by replacing the auxiliary m-g set with a low-loss, low-maintenance, quiet solid-state thyristor drive control.

23.16 Variable-Voltage, Variable-Frequency (VVVF) a-c Motor Control

See Fig. 23.9*e*. This system, which is entirely solid state like the thyristor controls described above, is in the opinion of many elevator experts the system of choice for all high-quality new installations of any speed or rise. The system consists of a rectifier, which changes the incoming 60 Hz a-c to d-c, and an inverter, which creates variable-voltage, infinitely variable frequency, three-phase a-c from the (rectified) d-c. This a-c is then applied to a standard squirrel-cage a-c motor, which operates essentially at the speed corresponding to the frequency of the input. By controlling both the voltage and frequency input to the traction motor, it is possible to provide continuously variable, highly accurate speed control at extremely high efficiencies throughout the full speed range of the motor. This arrangement is precisely what is required for high-quality geared and gearless installations, without the energy losses associated with the auxiliary

m-g set of UMV control. As a result, it is coming into increasing use in new installations, particularly in areas where high electric utility rates provide a short payback period for the higher initial cost of the system. This arrangement eliminates most of the disadvantages of the solid-state thyristor control system and has these characteristics:

1. Overall system efficiency is high at all motor speeds.
2. Traction motors are economical single-speed squirrel-cage a-c.
3. Motors are 10 to 15% smaller than equivalent drive systems.
4. System power factor is close to unity.
5. Line harmonics are lower than with thyristor controls.
6. Speed control and leveling are very high quality; equal to d-c traction motor control.
7. Equipment is 98% solid state, thus requiring less maintenance.
8. Starting currents are low.
9. System is applicable to all rises and speeds.
10. Machine rooms are smaller, cooler, and quieter than those using Ward–Leonard UMV controls.
11. First cost is higher than the competing alternatives.

23.17 Comparative Drive System Characteristics

Solid-state equipment will in time undoubtedly replace the traditional m-g set and its associated controls, because of inherent advantages. The principal drawback at present is the higher initial cost of solid-state equipment. However, when considering life-cycle cost, the relative amounts may be reversed.

(a) Energy and Cost Considerations. One of the principal advantages of solid-state elevator control lies in the energy savings possible. If we were to tabulate energy use of the various systems of motion control discussed above, on a relative scale of 1 to 10, the comparison would appear as in Table 23.1.

Considering that in many parts of the United States energy costs are well above 10 cents/kWh, an economic analysis (see Section 24.2 and Appendix E) may well demonstrate that the higher first cost of the electronic motion control system is economically justifiable, particularly when combined with lower maintenance costs.

Contract maintenance costs in major U.S. cities for high-rise gearless elevators exceed $1000 per month per car. Even a 15% reduction in this cost over an estimated 25- to 30-year equipment life gives a present value (PV) for life-cycle maintenance cost reduction of $25,000 to $35,000 per car, depending on cost of capital.

An ancillary cost benefit accrues due to the sharp reduction in the size of the forced-ventilation or air-conditioning equipment in the machine room, because of the lower heat loss of solid-state motion control equipment as compared to UMV equipment. This economic benefit is appreciable since it affects both first cost and operating cost of the cooling equipment.

(b) Physical Considerations. Although elimination of the m-g set in the solid-state drive system does save space, the corresponding cabinets for car controller and motor drive are larger than their UMV counterparts. Thus the machine room for a solid-state design is only slightly smaller than in the UMV arrangement. A typical solid-state car control panel for a 3500-lb, 800-fpm gearless elevator measures 80 in. H × 48 in. W × 24 in. D and weighs 800 lb.

(c) Car Operation. Somewhat better passenger service is obtainable when using electronic equipment because of better car control. This in turn is due to faster response of components and finer control, particularly of jerk (rate of change of acceleration). Jerk is the principal factor in passenger discomfort.

(d) Other Factors. Elimination of the m-g set and use of electronic motion control have other desirable effects:

TABLE 23.1 **Comparative Energy Use of Various Motion Control Arrangements**

Energy Use	*Relative Amount*
Hydraulic elevators (discussed in Section 24.10)	10
Rheostatic control; geared a-c traction motors	7.5–8.5
Thyristor control; geared a-c traction motors	7–7.5
UMV motion control; geared d-c traction motor	7–7.5
UMV motion control; gearless d-c traction motor	6–6.5
Thyristor control; geared d-c traction motor	5–5.5
Thyristor control; gearless d-c traction motor	4–4.5
Variable-voltage variable-frequency control, a-c traction motor	2.5–3.0

1. Elimination of current and kilowatt demand peaks, which are characteristics of motor starting operation. This will result in a reduction in electric bills. The overall reduction, including energy and demand changes, can reach 35%.
2. Reduction in noise and vibration in the machine room, which frequently is transmitted to other parts of the building.
3. Reduction in maintenance costs, because the periodic maintenance required for continuously rotating and sliding equipment is eliminated. Solid-state equipment maintenance is minimal.
4. Possible reduction in the size of the emergency generator required to operate an elevator, with concomitant cost reduction. This reduction is possible since the very high current inrush taken on m-g starting is eliminated. The generator must, however, be large enough to handle the regenerative braking current produced by a full car traveling down.

At this point we can summarize the discussion above with a tabular comparison of the various drive system in use today (Table 23.2). The exact degree of improvement possible when changing to solid-state equipment in a retrofit job depends on the quality of both the old and the new systems. It is greatest when a microcomputer group control system replaces a relay-logic terminal dispatch system.

23.18 Elevator Operating Control

Assuming the system to be energized and at rest, registration of a call from a station in the

TABLE 23.2 **Comparative Characteristics of Elevator Drive Systems**

Type	*Rise*	*Speed*	*Control*	*Initial Cost*	*Operating Cost*	*Performance*
Geared a-c	150	50–200	Rheostat	Low	Medium	Poor
	250	150–350	Thyristor	Medium	Medium	Fair
	300	150–450	VVVF	High	Low	Excellent
Geared d-c	175	50–450	UMV	Medium	High	Excellent
	250	50–450	Thyristor	Medium	Low	Very good
Gearless d-c	Unlimited	400–1200	UMV	Medium	High	Excellent
			Thyristor	Medium	Low	Excellent
Gearless a-c	Unlimited	400–2000	VVVF	High	Low	Excellent

Note: Life of equipment is generally indefinite except for worm and gear of geared unit, which has a 30- to 40-year life.

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lobby or an upper-floor corridor will activate the system. The particular elevator that will answer the call is selected by the supervisory system. In a UMV system, the m-g set related to that elevator car is started and comes up to speed slowly. In the case of solid-state motion control, power is available immediately, and the m-g set starting time is eliminated. This difference between m-g set and solid-state equipment disappears in the more usual case of an m-g set that is already running. With voltage available the elevator control is cut in and the car is put into operation. Switching devices in the car control panel release the brake, energize the elevator motor, and accelerate the car to its rated speed. Reverse operations are initiated when decelerating and stopping (landing) the car. When the car stops, the brake holds the sheave and elevator stationary.

The motion of a single car is determined by the action of three principal items of equipment: the car controller, the motor controls, and the system supervisory equipment. The action of this latter equipment is discussed in Sections 23.19 to 23.23. The function of the car controller panel is generally to duplicate the action of the elevators and to anticipate hall calls. This is accomplished in older controllers by the action of a sort of miniature elevator system that contains sets of contacts over which small sliding brushes move in synchronism with the corresponding car movements in the hoistway. Most recent systems utilize an electronic or optical position transducer, which is at least as accurate as its mechanical forerunner but does not require periodic alignment to maintain accuracy. This information, that is, the car position and both waiting hall calls and car calls, is fed into the group supervisory system. This system may reside in a separate panel or, as described below, in each car controller panel. It acts to initiate all the procedures necessary to answer all calls via the individual car controller panels. In almost all new systems the switching and control devices are solid state, although small low-rise, low-speed, single-car installations such as are found in small apartment houses and loft buildings may still use electromechanical switches (relays) and position devices to good effect.

SYSTEMS OF ELEVATOR OPERATION AND SUPERVISION

23.19 System Control Requirements

An operating system is that control, as stated above, that governs the automatic (operatorless) response of a single car or a group of cars, to calls for service. An effective system therefore must take cognizance of all hall calls and car calls, car travel directions, and car positions—in relation to each other and in relation to the call requirements, plus the relationships between up and down traffic and the trends of traffic. This last is required in order that the system anticipate demand rather than react to it, since only by anticipation can the system operate at maximum efficiency. The operating system considers all the above data and dispatches cars accordingly. Obviously, since traffic and calls are never static, the control that will satisfy all these demands in a large elevator system is an extremely sophisticated one. Without such control, however, large elevator systems will render poor service, to the dissatisfaction of owner and rider. On small systems the operating control is much simpler, as described below. Throughout the discussion that follows, reference to m-g sets applies, obviously, to UMV motion control. In solid-state systems, as explained above, drive voltage is available instantaneously.

23.20 Single Automatic Push-button Control

This system is the simplest of the passenger-operated automatic control schemes. It handles only one call at a time, providing an uninterrupted trip for each call. A single corridor button at each level can register a call only when the car is not in motion. To indicate availability of the car, an "in use" light is placed over the hall call button. Calls can be placed when the light is off. This control scheme is applicable only to a short-rise, inactive elevator, that is, one making five or fewer trips per hour. Such elevators are found in small apartment houses, residences, small professional buildings, and industrial buildings using freight elevators.

23.21 Collective Control

This system is no longer used in new installations in the United States, although it is common in other countries. With only a slight increase beyond very light traffic single automatic push-button control becomes unsatisfactory, because no call storage provision is made. Waiting periods can become extremely long, particularly with slow cars and moderately high rise. A control system therefore evolved that provides a single call button at each landing. The elevator stops at each floor that has registered a call to "collect" the waiting passenger. Hence the "collective" nomenclature. The car cannot differentiate between up and down calls since only a single button is provided. A car direction light is frequently placed adjacent to the call button. This will tell the prospective passengers whether the car that stops in response to their call is going in the right direction. As can readily be seen, this type of operating system is acceptable only for light residential or industrial service.

23.22 Selective Collective Operation

This type of collective operation is "selective" in that it is arranged to collect all waiting "up" calls on the trip up and all hall "down" calls on the trip down. The control system "stores" all calls until they are answered, and automatically reverses the direction of travel at the highes' and lowest calls. When all calls have been cleared, the car will remain at the floor of its last stop awaiting the next call, and its m-g set will stop after several minutes. Pressure on any "up" or "down" button at any landing, or on any floor button in the car, will start the m-g set and set the car into operation.

Selective collective control is standard in locations where service requirements are moderate such as in apartment houses, small offices, and hospitals. Since these locations often require more than one car, a control scheme is available for groups of one to three cars. It automatically assigns each landing call to the car best situated to answer it, prevents more than one car from answering a call, allows one car to be detached for freight duty while others serve passengers, and automatically parks all but one car at the ground floor, that car acting as a free car until service calls require the use of the parked cars.

Although selective collective control is standard for most residential and other light-to-moderate service requirement buildings, its inherent characteristics frequently result in long waiting periods for elevators. These characteristics are:

1. Highest call reversal.
2. Shutdown of the m-g set (where used) after calls have been answered.
3. Strong tendency toward bunching of cars.

The last characteristic is particularly annoying in groups of three cars. Frequently a passenger will arrive at a landing to find that all three cars have just passed, going in the same direction. The result is that service is only slightly better than that which would be rendered by a single car, except that load (handling) capacity is greater. For this reason, operation of more than two cars with this system is not recommended and operation of more than three cars is not feasible.

Although collective control furnishes adequate elevator service where requirements are light to moderate, it is still basically a signal-controlled system that weighs all calls equally and takes no cognizance of traffic patterns.

To overcome this shortcoming, elevator engineers over the years 1950 to 1980 developed numerous supervisory control systems, among which were multiple zoning arrangements and programmed traffic patterns. The former divided the building into zones and dispatched elevators within these zones, thus reducing waiting time. The latter recognized that most buildings exhibit repetitive traffic patterns—such as morning up-peak, evening down-peak, lunch hour up and down peaks, and so on—and arranged car travel accordingly to give optimum service. Choice of the mode of operation was generally left to the lobby attendant, whose judgment was relied on to select the mode appropriate to the need. This

was frequently less than satisfactory and was replaced by a system in which the operational mode was selected on a clock-time basis. The basic problem with all these older preprogrammed operating systems is that they can react in only a few modes because of physical limitations. The control system consists of relays, contacts, and hardwiring. As the system becomes more complex, the number of these devices increases enormously and places a practical limit on the sophistication of the system. This limitation disappeared with the advent of the computerized, microprocessor-controlled operating system.

23.23 Computerized System Control

The most advanced type of control system continuously monitors demand and controls each car's motion in response to demand only; that is, it analyzes all the possibilities and answers each call in optimum fashion. The term "optimum" depends, of course, on the system design strategy, and this varies between manufacturers. Such a system is possible only with the aid of a central computer combined with programmable microprocessor-controlled peripherals, since the amount of data that must be collected and processed is enormous.

All manufacturers attempt to optimize the parameters by which system quality is measured: specifically, to minimize interval, hall waiting time, and average trip time. How this is accomplished depends on the relative importance or weight assigned to each item of input data in an extremely complex computer algorithm. One manufacturer (Schindler's Miconic V) uses an algorithm that calculates a figure of merit for each car to answer each waiting hall call. The number arrived at represents the weighted sum of prospective passenger hall waiting time (interval and hall wait time) and traveling passenger delay (average trip time). The best figure of merit (minimum time) is selected by the group supervisory system and that car is assigned to the landing call. Another manufacturer (Armor/Kone, TM5 516) uses a somewhat simpler dynamic call allocation algorithm (see Fig. 23.10) which relies on the high-speed calculation capabilities of a central computer to make a last-moment decision as to which car answers which call. Another algorithm (Armor/Kone TMS 900), in addition to analyzing each car's capability to answer a call, calculates the effect of the decision on the overall elevator service quality for the building and uses this factor as well in the final decision.

Still another algorithm (Otis, Elevonic 411) uses a car dispatch program based on preprogrammed and learned traffic patterns modified by the history of the previous few minutes of operation. In the basic program, and within the constraints of a particular mode, each car computes its own response time to a waiting hall call, considering its own position, velocity, and car calls, and compares it to that of all other cars in the group. The car that will provide optimum hall call service time (waiting time plus trip time) answers the hall call. To facilitate this type of car "bidding" for calls, some systems are arranged so that each car controller is, in effect, a master group controller. At any one time, one car in the group acts as master, but if taken out of service, another car controller becomes the master.

In addition, this program (and that of several other manufacturers) uses an artificial intelligence module to learn traffic data and history and continuously change the car dispatching program. These changes consist in part of sectoring or zoning the building so that cars are dispatched and grouped to provide optimal service. This type of system is particularly useful in buildings with single- or multifloor use occupants, with repetitive traffic patterns. Another program option provides variable grouped or sectored floor assignments for cars leaving the lobby during periods of peak up traffic. The purpose of this function is to reduce the number of stops in a typical round trip, thereby reducing lobby waiting time.

Most algorithms permit overriding the present program mode in response to crowd sensors or to particularly heavy, concentrated, service demand such as might be the case if occupants of an entire floor left the building at an unusual hour. The algorithm possibilities are legion because of the large number of factors involved. These factors include:

1. Condition of each car, including its load; registered calls; priority status, if any; and status of its m-g set, if any.
2. Distance of each car from a registered hall call.
3. Car unloading calls ahead of and behind each hall call.
4. Special conditions, including delays, priority calls, and timing of registered lobby calls.

On the basis of all these data, the computer calculates not only which car is in the best position to answer a call but also travel time for the hall call *and* the calls already registered in that car. The computer also analyzes the traffic trends many times each second and reevaluates the importance of all factors in order to anticipate service requirements. It does this by recognizing traffic patterns as they begin to form and then comparing them to preprogrammed pattern responses for such traffic patterns as peak-up, peak-down, light, and balanced traffic. This recognition function permits anticipating the ser-

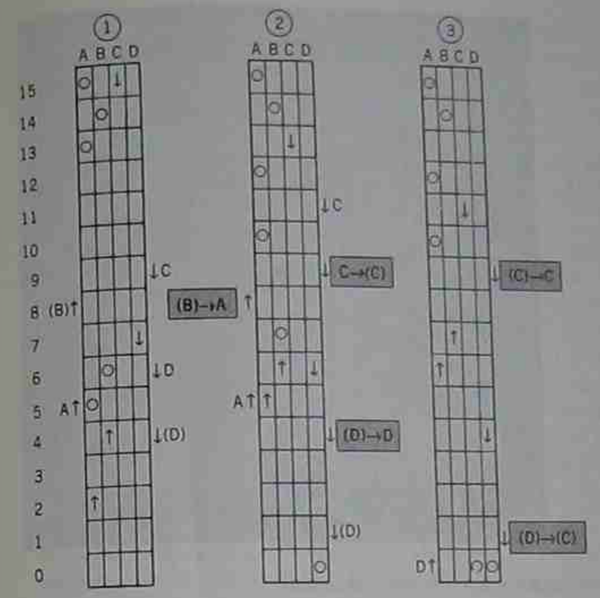

Fig. 23.10 *Simplified explanation of the algorithm logic for a group supervisory control system of medium complexity. Myriad timing calculations of acceleration, deceleration, and door operation go into each decision. These calculations are continuously repeated and updated, to provide a second-by-second picture of the entire system. (Courtesy of Kone Elevator Co.)*

TMS 516 Dynamic Call Allocation

The sequence on the left demonstrates the call assignment effect of the dynamic last moment decision principle of the TMS 516 in intensive day traffic with incoming, outgoing and interfloor traffice elements.

Stage 1: Due to coinciding car call to floor 5, A is assigned the up call on that floor, despite B being closer. Up call on floor 8 is pre-assigned to B. Vacant C is assigned the down call on floor 9, D is assigned floor 6 down call, and pre-assigned down call on floor 4.

Stage 2: A few seconds later, the up call on floor 8 is dynamically re-assigned to A as B has to stop for the intermediate car call to 7. C is assigned the new down call on floor 11, and the status of the down call on floor 9 is changed from assignment to pre-assignment. Opposite change occurs on floor 4. A new down call on floor 1 is pre-assigned to D.

Stage 3: Several seconds later, the pre-assignment of the down call on floor 1 is transferred to C, to enable fast service of the new main floor priority up call by D. Floor 9 down call pre-assignment is confirmed.

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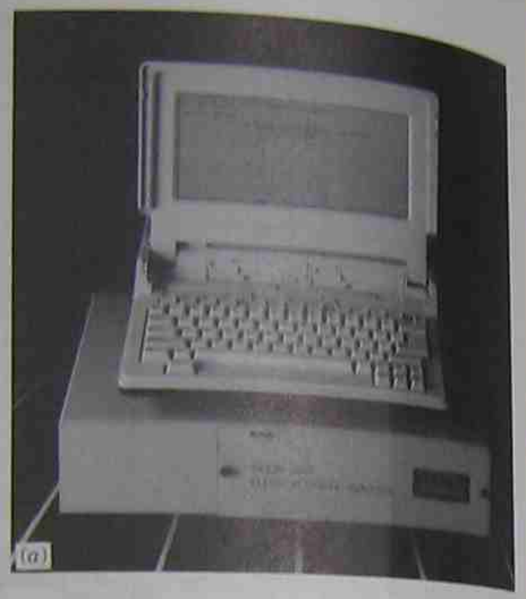

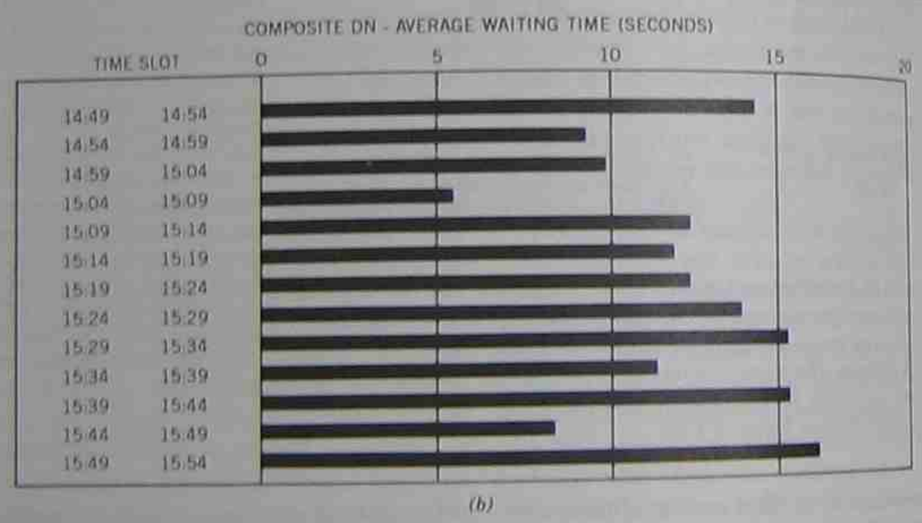

(b)

Fig. 23.11 *Building elevator traffic studies can be accomplished quickly and accurately using a traffic analyzer with multiple inputs to feed data via appropriate software into a conventional laptop computer* (a). *The unit illustrated has 64 inputs, all of which are scanned once per second, and is capable of unattended monitoring for a week. The accumulated data on call registration, response time, waiting time, maximum interval, cars in service, and so on, can be viewed visually on the computer's LCD screen or printed out as in* (b). *(Courtesy of Delta Elevator Equipment Corp.)*

vice requirements, rather than simply reacting to them, thus improving actual service.

The actual program logic for even a small group supervisory traffic control system is beyond the scope of this book, but its guidelines are not. An adequate system should:

1. Be programmed initially for the anticipated service needs. These needs can be analyzed in existing buildings with computerized traffic analyzers (see Fig. 23.11) and in planned buildings by detailed occupancy analysis using computerized elevator system simulation (see Fig. 23.12).
2. Be reprogrammable to meet changes in building needs at nominal cost and with minimum shutdown time. It must be possible to detach cars from the system during testing, reprogramming, and routine maintenance to provide minimal service even during off-hours.
3. In case of retrofit work, be adaptable not only to existing traction equipment but also to anticipated modernization, again without extensive outlay. When an existing group operating system is modernized by the installation of a microcomputer group controller, it is almost always also necessary to change the car controls to programmable solid-state equipment.
4. Provide for priority call calculation (based on landing waiting times), statistical analysis of traffic in order to anticipate patterns, adaptive (zoned) car parking to meet specific needs, adjustable door timing based on type of call (lobby, landing, car), backup dispatch means (in case of dispatch system failure), and automatic call cutout for constant (stuck) signals.
5. Provide means for lobby and management office viewing (monitor) and obtaining hard copy (printer output) of elevator traffic information in both real time and stored (see Fig. 23.13). This data-handling equipment must provide a fault mode that will store, display, and diagnose system operating faults. The owner/manager unit may have on-site control and reprogramming capabilities, if so required.
6. Provide additional functions such as emergency power elevator selection and control (see Section 24.4), priority service, selective hall/car call cutout, swing (separate) car operation, and hoistway access controls for maintenance.
7. Provide, where specifically required by the building management, a riot control feature (access limitation at entrance levels), crossover floor operation in a zoned system, convention service (intense short-time usage at selected levels), and controlled access at given floors and for specific occupants.
8. Be fully coordinated with the fire protection system in accordance with the local fire regulations (see Section 24.5).
9. Act in consonance with the elevator security equipment in accordance with predetermined security measures so that operation of security/alarm devices will initiate automatic elevator motion control procedures. This too must be coordinated with the local security authorities, and the automatic procedures must be subject to manual override (see Section 24.6).

Fig. 23.12 *Elevator system simulation. A computerized mathematic model of an automated elevator system permits the operator to enter building data and vary elevator control strategy. The results, displayed graphically, show the system response. (Courtesy of Otis Elevator Co.)*

Proper operation of the system should also result in:

1. All floors getting equal service, including the basement, if desired.
2. Proper handling of multifloor tenants in office buildings, to permit efficient interfloor traffic.
3. Appropriate action in emergencies, such as general or local circuit power failure or any type of abnormal car or signal operation.

23.24 Rehabilitation Work: Performance Prediction

The primary reason for rehabilitating an existing elevator system is to improve its operating performance. As mentioned above, the traction machinery has extremely long life, particularly in the gearless configuration. Thus the usual rehabilitation project consists of replacing the m-g set, car control panel, and group controller with solid-state, microprocessor-controlled programmable equipment, while retaining the original

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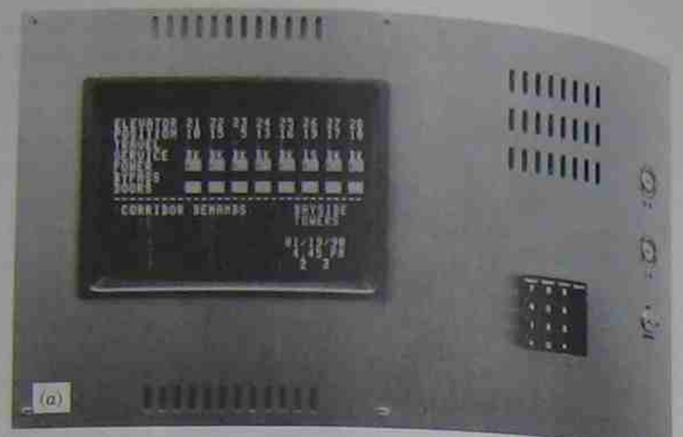

Fig. 23.13 Elevator system lobby panel, also known as a traffic director's station, or as in illustration (a)*; Schindler's Building Management Interface unit. The keypad at the lower right of the photo permits the operator to select the desired display. He can display elevator system status of selected banks in tabular form* (a) *or graphically* (b)*. Displayed data included car status, all waiting calls, special car modes, and system modes and messages. From the unit illustrated he can enable and disable various system modes and identify any malfunctions. Other building management units (not illustrated) permit the operator to alter system operation by changing its programming. (Illustrations courtesy of Schindler Elevator Corp.)*

traction equipment. The car door operator, which controls door action, is usually also replaced, since door opening and closing characteristics are an important factor in overall trip time, and therefore system performance.

Using computers, major manufacturers have developed elevator system simulators. These devices enable architects and owners to input proposed (or existing) building data, and to receive visual and printed readout on the performance of proposed systems (see Fig. 23.12). Since such programs are interactive, the operator can change the input data and the characteristics of the proposed equipment until the desired performance level is reached. These devices are particularly useful in modernization work, since the owner will see in advance the operation of a proposed system *in his building* and can make the required decisions on this basis.

23.25 Lobby Control Panel

A lobby control panel (also called a traffic director's panel or an information control center) is furnished with each bank of elevators and is usually mounted in a readily accessible and easily visible position in the building lobby.

The contents of the panel are generally these:

1. An information module that gives information on corridor calls, special status of cars, car movement direction and location of cars. The information can be displayed in tabular form (Fig. 23.13*a*) or graphically (Fig. 23.13*b*).
2. A communications compartment that permits two-way communications with cars and other selected locations.
3. A switch section containing a "power-on" and "in-service" switch for each car in the bank, plus special switches.

The panel provides for manual intervention to permit special types of operation. Thus a car can be:

1. Arranged to travel without operating the usual audible and visual signals (*inconspicuous riser*).
2. Taken out of supervisory control and operated manually (*attendant or independent service*).
3. Selected for night or weekend service while the other cars are shut down.
4. Assigned to a particular floor on a fixed- or priority-basis call (*convention feature or priority*).

Other operational features that can be provided are concerned with emergency service, including the "fireman's return" feature required by ANSI and many local fire codes (Section 24.5) and the controls related to switching of power between cars in the event that operation of an emergency generator is necessary.

Fig. 23.14 Car panel ergonometrically designed for convenient use by normal as well as handicapped passengers. Each floor button is lighted and adjoins a Braille plate (raised numbers). Four special buttons—door-open, door-close, alarm, and emergency stop—are placed at the bottom of the panel and marked with internationally recognized symbols. Firemen's controls and special access switches are at the top of the panel, along with speaker/microphone. This panel is also equipped with a voice synthesizer and an upper panel that can display any desired information, in addition to showing the car location. Note also the arrow on the door jamb, which clearly indicates the direction of car travel. (Photo courtesy of Otis Elevator Co.)

23.26 Car Panel

A typical modern car panel is illustrated in Fig. 23.14. Every car panel (station) is equipped with full-access buttons for call registry, door-open

and alarm, and switches for emergency stop and fireman control. Also always provided behind an unlocked door is a telephone or intercom device that permits communication with the lobby panel. A door-close button is sometimes provided if extensive hand operation of the car is anticipated. It is activated only when the car is under manual control. Controls that do not concern the normal passenger are grouped in a locked compartment in the car station. These include hand-operation switch, light, fan and power switches, and any special controls such as security and emergency devices. Finally, a compartment accessible only to technicians contains the devices controlling door motion, car signals, door and car position transducers, load-weighing control, door and platform detection beam equipment, speech synthesizer (if used), and visual displays.

ELEVATOR SELECTION

23.27 General Considerations

The selection of elevators for any but the simplest buildings requires the simultaneous consideration of several factors: adequate elevator service for the intended building usage, the economics of elevator selection, and the architectural integration of spaces assigned to elevators, including lobbies, shafts, and machine rooms. As must be obvious, these factors are interdependent; therefore, in large complex buildings many combinations are possible. The selection of a single optimum system for such cases is most practical with the aid of a computer, or simulator. For most buildings, however, certain guidelines can yield entirely satisfactory results with hand computation. These guidelines will be developed and explained below. The criteria of elevator service quality are:

1. Interval and average waiting time.
2. Handling capacity.
3. Travel time.

23.28 Definitions

A clear definition of terms, including variant usages, is imperative for the proper study of a subject. To that end, an abbreviated list of important definitions for our study follows.

Interval (I) or Lobby Dispatch Time. Average time between departure of cars from the lobby.

Average Lobby Time or Average Lobby Waiting Time. Average time spent by a passenger between arriving in the lobby and leaving the lobby in a car.

Registration Time. Waiting time at an upper floor after registering a call.

Round-Trip Time (RT). Average time required for a car to make a round trip, starting from the lower terminal and returning to it. The time includes a statistically determined number of upper-floor stops in one direction and, *when calculating elevator requirements based on up-peak traffic*, an express return trip.

Travel Time or Average Trip Time (AVTRP). Average time spent by passengers from the moment they arrive in the lobby to leaving the car at an upper floor.

Handling Capacity (HC). Figure of merit for an elevator system, indicating the maximum number of passengers that can be handled in a given period, usually 5 min; thus "5-min handling capacity." It is expressed as a percentage of the building population.

Zone. Group of floors in a building that is considered as a group, with respect to elevator service. It may consist of a physical entity—a group of upper floors above and below which are blind shafts—or it may be a product of the elevator group control system, changing with system needs.

23.29 Interval or Lobby Dispatch Time, and Lobby Waiting Time

In an ideal installation, at least from the riding public's point of view, a car would be waiting at the lower terminal on the rider's arrival or would be available after a short wait. Since cars leave the lobby separated in time by the *interval (I)* and passengers arrive at the lobby in random fashion, the average waiting time in the lobby should be half the interval. Field tests show, however, that it is actually higher than this, and the figure most used in the industry is 60%; that is,

$$\text{average lobby waiting time} = 0.6I$$

Excellent office building design provides an average lobby wait of 15 to 18 s during up peaks, with 22 s considered good and 26 borderline.

Since some control systems zone the building in such a way that some cars do not return to the lobby, the interval as a figure of merit can be somewhat misleading. As a basis of comparison, however, a 30-s interval is excellent, 35 s borderline, and 40 s just acceptable in other than center-city office spaces. Table 23.3 lists acceptable intervals for various building types.

With intervals in this range, riders will not be conscious of any irksome delay in elevator service. Consciousness of delay is considered a major drawback in rental desirability and should be sedulously avoided for all conditions of traffic except during morning and evening peaks, when a certain delay is expected and therefore tolerated, however grudgingly. Even in both these cases, a modern group supervisory system will recognize any *timed-out* call, that is, a call with registration time exceeding 50 s, as a priority call. Priority calls are answered by the first available car, usually within 15 s. If a considerable amount of interfloor traffic is expected during peak periods, as may be the case when a large company occupies several upper floors, elevator service must be increased by 20 to 40% over that calculated to maintain proper intervals.

23.30 Handling Capacity

The frequency, or interval, with which a car appears at the lobby is one of the two factors that determine the passenger capacity of an elevator system. The other is obviously the size or capacity of the elevator car. The systems's *handling capacity* is completely determined by these two factors—car size and interval, and is independent of the number of cars. This can be best understood by visualizing the system as a single set of doors that open periodically (interval) to remove a given number of passengers (car capacity) from the waiting group. Whether that set of doors represents a single car or many cars that take turns is immaterial. The only factors that fix handling capacity are passenger load (car capacity) and frequency of loading (interval) (see Table 23.4).

Note that cognizance is taken of the fact that during peak traffic periods cars are not loaded to maximum capacity, but only to about 80%—a figure determined by actual count in many existing installations.

As a convenient measure of capacity, the handling capacity of a system for 5 min is taken as a standard. This is because a 5-min rush period is used as a measure of a system's ability to handle traffic. This may be expressed thus:

TABLE 23.3 **Suggested Elevator Intervals**

Facility	Interval (s)
Office Buildings	
Center city	25–30
Investment	28–32
Suburban	32–35
Residential	
Prestige apartments	50–70
Middle-income apartments	60–80
Low-income apartments	80–120
Dormitories	60–80
Hotels—1st quality	30–50
Hotels—2nd quality	50–70

TABLE 23.4 **Car Passenger Capacity (*p*)**

Elevator Capacity (lb)	Maximum Passenger Capacity	Normal Passenger[a] Load per Trip
2000	12	10
2500	17	13
3000	20	16
3500	23	19
4000	28	22

[a]The number of passengers carried on a trip during peak conditions is approximately 80% of the car capacity.

TABLE 23.5 **Minimum Handling Capacities (HC)**

Facility	*Percent of Population to be Carried in 5 Min*
Office Buildings	
Center city	12–14
Investment	11.5–13
Single purpose	14–16
Residential	
Prestige	5–7
Other	6–8[a]
Dormitories	10–11
Hotels—1st quality	12–15
Hotels–2nd quality	10–12

[a]Due to more urgent traffic demands, particularly at the school and work exodus.

TABLE 23.6 **Population of Typical Buildings for Estimating Elevator and Escalator Requirements**

Building Type	*Net Area*
Office Buildings	*Square feet per person*
Diversified	
Large lower floors	140–160[a]
Upper floors	160–180
Average use	160
Single purpose	150
Hotels	*Persons per sleeping room*
Normal use	1.3
Conventions	1.9
Hospitals	*Visitors and staff per bed*[b]
General private	3
General public (large wards)	3–4
Apartment Houses	*Persons per bedroom*
High-rental housing	1.5
Moderate-rental housing	2.0
Low-cost housing	2.5–3.0

[a]Density may vary for different floors. Clerical and stenographic area may have a population density as high as 70 square feet per person.

[b]If visiting hours are restricted, visitor population will determine elevator requirements. If visiting is not restricted to a certain few hours, staff requirements may determine elevator design. Where traffic is heavy, a combination of passenger cars and larger "hospital" cars should be used to provide optimum service.

TABLE 23.7 **Office Building Efficiency**

Building Height	*Net Usable Area as Percentage of Gross Area*
0–10 floors	Approximately 80%
0–20 floors	Floors 1–10 approximately 75%
	11–20 approximately 80%
0–30 floors	Floors 1–10 approximately 70%
	11–20 approximately 75%
	21–30 approximately 80%
0–40 floors	Floors 1–10 approximately 70%
	11–20 approximately 75%
	21–30 approximately 80%
	31–40 approximately 85%

NOTE: Applicable to buildings with 15,000 to 20,000 gross square feet per floor.

Source: Reprinted from G. R. Strakosch, *Vertical Transportation, Elevators and Escalators*, 2nd ed. New York: Wiley, 1983.

handling capacity (HC)

$$= \frac{300 \text{ s} \times \text{passengers/car}}{\text{interval}}$$

or

$$HC = \frac{300p}{I} \qquad (23.1)$$

where p is individual car loading. When the interval is 30 s, the system handling capacity is $10p$, a convenient figure to remember.

To establish a figure of merit for building service, system capacity HC must be related to building size. This is normally done by establishing a minimum percentage of building population that the system will handle in 5 min. A good system for a diversified office building will handle no less than 12% of the building population. Similar figures are shown in Table 23.5 for various types of facilities.

In planning a building the population must, of course, be estimated. This is particularly difficult in speculative-type, diversified-use buildings. However, based on rental cost, area, and building type, a fair estimate can be made. Population estimates for office buildings are based on net area, that is, actual available area for tenancy. Table 23.6 gives suggested density figures, while Table 23.7 gives average office building efficiency figures for use in calculating net area.

23.31 Travel Time or Average Trip Time

The average trip time or time to destination is the sum of the lobby waiting time plus travel time to the median floor stop. Car round-trip time is also used as a criterion but is not as relevant or meaningful as trip time. In a commercial atmosphere a trip of less than 1 min is highly desirable, a 75-s trip acceptable, a 90-s trip annoying, and a 120-s trip the limit of toleration. Obviously, in the more relaxed atmosphere of a residence, where interval alone can account for a minute or more of trip time, these maxima are revised upward. From Fig. 23.15 we see that the 2000-lb and 2500-lb cars used in residential buildings can have a 17-story rise, even with 60-s interval, without excessive trip time. On the other hand, the 3500-lb car, which is almost universal in office buildings (Fig. 23.16), is limited to a maximum of 16 floors local run before exceeding the 90-s limit and about 6 to 8 floors to stay within the 75-s criterion.

An important reservation on the foregoing statements must be noted. The curves of Figs. 23.15 and 23.16 are based on statistical calculations, empirical data, and field observations, as discussed in the next section. This being so, the average values that these figures give should be considered to be ±15%, and borderline cases can be shifted either way. Designs that show high travel time on paper frequently work out well in the field, because lobby loading is often less than 80%, upper floor stops are less than the statistical figure due to groups of people going to the same floor, and staggered working hours relieve traffic peaks. Also, a feature called high-call reversal takes account of the fact that cars do not travel to the top on each trip, but reverse at the top call. This can reduce average trip time by 5 to 10%. Finally, sophisticated solid-state traffic controls allow more rapid acceleration and deceleration without discomfort, variable door closing time, and more efficient selection of landing call answers, all of which can further reduce trip time another 5%.

23.32 Round-Trip Time

The figure for round-trip time during up-peak traffic conditions, which are those used for calculating elevator requirements, is composed of the sum of four factors. They are: time to accelerate and decelerate, time to open and close doors at all stops, time to load and unload, and running time (see Figs. 23.17 to 23.19). It is physically the time consumed by a car from door opening at the lower terminal to door opening at the same terminal at the end of a round trip. Since the actual number of stops made by a car is unknown, a statistical probability figure is used, based on the passenger capacity of the car and number of local floors above the lower terminal. In calculating this round-trip time (RT), it is assumed that a car will depart the lower terminal when loaded. No intentional delay is included at either lower or upper terminal. The RT thus calculated is a median figure, with any single actual round trip taking more or less time. In detail, round-trip time consists of the time expended in:

1. Loading at the lobby.
2. Door closing at the lobby.
3. Accelerating from the terminal and from each stop.
4. Decelerating at each stop.
5. Passenger transfer at each stop.
6. Door operations at each stop.
7. Running time at rated speed between stops.
8. Return express run from the last stop.

These figures are obtained as follows:

1. *Field observations:*—items 1 and 5 are based on a 3 ft, 6 in. door opening. A smaller door opening increases passenger transfer time.
2. *Calculations:*—items 2, 3, 4, 6, 7, and 8.

Door-closing time is based on a 3 ft, 6 in. center-opening door with adjustable speed.

Acceleration and deceleration times are calculated with a maximum of 4 ft/s/s because anything beyond that results in physical discomfort to the passengers.

Running time at rated speed takes place after the car has accelerated and before it begins to decelerate. If we consider that it takes between 20 and 30 ft to accelerate to 700 fpm, depending on rate of acceleration, we see that in local runs the car never gets to rated speed. It simply

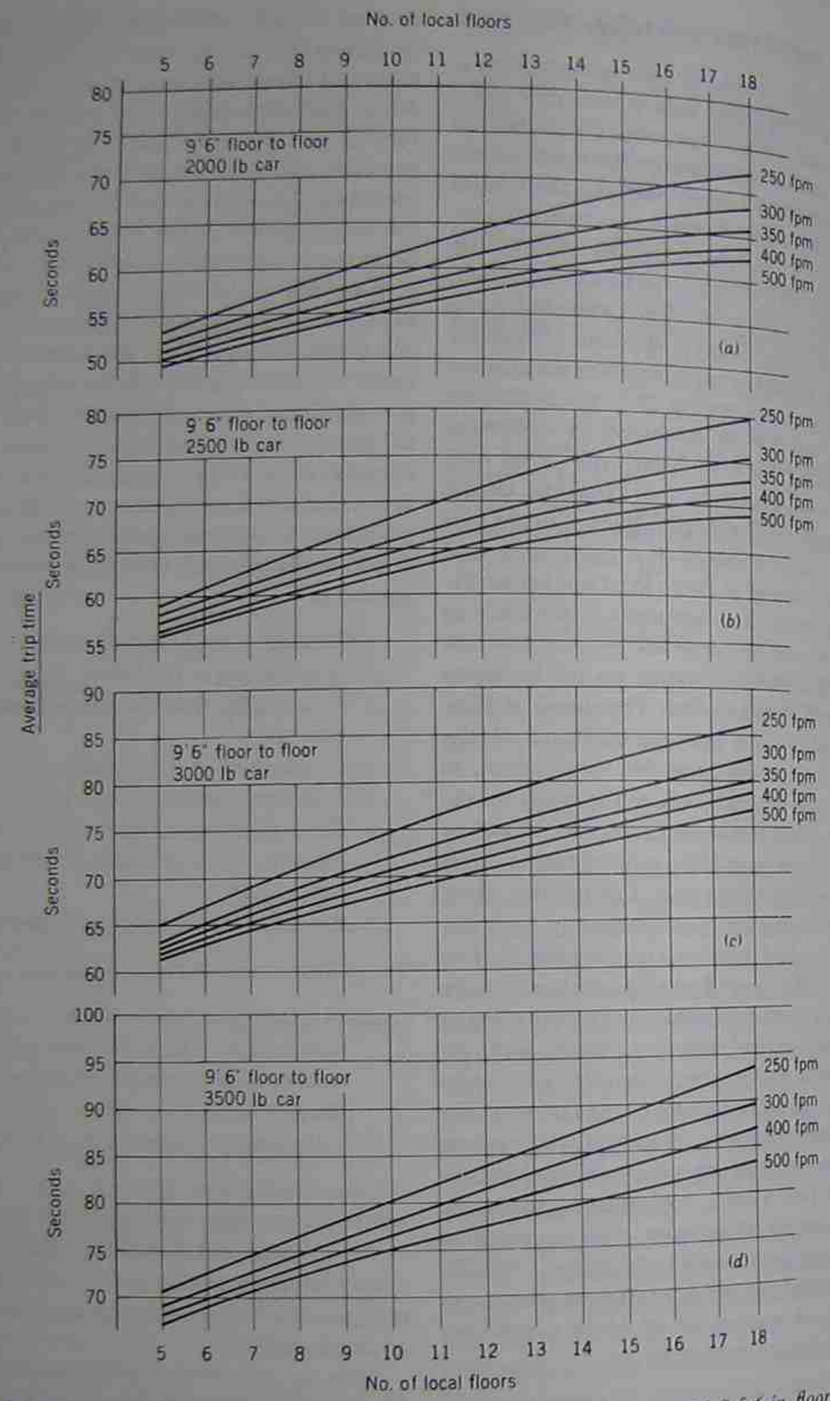

Fig. 23.15 *Plots of average trip time for various car speeds and capacities with 9-ft 6-in. floor height and 30-s interval.*

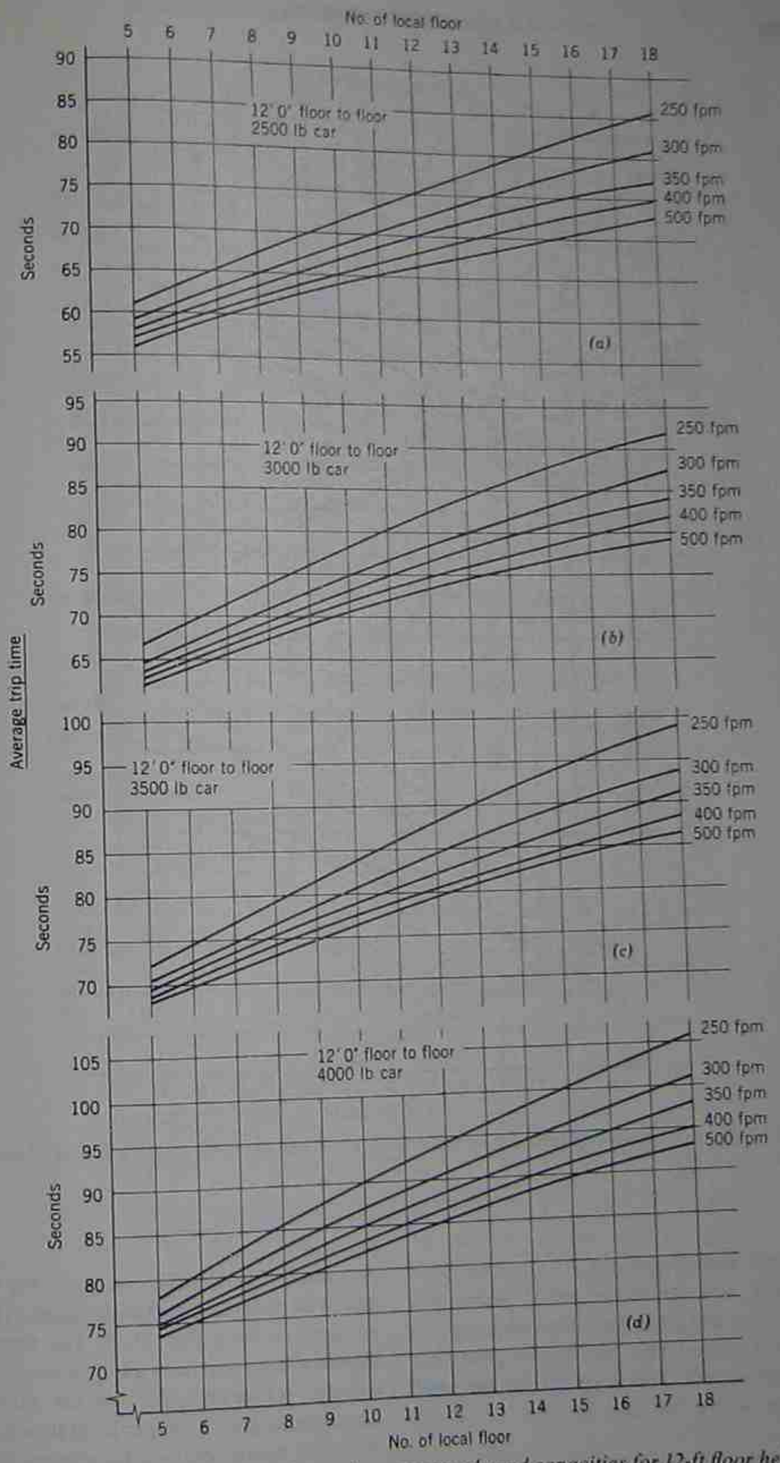

Fig. 23.16 *Plots of average trip time for various car speeds and capacities for 12-ft floor height and 30-s interval.*

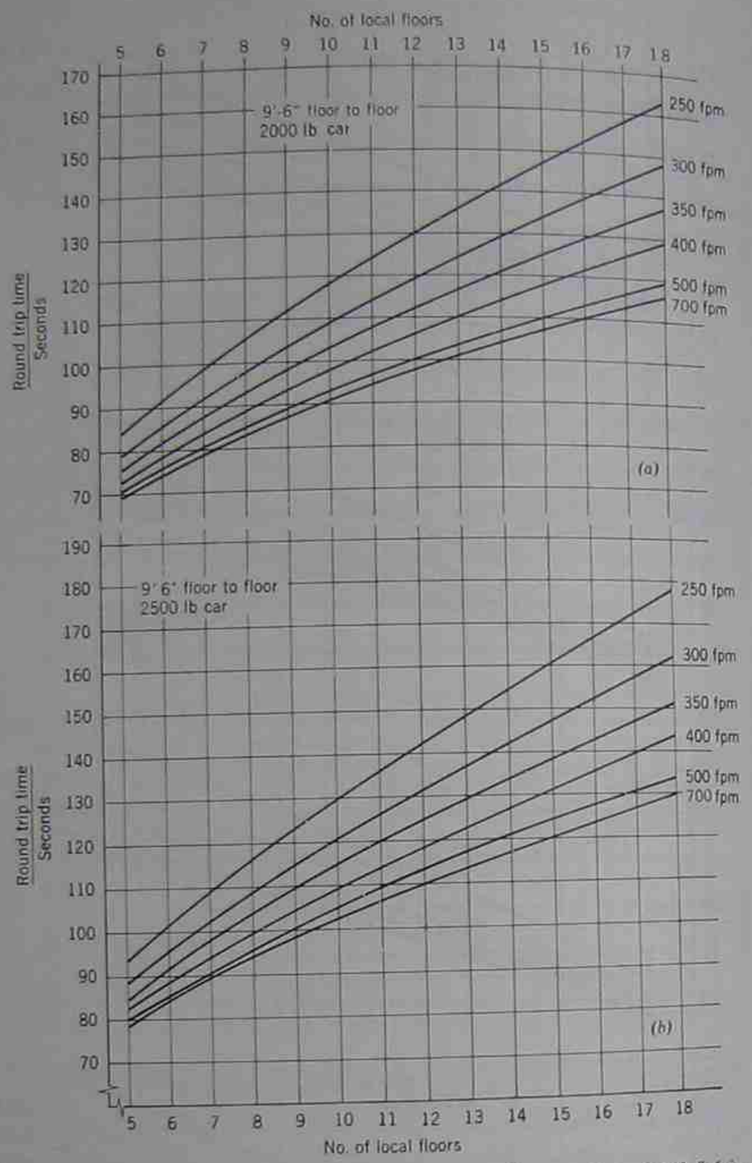

Fig. 23.17 *Plots of round-trip time for various car speeds and capacities with 9-ft 6-in. floor heights and 30-s interval.*

accelerates and decelerates. The higher speed equipment with its larger motor accelerates more quickly and gives some time advantage on the return express run, but has no great time advantage overall. This accounts for the small reduction above 500 fpm in Figs. 23.17 and 23.18.

In calculating round-trip time for cars in upper zones, it is necessary to know the time required to traverse the express floors. This may be obtained from Fig. 23.19. The times given therein are for *one-way* express runs. Thus to calculate *RT* for an upper zone car, take the *RT* corresponding to the upper local floors and add *twice* the figure obtained for express run time from Fig. 23.19.

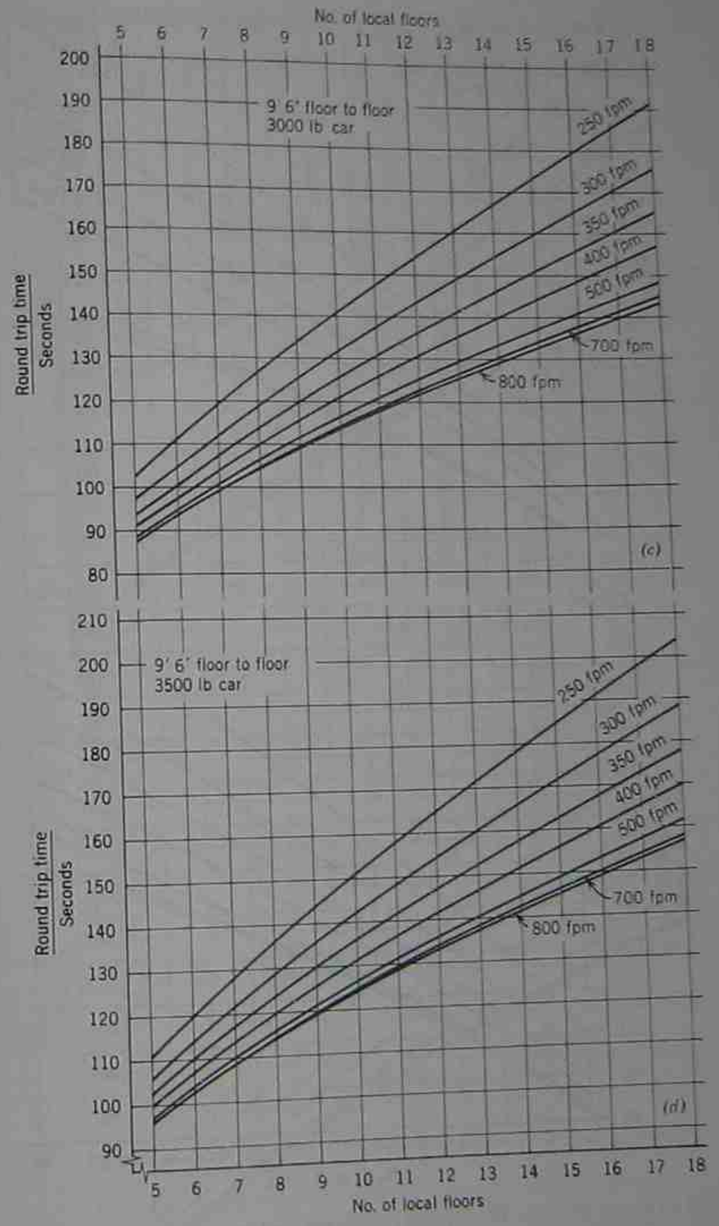

Fig. 23.17 *(continued)*

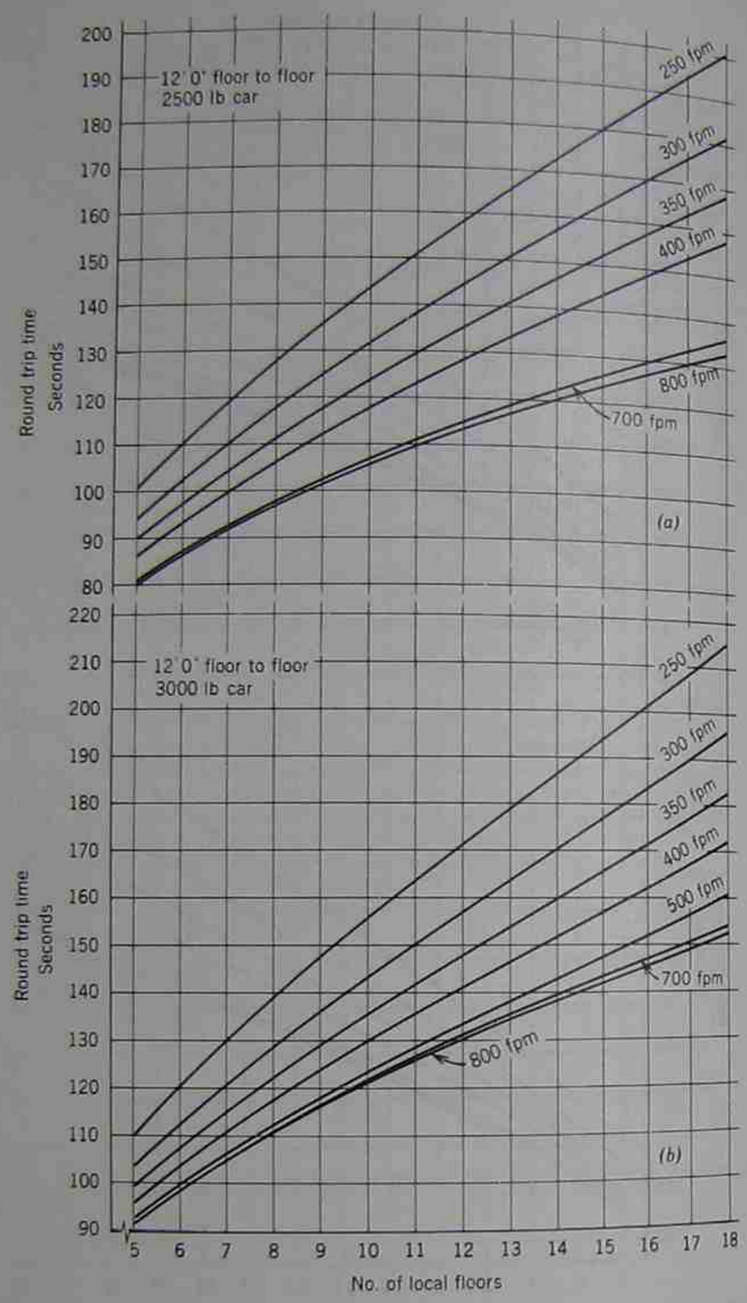

Fig. 23.18 *Plots of round-trip time for various car speeds and capacities with 12-ft floor height and 30-s interval.*

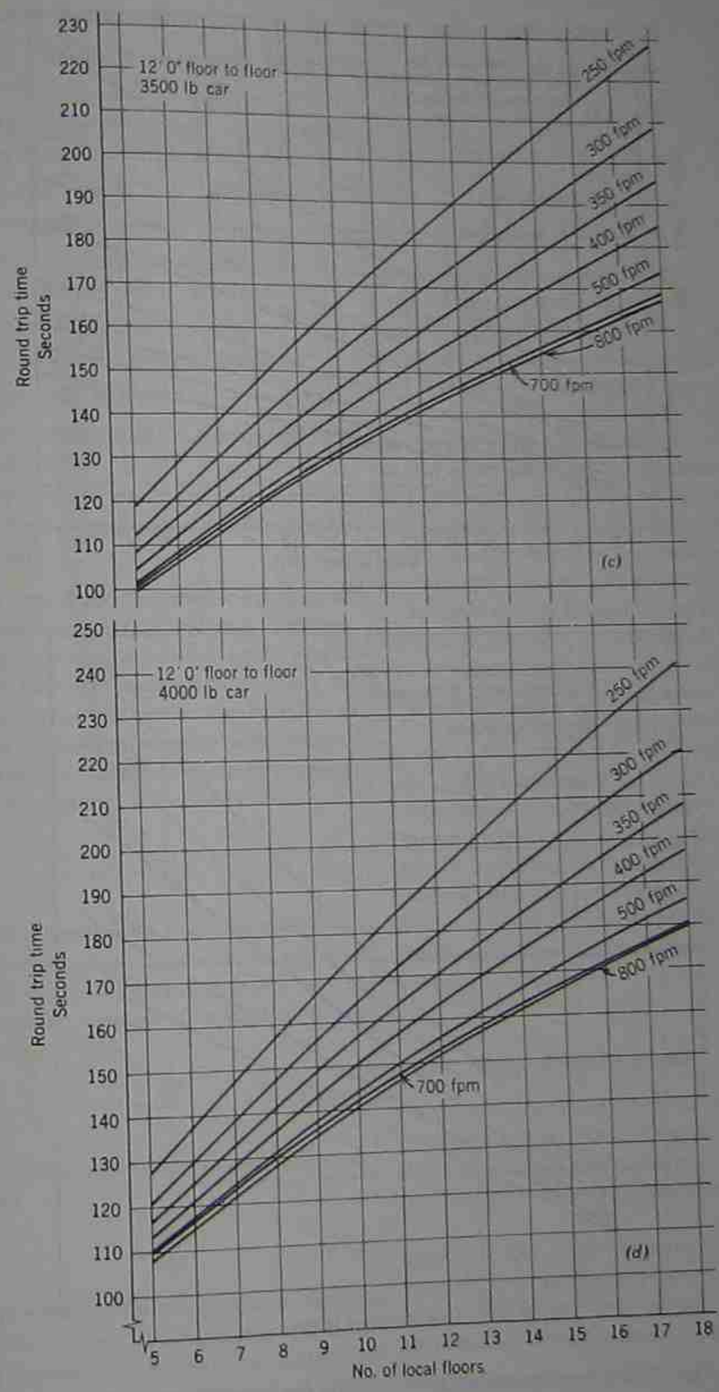

Fig. 23.18 *(continued)*

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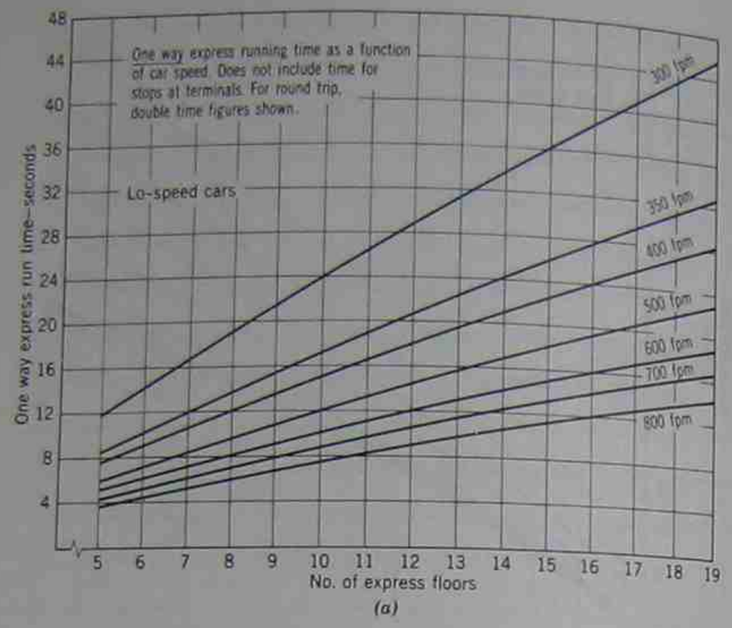

Fig. 23.19 *One-way express running time, not including terminal time.*

23.33 System Relationships

The symbols that will be used in all elevator discussions are:

p	Individual car capacity, equal to 80% of maximum during peak hours.
h	5-min capacity of a single car.
N	Number of cars in a system.
HC	System 5-min handling capacity, expressed in number of persons.
RT	Round-trip time, in seconds.
$AVTRP$	Average trip time, in seconds.
I	Interval, in seconds.
D	Population density, in square feet per person.
PHC	Percent of population to be moved in 5 min, expressed as a percentage figure.

Having considered the definition of interval, handling capacity, average and round trip time, it is well to demonstrate at this point the interrelationships between these quantities, and the other equations governing the remaining factors that define elevator systems. We have previously established that handling capacity is determined by car capacity p and interval I:

$$HC = \frac{300p}{I} \tag{23.1}$$

In a system comprising a single car the interval (I) is obviously equal to the round trip time (RT). In a system with more than one car, the interval will be reduced in proportion to the number of cars. Thus,

$$I = \frac{RT}{N} \tag{23.2}$$

The 5-min handling capacity (h) of a single car is then

$$h = \frac{300p}{RT} \tag{23.3}$$

if we remember that for a single car, its interval is its round trip time. It follows then that if the handling capacity of a single car is h, then the handling capacity of N cars is N times as much. Thus

$$HC = N \times h$$

or

$$N = \frac{HC}{h} \tag{23.4}$$

23.34 Car Speed

The selection of the car speed to be used is a matter of trial and error, the final selection being that required to give a round-trip time (RT) which will in turn give an acceptable interval. However, in order to establish a starting point, it has been found that a minimum car speed corresponding to a given building height, or in elevator parlance—rise, can be established. Similarly, although car size can be selected at any value, it has been shown that for certain facility types, specific-size cars are indicated. These recommendations are tabulated in Table 23.8.

It should also be borne in mind that elevator equipment falls into distinct speed categories. Thus most manufacturers will use geared equipment through 400 fpm and gearless thereafter. The next category is 500 fpm gearless, followed by 600 to 700 fpm, and so on. Therefore, it is wise to avoid moving into the next higher and more expensive equipment category, if possible. This may mean exceeding recommended interval or dropping slightly low in handling capacity. It will be found, however, that this can be done without injury to the elevator system, provided a good group supervisory control system is employed.

23.35 Single-Zone Systems

Having established the relationships that govern the design and performances of an elevator system, comprising a single zone, it would be helpful to follow through an illustrative example.

EXAMPLE 23.1. Office building, downtown, diversified use, 14 rentable floors above lobby, each 12,000 ft net. Floor-to-floor height—12 ft. Determine a workable elevator system.

SOLUTION. From Table 23.5, average HC is 13%. From Table 23.3, maximum recommended

TABLE 23.8 **Elevator Equipment Recommendations**

Usage		Car Capacity (lb)	Minimum Car Speed (fpm)	Car Travel (feet)
Office buildings	Small building	2500	350–400	0–125
	Medium building	3000	500–600	126–225
	Large building	3500	700	226–275
			800	276–375
			1000	Above 375
Hotels		2500 3000	As above	As above
Hospitals			150	0–60
			200–250	61–100
		3500	250–300	101–125
		4000	350–400	126–175
			500–600	176–250
			700	Above 250
Apartment houses*			100	0–75
		2000	200	76–125
		2500	250–300	126–200
			350–400	Above 200
Retail stores		3500	200	0–100
		4000	250–300	101–150
		5000	350–400	151–200
			500	Above 200

*FHA minimum requirements call for full-collective variable voltage control, minimum of two cars, and approximately 120 bedrooms per car, for all buildings exceeding seven stories in height.

interval is 30 s. From Table 23.6, average population density is 160 ft² per person.

Building population:

$$\frac{14 \text{ floors at } 12{,}000 \text{ ft}^2}{160 \text{ ft}^2 \text{ per person}} = 1050 \text{ persons}$$

Suggested minimum handling capacity:

$PHC = 13\%$

$HC = 0.13 \times 1050 = 137$ persons

rise = 14 floors at 12 ft = 168 ft

From Table 23.8 we select a recommended car size of 3000 lb at 500 fpm.

3000 lb
500 fpm

Then from Figs. 23.18*b* and 23.16*b*:

$RT = 143$ s $\quad AVTRP = 76$ s

Single-car capacity $h = 300p/RT$ (see Table 23.3 for p):

$$h = \frac{300(16)}{143} = 33.5 \text{ persons}$$

$$N = \frac{HC}{h} = \frac{137}{33.5} = 4.1 \text{ cars, say } 5$$

(four cars would give an excessive interval)

$$I = \frac{RT}{N} = \frac{143}{5} = 28.7 \text{ s}$$

$$\text{actual } PHC = \frac{5(13\%)}{4.1} = 15.9\%$$

These figures are excellent.

We should try faster cars, to reduce the number of cars, or slower cars, to reduce car cost. We select 700 fpm and 400 fpm.

3000 lb
700 fpm

$RT = 140 \quad AVTRP = 73$ s

$$h = \frac{300(16)}{140} = 34.3 \text{ persons}$$

$$N = \frac{137}{34.3} = 4 \text{ cars}$$

$$I = \frac{RT}{N} = \frac{140}{4} = 35$$

$$\text{actual } PHC = \frac{4(13\%)}{4} = 13\%$$

This solution, that is, 4 cars at 700 fpm, 3000 lb, is marginally acceptable. The interval is somewhat high, but the handling capacity is acceptable. Now, trying the slower car:

3000 lb
400 fpm

$RT = 152, \quad AVTRP = 77$ s

$$h = \frac{300(16)}{152} = 31.6 \text{ persons}$$

$$N = \frac{137}{31.6} = 4.34 \text{ say } 5 \text{ cars}$$

$$I = \frac{152}{5} = 30.4 \text{ s}$$

$$\text{actual } PHC = \frac{5(13\%)}{4.34} = 15\%$$

This is also an acceptable arrangement. Thus, of the three arrangements, the two most likely choices are

4 cars, 3000 lb, 700 fpm

5 cars, 3000 lb, 400 fpm

To reduce the interval of the four-car solution, we can try a high-speed smaller car, since a larger car will *increase* the interval.

2500 lb
700 fpm

$RT = 122$ s $\quad AVTRP = 66$ s

$$h = \frac{300(13)}{122} = 32 \text{ persons}$$

$$N = \frac{137}{32} = 4.28 \text{ cars}$$

Using four cars:

$$I = \frac{122}{4} = 30.5 \text{ s}$$

$$PHC = \frac{4}{4.28}(13) = 12.1\%$$

Handling capacity is insufficient. Using five cars:

$$I = \frac{122}{5} = 24.4 \text{ s}$$

$$PHC = \frac{5}{4.28}(13\%) = 15.19\%$$

Of these two solutions only the five-car arrangement is satisfactory, since four cars yield insufficient PHC. However, because interval is low and PHC high, we can drop the speed and still obtain a workable arrangement:

2500 lb
400 fpm

$RT = 139$ s $\quad AVTRP = 71$ s

$$h = \frac{300(13)}{139} = 28.0 \text{ persons}$$

$$N = \frac{137}{28.0} = 4.9, \text{ say } 5 \text{ cars}$$

$$I = \frac{139}{5} = 27.8 \text{ s}$$

$$PHC = \frac{5}{4.9}(13\%) = 13.3\%$$

which is acceptable, and obviously cheaper than five cars of 3000 lb capacity and 400 fpm speed.

We thus have two solutions to compare:

1. Four 3000-lb cars at 700 fpm, gearless, giving an interval of 35 s and a handling capacity of 13%.
2. Five 2500-lb cars at 400 fpm, geared, giving an interval of 27.8 s and a handling capacity of 13%.

The final selection should at this point be made on the basis of cost and core layout. When considering cost, note that first cost is the governing factor only in a speculative venture. With an owner-operator building, the cost comparison should be on a life-cycle basis. Cost figures must reflect the impact of elevator space requirements on net rentable area in the building.

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TABLE 23.9 **Relative First Cost[a] Figures for Passenger Elevators at Various Speeds (fpm) (for a Given Drive System)**

Car Size (lb)	Hydraulic	Geared Traction			Gearless Traction			
	100	200	350	500	500	700	1000	1200
2000	40	80	100	130	165	170	220	235
2500	43	85	115	145	175	180	235	250
3000	50	90	120	150	180	185	250	265
3500	58	95	125	155	190	195	265	275
4000	60	100	135	165	200	205	280	300
4500[b]	70	120	150	185	225	230	300	325
5000[b]	75	130	160	200	240	250	330	350

[a]Costs are ±10%; based on standard fixtures, cabs, and entrances, and average rise for the speed indicated.

[b]Service elevator or hospital elevator.

NOTE: See Table 23.8 for speed/rise recommendation.

Comparative relative cost figures are given in Table 23.9. Utilizing these data, we have:

1. Four 3000-lb cars at 700 fpm = 4 × 185 = 740 cost units.
2. Five 2500-lb cars at 400 fpm = 5 × 125 = 625 cost units.

The choice, *on a first-cost basis*, is clearly in favor of the geared 400-fpm units. However, the costs are sufficiently close that in a life-cycle cost analysis, even without considering the comparative space cost, which favors the four-car bank, the lower maintenance and energy costs of the gearless machine might reverse the results. Furthermore, 2500 lb cars are generally considered too small for office building use except for small suburban buildings not exceeding 10 floors as seen in Table 23.8. The recommendations in Table 23.8 are based on extensive field surveys and experience.

As mentioned in Section 23.23 and shown in Fig. 23.12, planners of new buildings today generally take advantage of elevator selection software provided by consultants, manufacturers, or by in-house capabilities. The results of one such program as applied to the problem just solved manually are shown in Fig. 23.20. This particular program was prepared by Otis Elevator Co. Note that the results in Fig. 23.20*a* correspond exactly to the results obtained manually (compare with the first trial calculation in the solution above). The correspondence is not surprising since the round-trip curves in Fig. 23.18 are based on a 3.3-s door time and a 4.0-ft/s^2 car acceleration, as shown in the figure. Note that high call reversal occurs at the top floor [13.5 (i.e., 14)] and that the number of up stops is 10 (9.7 from statistical calculations). The up-peak calculation assumes no counterflow traffic (i.e., an express down run and no interfloor traffic), as shown. These can be added, however, yielding much different results, as shown in Fig. 23.20*b*. We see there that counterflow traffic (down stops) of only 3% and interfloor traffic of 1%, both of which are reasonable, change the interval and handling capacity to borderline acceptability.

23.36 Multizone Systems

In general, buildings with less than 15 stories are elevatored with a single zone (i.e., all cars serve all floors), and buildings with more than 20 stories are split into two or more zones. The area in between—16 to 19 stories—can go either way, depending on population density and required interval. Actually, a modern group supervisory system can automatically zone a building when traffic requires it. However, such an arrangement, although efficient, is expensive both as to


```
OtisPlan Single Group Performance

Single Deck Up Peak

name: Sample problem
floors above lobby: 14                  population per floor:   75people
lobby height:  12.0ft                   % counterflow: 0.0
average floor height: 12.0ft            % interfloor:  0.0
express zone height:    0.0ft           number of cars: 5
door time:  3.3sec                      car speed:   500.0fpm
12ft flight time:  4.3sec               car capacity: 3000lbs
car acceleration: 4.00ft/sec/sec        up car loading: 16people/car
high call reversal:  0.0
up probable stops:  0.0                 added trip time:  0.0sec

(Use 0 to calculate high call
 reversal and probable stops)

                        *** RESULTS ***
round trip time:      144.0sec          high call reversal:    13.5
interval:              28.8sec          up probable stops:      9.7
up handling capacity: 15.9%/5 min
```

(a)

```
OtisPlan Single Group Performance

Single Deck Up Peak

name: Sample problem
floors above lobby: 14                  population per floor:   75people
lobby height:  12.0ft                   % counterflow: 3.0
average floor height: 12.0ft            % interfloor:  1.0
express zone height:    0.0ft           number of cars: 5
door time:  3.3sec                      car speed:   500.0fpm
12ft flight time:  4.3sec               car capacity: 3000lbs
car acceleration: 4.00ft/sec/sec        up car loading: 16people/car
high call reversal:  0.0
up probable stops:  0.0                 added trip time:  0.0sec

(Use 0 to calculate high call
 reversal and probable stops)

                        *** RESULTS ***
round trip time:      176.1sec          high call reversal:    13.5
interval:              35.2sec          up probable stops:      9.7
up handling capacity: 13.0%/5 min

Alt-H - Help Information
```

(b)

Fig. 23.20 *Printout of the results of a computerized elevator selection program. (a) Up-peak conditions, assuming no down stops (0% counterflow) and no interfloor traffic. The results correspond very closely to those obtained manually in Example 23.1 (see text). (b) Addition of even light counterflow and interfloor traffic can seriously affect the system's performance, as can be seen from the round trip, interval, and handling capacity figures. (Courtesy of Otis Elevator Co.)*

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equipment and from a construction viewpoint since it does not take advantage of the considerable savings engendered by blind lower shaftways for upper-zone elevators. Analysis of multizone systems is complex and today is rarely done by hand. The interested reader is referred to Stein et al. (1986) for a detailed explanation of the technique involved. Most designers and consultants use one of the many extant computerized simulation and selection programs. These have the advantage that in addition to using basic criteria and building parameters, they can also consider the effect of variations in traffic control. Furthermore, the best of these programs can evaluate the engineering and economic impact of such factors as varying rental rates for different floors, rental space, machine room and hoistway space, core layout, and the structural ramifications of the elevator system.

23.37 Other Elevator Selection Considerations

For commercial buildings rough costs can be estimated from Tables 23.9 and 23.10. Special considerations for various building types are given below.

(a) Office Buildings. All necessary design criteria can be selected from Tables 23.3 to 23.6. Supervisory group control is normally microprocessor based. Approximately one service car per 10 passenger cars should be provided, or alternatively one car for every 300,000 ft² of net area. Service cars should be 4000 lb or larger without dropped ceiling and, if also used for passenger service, equipped with wall pads. An oversized door (e.g., 4 ft, 0 in. or 4 ft, 6 in.) is particularly useful in handling furniture. Service elevators should have a shaftway door at every level plus easy access to the truck dock or other freight entrance as well as the lobby. These can operate as service cars normally but can serve as passenger cars in peak periods to alleviate congestion and delay. This fact is particularly useful in marginal service designs.

TABLE 23.10 **Office Buildings: Cost of Elevator and Electric Work**

Item	Number of Stories		
	20	35	60
Elevator work	10.9%	11.9%	12.2%
Electric work	13.3%	12.6%	12.2%

(b) Apartment Houses. Studies indicate that apartment house traffic depends not only on population but also on location and type of tenant. Houses with many children experience a school-hour peak; houses in midtown with predominantly adult tenancy exhibit evening peaks due to the homecoming working group and outgoing amusement traffic. Normally, a single elevator will suffice, although a second car functioning as a service and/or passenger car is sometimes indicated, particularly in buildings taller than six stories. The cars may be banked or separated, as desired. If a single car is used, it should be service elevator size.

Self-service collective control is the general choice, with provision for attendant control in prestige buildings. With smaller cars and short rise, a swing-type manual corridor door is acceptable; in larger installations both the cab and corridor door should be the power-operated sliding type.

Service elevators must be large enough to handle bulky furniture and should therefore be at least 3000 lb and preferably 3500 lb, with a 48-in. door and high ceiling. Hoistways must be isolated from sleeping rooms by lobbies or other space. Similarly, machine rooms must be isolated, since the starting and stopping of motors and other machine room noises are an effective barrier to sound sleep. Security arrangements are discussed in Section 24.6.

(c) Hospitals. As mentioned in Table 23.6, the governing factor in the determination of elevator requirements may be either normal hospital traffic or visitor traffic, depending on the visiting-hour schedule. Due to the large amount of vehicular traffic such as stretcher carts, wheelchairs, beds, linen carts, and laundry trucks, the elevator cabs are much deeper than the normal passenger type. This type of car when used for passenger service holds more than 20 persons and therefore gives slow service. For this reason, it is occasionally advisable to utilize some normal passenger cars in addition to hospital-size cars, particularly in large hospitals.

The use of tray and bulk carts in food service imposes a considerable load on the elevators before, during, and after meals, and passenger service is seriously disrupted. To alleviate this congestion and delay, many architects and hospital administrators prefer the use of dumbwaiter cars or another of the many types of materials-handling system that will handle a 15½ × 20 in. food tray. These systems can also be used for transporting pharmaceuticals and other items and are discussed in Sections 24.19 and 24.20.

Elevators should be grouped centrally, although separated by type of use. Car control is normally self-service collective.

Population of the hospital may be estimated from Table 23.6. Experience has shown that a carrying capacity of 45 passengers in a 5-min period is adequate (estimating each vehicle as equivalent to 9 passengers).

Intervals should not exceed 1 min. All recommendations for service to the handicapped should be adopted (see Section 23.11).

(d) Retail Stores. Retail stores present a unique problem in vertical transportation inasmuch as the objective is partially to transport persons to specific levels and partially to expose the passengers to displayed merchandise. For this reason modern stores rely almost exclusively on escalators, with one or two small elevators intended for use by staff and handicapped persons. When for some reason it is desired to equip a store with elevators, use the recommendations shown in Table 23.8, calculated for a load of between 10 and 20% of store population. Control should be automatic, selective collective. Cars are arranged in a straight line to facilitate loading and waiting.

THE PHYSICAL PROPERTIES AND SPATIAL REQUIREMENTS OF ELEVATORS

23.38 Shafts and Lobbies

The elevator lobbies and shafts form one of the major space factors with which the architect is concerned. The elevator lobby on each floor is the focal point from which the corridors radiate for access to all rooms, stairways, service rooms, and so forth. Such lobbies obviously must be located one above the other. The ground-floor elevator lobby (also called the lower terminal) must be conveniently located with respect to main entrances. The equipment within or adjacent to this area should include public telephones, building directory, elevator indicators, and control panels.

All lobbies should be adequate in area for the peak-load gathering of passengers to ensure rapid and comfortable service to all. The number of people contributing to the period of peak load (15- to 20-min peak) determines the required lobby area on the floor.

Approximately 5 ft² of floor space per person should be provided at peak periods for waiting passengers at a given elevator or bank of elevators. The hallways leading to such lobbies should also provide about 5 ft² per person, approaching the lobby. Under self-adjusting relaxed conditions, density is about 7 ft² per person. However, in peak periods, crowding occurs, reducing this to 3 to 4 ft². An acceptable compromise is 5 ft² per person.

The main lower terminal of elevator banks is generally on the street-floor level, although it may be on the mezzanine level, when the elevations of the street entrances vary so that one side of the building is at mezzanine level, while another entrance is lower. Such a situation is ideal for the use of escalators, which will economically and rapidly carry large numbers of persons between levels, thus making practical and efficient a single main lower elevator terminal. The upper terminal is usually the top floor of the building. Typical dimensional data and lobby arrangements are shown in Figs. 23.21 to 23.23.

23.39 Dimensions and Weights

Manufacturers and elevator consultants will supply standard layouts for elevators including dimensions, weights, and structural loads. Furthermore, to assist in preliminary design, major manufacturers have agreed upon, and publish, a set of Standard Elevator Layouts via their trade organization, the National Elevator Industry, Inc. (See Section 23.11 for NEII recommendation for the handicapped.) One such standard,

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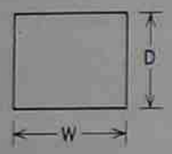


Car size	D	W
2500 lb	70"	8' 6"
3000 lb	7' 6"	8' 6"
3500 lb	8' 2"	8' 6"
4000 lb	8' 2"	9' 6"

Fig. 23.21 *Rough hoistway dimensional data to be used in architectural single-line planning stage.*

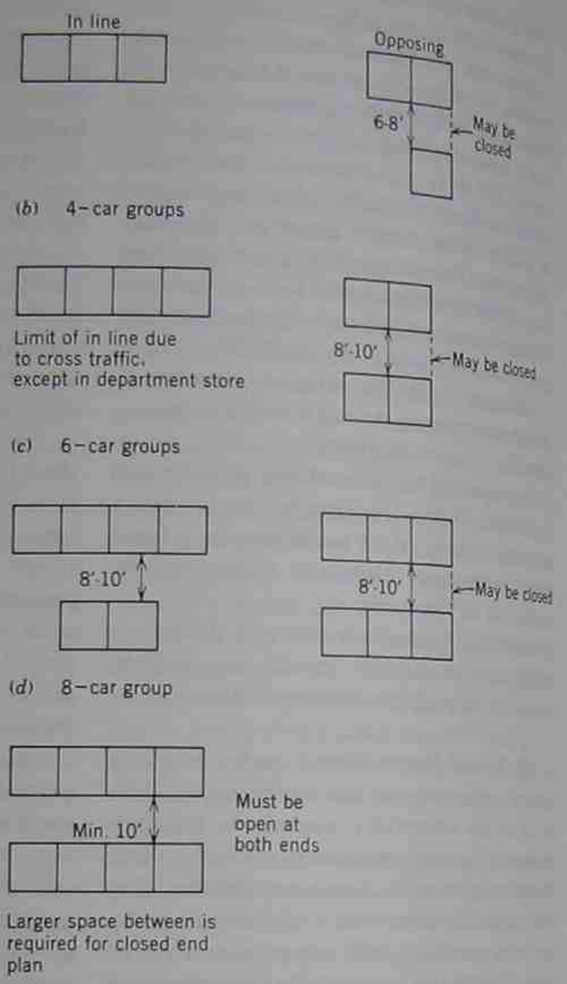


Fig. 23.22 *Lobby groupings for single zones: three-, four-, six-, and eight-car groups.*

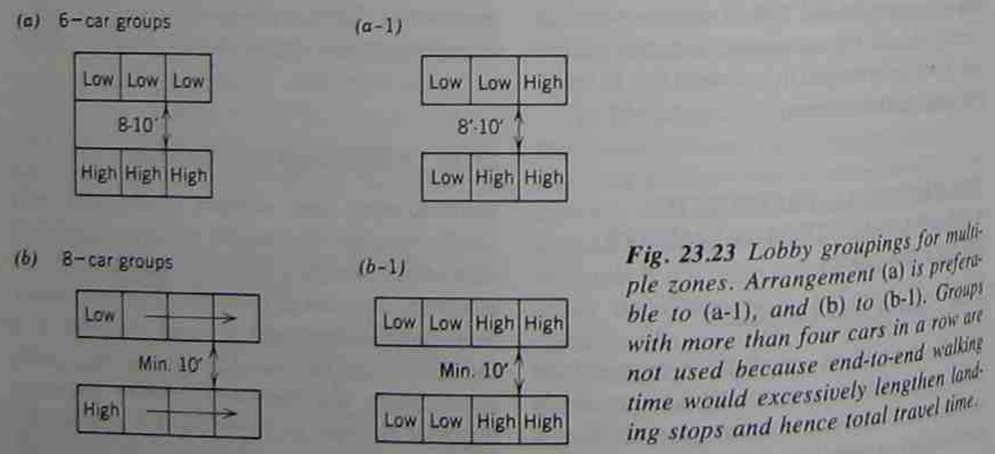


Fig. 23.23 *Lobby groupings for multiple zones. Arrangement* (a) *is preferable to* (a-1), *and* (b) *to* (b-1). *Groups with more than four cars in a row are not used because end-to-end walking time would excessively lengthen landing stops and hence total travel time.*

with applications, is reproduced in Fig. 23.24 for 500- to 700-fpm gearless units in the full range of car capacities. These standards are available from the NEII.

As may be seen from Fig. 23.24, it is necessary, in providing for an elevator installation, to consider such factors as the depth of the pit, the dimensions of the hoistway, the clearance from the top of the hoistway to the floor of the penthouse, the size of the penthouse, and the loads that must be carried by the supporting beams.

The penthouse floor and secondary level floor are located above the shaft of each elevator and need approximately 1½ stories of additional height above the top of the support beam of a given elevator when it is standing at its top-floor location. The actual floor area required by the elevator traction machine and its controls is roughly two times the area of the elevator shaft itself. The required area of the floor of the secondary level is no larger than the elevator shaft it serves. The machine room contains the bulk of the elevator machinery. Since some of this equipment will have to be moved for maintenance, it is advisable to furnish an overhead trolley beam that can be used during installation as well. The maximum beam load will be supplied by the elevator manufacturer.

Some typical machine room dimensional data follows, taken from actual installations. Because of the multiple drive options and the flexibility in equipment arrangement, no general conclusions can be drawn from these figures; they are listed simply to give a conceptual picture.

Bank Description	*Machine Room Dimensions (Rounded to Nearest Foot)*
2—2500 lb 125 fpm	16 × 18
3—2500 lb 350 fpm	19 × 26
3—2500 lb 700 fpm	21 × 26
6—3500 lb 500 fpm	26 × 29
6—3500 lb 700 fpm	27 × 27
6—3500 lb 1000 fpm	27 × 27
6—5000 lb 450 fpm	31 × 33

A manufacturer's layout giving dimensional data for hoistway and machine room is shown in Fig. 23.25.

When penthouse space is not available and a hydraulic unit is not desired, a basement traction unit, also referred to as an underslung arrangement, can be used. These units are low speed (100 to 350 fpm) and are therefore applicable where rise is limited and traffic light to medium. Figure 23.26 shows a shaft section with car and dimensional data.

23.40 Structural Stresses

For the purpose of structural design it is necessary to know the overhead load that must be supported by the foundations, by structural columns extending upward to the penthouse, and by the main beams that support the penthouse floor and subfloor. These loads (reactions) are supplied by manufacturers and usually include the actual dead weights of equipment when the elevator is not in motion, plus the added weight caused by the momentum of all moving parts and passengers when the elevator is at top speed and is suddenly caused to stop rapidly by the safety devices.

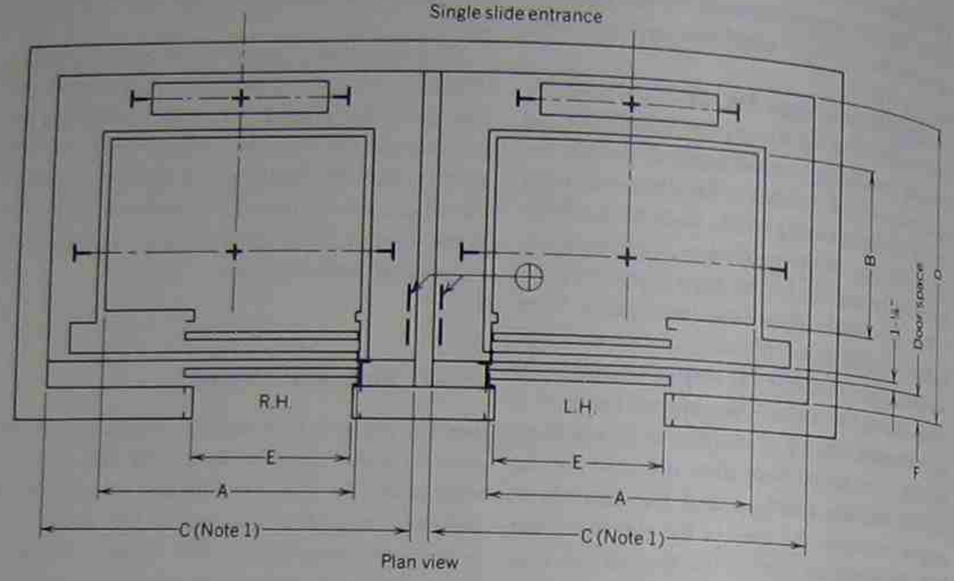
23.41 Linear Elevator Motor Drive

A revolutionary elevator dreive design developed by OTIS utilizes a linear induction motor build into the counterweight frame. Motive power is therefore supplied at the counterweight, thus entirely eliminating the overhead traction machine and machine room. Trial installation is in progress at this writing in several locations outside the USA. The inherent architectural, construction, energy usage, maintenance and cost advantages of this elegant design will make it an extremely attractive option for American building designers once it has achieved the required Code and jurisdictional approvals. However, because the Code is predicated on the use of a traction machine, which in this design is entirely absent, an essentially new section of Code will have to be prepared to

TRANSPORTATION

Vertical Transportation Standards
Electric Passenger Elevators

Single slide entrance



Plan view

Note 1. "C" dimension does not include any allowance for rail backing.

Rated Speeds 500–700 fpm

Rated Load (lb)	Area[a]	Dimensions (ft–in.) +A	+B	C	D	E	Entrances Type		F min (in.)
Application: Office Bldg. Apartment Houses, Hotels, Banks, Etc.									
2000	24.2	5–8	4–3	7–5	6–11	3–0	Single slide[b]	Center opening	5
2500	29.1	6–8	4–3	8–6	6–11	3–6	Single slide[b]	Center opening	5
3000	33.7	6–8	4–7	8–6	7–4	3–6	Single slide[b]	Center opening	5
3500	38.0	6–8	5–3	8–6	8–0	3–6	Single slide[b]	Center opening	5
4000	42.2	7–8	5–3	9–6	8–0	4–0	Center opening[b]		5

[a]Maximum allowable inside car area in square feet.

[b]These car sizes and entrance types comply with NEII suggested minimum passenger elevator requirements for the handicapped; 2000 lb rated load will not accommodate ambulance-type stretcher.

Fig. 23.24 *Typical elevator installation dimensional data. (Reproduced with permission of National Elevator Industry Inc., 185 Bridge Plaza North, Fort Lee, NJ 07024. Copyrighted 1983,* Vertical Transportation Standards.*)*

Vertical Transportation Standards
Electric Passenger Elevators

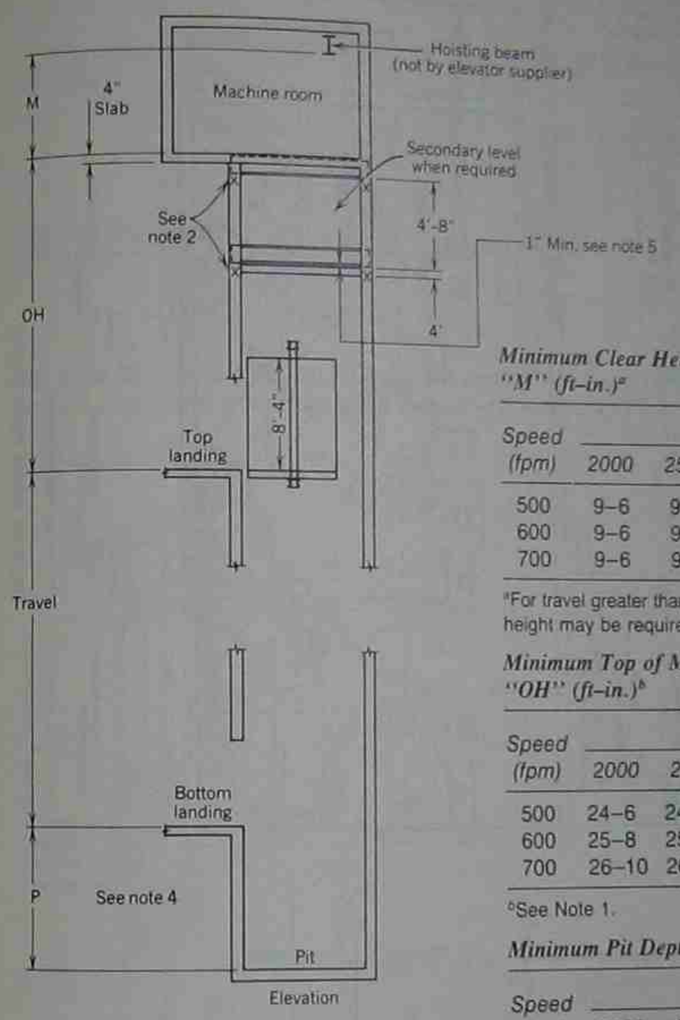


Fig. 23.24 *(continued)*

Notes

1. "OH" dimensions are based on an 8 ft, 4 in. overall car height.
2. Supports for elevator machine beams at X-X in elevation, not by elevator supplier.
3. Machine room floor slab is flush with or above top of machine beams.
4. For travel greater than 400 ft, increased pit depth may be required. Consult elevator supplier.
5. Top of support to be 1 in. above top of slab.

Minimum Clear Height of Machine Room "M" (ft–in.)[a]

Speed (fpm)	Rated Load (lb) 2000	2500	3000	3500	4000
500	9–6	9–6	9–6	9–6	9–6
600	9–6	9–6	10–0	10–6	10–6
700	9–6	9–6	10–6	10–6	10–6

[a]For travel greater than 500 ft, increased machine room height may be required.

Minimum Top of Machine Room Floor "OH" (ft–in.)[b]

Speed (fpm)	Rated Load (lb) 2000	2500	3000	3500	4000
500	24–6	24–6	24–6	24–6	24–6
600	25–8	25–8	25–8	25–8	25–8
700	26–10	26–10	26–10	26–10	26–10

[b]See Note 1.

Minimum Pit Depth "P" (ft–in.)[c]

Speed (fpm)	Rated Load (lb) 2000	2500	3000	3500	4000
500	11–0	11–0	11–0	11–0	11–0
600	12–9	12–9	12–9	12–9	12–9
700	12–9	12–9	12–9	12–9	12–9

[c]See Note 4.

TRANSPORTATION

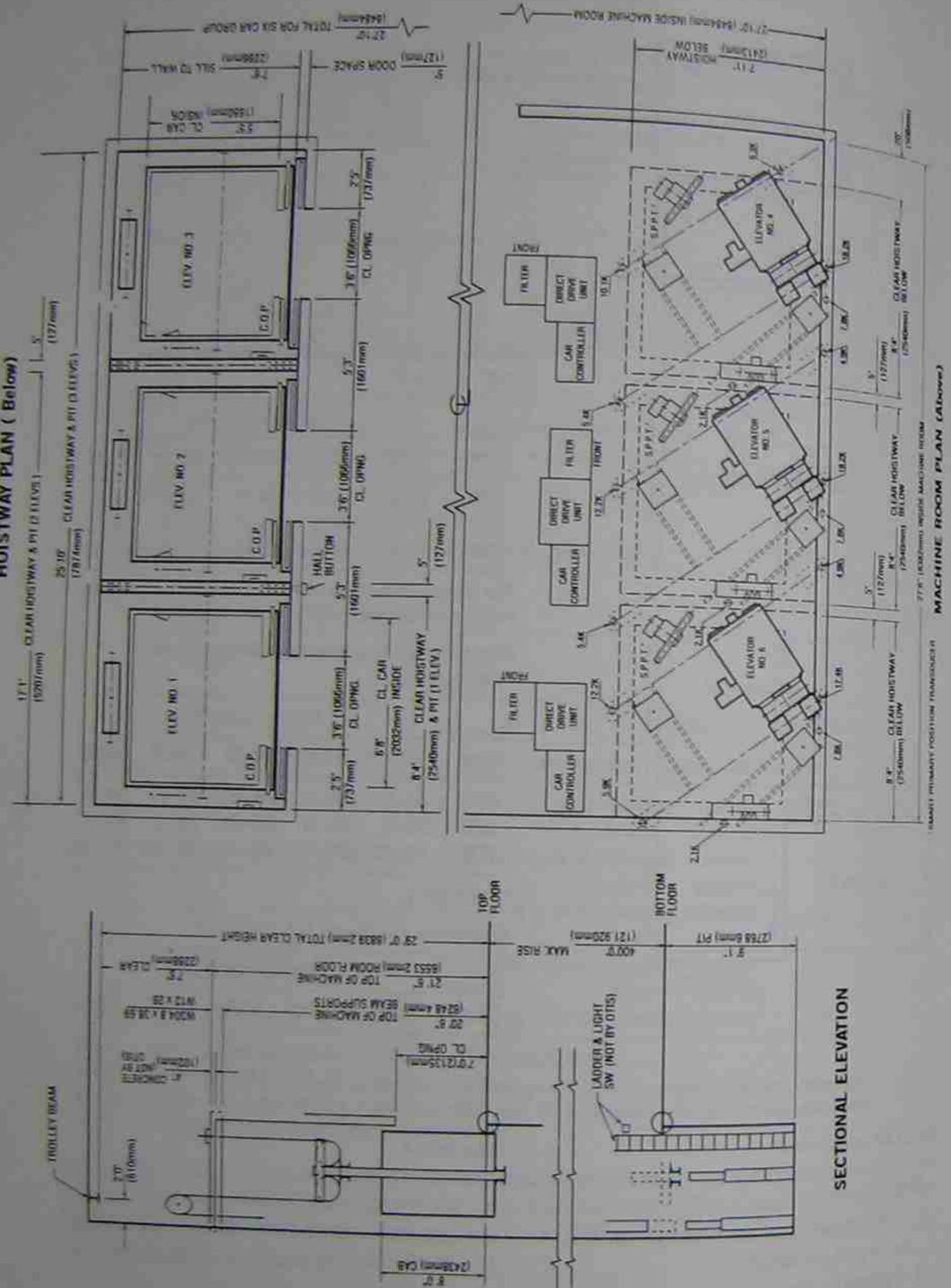
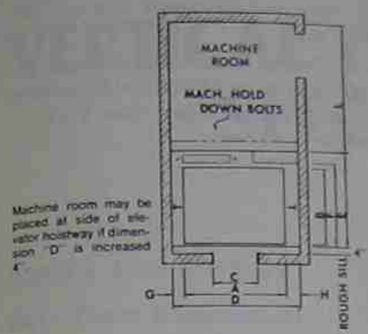
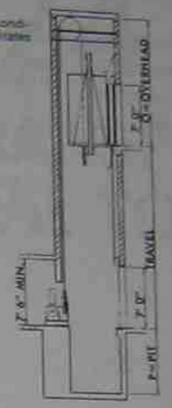


Fig. 23.25

Basement Traction — medium and low speed

Basement traction elevators are utilized for limited overhead conditions in new and existing buildings. This type of elevator facilitates future floor expansion.





2:1 ROPING ARRANGEMENT

permits a minimum overhead installation. Because of the sheave arrangement, it is necessary to have a greater pit depth than for a comparable 1:1 installation.

RECOMMENDED SIZES & CAPACITIES

TYPE BUILDING	SMALL APARTMENT	SMALL OFFICE	AVERAGE OFFICE HOTEL	
CAPACITY	1200#	2000#	2500#	3000#
A	5'-0"	6'-4"	7'-0"	7'-0"
B	4'-0"	4'-5"	5'-6"	5'-6"
C	5'-6"	5'-0"	5'-6"	5'-6"
D	8'-10"	8'-2"	8'-10"	8'-10"
E	5'-4"	5'-9"	6'-4"	7'-0"
F	4'-5"	4'-10"	5'-5"	5'-11"
G	10"	10"	10"	10"
H	12"	12"	13"	13"

RECOMMENDED MACHINE ROOM OVERHEAD & PIT DIMENSIONS

SPEED	150	200	250	300
L	13'-0"	13'-6"	13'-6"	13'-6"
O	12'-10"	12'-0"	13'-5"	13'-5"
P	5'-6"	6'-6"	6'-11"	7'-4"

Fig. 23.26 Typical data for basement traction machine (underslug) arrangement, used where penthouse is unavailable or undesirable. (Courtesy of Montgomery Elevator Co.)

LINEAR INDUCTION MOTOR ELEVATOR SYSTEM

Fig. 23.27 Schematic drawing of OTIS' new Linear Induction Motor (LIM) elevator design. Because the motor is built into the counterweight and supplies motive power linearly (vertically), the conventional overhead rotary traction machine is entirely eliminated, as is also therefore, the machine room. The system operates more efficiently, quietly and smoothly than the conventional design. (Courtesy of OTIS Elevator).

Fig. 23.25 Manufacturers layout data for a bank of six 3500-lb (1588-kg), 700-fpm (3.56-m/s) gearless passenger elevators. Equipment shown in the machine room is thyristor control for d-c traction machines. Since each controller has the capability of group supervisory control in this design (Otis Elevonic 411), no separate group supervisory equipment is shown. No additional space would be required if a UMV drive with m-g sets were selected rather than thyristor control. (Courtesy of Otis Elevator Co.)

cover this design, and in particular its safety aspects. It should not be expected that so extensive a Code revision will be a short-term project. A schematic diagram of the design is shown in Fig. 23.37.

REFERENCES

Strakosch, G. R. (1983). *Vertical Transportation, Elevators and Escalators*, 2nd ed., Wiley, New York.

Stein, B., Reynolds, J., and McGuinness, W. (1986). *Mechanical and Electrical Equipment for Buildings*, 7th ed., Wiley, New York.

24

VERTICAL TRANSPORTATION: SPECIAL TOPICS

POWER AND ENERGY

24.1 Power Requirements

The power required by an elevator is that amount necessary to perform the necessary traction work and to overcome friction. Since power is equal to the *rate* at which work is done the elevator motor size is directly proportional to the speed of the system. In other words, it requires proportionately more power to lift a 3000-lb car at 700 fpm than at 200 fpm. This relationship is shown in Fig. 24.1, which shows the minimum size of a d-c elevator traction motor as a function of speed, for different capacity cars. This motor supplies the system friction in addition to the required traction power. (For power data on hydraulic elevators, see Section 24.10.) Since friction is higher in geared machines than in gearless units, the traction motor must be larger. The m-g set motor size (where used) is approximately 20% larger than the value shown, to compensate for the set losses.

When solid-state control is used (and the m-g set eliminated), the values shown in Fig. 24.1 are still valid inasmuch as the size of the traction motor is unaffected by the type of variable-voltage or -frequency supply.

An elevator moves only about 50% of the time, the remainder being spent standing at various landings. As the number of cars in a bank increases, the probability of *all* the cars being in operation simultaneously decreases, resulting in a system demand factor less than 1.0. The factor is shown directly in Fig. 24.1.

As an example of the use of the curves, consider a bank of five 3500-lb, 600-fpm units. From Fig. 24.1, each car requires 48 hp:

$$\text{group demand factor} = 0.67$$

$$\text{total instantaneous power required} = 5 \times 48 \times 0.67 = 160 \text{ hp}$$

Note that this is the *traction motor* power requirements. Assuming an overall efficiency (eff) of 80% for an m-g set, the elevator system power requirement is

$$\text{system power} = \frac{160 \text{ hp}}{80\% \text{ eff}} = 200 \text{ hp}$$

which would have to be provided by the building power system. When using solid-state control, with an efficiency in excess of 90%, system power requirements would be reduced proportionately.

24.2 Energy Requirements

The energy used by an elevator is essentially the system friction, including the heat generated by the brakes plus the electrical losses in the traction motor and power supply equipment—rotary or solid state. The energy expended in raising the car and its passengers is simply stored as potential energy. It is *returned to the power system* when the car and passengers descend, via the system of regenerative braking in use in almost all elevator systems. Refer to Fig. 24.2, which shows the approximate efficiencies of the components of a typical system. With these data, we are able to calculate a system's energy consumption.

EXAMPLE 24.1. Given a system of five 3500-lb, 600-fpm (gearless) cars calculate:

(a) Heat generated in the machine room during peak periods. Assume solid-state control.

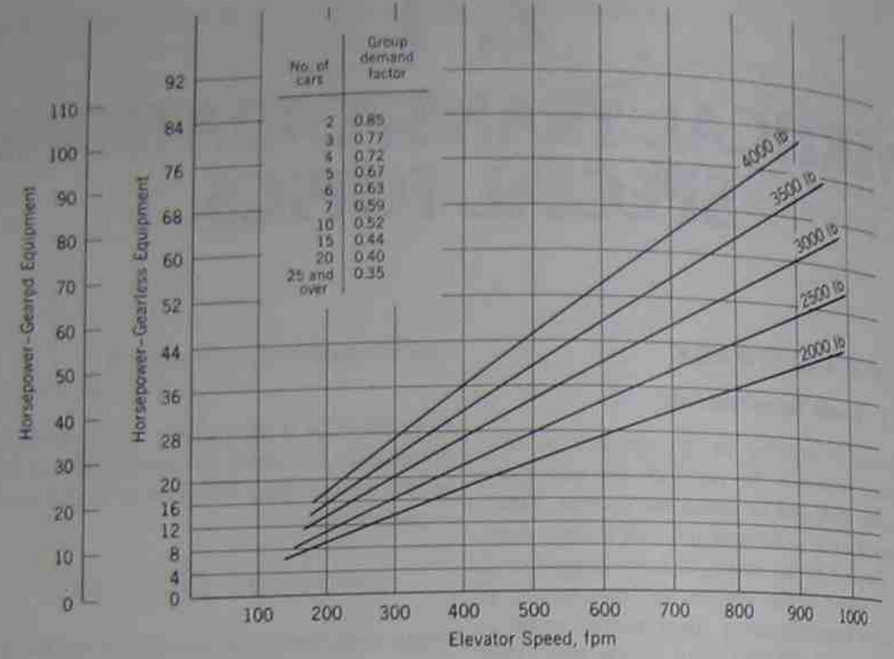


Fig. 24.1 Elevator traction motor power requirements per car. The m-g set motor (if used) is approximately 20% larger than the traction machine.

(b) Approximate monthly energy cost using a combined demand/energy rate of \$0.08/kWh.

SOLUTION. (a) During peak periods the traction motor operates approximately 50% of the time and is at standstill the other half. Assume that while operating it draws 90% of full load. Therefore, for one car, from Fig. 24.1,

$$\frac{48 \text{ hp}}{0.9 \text{ eff}} \times 90\% \text{ load} \times 50\% \text{ operation} \times 10\% \text{ loss} = 2.4 \text{ hp}$$

traction motor = 48 hp

Total loss per machine:

In controls:

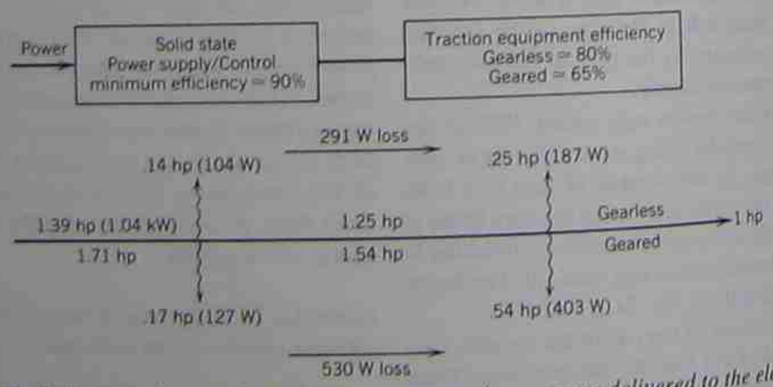


Fig. 24.2 Block diagram showing losses in the system per horsepower delivered to the elevator car, and the equivalent wattages. Note that the losses in a geared system are almost double those of a gearless one. Figures shown are for solid-state controls.

In traction motor:

$$48 \text{ hp} \times 90\% \text{ load} \times 50\% \text{ operation} \times 20\% \text{ loss} = 4.32 \text{ hp}$$

$$\text{Total} = 6.72 \text{ hp} = 17{,}100 \text{ Btu/h}$$

Since there are five elevators operating, the total heat generated is

$$5 \times 17{,}000 \text{ Btu/h} = 85{,}500 \text{ Btu/h}$$

This is the rating of a home furnace. As a result, machine room temperature in warm climates frequently reach 120°F! (No diversity is taken since all the machines are operating and the heating is additive; diversity is applicable only in calculating instantaneous load.)

Since the solid-state elevator equipment now used is much less tolerant of high ambient temperatures than were the old electromechanical switches and relays that preceded them, the machine room should be held to a maximum dry bulb temperature of 90°F. (Temperatures above 90°F can result in unreliable elevator system performance.) This can sometimes be accomplished by thermostatically controlled forced ventilation, particularly if spill air from an air-conditioning system is present. However, since machine rooms are frequently on the building roof and exposed on all surfaces to direct solar radiation, air conditioning may be necessary. It is also important to prevent machine room temperature from dropping below 55°F, for the same reason as mentioned above. This can usually be done with one or more unit heaters, which will normally operate only during the winter, and then only nights and weekends.

In actual design situations, accurate heat loss figures, which are available from manufacturers, should be used, along with accurate heat gain and heat loss calculations for the specific machine room being designed. Frequently, use of thermal insulation, thermostatic louvers, and sunshading can ease the thermal load and result in appreciable financial and energy savings. Because of the very high initial and operating cost of air conditioning, an effort is now being made to produce solid-state elevator controls using components that are specifically designed to operate at elevated temperature. As of this writing such equipment is not commercially available.

(b) To calculate the monthly energy cost, an estimate must be made of the total usage of the system. Assuming the system to be in an office building, a reasonable breakdown of operation during a 24-h day would be

2 h peak use
2 h 70% of peak
6 h 50% of peak
14 h 10% of peak

This gives an average of 30% of peak load for the bank. Therefore, per car

$$\text{energy} = 30\% \times \text{total losses} \times 24 \text{ h}$$
$$= 0.3 \times 6.72 \text{ hp} \times 24 \text{ h}$$
$$= 48 \text{ hp-h} = 36 \text{ kWh/day/car}$$

Monthly cost would be

$$36 \frac{\text{kWh}}{\text{day}} \times 25 \text{ days} \times \$0.08$$
$$= \$72/\text{month/car}$$
$$= \$360/\text{month for the bank}$$

In a design using m-g sets in lieu of the solid-state controls, the monthly cost would be \$630 for the bank.

24.3 Energy Conservation

A reduction in energy consumption can be accomplished by implementing the following recommendations:

For Existing Elevators

1. Increase interval during nonpeak hours.
2. Replace m-g sets with thyristor controls. This conserves energy not only due to higher efficiency of solid-state gear but also because energy consumption of idling machines is eliminated.
3. Recycle machine room waste heat.
4. Shut down some units completely during off hours.

For Building in the Planning Stage

1. Design for maximum trip time.
2. Use the lowest speeds possible, within a type—that is, geared and gearless.
3. Use gearless equipment whenever possible (see Fig. 24.2).
4. After construction, implement the recommendations for existing elevators above.

Since elevator shafts have a powerful stack effect, measures should be taken to counteract this during the heating season.

24.4 Emergency Power

Major power failures and local "brownouts" have demonstrated forcefully the need for a standby or emergency power source of adequate size to operate a building's elevators. Few experiences are so harrowing as being trapped in the crowded confines of a small box suspended in a long vertical shaft, with little or no light, and complete strangers for companions.

A common misconception relative to elevators is that on failure of power, the cars will automatically descend to the nearest landing where exit will be possible. In actuality, the brake is set immediately on power outage and the car remains stationary. Hydraulic cars can be lowered by operation of a manual valve; *small* traction cars can be cranked to a landing by hand; but large cars are fixed in position. This is particularly bad for cars in blind shafts, that is, express shafts with no shaftway doors. In such cases escape from the cars via hatchway is not practicable and, when emergency power is not available, breaking through the shaftway walls is the only recourse.

In addition to simple inconvenience, loss of elevator service in facilities such as hospitals, mental institutions, and jails constitutes a danger to life. For this reason most codes require that emergency power be available in public buildings to operate at least one elevator at a time, and for lighting and communications. Most installations separate the emergency power functions, providing a diesel generator for traction power and separate individual elevator battery packs for communications, lighting, and preferably, also the car fan. The latter two items can be furnished by the elevator manufacturers with the cars, as an option.

The generator is normally sized to supply one elevator motor at a time, with manual or automatic switching arranged between unit controllers. Thus each car in turn can be brought to a landing and thereafter a single car retained in service. Obviously, if it is desired to operate more than one car, a larger generator can be installed. This might well be the case in a multiwing building with critical service requirements, such as a hospital.

The amount of power required, the size of the emergency generator, and the equipment size necessary to absorb regenerative power are all data that can be furnished by the consulting engineer and the elevator manufacturer.

OTHER CONSIDERATIONS

24.5 Fire Safety

Most codes specify the procedures that the elevator control equipment must implement once a fire emergency has been initiated. Details vary somewhat, but in general the actions are these:

1. All cars will close their doors and return nonstop to the lobby or other designated floor, where they will park with doors open. Thereafter they will be operable in manual mode only, by use of the firemen's key in the car panel.
2. All car and hall calls are canceled and call registered lights and directional arrows extinguished.
3. The fire emergency light or message panel in each car is activated to inform passengers of the nature of the alert and that cars are returning to a designated terminal.
4. Door sensors and in-car emergency stop switches are deactivated.
5. Traveling cars will stop at the next landing without opening doors and then proceed to the designated terminal.

The cars can then be used by trained personnel to transport fire personnel and equipment, and for evacuation. In the event of a false alarm, the emergency procedure can be overridden at the lobby panel and the system returned to normal while the source of the alarm is located. (This is a particularly important feature in large buildings with automatic fire alarm systems containing hundreds of fire, smoke, and water-flow detectors. See Section 13.20.)

24.6 Elevator Security

Elevator security has two aspects: physical security of riders, and consideration of the elevator as a portal in a building-access security system.

(a) Rider Security. This problem is particularly difficult inasmuch as the traveling elevator is an enclosed space that can be rendered inaccessible simply by pressing the emergency stop button. Thereafter, an attacker can escape at the floor of his choice. To ameliorate this danger to an extent, elevators are equipped with alarm buttons, which alert residents and security personnel, if any. Every elevator, by code, must be equipped with communication equipment, but a hand-held phone is not practical in a security-emergency situation. More effective is an open two-way communication system with "no-hands" operation, in the car. When a closed-circuit TV monitor is added, utilizing a wide-angle camera in each car (see Fig. 24.3), the security problem will have been addressed to a considerable extent. Obviously, using a communication and TV system presupposes continuous manning of the building security desk.

Fig. 24.3 Wide-angle TV camera intended for elevator cab surveillance. A prominent, printed warning in the cab is an integral part of the system's effectiveness. (Photo courtesy of Visual Methods, Inc.)

At least one major manufacturer now markets a device that will alarm automatically on detecting sudden violent motions or a sharp pointed instrument. The matter of handling the alarm is problematic, since an automatically locked door can be forced open manually, and, furthermore, the advisability of locking a violent person *in* the elevator with potential victims is questionable.

(b) Access Control. This is often a matter of restricting access to (and from) a floor or car. This can be accomplished by pushbutton combination locks or coded cards, the proper use of which will permit access (see Chapter 22). However, if a second person happens to accompany the authorized person, the effectiveness of this type of access barrier is seriously compromised. In sum, the most effective security system is a combination of automatic monitoring and access devices, coupled with continuous supervision by persons who know the appropriate action to take in an emergency.

24.7 Elevator Noise

As already noted, elevator operation, with its rotating, sliding, and vibrating masses, can be a cause of serious noise disturbance to quiet areas such as sleeping rooms, libraries, and certain types of office space. Noise can be reduced by the appropriate application of vibration isolators (e.g., between guide rails and the structure) and by proper control, but primarily by placing noise-sensitive areas away from shafts and machine rooms. Furthermore, the clatter and whirring sound of the older machine room, caused by relays, step switches, m-g sets, and sliding contacts, can be entirely eliminated by the use of solid-state equipment.

24.8 Elevator Specifications

Two basic types of specification for elevator equipment, as for other types of equipment, are utilized. The performance specifications describe job conditions and invite contractors to submit detailed proposals including full engineering. The burden of comparing proposals then falls on the owner, who—if competent to properly perform such an evaluation—would most probably do better to utilize the equipment-type specification.

In recent years the use of performance specifications has increased because of the advent of preengineered, premanufactured systems. These are supplied by the major manufacturers and have these advantages:

1. Approximately 10% lower cost than a custom-designed system.
2. A complete engineered and tested system whose performance and cost are known exactly.
3. Rapid delivery.
4. Minimum supervision required by the owner and architect.

If architects decide to use a custom-designed system, they must prepare detailed drawings and specifications. The specifications must include:

Elevator type, rated load and speed.

Maximum travel.

Number of landings and openings.

Type of control and supervisory system.

Details of car and shaft doors.

Signal equipment.

Characteristics of power supply.

Finishes.

This last item can be left as a dollar allowance for architectural treatment of the car interior. Since the selection of, and technical specifications for, elevators are specialized and complex, the services of an elevator consultant are usually required.

In addition to the technical portions of the specifications, it is imperative that the following items be covered in detail.

(a) Owner's Responsibility. The *construction* contractor normally provides:

1. The hoistway, including properly designed, lighted, drained, waterproofed, and ventilated machine room and pit.
2. Access doors, ladders, and required guards.
3. Guide rail bracket supports, and support for machine and sheave beams.
4. Electric feeder terminating in switch in machine room.
5. Hoistway outlets for light, power, and telephone.
6. Temporary light and power during construction.
7. Concrete machine foundations.
8. Vents, holes, and other work to satisfy fire codes.
9. All cutting, patching, and chasing of walls, beams, masonry, and so on.
10. Coordination of all work.
11. Any special work, as negotiated.

(b) Elevator Contractor's Responsibility. Provide complete, working, tested, and approved system in accordance with specification, plus any special work such as painting, special tests, scheduling of work, and temporary elevator service.

(c) Special Job Conditions. These include work restrictions, scheduling, penalties or bonuses, test reports, and the like.

In alteration and modernization work, the problems of coordination are more complex, and an elevator contractor experienced in this type of work must be selected. To this end, in all elevator contract work, bids should be solicited from parties named on qualified bidder lists. Part of an elevator contract comprises maintenance of the installation for a specific period after completion. Contractors with poor maintenance facilities should be avoided.

SPECIAL ELEVATORS

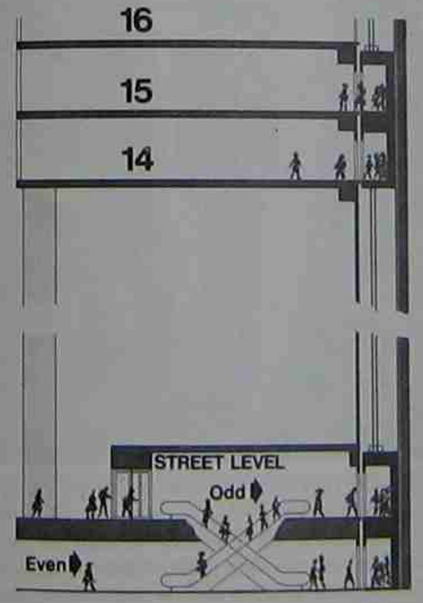
24.9 Unique Traction Designs

Elevator engineers have always provided interesting and original solutions to unusual problems. A detailed analysis of these solutions is beyond our scope here; however, a rapid review is of interest. For more details see Strakosch (1983).

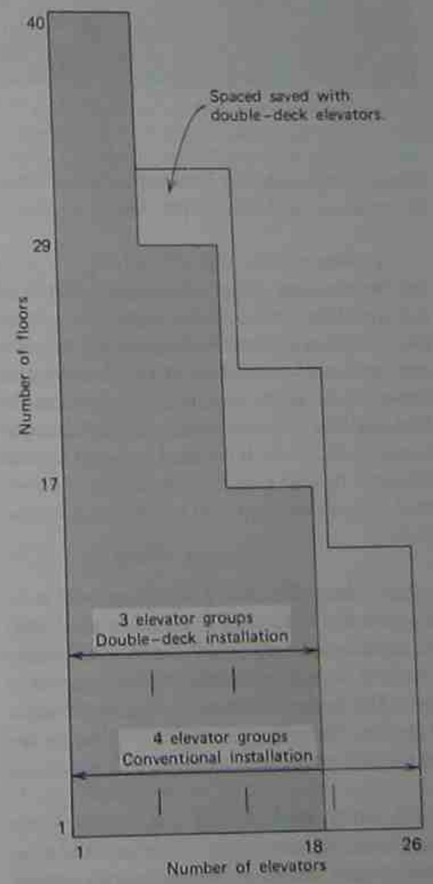
(a) Sky-Plaza System. For skyscraper buildings such as the World Trade Center in New York and multiple-use buildings such as the John Hancock Center in Chicago—both of which are, in effect, stacked multiple buildings—the elevator solution involves transporting large groups of people from the street lobby to an upper lobby called a sky plaza. At this point the passengers transfer to another elevator to continue their upward journey. The advantages of this system are

1. Reduction in the space occupied by elevators, since the shafts do not extend the entire height of the buildings.
2. Interrupting the otherwise lengthy vertical trip by the horizontal break at the sky lobby.

(b) Double-Deck Elevators. This is an old technique, recently revised to answer the needs of tall buildings such as the Sears and Citicorp Towers. The principal purpose is to limit the otherwise prohibitively large amount of space occupied by elevator shafts (see Fig. 24.4). The double-deck car increases shaft capacity, decreases the number of local stops, and increases the rental area available. This technique can also



(a)



(b)

Fig. 24.4 (a) *The double-deck car serves to increase cab capacity and decrease shaft space. Coincidence of calls in the upper and lower cabs reduces the number of local stops made by the double car.* (b) *Graphical representation of the space saved in a 40-story building by the use of double-deck elevators. (Courtesy of Otis Elevator Co.)*

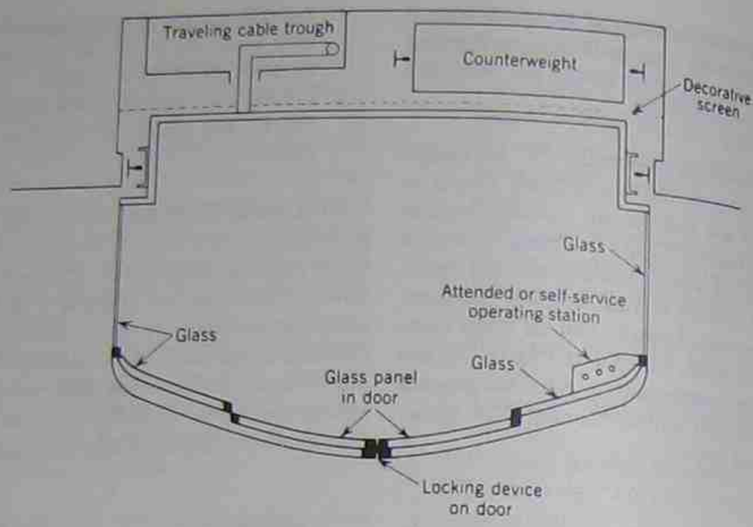


Fig. 24.5 Basic design of a traction-type observation elevator. Cars are small to permit all the occupants to enjoy the view through the cab's glass walls. [From Strakosch (1983); reprinted with permission of John Wiley & Sons.]

be combined with sky lobbies for further space economy, as was done in the Sears Tower.

(c) Observation Car Elevators. By placing the traction lifting mechanism *behind* the car, attaching the car at the back, and using a glass-enclosed, observation-style car, a spectacular unit can be constructed that becomes an attraction in itself. The basic construction is shown in Fig. 24.5, and a well-designed example is seen in Fig. 24.6. If the back screen is treated properly, the car give the impression of movement without any apparent motive force or machinery.

(d) Slant Elevators. Although elevators are normally conceived as traveling vertically, this is not necessarily so. Slant or inclined elevators have been constructed in numerous locations. The design varies depending on the angle of incline. Figure 24.7 shows a well-known application of an inclined elevator.

(e) Rack and Pinion Elevators. These operate on the straightforward principle of a rotating cogged wheel pinion attached to a vertical

Fig. 24.6 Twin installation with unusual car design, at the Hilton Hotel in Atlanta. Note the effectiveness of the screening, making the traction equipment barely visible. (Photo courtesy of Hauenstein and Burmeister, Inc., which supplied the cars for this installation.)

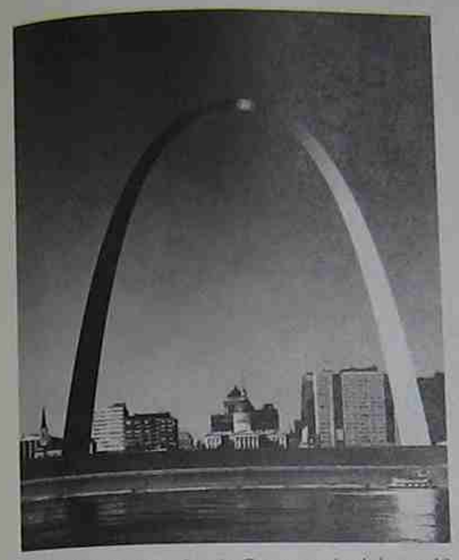


Fig. 24.7 The St. Louis Gateway Arch has a 10-passenger, inclined elevator in each leg. Placement of doors, arrangement of counterweight, and size of shaft all depend on the angle of incline. The car moves 82 ft horizontally during its 386 ft of total travel, at an incline of approximately 12°. (Photo courtesy of Bethlehem Steel Corporation, which supplied the elevator rope for this installation.)

Fig. 24.8 The basis of the rack and pinion drive is simply a driven pinion on a stationery rack; rotation of the pinion forces the structure attached to the pinion to move along the rack. (Courtesy of Alimak Elevator Co.)

rack. Rotation of the pinion forces the attached cab up and down along the rack (see Fig. 24.8). The advantages of this system are its inherent simplicity and safety, unlimited rise, low maintenance and operating costs, plus minimum space requirements. This last characteristic was primarily responsible for the selection of a rack and pinion design for a 210-ft-rise emergency elevator installed as part of the renovation and rehabilitation of the Statue of Liberty in 1986. The elevator is used primarily to evacuate victims of heart attacks, which average one a month. Carrying them down the 171-step spiral staircase which connects the main upper landing to the observation platform in the crown is obviously not practical. The tight headroom available—less than 9 ft—ruled out a traction unit, as did the extremely tight shaftway, which measures only 2 ft ½ in. × 4 ft 10 in. The car itself (see Fig. 24.9) measures only 1 ft 11 in. × 3 ft 10 in. outside dimensions. Space was so tight that the drive was divided between two motors, both of which are mounted under the passenger compartment. Rack and pinion lifts are used both indoors and outdoors primarily in industrial environments for both passengers and material vertical transport.

24.10 Hydraulic Elevators

Most of the foregoing elevators are traction types; that is, they are raised and lowered as a result of the tractive force of cables attached to, or passing under, the car. In contrast to these, the conventional hydraulic or plunger elevator is raised and lowered quite simply, by means of a movable rod (plunger) rigidly fixed to the bottom of the elevator car. The absence of cables, drums, m-g sets, elaborate controllers and safety devices, and penthouse equipment makes this system inherently inexpensive and often the

High-speed emergency elevator in Statue of Liberty.

Fig. 24.9 *The rack and pinion principle is used in the very small Statue of Liberty emergency elevator. The rack extends the entire length of the shaft and the car moves along the rack, driven by two motorized pinions below the passenger compartment. (Courtesy of Alimak Elevator Co.)*

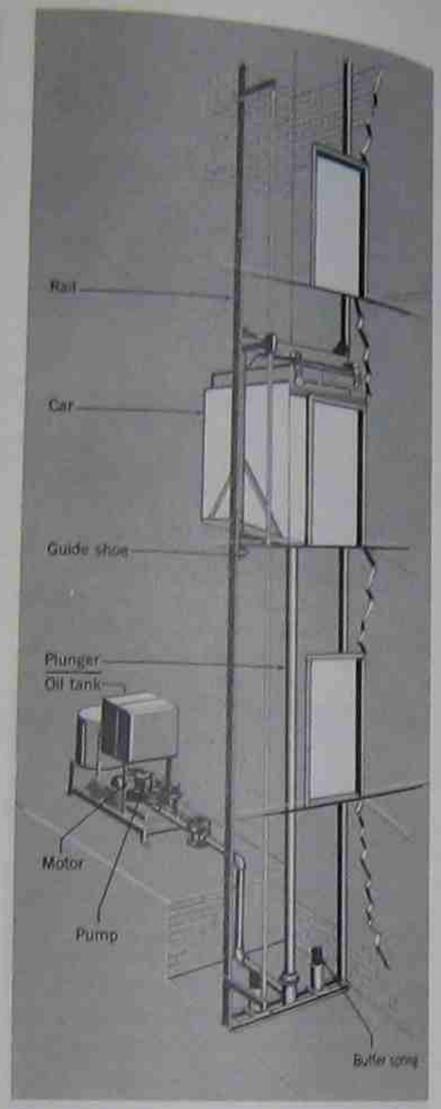
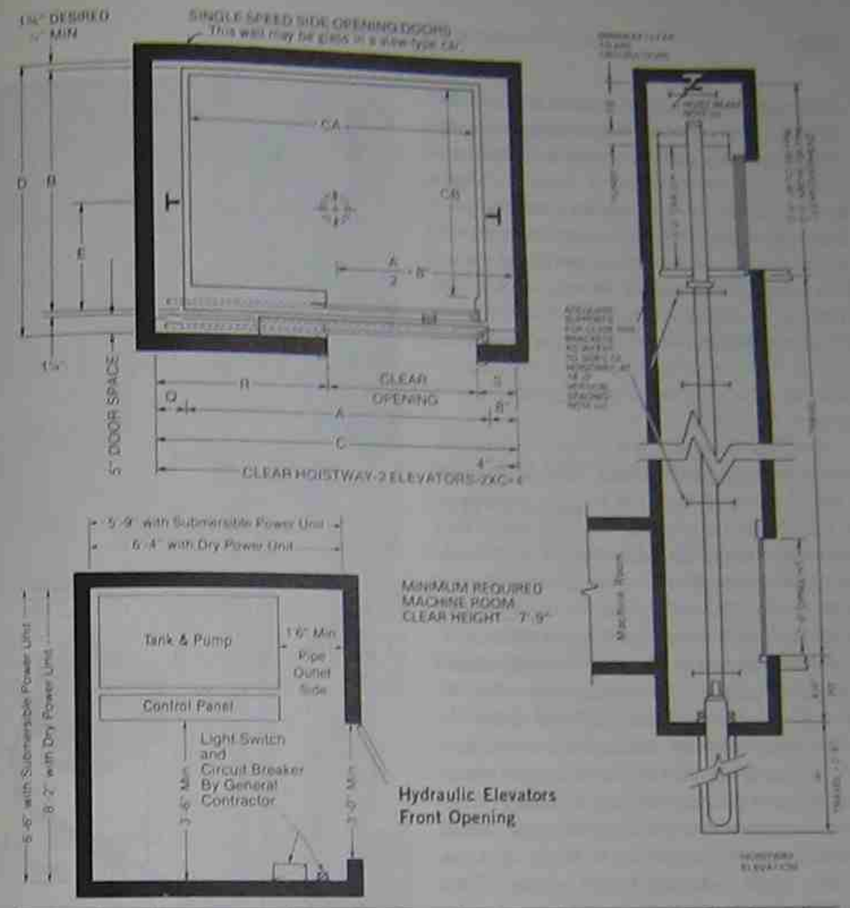


Fig. 24.10 *Phantom view of a typical plunger-type hydraulic elevator installation. (The oil pump is actually inside the tank, but it is shown outside for clarity.) (Courtesy of Schindler Elevator Corp.)*

indicated choice for low-speed (up to 200 fpm), low-rise (up to 65 ft) applications, where construction of the plunger pit does not present difficulties and absence of a penthouse is desirable.

The components of a typical hydraulic unit are shown in Fig. 24.10. This system operates very much the same way as a hydraulic automobile jack. Oil from a reservoir is pumped under the plunger thereby raising it and the car. The pump is stopped during downward motion, the car being lowered by gravity and controlled by the action of bypass valves, which also control the positioning of the car during upward motion. Control systems normally used are similar to those for traction types, for example, single pushbutton, collective, and selective collective. Similarly, door arrangements are the same as in traction types, that is, single slide, center opening, and two speed. Automatic leveling is readily available and is standard on all automatic units. Typical layout and dimensional data for standard plunger units are given in Fig. 24.11, along with capacities and application recommendations.



CAPACITY (LBS)	STD. SPEED (FPM)	MAXIMUM STANDARD OPENINGS	MAXIMUM STANDARD TRAVEL (ft)	CLEAR OPENING (in)	PLATFORM SIZE A WIDTH	PLATFORM SIZE B DEPTH	MINIMUM CLEAR CAB INSIDE CA WIDTH	MINIMUM CLEAR CAB INSIDE CB DEPTH	HOISTWAY C CLEAR WIDTH	HOISTWAY D(in) WALL TO WALL	R	S	E	Q
2000	100	8	70'-0"	3'-0"	6'-0"	5'-1"	5'-4"	4'-3"	7'-4"	5'-3"	9'-0"	11"	2'-1"	8"
	125		77'-0"											
2500	100	8	70'-0"	3'-6"	7'-0"	5'-1"	6'-8"	4'-3"	8'-4"	5'-3"	3'-11"	11"	2'-11½"	8"
	125		76'0"											
	150		76'-0"											
3000	100	8	70'-0"	3'-6"	7'-0"	5'-7"	6'-8"	4'-9"	8'-4"	5'-8"	3'-11"	11"	2'-4⅛"	8"
	125		72'0"											
	150		73'-0"											
3500	100	8	69'-0"	3'-6"	7'-0"	6'-3"	6'-8"	5'-5"	8'-4"	6'-11"	3'-11"	11"	2'-8⅛"	8"
	125		69'0"											
	150		69'-0"											
4000	100	8	66'-0"	4'-0"	8'-0"	5'-3"	7'-8"	5'-4"	9'-4"	6'-11"	—	—	2'-4½"	8"
	125		66'-0"											
	150		66'-0"											

Fig. 24.11 *Typical dimensional, capacity, and layout data for conventional plunger-type hydraulic elevator. Door systems are single slide (SS) or center opening (CO). The car can be used as a viewing type unit by utilizing a glass wall at the back of the car. (Extracted with permission from published data of Schindler Elevator Corp.)*

Where drilling a plunger hole presents difficulties, a hydraulic installation using a telescoping plunger or a roping arrangement can be installed. The latter, which is simpler, cheaper, and less prone to maintenance than a telescoping plunger, has for these reasons become popular. It consists of a single-action plunger which lifts a rope crosshead, or pulley, which is then roped to the car (see Fig. 24.15). These cars are very limited in rise and speed and are applicable only to small two- to three-story buildings. A cutaway of a twin telescoping plunger unit is given in Fig. 24.12.

From the point of view of the construction, the major inherent advantage of hydraulic units is the absence of overhead traction equipment. In Fig. 24.10 we see that only the guide rails project above the car and, if these are camouflaged, the impression of a freestanding elevator car is given. This effect can be used to good advantage *inside* large, open spaces such as exist in shopping malls and stores; when combined with glass-enclosed, observation-type cabs, the effect is striking (see Figs. 24.13 and 25.3).

The major inherent *disadvantage* of the standard hydraulic elevator is its operating expense. Since it is not counterweighted, it requires a relatively large motor to drive the oil pump, and *all* the energy is lost in heat (see Table 23.1). As an example of the operating cost, consider a 3500-lb, 125-fpm hydraulic unit in a department store. Such a unit requires a 40-hp motor. Assuming the unit to be in operation 10 h/day, 6 days a week, and assuming a normal 60% time-in-operation figure, we have (remembering that the motor operates only in the up direction)

$$\text{energy used/day} = \frac{40 \text{ hp}}{0.82 \text{ eff}} \times \frac{0.746 \text{ kW}}{\text{hp}} \times 60\% \times 10 \text{ h} \times \tfrac{1}{2}$$

$$= 110 \text{ kWh/day}$$

At \$0.08/kWh we have

$$\text{monthly energy cost} = 110 \times \frac{6 \text{ days}}{\text{week}} \times \frac{4.33 \text{ weeks}}{\text{month}} \times \$0.08$$

$$= \$229/\text{month}$$

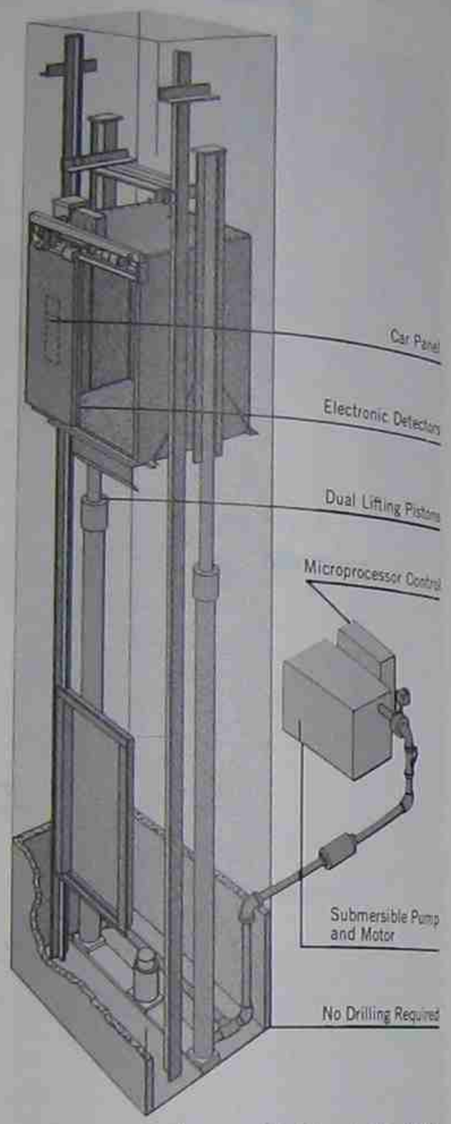


Fig. 24.12 *The illustrated holeless hydraulic elevator is similar in construction to standard plunger-type except that it uses two telescoping jacks to lift the car. Service for this unit is limited to two stops, a maximum rise of 15 ft, and a car rating of 2000 or 2500 lb. (Courtesy of Otis Elevator Co.)*

Compare this to the previously calculated (Section 24.2) monthly energy cost of \$72 when using solid-state equipment and \$126 with m-g set power supply, for a 3500-lb, 600-fpm traction car, for an appreciation of the value of a counterweight.

Fig. 24.13 *This four-story-high, exterior-plunger elevator in the Los Angeles rapid transit system is practical and fulfills viewing function. (Photo courtesy of Montgomery Elevator Co.)*

24.11 Residential Elevators and Chair Lifts

Although the special needs of the handicapped have only within the last decade been widely recognized officially in legislated requirements, the elevator industry has been providing for the handicapped for years, on a voluntary basis. Small private residence elevators can double as wheelchair lifts, and are available in a wide range of designs, including winding-drum units (Figs. 24.14 and 24.15), roped hydraulics (Fig. 24.16), and worm and screw units. Standard traction designs are used infrequently due to the overhead space requirement. Similarly, standard hydraulics requiring a plunger bore hole are rarely used. Chair lifts and wheelchair platform lifts also come in a variety of designs. The screw worm and cog design chair lift shown in Fig. 24.17 is also utilized as a wheelchair lift that can negotiate stair turns, by adding a second upper screw worm to support a chair platform. The hydraulic scissor-jack type of wheelchair platform lift is most frequently found in public and institutional buildings because it is particularly applicable to short-rise, heavy-load, frequent-duty applications, and requires minimal maintenance.

All of these units are covered by various sections of the elevator code and must be installed in accordance with code requirements, including safeties and controls. Residential units are normally arranged to operate on 120 V a-c, although heavy-duty units may require 240-V service.

FREIGHT ELEVATORS

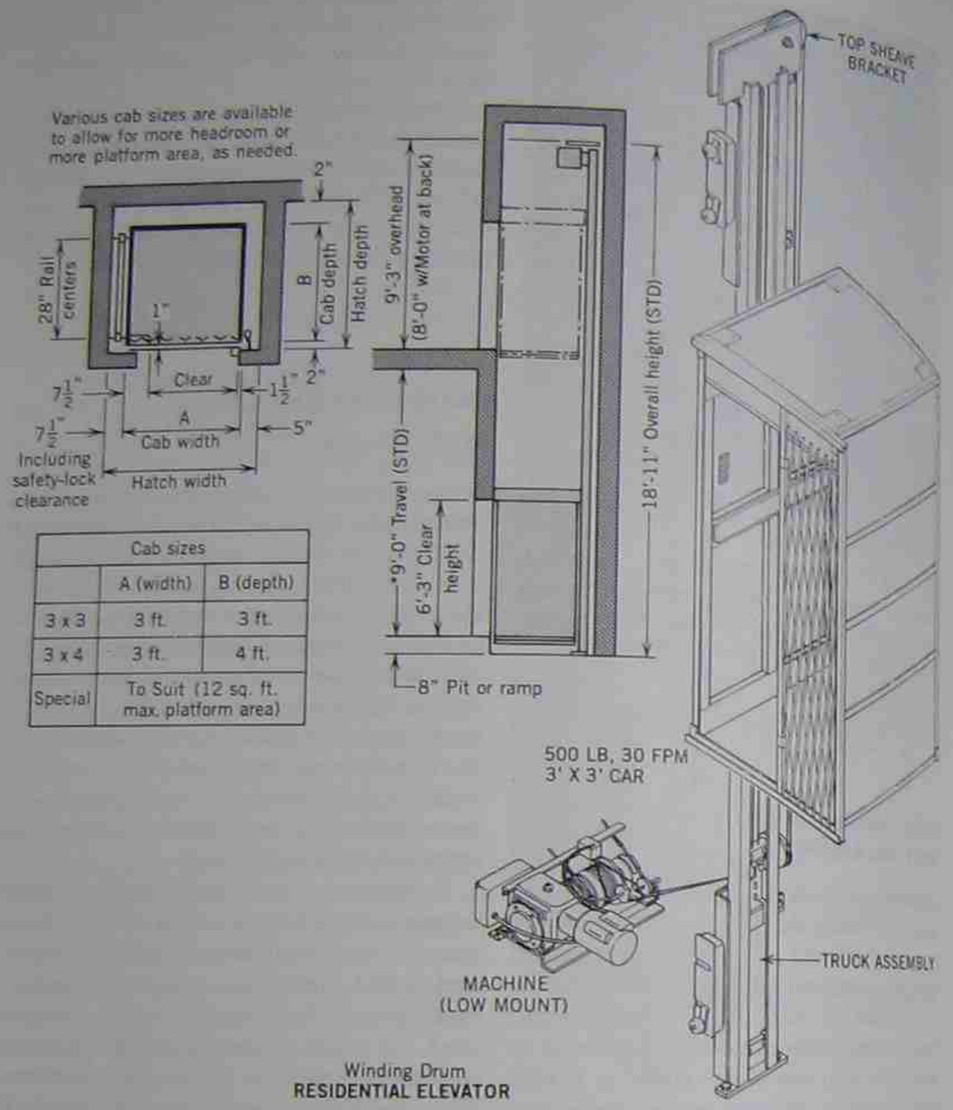
24.12 General

The preceding material, which dealt with passenger traffic, had as its prime consideration the most effective solution to the problem of vertically transporting a given number of persons. The problem with respect to freight elevators is similar: to transport a given tonnage of freight efficiently, economically, and quickly. The service car in a facility can be considered to be a freight car but, if utilized for passenger duty at all, it must meet passenger service requirements. If passenger duty is not required, or if much freight is to be handled, a car designed specifically for freight is used.

Factors to be considered in freight elevator selection, in addition to tonnage movement per hour, are size of load, method of loading, travel, type of load, type of doors, and speed and capacity of cars. Since these factors are interrelated, the actual process of selection involves making assumptions on the basis of recommendation and then arriving at a solution, very much as was done for passenger elevators.

It is beyond the scope of this book to discuss in detail the selection of material-handling elevators because of the large number of considerations involved. Therefore we shall restrict ourselves in the following paragraphs to descriptive material and recommendations. Also, since freight elevators form such an important link in industrial processes, a careful and detailed material-flow study should be made before freight elevators are selected. Elevator manufacturer's representatives and materials-handling consultants can be very helpful in this regard.

TRANSPORTATION



Cab sizes		
	A (width)	B (depth)
3 x 3	3 ft.	3 ft.
3 x 4	3 ft.	4 ft.
Special	To Suit (12 sq. ft. max. platform area)	

Fig. 24.14 Isometric drawing of a typical residential elevator of the winding drum design. Units of this type are usually limited to 500-lb car capacity, 40-ft rise, and 30-fpm speed. The cab is rigidly attached in cantilever fashion to a rolling truck, which is raised and lowered by cables attached to the winding drum. The driving motor and winding drum shown here at the base of the assembly can be installed at any floor stop along the hoistway, or overhead. Control is normally pushbutton automatic with limit-switch leveling. A 6-in. pit is required at the bottom of the hoistway. Door interlocks, cable failure, and overrun safeties are standard items in such installations, which must meet elevator code requirements. (Courtesy of Waupaca Elevator Co., Inc.)

Fig. 24.15 Winding-drum residential elevator specially designed and adapted for use by handicapped. Car floor area is 12 ft² to accommodate a wheelchair and another passenger. Note also that the car is arranged with front and back access for maximum flexibility. (Courtesy of Waupaca Elevator Co., Inc.)

24.13 Freight Car Capacity

Figure 24.18 is a section through a typical traction type freight car shaft. Capacities corresponding to a specific platform size are due to the varying square-foot loads that are permissible. Cognizance of this is taken by the ANSI Code (A17.1) for Elevators, which has established five load classifications for freight elevators.

Class A. General Freight Loading, by hand truck. Single items may not exceed 25% of the car-rated load. Rated load is based on 50 pounds per square foot (psf) of net inside platform area.

Class B. Motor Vehicle Loading. Car will carry automobiles or automobile trucks. Rating is based on a load of 30 psf of net inside platform area.

Class C1. Industrial truck loading; truck carried.

Class C2. Industrial truck loading; truck not carried.

Class C3. Concentrated loading; no truck used; increments greater than 25% rated capacity.

For classes C1, C2, C3-rated load based on 50 psf; cars have automatic leveling.

24.14 Freight Elevator Description

Since speeds are generally between 50 and 200 fpm, a geared-type traction machine is used almost universally.

The preferred system of control is collective, with variable-voltage, d-c supply. However, if the car is used infrequently (fewer than five trips a day), economy is very important, accurate leveling is not essential, and a rougher ride is tolerable, then a-c rheostatic control may be used. For low-rise jobs, a hydraulic unit is most often employed. These, as with the variable-voltage d-c traction units, provide accurate control, smooth operation, and very accurate automatic leveling. Hydraulic units rarely exceed 60 ft in height, and operate at speeds up to 125 fpm. Accessories such as governors, safeties, and brakes are similar to those for passenger elevators previously described.

General-purpose freight elevators, whether traction (Fig. 24.19) or hydraulic (Fig. 24.20), in load ranges up to 20,000 lb, are standard design items, applicable to all types of commercial and industrial buildings. Heavier units are individually engineered. Units 20,000 lb and over require special safeties. As with passenger elevators, structural reactions are supplied by the manufacturer to the architect, who is responsible for adequate structional supports. This item is of great importance in larger car installations, since traction unit rails must be supported every few feet and additional steel provided to accomplish this.

TRANSPORTATION

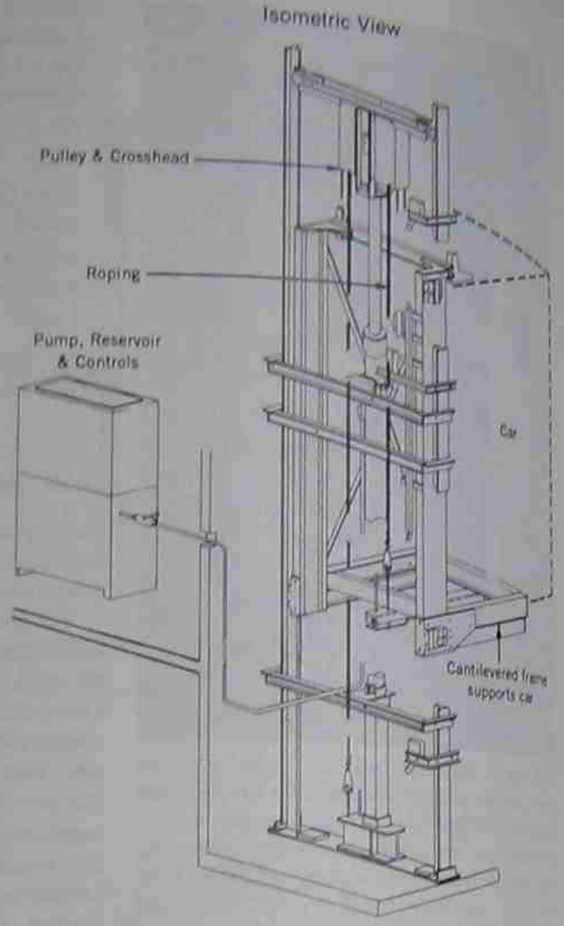


Fig. 24.16 *Low-rise residential-type elevator of the roped hydraulic design. The cantilevered car is lifted by cables attached to the cable crosshead, which is in turn lifted (and lowered) by the single-section telescoping piston (jack). The power unit, which includes the oil tank, pumps, and control, is usually mounted at the lower level. Control is automatic, including automatic leveling. Depending on the specific design, the car is a 700- to 750-lb, 30- to 36-fpm unit, normally with a single-story rise. The hatchway is 16 to 26 ft² with the larger size used for a car intended to accommodate a wheelchair. (Courtesy of CEMCO, Corbett Elevator Co.)*

24.15 Freight Elevator Cabs, Gates, and Doors

Cabs for freight service are normally built of heavy-gauge steel with a multilayer wooden floor, the entire unit being designed for hard service. Guarded ceiling light fixtures are required. Cab gates slide up vertically and are a minimum of 6 ft high. Hoistway doors are normally vertical lift, center-opening, manual or power operated. Both cab gate and hoistway doors are counterweighted and open fully to give complete floor and head clearance (see Fig. 24.21).

24.16 Freight Elevator Cost Data

The cost of a freight elevator installation, as with passenger elevator installation, is dependent on many factors, principally: capacity, type of control, use, and type of door operation.

Since exact pricing, like actual selection, is outside our scope, it is our recommendation that a reputable manufacturer or elevator consultant be consulted for such information. We can, however, make some general remarks on pricing, as follows:

1. Variable-voltage controlled equipment, depending on type, costs 20 to 50% more than rheostatically controlled equipment.
2. Above a basic two-floor rise, the cost increases linearly with rise.
3. Electric door operation can increase the cost of a car installation 10 to 25%.

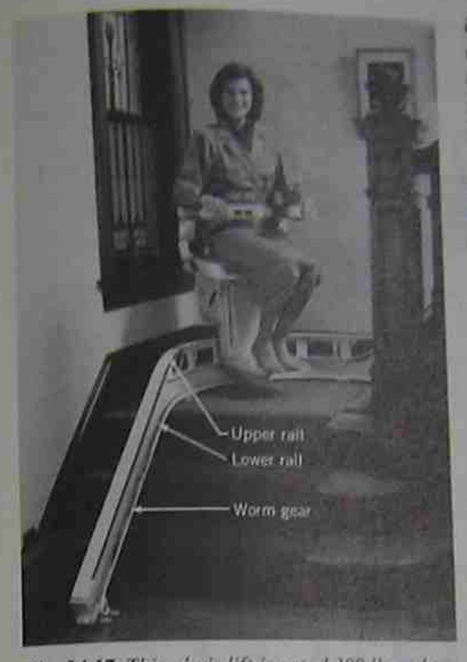


Fig. 24.17 *This chair lift is rated 300 lb and travels at 25 fpm. The chair itself, which is of the folding seat and arm design for space economy when not in use, is rigidly attached to a roller carriage that rides on a double-rail section. Motive power is provided by a motor-driven rotating cog which engages a fixed worm in the lower rail section. The worm is clearly visible in the photo. This type of positive-engagement gear drive gives the lift the distinct advantage over traction cable designs of being able to negotiate curves, as illustrated. Safeties include obstruction sensors and an overspeed brake. (Courtesy of Cheney.)*

As an example, of *comparative* pricing, using a nominal 100 for an 8000-lb, 75-fpm, four-floor, manual door car with a-c rheostatic control and automatic leveling, the same car with variable-voltage control, 150 fpm, and electrically operated doors would cost approximately 180.

24.17 Garage Car-Parking Facility

Multistory automobile parking facilities that increase parking space by replacing interfloor ramps with freight elevators have the characteristic of very slow service. Since this is obviously unacceptable in a downtown commercial application, an alternative arrangement using a materials-handling approach is available. One such system consists of a central structural tower that supports a continuous loop of car-carrying "baskets," that is, a sort of Ferris wheel. An automobile enters a cage at a terminal, which can be anywhere in the loop—top, bottom, center—and is "parked" by the simple expedient of operating the controls at the terminal. The loop rotates, the car remains in its cage, and an empty cage is presented at the terminal. A car is retrieved by calling back the appropriate cage. In principle, the system is similar to the vertical conveyor described in Section 24.22.

The advantages of this parking system are as follows.

1. Very high space utilization efficiency; approximately 40 m³ (1400 ft³) per midsize car.
2. Minimal horizontal space requirement.
3. Simplicity of operation with minimum labor.
4. High degree of security to parked vehicles and to drivers.
5. Rapid operation.

Where height of the structure is limited but horizontal site is not, a similar arrangement can be constructed horizontally. In effect the vertical structure described above is lying on its side and is two "stories" high, and as wide as necessary to accommodate the required number of vehicles.

This parking system is used principally overseas because of the prevalence of small cars, which readily fit into the carrying cage. With the increasing number of compact cars in the United States, it may find increasing application in congested areas of American cities, as well.

MATERIAL-HANDLING EQUIPMENT

24.18 General

The material-handling equipment discussed briefly here is that which finds application in commercial and institutional buildings. Industrial materials handling is an entirely separate

TRANSPORTATION

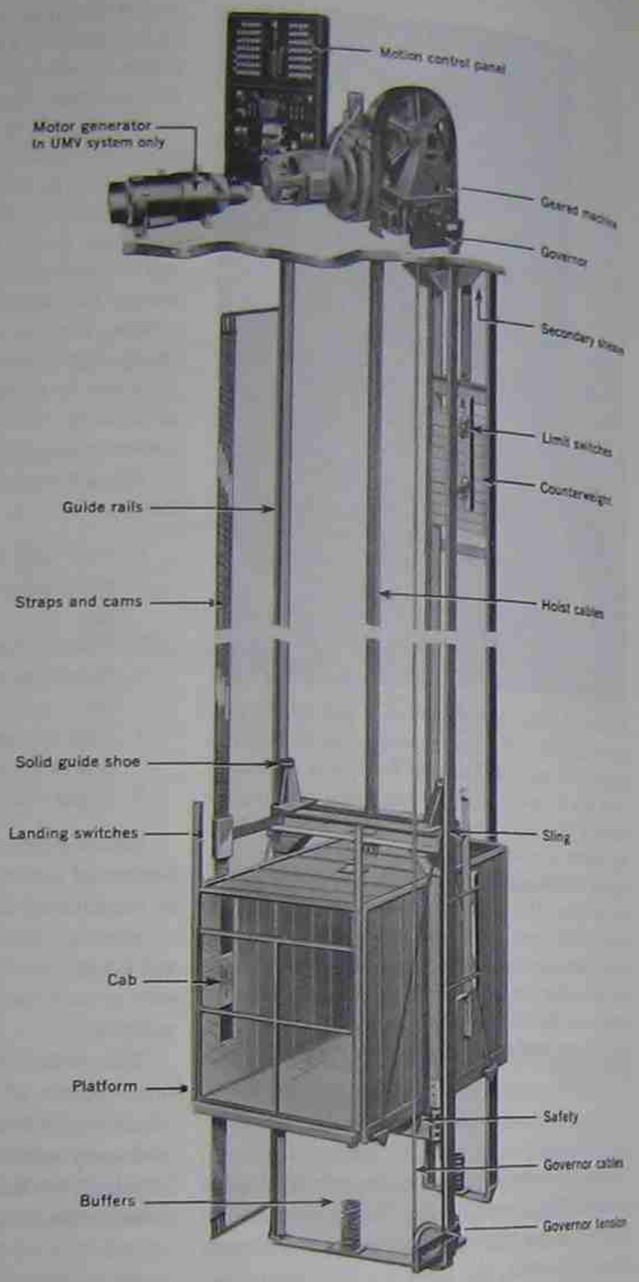


Fig. 24.18 *Components of a typical freight elevator installation utilizing a variable-voltage-controlled geared traction machine. The sling that lifts the car is frequently arranged with double sheaves over which the hoisting ropes pass. This roping arrangement increases the mechanical advantage of the lifting ropes.*

subject not germane to our purpose. The need to transport material within a building has always existed and until approximately a decade ago was done largely manually, with mechanical assistance. Thus offices used messengers; hospitals used dumbwaiters, service elevators, conveyors, and chutes. The single exception to this situation was (and still is) the extensive use of pneumatic tube systems in large stores, although in new installations their use is declining. Today's systems accomplish the same end—that is, the transfer of materials—but automatically

Freight Elevators — Traction

LIGHT AND MEDIUM DUTY FREIGHT ELEVATORS						HEAVY DUTY POWER TRUCK FREIGHT ELEVATORS						
CAPACITY	2500#	3000#	4000#	6000#	8000#	CAPACITY	10,000#	12,000#	16,500#	16,500#	20,000#
A	5'-4"	6'-4"	6'-4"	8'-4"	8'-4"	A	8'-4"	10'-4"	10'-4"	10'-4"	12'-4"
B	7'-0"	8'-0"	8'-0"	10'-0"	10'-0"	B	12'-0"	14'-0"	14'-0"	16'-0"	20'-4"
C	5'-0"	6'-0"	6'-0"	8'-0"	8'-0"	C	8'-0"	10'-0"	10'-0"	10'-0"	12'-0"
D	7'-10"	8'-10"	8'-10"	10'-10"	10'-10"	D	11'-4"	13'-4"	14'-0"	14'-2"	16'-6"
L	13'-0"	14'-0"	14'-0"	14'-0"	14'-0"	L	14'-0"	15'-0"	15'-0"	17'-0"	21'-0"

MINIMUM PIT & OVERHEAD DIMENSIONS FOR LIGHT & MEDIUM DUTY FREIGHT ELEVATORS				
CAR SPEED	50	75	100	200
O	16'-0"	16'-0"	16'-0"	16'-0"
P	5'-6"	5'-6"	5'-6"	8'-0"

H = 7'8" for light and medium duty doors
8'0" for heavy duty doors

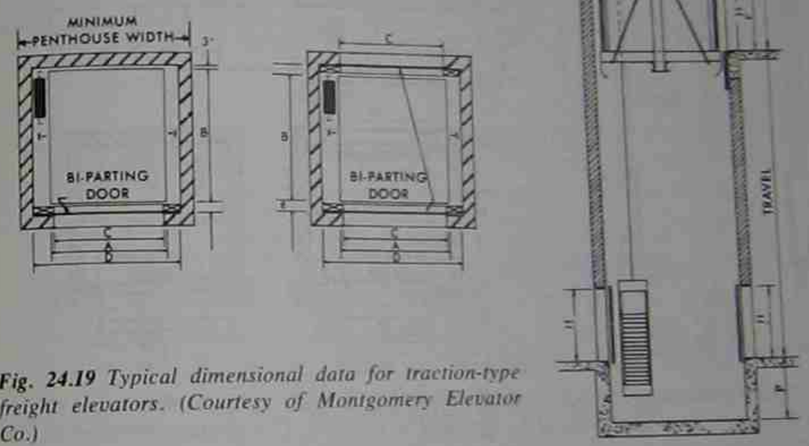


Fig. 24.19 *Typical dimensional data for traction-type freight elevators. (Courtesy of Montgomery Elevator Co.)*

and, in general, much more rapidly. First cost of these systems is frequently high, but the reduction in labor and increase in speed generally yield a short payback period combined with a marked rise in efficiency.

Modern, commercial material-handling systems can be grouped roughly into four categories:

1. *Elevator-type systems*. These are vertical lift, car-type systems including the common dumbwaiter and ejection lifts, which are basically automated dumbwaiters.
2. *Conveyor-type systems*. These include horizontal and vertical conveyors.
3. *Pneumatic systems*. These include sophisticated pneumatic tube systems and pneumatic trash and linen systems.
4. *Other systems*. Systems that do not fit easily into any of the above categories include automated messenger carts and automatic track-type container delivery systems.

24.19 Manual Load/Unload Dumbwaiters

Dumbwaiters often provide the most convenient and economical means of transporting relatively small articles between levels. In department stores, such units transport merchandise from stock areas to selling or pickup counters; in hospitals dumbwaiters often transport food, drugs, linens, and other necessary small items. In multilevel restaurants, office dining rooms, and the like, dumbwaiters are almost always used

TRANSPORTATION

Freight Elevators — Oil Hydraulic

LIGHT AND MEDIUM DUTY HYDRAULIC FREIGHT ELEVATORS							
CAPACITY	2000#	3000#	4000#	5000#	6000#	8000#	
A	5'-0	5'-6	6'-6	8'-6	8'-6	8'-6	
B	6'-0	7'-0	8'-0	10'-0	12'-0	12'-0	
C	4'-8	5'-2	6'-2	8'-2	8'-2	8'-2	
D-manual doors	6'-4	6'-10	7'-10	9'-10	10'-6	10'-6	
D-power doors	6'-10	7'-4	8'-4	10'-4	10'-6	10'-6	
P	4'-6"	4'-6"	4'-6"	4'-6"	4'-6"	5'	

HEAVY DUTY POWER TRUCK HYDRAULIC FREIGHT ELEVATORS					
CAPACITY 10,000#	12,000#	15,000#	18,000#	20,000#	
A	10'-6	10'-6	10'-6	10'-6	12'-6
B	14'-0	14'-0	16'-0	16'-0	20'-0
C	10'-2	10'-2	10'-2	10'-2	12'-6
D-manual doors	12'-6	12'-6	12'-6	12'-6	14'-6
D-power doors	12'-6	12'-6	12'-6	12'-6	14'-6
P	6'	6'	6'	6'	6'

PIT AND OVERHEAD DIMENSIONS				
SPEED FPM	25	50	75	100
P	4'-6	4'-6	5'-0	5'-0
O (7'-0 Door)	13'-2	13'-2	13'-2	13'-2
O (8'-0 Door)	14'-2	14'-2	14'-2	14'-2

H = 7' for light duty; 8' for heavy duty

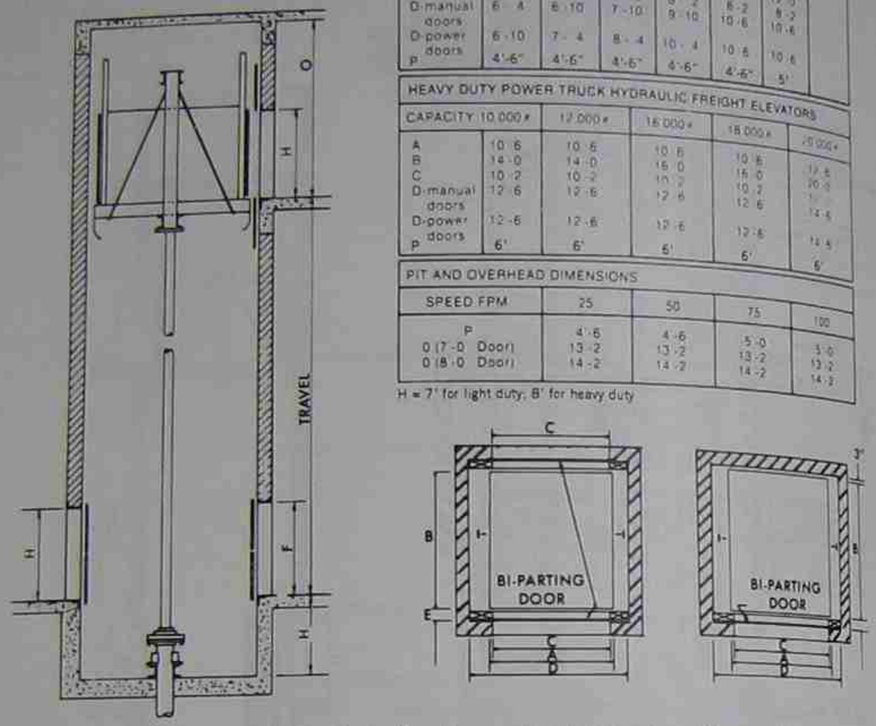
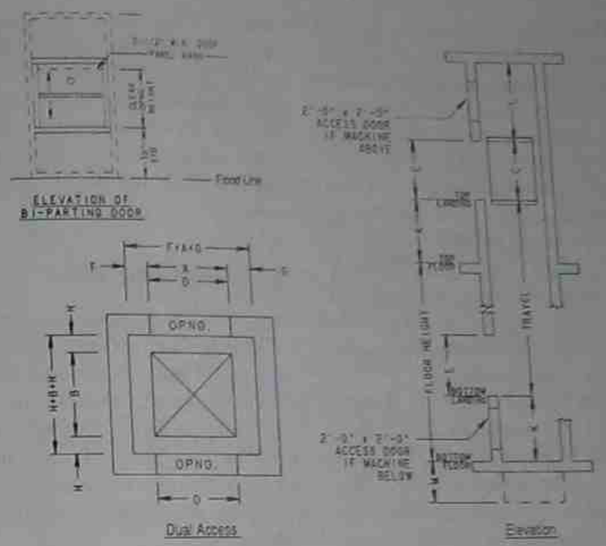


Fig. 24.20 Typical dimensional data for hydraulic-type freight elevators. The machine room, preferably at the lowest landing level, should be arranged to maintain a temperature between 65 and 100°F for proper elevator operation. The dimensions shown are for biparting car doors. (Courtesy of Montgomery Elevator Co.)

Fig. 24.21 A pair of large hydraulic freight elevators for automotive use. These units are automatic, self-leveling, and equipped with power-operated biparting shaftway doors and cab gate. As with many freight installations, both ends of the cab are open. Note that two control stations are provided in the cab, one at each gate. (Photo courtesy of Harris-Preble Co., which supplied the doors in this installation. Hydraulic lifts are by Becker.)



RATED LOAD lb	VOL ■ ft³	DIMENSIONS in.												
		CAR			DOORS *		HOISTWAY							
		A WIDTH	B DEPTH	C HEIGHT	D WIDTH	E HEIGHT	F	G	H	J	K †	L	M **	
(MACHINE OVERHEAD OR BELOW) RATED SPEED 50-150 fpm														
APPLICATION - BULK SUPPLY, FOOD SERVICE (TRAY) & MATERIAL HANDLING														
100	8.33	20	24	30	20	30	6 1/2	7	5	3	30 †	48	6	
200	12	24	24	36	24	36	6 1/2	7	5	3	30 †	48	12	
300	17.5	30	24	42	30	42	6 1/2	7	5	3	30 †	48	18	
400	30	36	30	48	36	48	6 1/2	7	5	3	30 †	48	24	
500	36	36	36	48	36	48	6 1/2	7	5	3	30 †	48	24	

Notes: * ONE OPENING MUST BE LARGER THAN THE CAR SIZE SO THE ASSEMBLED CAR CAN BE PLACED INTO, OR REMOVED FROM THE DUMBWAITER HOISTWAY.
** DEPTH OF PIT REQUIRED IF SLIDE DOWN TYPE DOORS ARE USED.
† IF BASEMENT MACHINE (DRUM OR TRACTION) 42 in.

Fig. 24.22 Typical layout of counter-height dumbwaiter. The shaft openings may be single (one side) or dual access. Doors can be biparting, slide up or slide down. In addition to the sizes shown in the table, light-load cars rated 25 and 50 lb at 50 fpm are available in standard designs. (Reproduced with permission of National Elevator Industry, Inc., 185 Bridge Plaza N., Fort Lee, NJ 07024; copyrighted 1983, Vertical Transportation Standards.)

for delivery of food from the kitchen and for return of soiled dishes.

Dumbwaiter cars are limited to a platform area of 9 sq ft and a maximum height of 4 ft. The car may be, and frequently is, compartmented by shelves. Normal speed ratings are 50 to 150 fpm, with a capacity of up to 500 lb. Cars may be of the traction (counterweighted) or drum (direct pickup) type. Control is normally "call and send" between two floors, although multibutton selector switch or central dispatching arrangements are available for applications with more than two floors. Loading may be floor, counter, or any other specified height. (See Fig. 24.22 for typical layouts.)

24.20 Automated Dumbwaiters

These units are also known as ejection lifts because of the method of delivery (see Fig. 24.23). They find their best application in institutions and other facilities that require rapid vertical

movement of relatively large items. Thus, this device is ideally suited for delivery of food carts, linens, dishes, bulk liquids containers, and so on. The load can be a cart (Fig. 24.24) or a basket (Fig. 24.23) containing the items being transported. At the delivery terminal the item must be picked up and transferred horizontally to its final destination if remote from the delivery point. Loading can be manual or automatic. Sophisticated ejection lifts use programmable controllers for automated loading, dispatch, and ejection; electronic sensors to determine whether space is available for a load; and automated return of the unloaded cart.

Payload capacity for cart systems is available up to 1000 lb and car speeds up to 350 fpm. Maximum cart size is approximately 32 in. W × 68 in. L × 70 in. H. Round-trip time for a 200-fpm unit with 5 loading stations is approximately 2 min; with 10 stations about 2.5 min. Major considerations for these units are their relatively high cost and the large shaft area required.

24.21 Horizontal Conveyors

Although horizontal conveyors find their best application in industrial facilities, they are also usable in commercial buildings such as mail-order houses, which require a continuous flow of material. Restrictions in application stem from inflexible right-of-way requirements, noise generation, and a degree of danger if left unprotected or exposed to unauthorized persons. Cost is relatively low, and capacity is virtually unlimited.

24.22 Selective Vertical Conveyors

The action of this system is similar to the automated dumbwaiter in that the system transfers vertically and automatically loads and unloads, but the similarity ends there. Vertical conveyors are constructed with a moving continuous-loop chain to which are attached carriages that pick up and deliver tote boxes. At sending and receiving stations the operator places the items to be moved (up to 60 lb) in the tote box, "addresses" the box in one of several ways depending on the system, and places it at a pickup point (see Fig. 24.25). The first empty carriage on the chain will pick up the box and deliver it to its address. Functions in modern vertical conveyors are monitored by a microprocessor, which tracks system operation and furnishes maintenance data and operational diagnostics. Drawbacks of this system are the large shaft required, noise, and cumbersome arrangements when interfacing with horizontal conveyors. Cost is moderate.

24.23 Pneumatic Tubes

This well-tried system will undoubtedly continue in use where physical transfer of an item is required. Where information must be moved, electronic data reproduction will completely replace the transfer of pieces of paper between two points. Pneumatic tube systems are available with 2¼- to 6-in. ranges of tube diameters (special shapes are also used) and with single or multiple loops.

Whereas older systems were generally pressurized using a single large noisy compressor, newer systems are computer controlled, utilize a small blower in each of the zones, operate basically on vacuum but also on pressure, are relatively quiet, and are capable of being constructed in unlimited system length. Carriers travel at 25 fps. The computerized control center provides information and control of all system components, including status, traffic data, station assignments, scheduling, and the like. Overall, pneumatic tube systems perform their task reliably, rapidly, and efficiently at relatively low cost if installed during initial building construction. Typical system components are shown in Fig. 24.26.

24.24 Pneumatic Trash and Linen Systems

Rapid movement of bagged or packaged trash and linen from numerous outlying stations to a central collecting point is usually handled by this system. (Health codes require using separate tubes for trash and linen.) Linen systems are found generally in hospitals; trash systems in various facilities, frequently in conjunction with compactors. The system is basically a network of large pipes, negatively pressurized, with numerous loading stations throughout the building. Pipes are 16-, 18-, or 20-in. sizes, operating at

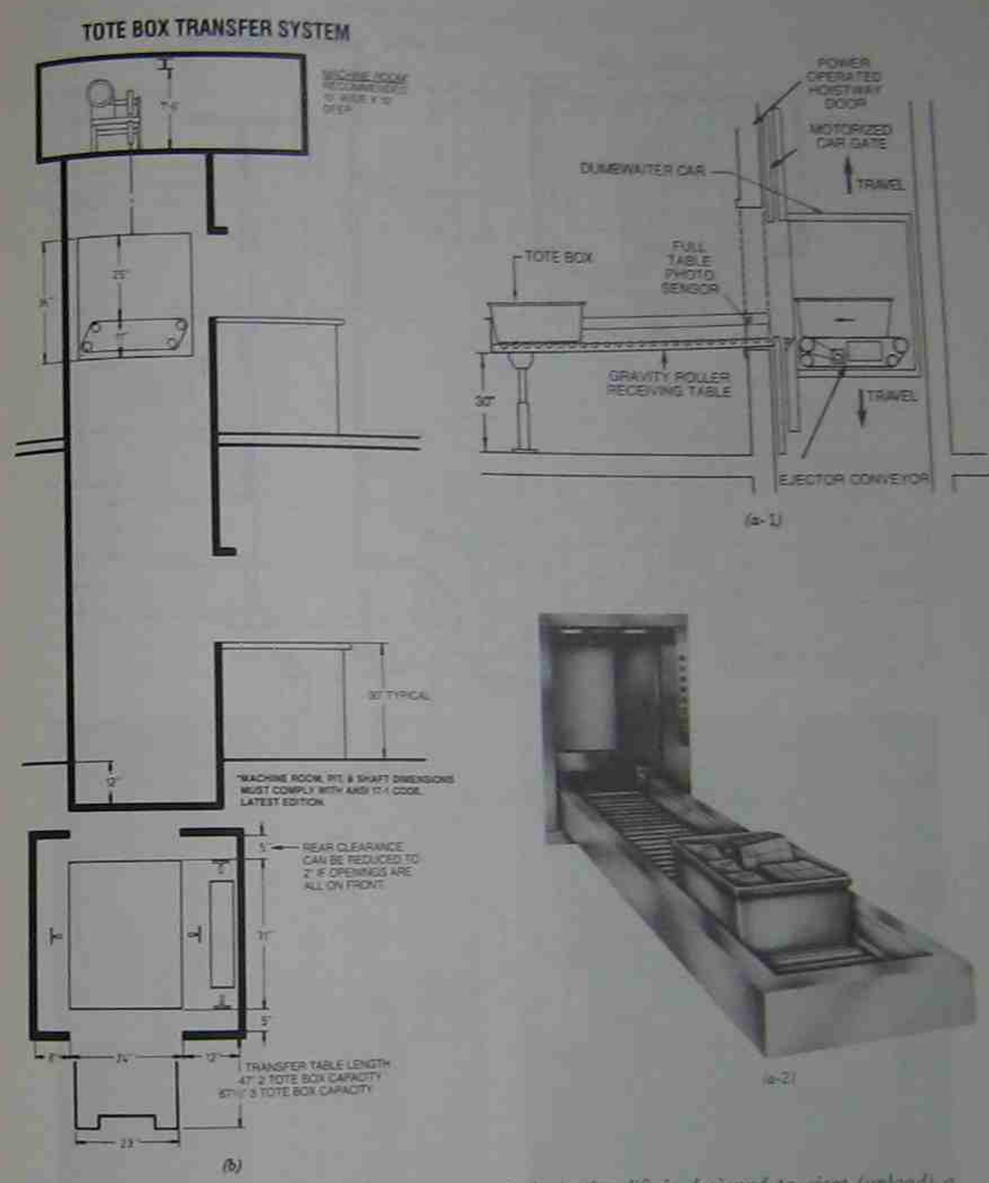
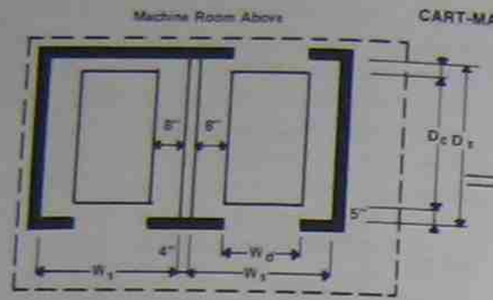


Fig. 24.23 This automated dumbwaiter or vertical ejection lift is designed to eject (unload) a container automatically at a preselected station, after manual loading and dispatching of the container (tote box) at another station. (Systems are available with automatic loading as well.) The tote box is carried on an ejection conveyor (a), *which electrically senses arrival at its destination and effects ejection. Station doors are automatically electrically operated. The dumbwaiter car drive mechanism is a counterweighted traction drive. Car capacity is 300 lb, although containers are normally limited to 50 lb for ease of handling. Car speeds are normally 50 to 150 fpm, with higher speeds available for large rise. A typical hoistway section is shown in* (b). *Vertical travel is not limited. (Courtesy of D. A. Matot.)*

TRANSPORTATION



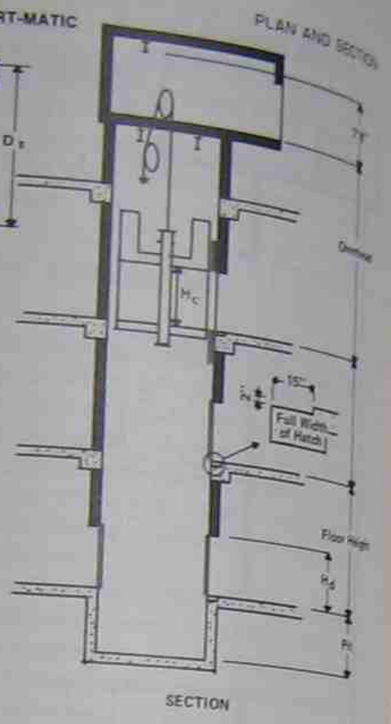


TABLE OF STANDARDS

Capacity	Inside Car Dimensions			Inside Shaft Dimensions		Hoistway Door Frame Dimensions		Pit **	Overhead **
Lbs.	Wc	Dc	Hc	Ws	Ds	Wd	Hd		
500	28"	46"	48"	48"	56"	28"	50"	46"	14'4"
1000	30"	55"	67"	56"	65"	30"	69"	60"	16'8"
1000	34"	72"	72"	60"	82"	34"	74"	60"	17'4"

** May vary with local codes

(a)

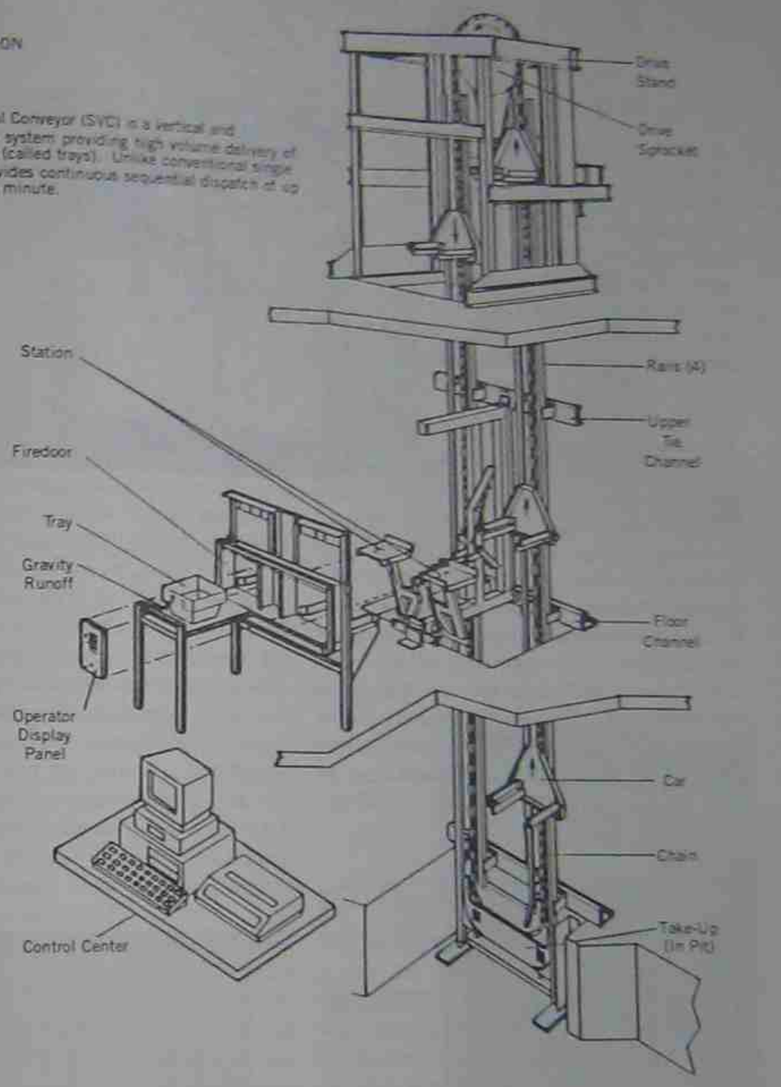
Fig. 24.24 (a) *Plan, section, and dimensions for vertical ejection lift system (automated dumbwaiter).* (b) *Open ejection-lift unit showing cart ejection mechanism. Shaftway doors are vertical biparting.* (c) *The same unit being loaded with food carts and dispatched to the various floors of the hospital. At the upper floors the carts are rolled away by the attendants. Later the lifts are used to return soiled dishes and trays. (Courtesy of Courion Industries, Inc.)*

Selective Vertical Conveyor Mechanical Components

SYSTEM DESCRIPTION

General

The Selective Vertical Conveyor (SVC) is a vertical and horizontal conveying system providing high volume delivery of fiberglass tote boxes (called trays). Unlike conventional single car lifts the SVC provides continuous sequential dispatch of up to 14 containers per minute.



(a)

Fig. 24.25 (a) *System diagram showing operation of a selective vertical conveyor. Tote-box addressing and dispatching can be accomplished remotely from the control center.* (b) *Typical sending and receiving terminal. Stations are arranged vertically in a common shaftway. Each station contains a keypad for addressing and dispatching boxes. (Courtesy of TransLogic Corp.)*

TRANSPORTATION

Fig. 24.25 (continued)

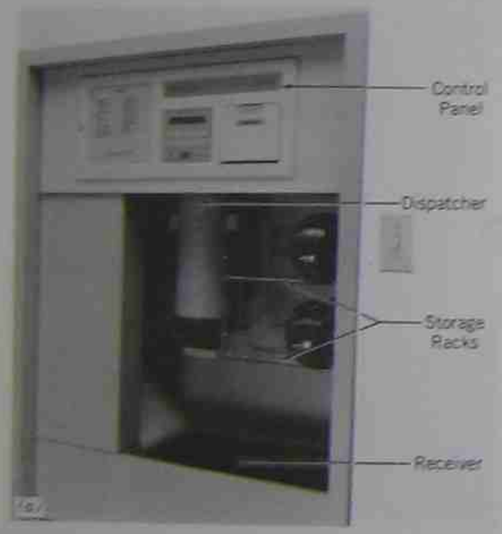


Fig. 24.26 The recessed tube station illustrated is a full-facility combined sending and receiving point. Dispatching and receiving share the same pipe but operate independently automatically. Arriving carriers (b) are decelerated by an air cushion and drop into the front bin on arrival. (b) Carriers (3¾ in. D × 15½ in. L and 5¼ in. D × 16 in. L) are made of impact-resistant transparent polycarbonate plastic. Liners are used with fragile items. The bands around the carriers that maintain the air seal in the transport tubes are replaceable. (Courtesy of TransLogic Corp.)

high static pressure. A system normally can handle only one unit load at a time, but moves it so quickly (20 to 30 fps) that system capacity is large and delays are not encountered. Material placed into a loading station is picked up as soon as the previous load clears. Compressors are large and very noisy, requiring considerable space allocation and acoustical isolation. In addition to the main vacuum system, a high-pressure air line is required to operate the doors, and sprinkler heads must be installed every few floors. Overall costs are low to moderate. For the specific task performed, a cheaper and more efficient transfer technique is difficult to find.

24.25 Automated Container Delivery Systems

This ingenious arrangement employs captive and secure containers locked onto a motorized carriage that, in turn, is locked onto the track system. Power for the motor in the carriage is picked off a third rail at 24 V d-c. The entire assembly moves horizontally or vertically with equal ease. Containers move at a constant 120 fpm horizontally but slower on rises, depending on container load and the steepness of the rise. Containers are available in a number of shapes and volumes to suit the particular installation. Two standard sizes are approximately 18 in. × 6 in. × 13 in. narrow profile and 18 in. × 12 in. × 8 in. low profile. Normal payload is 20 lbs, although for horizontal runs only considerably heavier loads can be carried.

In simple single- or dual-track point-to-point or loop systems, right-of-way conflicts cannot occur and routing is simply a matter of addressing the car. For complex systems involving loops and branches, routing is decided by a central computerized controller that finds the shortest route for each car (up to 250 cars per system), side-tracks, parks cars, and in effect, operates a miniature railroad type system. Addressing the cars is done at each station simply by dialing an address code and dispatching the car. Cars move quietly, unobtrusively, and rapidly throughout the system. The system is easily added onto a structure as a retrofit operation because of track flexibility and small size. Its major drawback is its high cost. Components are shown in Fig. 24.27.

24.26 Automated Self-Propelled Vehicles

These robot battery-powered vehicles follow a route determined by a passive guidance floor tape. They can be arranged to interface automatically with vertical transport means (elevators) so that the route can cover various levels in a facility. The floor tape, which can be installed below carpets, tile, and wood and directly on concrete, is entirely passive. It determines only the path that the vehicle will follow. All sensing, instruction, motive power, and vehicle control are located on the vehicle itself, which can carry approximately a 300-lb payload and can operate a full 8-h day without recharging its on-board batteries. Vehicle speeds are variable, ranging from 20 to 120 fpm. Programming of route, stops, vertical interfaces, changing of cycle, and other functions is accomplished with an external programming device and an on-board programmable controller. Applications for an automated vehicle of this type are limitless: parts delivery and pickup in industrial facilities, food and supplies distribution in hospitals, and mail and document pickup and delivery in offices are among its basic functions. Typical units are shown in Fig. 24.28.

24.27 Conclusion

The foregoing very brief summary simply describes the types of equipment available. For each facility being planned, the architect must study the material transfer problems, remembering that buildings not only handle and process but also generate material; an office building generates about a pound of waste per 100 ft² per day—a prodigious amount in today's large office structures. This type of dry waste can be compacted, bailed, and sold, unlike garbage and wet waste. In addition to considerations of the type of material being handled, there are factors of speed, scheduling, location of stations, labor and material costs, space requirements, noise generation, and energy requirements. To con-

sider and evaluate all these factors in a large and complex facility is generally beyond the ability of the architect alone. Thus expert advice from consultants who specialize in materials handling and from manufacturers' representatives must be sought.

REFERENCE

Strakosch, G. R. (1983). *Vertical Transportation, Elevators and Escalators*, 2nd ed., Wiley, New York.

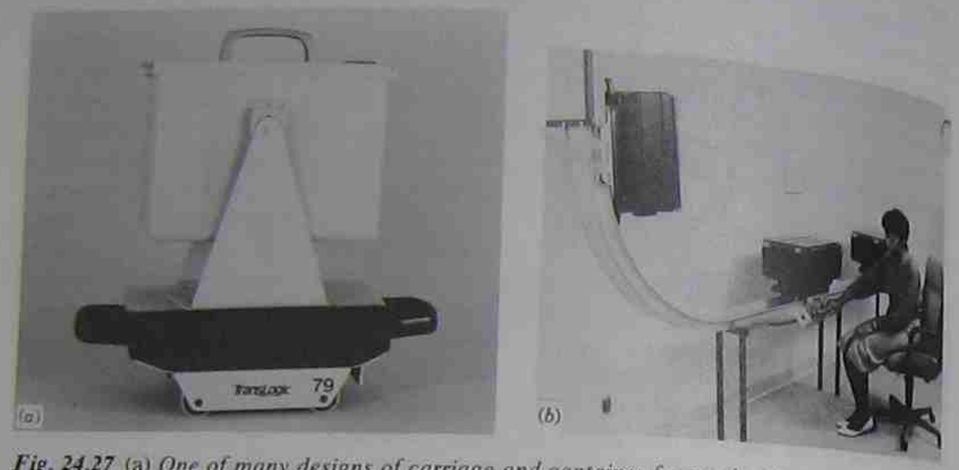
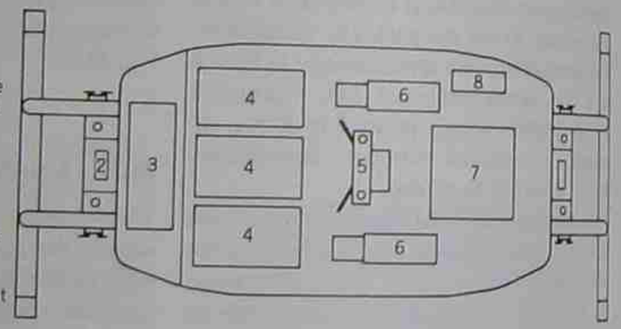


Fig. 24.27 (a) *One of many designs of carriage and container for an electric track vehicle system. This design uses a pivoted container that is maintained in a vertical position regardless of the carriage position, which may be horizontal, vertical, sloped, or even inverted.* (b) *Dispatching and receiving station for a track vehicle system. (Courtesy of TransLogic Corp.)*

1 Pneumatic Safety Bumper
2 Sensor Panel
Contains metal detection sensors which confirm presence of the guide tape to the vehicle guidance system.
3 Steering System
Tricycle wheel design.
4 Batteries
5 Coupling Unit
Transcar tows trolleys. This device is activated to couple Transcar with trolley for transport. When trolley is delivered to destination, coupling unit retracts and vehicle drives from underneath trolley.
6 Drive Motors
Each drive wheel is powered by a 24 VDC motor.
7 Control Unit
Includes all electronic equipment
8 Charging System



(a)

Fig. 24.28 *Components of the automated vehicle are shown in this block diagram* (a). *The vehicle fits underneath its load, as can be seen in* (b) *and* (d), *which show two typical applications: automated food cart delivery in a hospital and automated mail service in a large office. The external programming device is seen in* (c). *(Courtesy of TransLogic Corp.)*

Fig. 24.28 (continued)

25

MOVING STAIRWAYS AND WALKS

MOVING ELECTRIC STAIRWAYS

25.1 General

The moving stairway is also referred to as an escalator or as an electric stairway. This section uses all three names. The escalator was first operated at the Paris Exposition in 1900. Its successors not only deliver passengers comfortably, rapidly, and safely, but also continuously receive and discharge their live loads at a constant speed with practically no delay at any landing. The annoyance of waiting for elevators is not present. Also, time is not lost by acceleration, retardation, leveling, or door operation nor by pressing hall buttons, by passenger interferences in getting in or out of the cars, and so on. One seldom sees a waiting passenger or congestion of passengers at the lighted combplate of an escalator.

Instead of formal lobbies and hallways leading to a bank of elevators on each floor, the electric stairway is always in motion, inviting passengers to ride. The corridors, aisles, and other passageways in existing buildings usually provide space for floor openings adequate for the installation of escalators. In contrast, it would in most cases be almost impossible to install an adequate bank of elevators in an existing building to meet the need for vertical transportation. Elevator hoistways must be vertical from bottom to top floors; an escalator installation can be "staggered" at various appropriate locations (see Fig. 25.1).

A standard stairway is assembled from three separate sections of structural truss—an upper section, a middle section, and a lower section similar to the upper one (see Fig. 25.7*a*). The middle straight section may be any desired length to provide rises for floor heights from 10 to 30 ft, for example. When the rise exceeds approximately 25 ft, depending on the unit's width and type, an intermediate support is located between the two end supports of the stairway where such is feasible. Generally, the upper corners of the bottom and top ends of the truss, after assembly, carry the complete weight of the stairway mechanism and its live load.

25.2 Parallel and Crisscross Arrangements

Moving stairs can be installed in a crisscross arrangement, as in Fig. 25.1*a*, or in either of two parallel arrangements, shown in Fig. 25.1*b* and *c*. The essential difference between the two plans is that in the crisscross arrangement the entrances (exit) to the up and down escalators are separated by the horizontal length of an escalator (see Fig. 25.2), whereas in either of the parallel arrangements the two escalators face in the same direction (see Fig. 25.12).

Thus in the crisscross plan little possibility of confusion exists since at each escalator location only one choice exists. This is considered by most designers to be a definite advantage, particularly in crowded buildings such as stores and where riders are generally unfamiliar with the layout. Furthermore, the crisscross arrangement is more economical of space than the standard parallel arrangement (Fig. 25.1*c*), as can be seen clearly from the plan. The stacked parallel arrangement (see Figs. 25.1*b* and 25.3) must be used with caution because of the inconvenience to the rider of an enforced long walk-around to continue the trip. This arrangement is found most often in mass-purchase-type facilities and in malls, since its raison d'être is to expose the

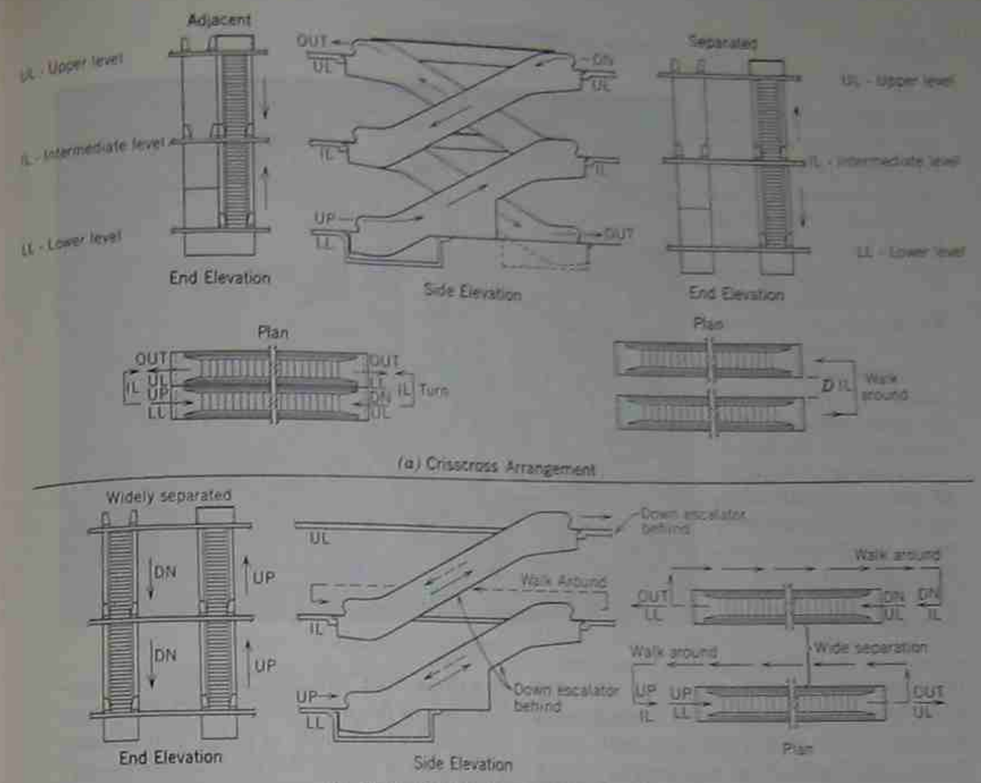


Fig. 25.1 *Side and end elevations and plan views of escalators in* (a) *crisscross,* (b) *stacked, and* (c) *parallel arrangements. In the crisscross arrangement* (a) *separating the escalators forces the rider to walk distance* D *to continue a trip. In the parallel arrangement* (c) *the separation* D *has no effect on the rider, who simply makes a turn to continue in the same up or down direction. In the stacked arrangement* (b) *the rider must traverse the entire length of the escalator at each level in order to continue since the escalators are stacked vertically on each floor.*

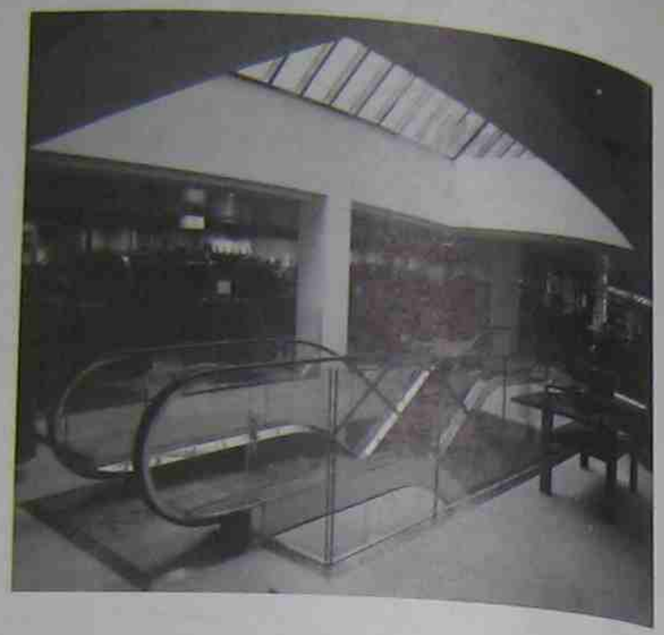


Fig. 25.2 Upper terminal of two elegant glass balustrade escalators in crisscross arrangement. The large horizontal distance between the two is considered an advantage of the crisscross plan since it effectively eliminates confusion for riders. (Photo courtesy of O&K Rolltreppen, West Germany.)

rider to attractive special sale and impulse purchase items which are deliberately placed along the length of the walk-around in a single store. In malls (see Fig. 25.3) this arrangement is much less objectionable since many of the people are there specifically to browse and window-shop, rather than to purchase and leave, as is the case in a single store. In a store, however, the inconvenience of this walk, which is frequently compounded by the crowds of people that normally congregate at special sale merchandise displays and counters, rapidly engenders annoyance. Thus the stacked arrangement is rarely used above two floors (one such walk-around), and

Fig. 25.3 The stacked parallel arrangement of escalators at Stix, Baer & Fuller's Independence Mall store (Kansas City, Mo.), requires riders to walk around when traveling more than one floor. To avoid the annoyance of excessively long trips, riders are provided with the alternative of glass-cab hydraulic elevators. The glass escalator balustrades are architecturally consonant with the glass cab and the glass-protective barriers around the center well of the store. (Photo courtesy of Montgomery Elevator Co.)

when it is, riders can be expected to gravitate to elevators. A similar, but generally much shorter and therefore less objectionable walk-around exists in the case of the crisscross plan, where the escalators are separated by distance D (see Fig. 25.1*a*). This distance is usually limited to about 10 ft because any greater distance places the trip-continuation escalator out of sight and causes not only annoyance at the enforced walk but also confusion and consequently resentment. Separation of the escalators is frequently an architectural consideration and does have the advantage of easier mixing of riders entering at the various levels with riders making a continuous trip. Designers must, however, be continuously aware of the possibility of a negative reaction to separation of escalators, which can be further reinforced when:

1. Insufficient floor space is provided for the transit between escalators, causing crowding, pushing, and delay.
2. Insufficient elevator service is provided for passengers wishing to travel at least three floors. This forces people to make a multistory escalator trip, which in itself can be wearying, particularly when carrying parcels. If such a trip is further lengthened by an enforced walk-around at each floor, it becomes a source of severe irritation, often sufficient to keep customers away from the store.

The consideration of division of rider traffic between elevators and escalators in a store is an important one. The general philosophy of store owners is to make escalators the primary means of vertical transportation, for the obvious reason of merchandise exposure. As a result, elevators are frequently placed at one or both ends of a store while the escalator banks are central. However, care must be taken to provide sufficient elevatoring in stores exceeding three floors, particularly in stores using the stacked or separated crisscross plans, because of the inconvenience of multifloor escalator trips.

25.3 Location

Because escalators are constantly moving and are generally part of a horizontal and vertical trip, they must be placed directly in the main line of circulation. This is in contrast to the elevator bank, which, being a vertical transportation unit, can be set off as an element on its own, for people to approach and utilize. Escalators must therefore be placed in the area served, and with a total and even dominating view of it. This allows potential riders to immediately:

1. Locate the escalators.
2. Recognize the individual escalator's destination.
3. Easily and comfortably move toward the escalator.

One of the most effective ways to disorient traffic movement is to inadequately or poorly mark escalator destinations. The resultant milling about, false starts, and general unhappiness can be observed in numerous otherwise well-designed buildings.

Sufficient lobby space must be provided at the base for queuing where anticipated, and most particularly at discharge points. A restricted or poorly marked area here will cause passenger hesitation and traffic backup. Since the escalator discharges continuously, backup of traffic is dangerous and therefore intolerable. This is particularly crucial in theaters and stadiums, where even momentary hesitation during peak traffic periods could be disastrous. To avoid this, four design steps, in descending order of importance, are taken:

1. Provide well-marked escalators with sufficient traffic-carrying capacity.
2. Provide collecting space at intermediate landings so that pressure can be relieved.
3. Provide a physical divider at intermediate landing turnaround points which will guide riders away from the discharge point and provide adequate space (and time) for riders either to leave at that level or to follow the guide around and continue the trip (see Fig. 25.4).
4. Provide a slight setback for the next escalator so that the necessary 180° turn can readily be negotiated (see Fig. 25.5).

At the landing, an escalator should discharge into an open area with no turns or choice of direction necessary. Where such is unavoidable,

Fig. 25.4 Bank of glass balustrade escalators with mirrored sides, in a crisscross plan. Note the dividers at the turn-around at the intermediate level whose function is to guide traffic smoothly either away from the escalator or to the turn point. This effectively eliminates undesirable bunching and crowding. (Photo courtesy of O&K Rolltreppen, Germany.)

large clear signs should make hesitation unnecessary. Landing space beyond the escalator newels should be 8 ft for a 32-in. unit and 10 ft for 40- and 48-in. units *minimum* for a standard 100-fpm speed. For escalators that will be reversed to accommodate change in traffic direction, this landing space must be provided at top and bottom.

The crisscross arrangement is generally favored because of lower cost, minimum floor space occupied, and lowest structural requirements. The parallel arrangement, being less efficient and more expensive, has as its only virtue a very impressive appearance that strongly draws people to it. For this reason it is frequently employed, particularly in multiple banks of three or four, in transportation terminals (see Fig. 25.6). In such installations, flexibility is maintained by operating all but one escalator in the direction of heaviest traffic. Reversibility of escalators provides this most desirable feature.

Fig. 25.5 Single, 32-in. crisscross escalator in Lord & Taylor's Oakbrook Center store (Chicago). Note the setback of the descending escalator, which is helpful in making a smooth turn to the next escalator. By separating the two escalators horizontally, an enforced walk-through can be created. (Photo courtesy of Montgomery Elevator Co.)

Fig. 25.6 The largest moving stairways in Western Europe are installed in the Stockholm subway system. This parallel bank of three escalators is 70 m (230 ft) long with a 33-m (108-ft) rise. Unlike American standards of 30° incline, 100-fpm speed, and 32- or 48-in. size, these units are at 27.3° incline, 45-m/min (147.6-fpm) speed, and 1000-m (40-in.) width. (Photo courtesy of O&K Rolltreppen, Germany.)

25.4 Size, Speed, Capacity, and Rise

Moving stairs are built according to manufacturers' and industry standards and are therefore available in standard designs. However, all major manufacturers will also produce special designs for particular applications. The data that follow refers to standard designs.

All escalators in the United States are installed at an angle of 30° from the horizontal, with a minimum vertical clearance of 7 ft for escalator passengers (see Fig. 25.17). The 30° inclination means that the rise is equal to 57% of the unit's projected floor area for its inclined portion. The length of the horizontal portions of the stairway depends on the specific design. Elongated newels (see Figs. 25.2 and 25.17) require at least two horizontal treads before the landing plate, whereas short newels (Fig. 25.5) use only a single horizontal tread at the landing. In older designs standard units were available in either 90- or 120-fpm speeds, with the latter requiring a longer horizontal entrance and exit to permit passengers to use the stair safely. Today, although the maximum linear speed permitted by the safety code (ANSI/ASME 17.1) is still 125 fpm, the industry has standardized on a single speed of 100 fpm. Sports facilities and transportation terminals which experience very heavy traffic for short periods are frequently equipped with two speeds (100 and 120 fpm), with the higher speed used only during heavy traffic since the 120-fpm speed presents some difficulty to the less agile or hesitant passenger.

A recent change in the code has redefined the size designation of escalators. The previous *width* designations of 32, 40, and 48 in. referred to the distance between balustrades at the hip level (i.e., between handrails). Since this was not a particularly useful figure, and one that varied slightly with unit design, the new *width* designation refers to the width of the stair tread, in inches. The old width dimension now is referred to as *size*. The standard sizes and widths are:

Escalator Size (in.)	*Tread Width (in.)*
32	24
40	32
48	40

Treads are nominally 16 in. deep with an 8-in. rise.

Although units are available in all three sizes

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TABLE 25.1 **Escalator Passenger Capacity**

Size (in.)	Tread Width (in.)	Speed (fpm)	Passengers per Hour		
			Maximum[a]	Design[b]	Observed[c]
32	24	100	5200	4000	2300
40	32	100	7300	5300	2900
48	40	100	9000	6750	4500

[a]Theoretical maximum (see text).
[b]Heavy loading (see text).
[c]Average long-period loading.

(32, 40, 48 in.), the bulk of manufacture is concentrated in the 32- and 48-in. sizes (24- and 40-in. tread width) because of carrying capacity. Although theoretically the intermediate-size 40-in. escalator (32-in. tread) can carry 40 to 50% more passengers than the 32-in. size (24-in. tread width), in actual practice this is not the case and little advantage is gained from the additional cost of the 40-in. size over the 32-in. size moving stair. As a result, the 40-in. size escalator is something of a novelty. Table 25.1 lists theoretical, nominal (design), and observed average escalator passenger capacities. Maximum loads assume approximately 1¼ persons per tread for a 32-in. unit, 1½ persons per tread for a 40-in. unit, and almost 2 persons per tread for a 48-in. unit. In actuality, maximum capacity is approached only during peak-load periods in transportation terminals and stadiums. At other times full (heavy) load is represented by the nominal capacity figure and average (long period) load by the observed capacity figure. Although a 40-in. tread can indeed carry 2 persons, psychological factors plus physical ones, such as bulky clothing, packages, purses, and briefcases, mitigate against such loading. As a result, on 40-in.-wide treads one person uses each step in a diagonal pattern and on 24-in. stairs one person occupies every other tread. The 32-in. tread has slightly larger capacity than the 24-in. unit.

Some major manufacturers make two standard models (not styles) of moving stairs: a standard-duty unit intended for general indoor use, which provides low to medium rise, and a heavy-duty, sturdier unit intended for all-weather heavy-traffic use such as at transport terminals. The latter, because of stiffer heavier construction, can provide a greater maximum rise than that of standard units. Maximum rise for off-the-shelf design units varies among manufacturers. Approximate maximum figures are given in Table 25.2.

Specially designed units are available with rises of up to about 60 ft. In escalator design all the motive power is delivered at one point; that is, the drive motor drives the main chain, which drives the top sprocket, which drives the step chain, which pulls up the steps, causing the entire assembly to move. This arrangement is suitable for moderate rises of up to approximately 25 ft. Beyond that, the design becomes increasingly inefficient. As the rise increases, the loads on all the drive components, including chains and sprockets, increase sharply. Furthermore, to accommodate the heavier equipment necessitated, truss width increases, as does wellway size and balustrade decks. For rises above 25 to 35 ft (depending on unit width) the drive motor is too large to fit inside the truss and requires a separate machine room below the truss, with attendant cost. All these factors combine to limit escalators to a maximum rise of 60 ft (varies slightly between manufacturers).

TABLE 25.2 **Approximate Maximum Escalator Rise**

Unit Size (in.)	Type	Supports	Maximum Rise (ft)
32	Standard	Ends	24
40			20
48			16
32	Standard	Ends and center	30
40			24
48			20
32	Heavy	Ends	24
40			20
48			18
32	Heavy	Ends and center	40
40			30
48			20

25.5 Components

The major components of a standard escalator installation are shown in Fig. 25.7. Safety devices are discussed in Section 25.6.

The truss is a welded steel frame that supports the entire apparatus. The tracks are steel angles attached to the truss on which the step rollers are guided, thus controlling the motion of the steps. The sprocket assemblies, chains, and machine provide the motive power for the unit, somewhat similar to the chain drive of a bicycle. The control cabinet, which is normally located near the drive machine, contains malfunction indicators in addition to the drive controls. The cabinet may also contain a microprocessor malfunction analyzer and communication means for transmitting escalator operating conditions to a central control point. An emergency stop button wired to the controller and placed near or on the escalator housing at both ends will stop the drive machine and apply the brake (see lower left of escalator, Fig. 25.5).

Key-operated control switches at the top and bottom newels will start, stop, and reverse the stairway. The handrail is driven by sheaves powered from the top sprocket assembly. It is synchronized with the tread motion to provide stability to riding passengers and a support for entering and leaving passengers. Handrails disappear at inaccessible points at newels. The balustrade assembly is designed for maximum safety of persons stepping on or off the escalators.

A particularly attractive design utilizing a transparent balustrade made of tempered glass is illustrated in Fig. 25.2. They are frequently referred to as crystal balustrades. In these units, the handrail is pinch-driven within the truss. In addition to metal and glass as balustrade materials, fiberglass, wood, and various plastic materials are also used.

25.6 Safety Features

Protection to passengers during normal operation is assured by a number of safety features associated with moving stairways:

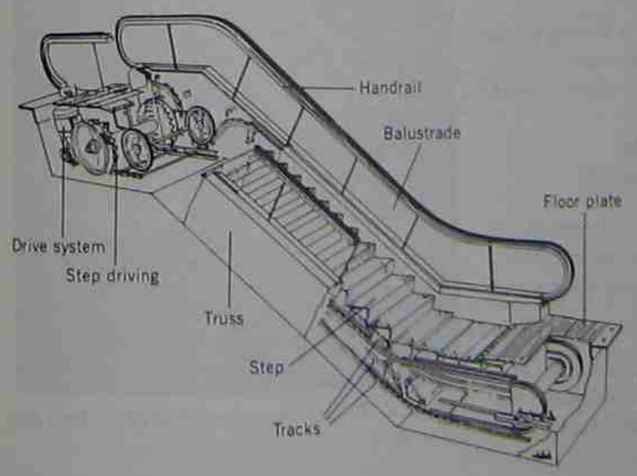

Fig. 25.7 Cutaway view of a standard escalator showing principal parts. (Drawing courtesy of Kone.)

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1. Handrails and steps travel at exactly the same speed (100 fpm) to assure steadiness and balance and to aid stepping on or off the combplates.

2. The steps are large and steady, and are designed to prevent slipping.

3. Step design and step leveling with the combplates at each landing prevent tripping upon entering or leaving the escalator. This is accomplished with two or three (depending on manufacturer) horizontal steps at each end of the escalator.

4. The balustrade is designed to prevent the catching of passengers' clothing or packages. Close clearances provide safety near the combplates and step treads.

5. Adequate illumination is provided by the building at all landings, at the combplates, and completely down all stairways. Some escalator designs provide built-in lighting, as discussed in Section 25.8.

6. An automatic service brake will bring the stairway to a smooth stop if:

(a) The drive chain or the step chain is broken or abnormally stretched.
(b) A foreign object is jammed into the handrail inlet, between the skirt guard and step or between steps, causing them to separate.
(c) A power failure occurs.
(d) The emergency stop button is operated (one is located at each end of the escalator).
(e) Any of the fire safety system devices operates (see Section 25.7).
(f) A tread sags, rises, or breaks.
(g) A drive motor malfunction occurs.

7. In case of overspeed or underspeed, an automatic governor shuts down the escalator, prevents reversal of direction (up or down), and operates the service brake.

If the escalator is stopped by operation of a safety device, passengers can then walk the steps as they would any stationary stairway.

25.7 Fire Protection

Four methods of affording protection in case of fire near escalators are available: the rolling shutter, the smoke guard, the spray-nozzle curtain, and the sprinkler vent. One of these methods is required by code when more than two floors are pierced. Figure 25.8 illustrates clearly how the wellway at a given floor level may be entirely closed off by the fire shutter, thus preventing draft and the spread of fire upward through escalator wells. The movement is actuated by temperature and smoke relays that automatically actuate the motor-driven shutters. The shutter in Fig. 25.8 is shown at the third floor level, but other shutters may be installed at the tops of horizontal wellway openings at any floor.

Figure 25.9 illustrates the smoke-guard method of protection. It consists of fireproof baffles surrounding the wellway and extending downward about 20 in. below the ceiling level. Smoke and flames rising upward to the escalator floor opening meet a curtain of water automatically released from sprinkler heads of the usual type, shown at the ceiling level. The baffle is a

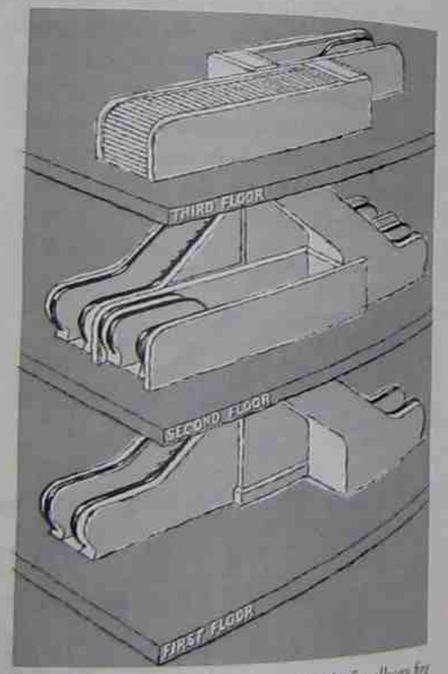
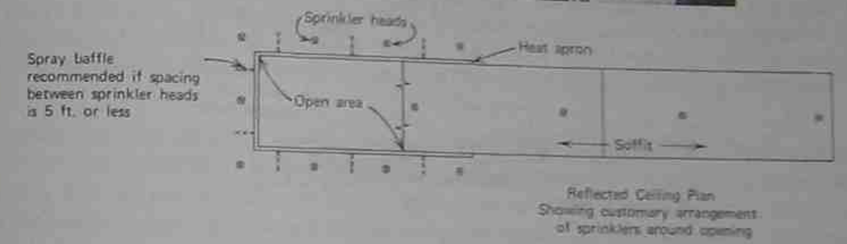
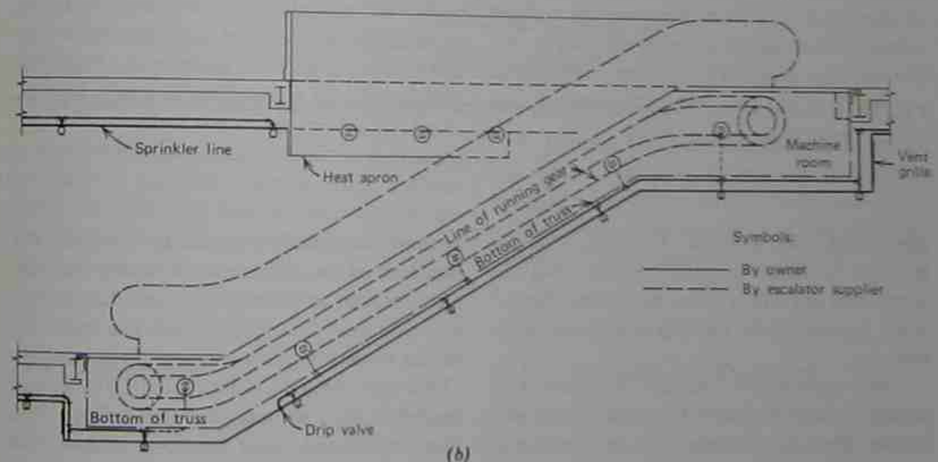


Fig. 25.8 Rolling-shutter method of wellway fire protection.





(b)

Fig. 25.9 (a) *Smoke-guard method of fire protection for a 32-in. moving stairway, crisscross type. The escalator floor opening (per floor) is approximately 4 ft 4 in. by 14 ft 8 in.* (b) *Reflected ceiling plan and section showing baffle and sprinkler layout. (Courtesy of Otis Elevator Co.)*

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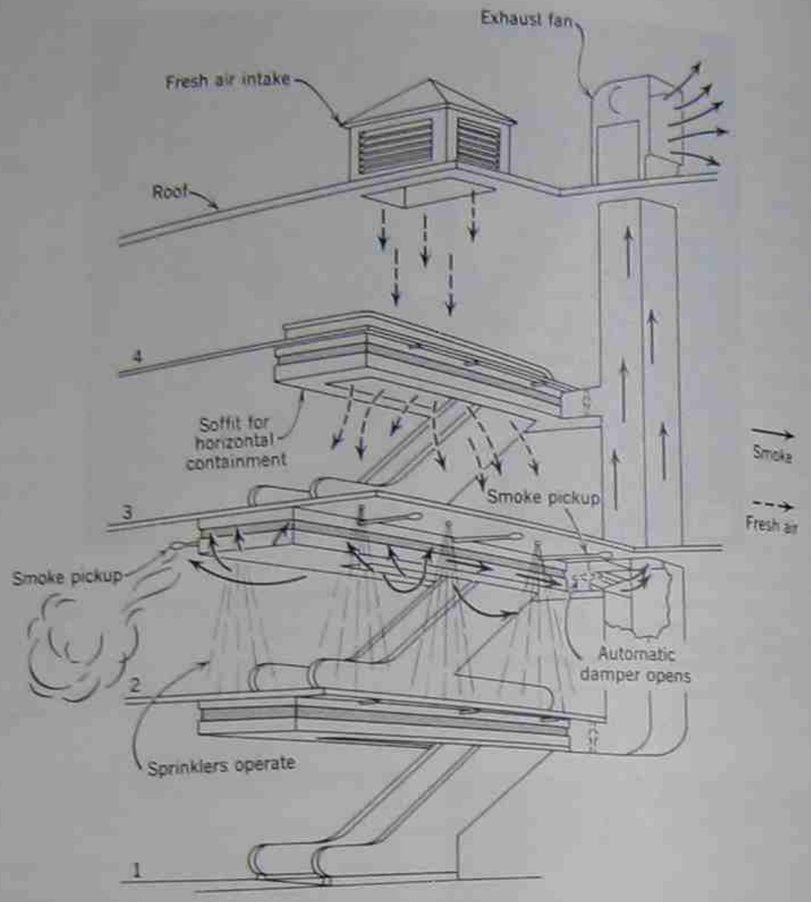

Fig. 25.10 Sprinkler vent fire protection for escalator openings. An exception (with control) to the rule against perforation in floors.

smoke and flame deflector. The vertical shields between adjacent sprinklers ensure that the spray from one will not cool the nearby thermal fuses, preventing the opening of adjacent sprinklers.

The spray-nozzle curtain of water (not shown) is quite similar to the smoke-guard protection. Here closely spaced, high-velocity water nozzles form a compact water curtain to prevent smoke and flames from rising through the wellways. Automatic thermal or smoke relays open all nozzles simultaneously.

The sprinkler-vent fire control is shown in Fig. 25.10. The fresh air intake housed on the roof contains a blower to drive air downward through escalator floor openings, while the exhaust fan on the roof creates a strong draft upward through an exhaust duct; this duct in turn draws air from the separate ducts just under the ceiling of each moving stairway floor opening. Three such separate wellway ducts are shown. Each duct has a number of smoke-pickup relays that automatically start the fresh air fans. The usual spray nozzles on the ceiling near the stairways aid in quenching the fire.

25.8 Lighting

Adequate illumination of a moving stairway, particularly at the landings, is important from

Fig. 25.11 The balustrade section of an escalator can be used to supply the required task (stair) lighting. (a) *A continuous flourescent strip is installed at the balustrade base at Fox Hills Mall (Culver City, Calif.).* (Courtesy of Montgomery Elevator Co.) (b) *A similar source is placed under the handrail of the crystal balustrade in this covered mall in West Germany. Note the additional light at the base for illuminating the combplate.* (Courtesy of O&K Rolltreppen, Germany.)

decorative as well as safety standpoints. In a stairwell-type installation, where general-area lighting does not provide sufficient illumination for the escalator, lighting consonant with the adjacent illumination is installed on the ceiling above the stairway, with special emphasis on lighting the combplate. Thus for instance in Fig. 25.5 the general illumination is supplemented by down-lights above the stairs. In Fig. 25.6 banks of fluorescent lights are placed across the escalator bank at frequent intervals along the rise. Note the additional concentrated light at the combplate. Two different lighting treatments of similar installations are shown in Fig. 25.11.

25.9 Application

1. Main floor locations should be chosen in the direct flow of traffic to assure maximum use.

2. Vertical arrangements should be made to accomplish specific purposes, such as exposure of merchandise, maximum passenger capacity, and maximum accessibility to various areas.

3. The aspect of reversibility of an electric stairway should be considered in applications where major traffic flow is unidirectional. Light traffic in the reverse direction can be handled by a normal fixed stair, adjacent to the escalator (see Fig. 25.12). Similarly, a bank of two escalators can operate either both up, both down, or one up and one down to handle variable traffic conditions in such areas as office buildings and transportation terminals.

4. Exterior escalators can provide an attractive, interesting, and economical solution to transporting people to selected entry points in a building without the necessity of extending the building to cover the entrance (see Fig. 25.13).

25.10 Elevators and Escalators

The use of elevators and escalators should be considered together, as a single problem in vertical transportation as applied to the particular facility being designed. In this connection, and particularly in case of modernization, Fig. 25.14 provides an interesting comparison.

In certain facilities there are times during which demand for vertical transportation is so large that elevators are not a feasible solution. A

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Fig. 25.12 A conventional arrangement provides a parallel bank of two electric stairways separated by a fixed stair in this Canadian application (Place des Jardins, Montreal). Reversibility of the escalators provides the desired flexibility, although normal operation is one up and one down. The fixed stair accommodates those who cannot or will not use a moving stair, as well as reverse traffic when both escalators are operating in the same direction. (Photo courtesy of Montgomery Elevator Co.)

prime example is the school building. During class change, virtually the entire building population moves, with as much as 80% moving between floors. Since class change time is at most 10 min, the only reasonable solution is the combined use of fixed and moving stairs. In other buildings such as multifloor stores, the escalator provides for short trips of one or two floors, and the elevator generally transports passengers traveling three or more stories.

A comparison of travel time between escalator and elevator is of interest. Using a normal speed of 100 fpm, a 12-ft floor requires 14.4 s for travel plus about 5 to 6 s to turn, for a total of approximately 20 s. Thus a four-story trip would take approximately 80 s. A similar elevator trip would take at most 60 s. The additional escalator time is not noticed in the activity of boarding, turning, and riding. However, a trip of more than four stories becomes tiresome, and all the more so with the enforced "walkaround" at each floor in the separated arrangement (see Section 25.2).

Fig. 25.13 An attractive exterior escalator installation avoids the necessity of interior stairs and escalators, while providing an item of architectural interest at San Francisco's Candlestick Park. (Courtesy of Montgomery Elevator Co.)

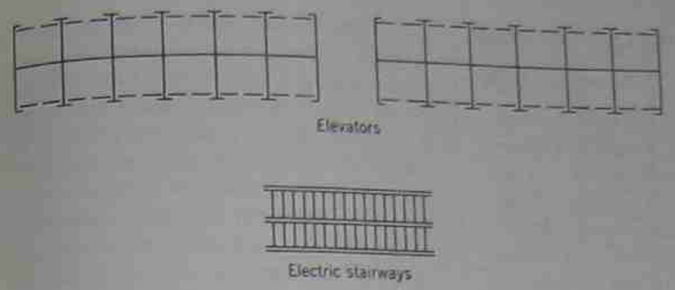

Fig. 25.14 Comparative space requirements for equivalent passenger-handling capacity. Note the marked space savings offered by escalators.

25.11 Electric Power Requirements

Standard American electric stairways are driven by three-phase, 60-Hz, a-c induction motors at standard voltages (208, 230, and 460 V). Horsepowers of driving motors are shown in Table 25.3.

It is recommended that no more than four escalators be served by a single electric feeder, and further that not all the escalators of an installation, whatever the number, be served from the same feeder.

Since obviously one cannot be trapped on an escalator, emergency power is rarely required. Ventilation for the machinery should be supplied for approximately 40% of the power to be dissipated as heat. Thus a 10-hp motor would require the dissipation of 0.40 × 10 × 2500 Btu/hp or approximately 10,000 Btu/h.

TABLE 25.3 **Typical Standard-Duty Escalator Motor Sizes**

Escalator Size (in.)	Maximum Rise (ft)	Size of Motor (hp)
32	14	5
	22	7½
	30	10
48	10	5
	15	10
	20	15

25.12 Special-Design Escalators

As with elevators, escalators of nonstandard design are available on special order. These include units with slopes other than 30°, speeds other than 100 fpm, and rises beyond normal. The most unusual of these special designs, illustrated in Fig. 25.15, is the curved escalator, which made its debut overseas and is now available in the United States. This design, which solves the very common problem of directing

Fig. 25.15 Exposition model of a curved escalator which makes a 90° turn in it rise. These unconventional units offer an elegant (and expensive) solution to the problem of directing traffic to turn after arriving at the escalator's upper terminal. (Photo courtesy of Otis Elevator Co.)

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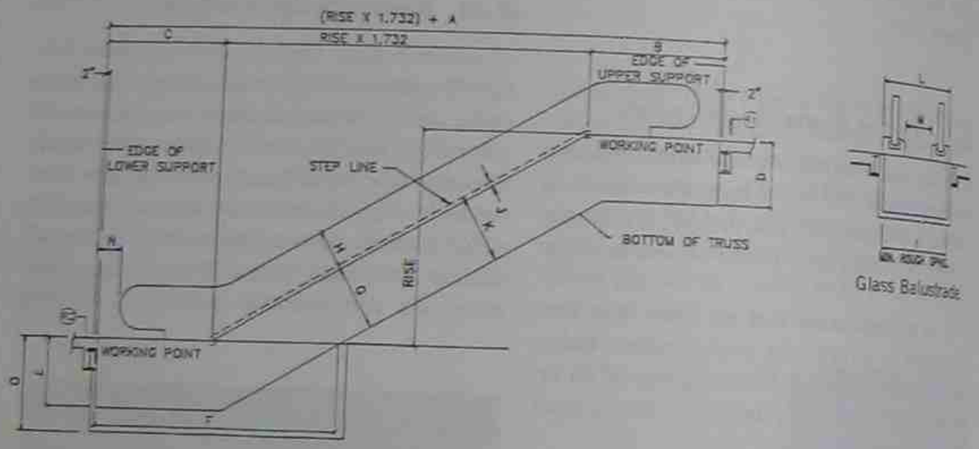
Fig. 25.16 *Escalator dimensional data in a range representing most of the major manufacturers. These data can be used for preliminary planning only.*

		Range	
		From	To
A		13'-2"	16'-10"
B		7'-5"	9'-4"
C		5'-9"	7'-6"
D		3'-3"	4'-2"
E		3'-3"	3'-9"
F		12'-5"	14'-10"
G		2'-11"	3'-1"
H		2'-7"	2'-9"
I	32"	3'-11"	4'-6"
	48"	5'-3"	5'-8"
J		0	1"
K		2'-11"	3'-2"
L	32"	4'	4'-4"
	48"	5'-3"	5'-10"
M	32"	2'	2'
	48"	3'-4"	3'-4"
N		1'-9"	2'-2"
O		3'-6"	4'-0"



PRELIMINARY ESCALATOR SPACE REQUIREMENTS

passengers to make a 90° turn as they leave the escalator, is an engineering tour-de-force. The entire drive mechanism had to be designed anew because tread speed along the inside curve must be lower than that on the outside curve. Handrail drive was less of a problem since the handrail is narrow and therefore speed variation within it is minimal. As of this writing, these units are coming on the market in the 90° turn design, but the drive problem having been solved, other angles will be available as well.

25.13 Preliminary Design Data and Installation Drawings

At the preliminary design stage, the architect requires rough dimensional and structural data for escalators. Since at this stage of design a specific manufacturer for the stairs has not yet been selected, and because these data vary from one supplier to another, the information in Fig. 25.16 is given as a range that covers most of the major manufacturers. Similar data are available from the NEII. Once construction contracts have been awarded and an escalator supplier selected, exact data on space requirements and structural reactions, similar to that shown in Fig. 25.17, are made available. It will be seen that two "working points" are identified, between which a very strong steel wire is tightly stretched. From these two points all other measurements are made, that is, locating the centerline of the truss sections, placing the lower and upper landing truss support beams, and so on.

25.14 Budget Estimating for Escalators

The cost of an escalator includes the cost of the associated mechanical and electrical equipment, plus the shipping installation charges. The manufacturer provides expert engineering and a field erector who supervises the installation.

A tabulation of *relative* escalator prices on a base of 100, is given in Table 25.4. Prices for units with rise above 35 ft rise very rapidly and depend on the type of unit used. The designer is referred to the suppliers for quotes on all units. To these figures must be added the cost of builder's work, wellway protection, lighting, outside balustrades, and plaster.

TABLE 25.4 **Relative[a] Escalator Prices**

Rise (ft)	Width 32 in.	Width 48 in.
14	100[a,b]	118
16	103	121
18	105	124
20	108	127
22	111	130
24	113	133
26	115	135
28	118	138
30	120	141

[a]Base price figure is 100 for the shortest, narrowest, slowest unit (i.e., 14-ft rise, 32 in. wide). All units are 100 fpm. Add 5% for glass balustrade for any unit.

MOVING WALKS AND RAMPS

25.15 General

Moving walks and ramps are different from moving stairways in application, function, construction, and capacity. Escalators have as their primary function the movement of large numbers of people vertically, when such vertical distance does not exceed approximately five stories, as noted above. This specific transportation function the moving stair performs extremely well with minimum cost, space, and maintenance.

When vertical transportation of wheeled vehicles and large parcels is required, the use of an electric stairway is awkward, if not entirely impossible. For such functions and others discussed below, the moving ramp may best be utilized.

Unlike the elevator and escalator, the moving walk or ramp serves a dual function, that is, horizontal transportation only, or a combined function of horizontal and vertical transportation. For the purpose of our discussions, we will define a moving *walk* as one with an incline not exceeding 5° where the principal function is horizontal motion and inclined motion is incidental to the horizontal. A moving *ramp* is a device with an incline limited by code to 15°, where vertical motion is as important as or more important than the horizontal component. It should be understood that the walk and ramp are physically the same device, differently applied.

25.16 Application of Moving Walks

The principal uses of moving walks or moving sidewalks, as they are sometimes called, are to:

1. Eliminate and/or accelerate burdensome walking.
2. Eliminate congestion.
3. Force movement.
4. Easily transport large, bulky objects.

Anyone who has walked the seemingly endless distances in a major airport, carrying a heavy suitcase, can appreciate the near-absolute necessity for a moving walkway. It is for this reason that transportation terminals have become

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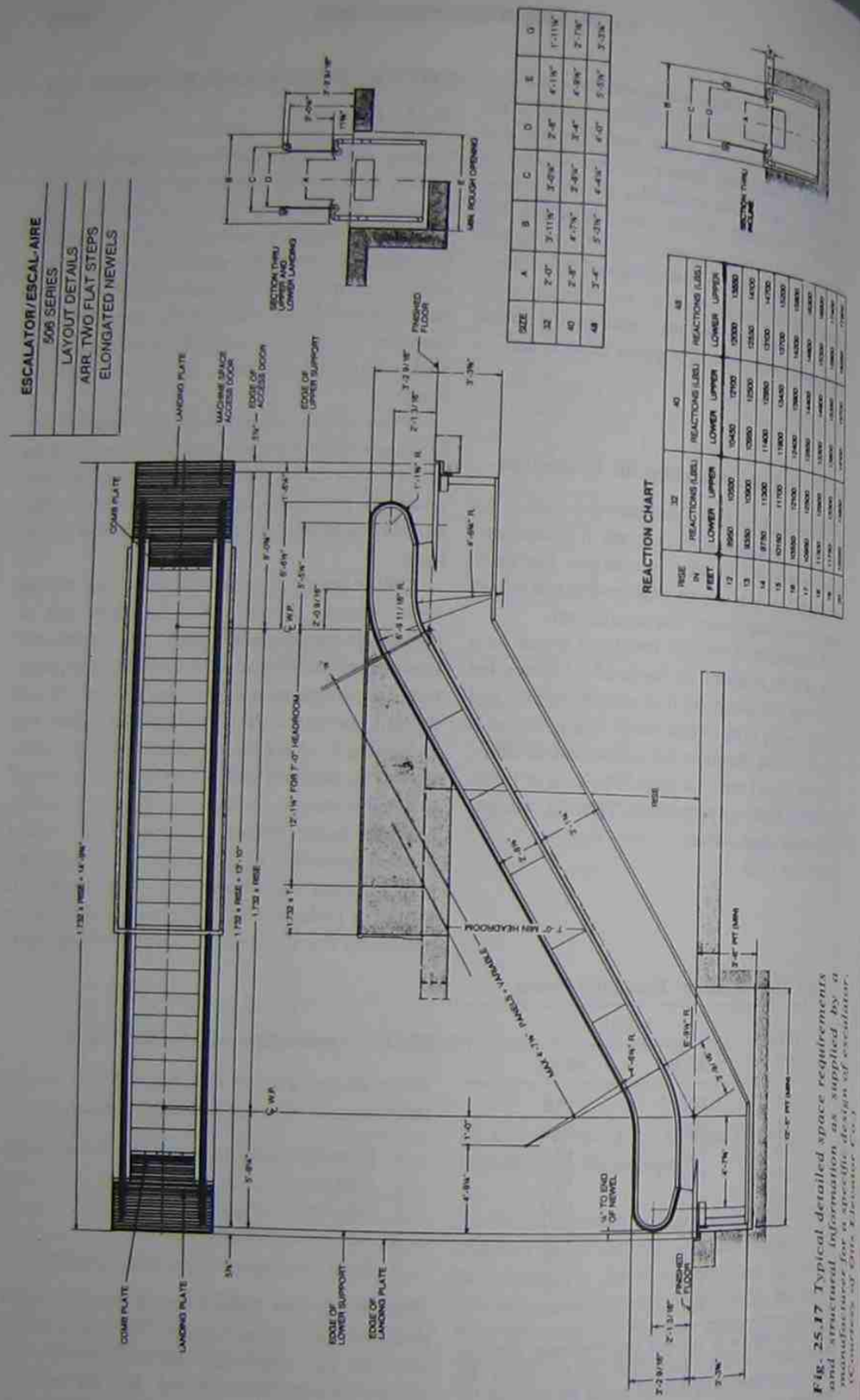

Fig. 25.17 Typical detailed space requirements and structural information as supplied by a manufacturer for a specific design of escalator. (Courtesy of Otis Elevator Co.)

Fig. 25.18 Twin autowalks at Manchester Airport, England. These are the pallet type with glass balustrades and continuous built-in fluorescent lighting. These walks, which are each 1 m (40 in.) wide and 55 m (180 ft) long, travel in opposite directions. Because a single-loop drive runs both walks, they cannot both be operated in the same direction. (Photo courtesy of O&K Rolltreppen, Germany.)

major users of this item (see Fig. 25.18). Other transportation terminals, such as rail and ship terminals, also can often find excellent applications for the moving walk, since much heavy and bulky luggage is moved in these areas.

Application of the apparent distance compression that moving walks provide permits placement of parking areas remote from the pedestrians' destination. Thus, a store can extend its parking area with no annoyance to patrons who must make the long trip to their cars with bulky packages or shopping carts. These advantages are all the more appreciated by persons with a walking impediment.

A second application of walks, as noted above, is the routing of traffic to avoid congestion, milling about, and lost time and motion. This is particularly applicable in transportation terminals, where persons are always traveling in opposite directions through the same and often restricted area, such as in "fingers" leading from airplanes to the main air terminal.

Moving walks are also useful to move people past a display window or some other point where congestion caused by stopping, is undesirable. This "movement of objects" application demonstrates clearly that the moving walk is in function simply a large conveyor belt, regardless of its construction.

25.17 Application of Moving Ramps

The moving ramp that combines horizontal and vertical movement is principally applicable as follows:

1. To move persons and wheeled vehicles vertically.
2. To move persons who lack the agility required to use an escalator.
3. To vertically move large, bulky objects.

Ramps have found a fertile field of application in multilevel stores where escalators are not feasible for shopping-cart users. Such stores may also utilize rooftop parking that is made accessible to cart users via a moving ramp. Since luggage carriers do not easily adapt to usage on escalators, transportation terminals, which are almost always multilevel, also find extensive application for the moving ramps (see Fig. 25.19).

25.18 Size, Capacity, and Speed

The speed, physical dimensions, and therefore passenger capacity of walks and ramps are not as extensively standardized as is the case with escalators. Manufacturers utilize several different tread widths, combined with various speeds and ramp angles of incline. The combinations are designed to suit the situation. Furthermore, since the maximum permissible walk ramp speed varies with angle of slope, and with design of entering point, passenger capacity ratings vary with each design. Higher speeds are allowed by code for level entrance than with sloping entrance, for the obvious reason that the level entrance is easier to board. Tables 25.5 and 25.6 and Fig. 25.20 give data for typical units.

Since capacity varies with width, speed, and type of entrance, exact capacity figures must be obtained for each specific design. Maximum

Fig. 25.19 (a) *Moving ramps in weatherproof design provide direct access to upper floors. This 12° ramp leads to the second floor of a store in Copenhagen. Note the glass balustrade and continuous flourescent lighting fixtures below the handrail. (Photo courtesy of O&K Rolltreppen, Germany.)*

Fig. 25.19 (b) *Palletized inclined moving ramps are particularly useful in installations that do not lend themselves to the use of escalators because of the need to transport wheeled carts in addition to passenger traffic. (Photo courtesy of Schindler Wertheim.)*

TABLE 25.5 **Maximum Permissible Operating Speeds of Moving Ramps**

	Maximum Speed [fpm (m/s)]	
Angle of Incline	Level Entrance	Sloping Entrance
0–3°	180 (0.9)	180 (0.9)
3–5°	180 (0.9)	160 (0.8)
5–8°	180 (0.9)	140 (0.7)
8–12°	140 (0.7)	130 (0.65)
12–15°	140 (0.7)	125 (0.625)

practical lengths at present are approximately 1000 ft, with longer units in design.

25.19 Components

Moving walks are manufactured in only one design: a derivative of the escalator, which uses a flattened pallet in place of a step. In all other respects—the drive mechanism, safeties, brake, handrails, and so on—the unit is similar to an escalator. Preliminary layout data and detailed plans are, as with moving stairs, available from vendors, who generally are the same vendors as supply escalators.

25.20 Horizontal Shuttles

The last item in our discussion is not strictly a building construction item since the bulk of its

TABLE 25.6 **Moving Walks/Ramps: Commercial Sizes**

Angle (deg)	Pallet Width [in. (mm)]	Ramp Speed [fpm (m/s)]
0–3	32 (800)	100 (0.5), 130 (0.65), 150 (0.75)
Walk	40 (1000)	100 (0.5), 130 (0.65), 150 (0.75)
	62 (1400)	90 (0.45), 100 (0.5), 130 (0.65)
10, 11, 12	32 (800)	100 (0.5), 130 (0.65)
Ramp	40 (1000)	90 (0.45), 100 (0.5), 130 (0.65)

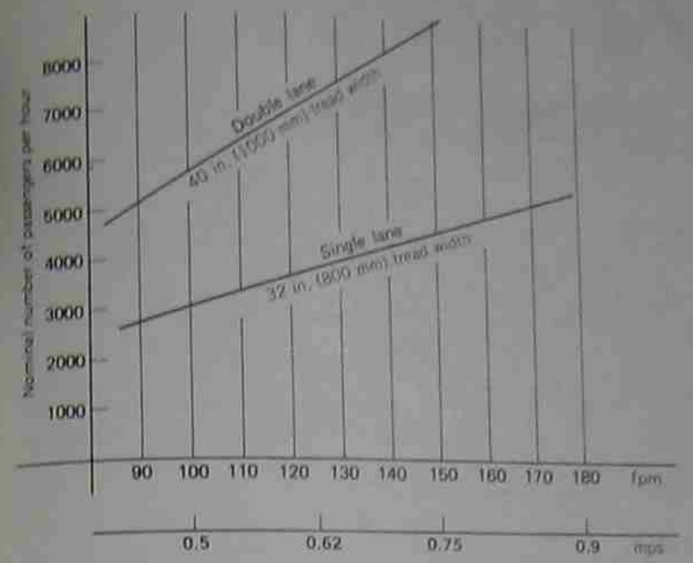

Fig. 25.20 The capacity of moving walks varies with speed, angle of incline, and tread width. Capacity shown is for maximum incline permitted at that walk speed. Because of the requirement for handrail support, tread widths greater than double lane are not often utilized.

construction generally exists outside the facility. Horizontal shuttles, also called horizontal elevators, people movers, transit shuttles, and the like are a relatively new item whose use and technology are burgeoning rapidly. The essential construction consists of a car or gondola, generally completely enclosed, which transports groups or batches of riders between two or more terminals. The greater similarity to an elevator than to a moving walk is obvious since passengers are grouped rather than transported continuously, and entry and exit are door and stop dependent rather than continuous. Technologies vary among manufacturers. One supplier uses a hovercraft design with the car supported on a blower-controlled air cushion. Another supplier uses the magnetic levitation principle combined with a linear drive motor, and so on.

The building designer must be concerned with terminal space requirements, effect of the vehicle entry on the HVAC system since the vehicle frequently enters from outdoors, and the movement of batch traffic from the shuttle terminal to other parts of the facility. Shuttles find application in airports, large recreational facilities such as holiday villages, and multibuilding industrial and educational campuses. Details of the vehicles and terminals are far too variegated to be detailed here, but it behooves the modern architect to be fully aware of even the more unusual people transport facilities and their impact on building design.

REFERENCE

Vertical Transportation Standards (1983). National Elevator Industry, Inc. (NEII).

PART IX
ACOUSTICS

The best (and simplest) distinction between the terms "sound" and "noise" is a subjective one—the former is desirable, the latter is not. This definition does not consider the content of the sound. For example, speech, which is a desirable sound in most instances, can become a "noise" when emanating from a neighbor's apartment or an adjoining office. In such a case an air conditioner, which is most often considered to be a "noise," can provide a desired "sound" by masking the intruding speech. The function of architectural acoustics is simply to reinforce this definition; that is, to enhance desired sound and to maximally attenuate noise.

Chapter 26, Fundamentals of Architectural Acoustics, introduces the subject with a discussion of physical sound theory and physiological hearing phenomena. The latter include the negative effects of noise, which are primarily psychological (annoyance) at low levels but become physical and can result in hearing damage at high levels. Criteria of the U.S. Occupational Safety and Health Administration (OSHA) are given. The discussion moves to the core of the subject—room acoustics—with an explanation of absorption and reverberation, and develops acoustic design criteria for various indoor activities. The chapter concludes with a description of high-grade sound reinforcement systems.

Chapter 27 is devoted to noise control. Noise within a space is controlled by absorption, whereas control of noise transference between spaces is a matter of isolation. The chapter begins with a discussion of the application of absorptive materials for room noise reduction. It treats the problem of interspace noise conduction, dividing the problem into two parts (airborne noise and structure-borne noise), since the solutions are different. Relevant criteria, including sound transmission class (STC) and impact isolation class (IIC), are adduced and explained, and solutions to noise transference problems of different types are suggested. The chapter offers sections on mechanical system noise control and on acoustic recommendations and criteria, ending with a section on exterior acoustics.

26

FUNDAMENTALS OF ARCHITECTURAL ACOUSTICS

SOUND THEORY AND HEARING PHENOMENA

26.1 General

Architectural acoustics may be defined as the technology of designing spaces, structures, and mechanical systems to meet hearing needs. With proper design, "wanted" sounds can be heard properly and "unwanted" sounds, or "noise," can be attenuated or masked to the point where it does not cause annoyance. However, achieving good acoustics has become increasingly more difficult for a variety of reasons. To cut costs, the weight of construction materials used in many of today's buildings is reduced. Since light structures generally transmit sound more readily than heavy ones, this practice poses major acoustical problems. Forty percent or more of a building budget may be allocated for mechanical systems—most of which make noise. Outside noise sources such as cars, trucks, trains, and airplanes present problems in isolating interior spaces from exterior sound.

Building owners and tenants are aware that good acoustic environments in buildings are possible, and the architect is expected to provide them. A clear understanding of the principles explained in this and the following chapter will assist the architect in accomplishing straightforward designs alone and, in more complex instances, cooperating knowledgeably with the project's acoustic consultant. The importance of proper acoustic design is all the more critical, since after-the-fact acoustic "repair" is often difficult and frequently impossible without substantial structural alterations.

All acoustics situations have three common elements—source, transmission path, and receiver. The source can be made louder or quieter and the path can be made to transmit more or less sound. The listener's reception of sound also may be influenced. This chapter presents essential aspects of architectural acoustics to assist a designer in defining acoustic goals. Moreover, it describes the achievable goals as well as various methods for reaching them through design.

26.2 Sound: Definition and Generation

Sound can be defined in a number of different ways depending on the aspect we desire to study. Thus sound is a physical wave, or a mechanical vibration, or simply a series of pressure variations, in an elastic medium. For airborne sound, the medium is air. For structure-borne sound, the medium is concrete, steel, wood, glass, and combinations of all these materials. A much more limited definition, more appropriate to our study, is to define sound simply as an audible signal. This means that the science of architectural acoustics is concerned with the building occupant, and sounds that he or she cannot detect are generally not our concern. To further clear the air, it is always assumed that the hearer has a pair of healthy young ears with a detection range of 20 to 20,000 Hz. With these givens, it is probably best to view sound as a series of pressure variations. In air, these pressure variations take the form of periodic compressions and rarefactions. Refer to Fig. 26.1. The bell radiates a pure tone in all directions equally, that is, it creates a circular wave front.

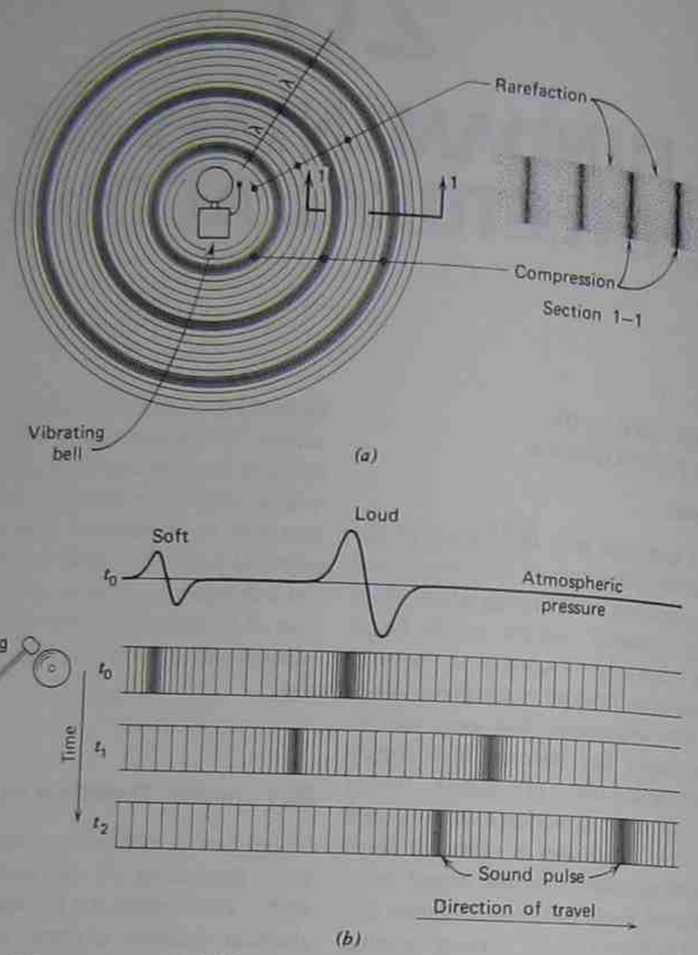

Fig. 26.1 Sound pressure waves. (a) *The continuous vibration from the bell causes a series of compressions and rarefactions of the air to travel outward longitudinally from the source. Amplitude information is carried by pressure; that is, greater amplitude means greater compression and greater rarefaction. (Compression and rarefaction are shown diagrammatically as line density, although they are actually molecular phenomena, as shown in the upper drawing).* (b) *Two single impulses of different magnitude (amplitude) traveling away from the source. Note how amplitude information is carried by difference in pressure.*

As the bell vibrates, it sets up vibrations in the air, of the same frequency, which can best be visualized in the form of a sectional view. Notice that the pressure changes containing the sound information travel in the same direction as the wavefront—longitudinally. This is unlike a radio signal, for instance, in which the wave travels longitudinally but the information—that is, the modulation, is expressed in wave height and shape—is transverse. Sound is therefore *longitudinal* mechanical wave motion.

26.3 Frequency

The number of times the cycle of compression and rarefaction of air occurs in a given unit of time is described as the frequency of a sound. For example, if there are 1000 such cycles in 1 second, the frequency of the sound is 1000 cps or 1000 hertz (Hz) in the standard nomenclature. Thus in Fig. 26.1*a*, higher frequencies would be shown by compressions and rarefactions that are closer together and lower frequencies by

those that are further apart. In sound, the concept of frequency is often referred to by a term borrowed from music—*pitch*. The higher the frequency, the higher the pitch, and vice versa. As stated, the approximate frequency range of a healthy young person's hearing is 20 to 20,0000 Hz. The upper limit decreases with age as a result of a process called presbycusis. Recognition of this phenomenon can be of importance in schools, since very high-pitched sounds that are inaudible to most adults (the loss is more pronounced in men than women) can be a source of extreme annoyance to students. For example, dentists report that high-speed turbine drills and teeth-cleaning devices cause extreme auditory discomfort to many young patients. These devices produce sounds in the 15- to 20-kilohertz (kHz) Range (see Fig. 26.2).

The human speaking voice has a range of approximately 100 to 600 Hz in *fundamentals*, but harmonics (overtones) reach to approximately 7500 Hz. Most speech information is carried in the upper frequencies, while most *acoustic energy* exists in the lower frequencies. The critical frequency range for speech communication is 300 to 4000 Hz. Overtones outside these frequencies give the voice its characteristic sound and specific identity. Telephone and radio communication are accomplished in a considerably narrower frequency band by sacrificing some voice quality and intelligibility. (See Figs. 26.14 and 26.20.)

A sound composed of only one frequency is a pure tone. Except for the sound generated by a tuning fork, few sounds are truly pure. Musical sounds (tones) are composed of a fundamental frequency and integral multiples of the fundamental frequency (harmonics). Most common sounds are complex combinations of frequencies. Figure 26.3 shows examples of pure tones, musical notes, and common sounds; Fig. 26.4 shows the frequency ranges of some common devices and phenomena. The frequencies in the scale of Fig. 26.4 all stand in the ratio of 2 : 1 to each other, that is, 16 : 32 : 63 : 125 : 250, and so on. Borrowing again from musical terminology,

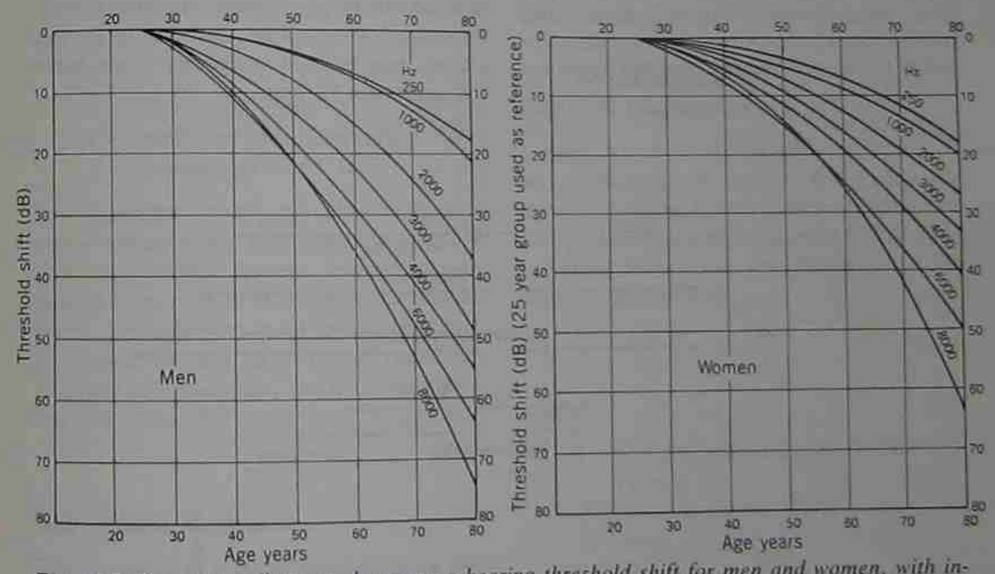

Fig. 26.2 The curves illustrate the average hearing threshold shift for men and women, with increasing age relative to 25-year-old reference group. Note that at age 60 the male threshold shift at upper speech frequencies (4000 Hz) is 30 db as compared to 20 db for women, a difference of 10 db or one-half the subjective loudness (see Table 26.3). For men older than 50 and women older than 60, frequencies above 10 kHz are effectively inaudible, and even at normal speech frequencies of 1000 to 2000 Hz subjective loudness is reduced to one-half of that of a 25-year-old listener. (Reproduced with permission from F. A. White, Our Acoustic Environment, *Wiley, New York, 1975.)*

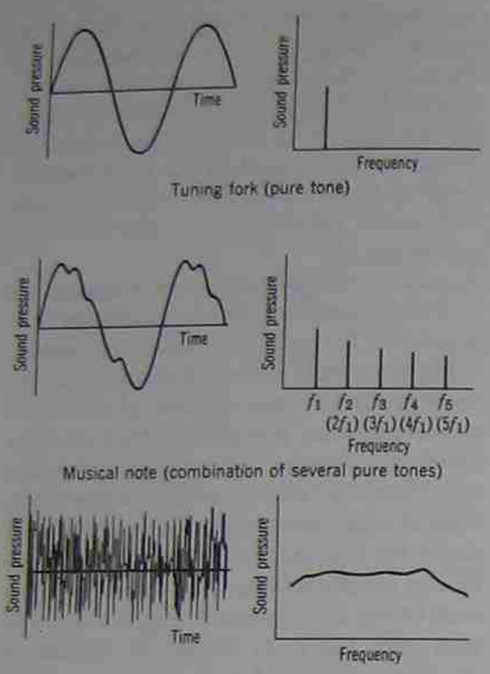

***Fig. 26.3** Schematic representations of a pure tone, a musical note, and more complex sounds (speech, music, and noise), showing the variation of sound pressure with time and frequency.*

they are one *octave* apart. These particular frequencies are also accepted internationally as the center frequencies of octave bands used for the purpose of sound specification. For technical reasons, a geometric mean is used. Thus 250 is the center frequency of an octave band ranging from $250/\sqrt{2}$ to $250\sqrt{2}$ and that particular octave is known as the 250-Hz octave. If finer division is required, ½-octave and ⅓-octave bands are used.

26.4 Velocity of Propagation

Sound travels at different velocities depending on the medium. In air, at sea level, sound velocity is 344 m/s or 1130 fps. This corresponds to 770 miles per hour or 1239 kilometers per hour—slow indeed when compared to light, which has a velocity of 186,000 miles per *second*. Since sound travels not only in air but also through parts of a structure, it is of interest to know the velocities in other media (see Table 26.1). For our purposes, velocity changes due to temperature and altitude (atmospheric pressure) may be ignored and, for rough calculation, 1100 fps and 350 m/s may be used as velocity in air, since both are within 3% error.

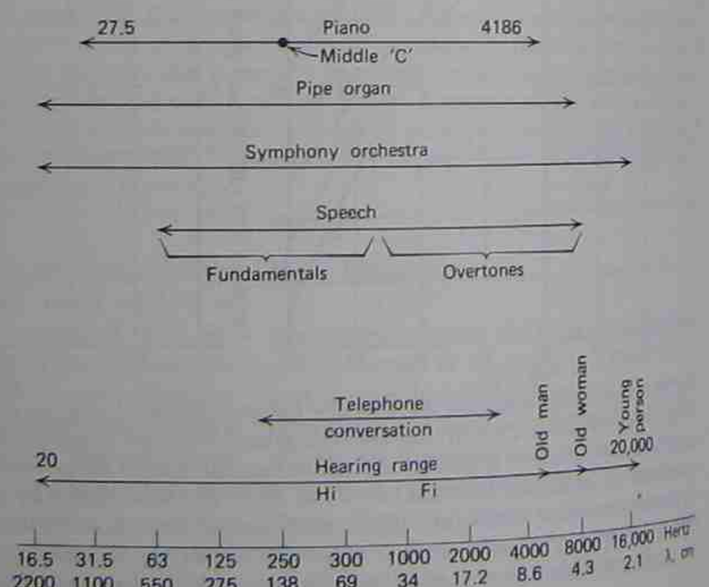

***Fig. 26.4** Frequency ranges of common instruments. Wavelength (λ) is calculated on an assumed propagation velocity of 344 m/s.*

TABLE 26.1 Sound Propagation Velocity in Various Media

Medium	Velocity	
	Meters per Second	Feet per Second
Air	344	1130
Water	1410	4625
Wood	3300	10,825
Brick	3600	11,800
Concrete	3700	12,100
Steel	4900	16,000
Glass	5000	16,400
Aluminum	5800	19,000

NOTE: These figures are approximate, since the listed materials vary in density. Average frequency is used.

26.5 Wavelength and Types of Propagation

The wavelength of a sound may be defined as the distance between similar points on successive waves or the distance the sound travels in one cycle. The relationships between wavelength, frequency, and velocity of sound is expressed as

$$\lambda = \frac{c}{f} \qquad (26.1)$$

where

λ = wavelength, ft (m)
c = velocity of sound, fps (m/s)
f = frequency of sound, Hz

Low-frequency sounds are characterized by long wavelengths and high-frequency sounds by short wavelengths. Sounds with wavelengths ranging from ½ in. to 50 ft can be heard by humans. A simple nomograph presented later in this chapter (see Fig. 26.29) permits rapid determination of wavelength, given the frequency, and vice versa.

26.6 Sound Magnitude

The magnitude of a sound signal is a much more complex subject because of the different terms in use and because of the great range of numbers involved. When we speak of sound magnitude, we think of loudness, which is a subjective, ear-oriented reaction not linearly related to the sound power (watts). The strength of sound is described variously as sound power, sound pressure, sound pressure level (SPL), sound intensity, and sound intensity level (IL), all of which differ from each other, and from subjective loudness. To clearly understand these concepts, and it is imperative that they be so understood, a comprehension of how we hear and how sound is propagated in free space is necessary.

26.7 Sound Intensity; Free Field Propagation

A point sound source of constant power P (watts) radiating in free space, that is, at a distance far from the effects of any reflecting surface, is represented in the drawing of Fig. 26.5. The *sound intensity* at any distance from the source is expressed as

$$I = \frac{P}{A} \qquad (26.2)$$

where

I = sound (power) intensity, W/cm² (W/m²)
P = acoustic power, Watts
A = area, cm² (m²)

Since it is traditional in architectural acoustics to express area in square centimeters although the MKS (SI) system would require area to be stated in square meters we will use square centimeters. Conversion data are supplied in Table 27.15. See also Table 27.16 for a listing of sym-

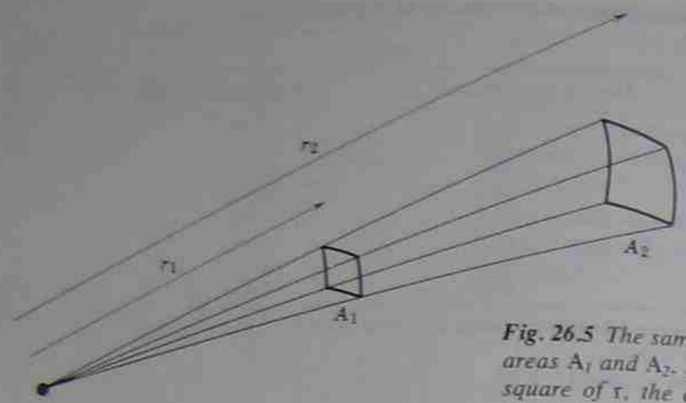

Fig. 26.5 The same total energy passes through areas A_1 and A_2. Since A is proportional to the square of r, the energy density or intensity is inversely proportional to r^2.

bols and abbreviations. Since the sound radiates freely in all directions,

$$I = \frac{P}{4\pi r^2} \quad \text{W/cm}^2 \qquad (26.3)$$

where r is the radius of an imaginary enclosing sphere, which is a form of the classic *inverse square law*, stating that *intensity is inversely proportional to (distance)^2 from the source*. [In English units this is

$$I = \frac{P}{930 \times 4\pi r^2} \quad \text{W/ft}^2 \qquad (26.4)$$

since 1 ft^2 = 930 cm^2.] Using equation 26.3 to determine the intensities I_1 and I_2 at distances r_1 and r_2 from point source P, and dividing the equations, we find that the intensities at distances r_1 and r_2 from the source stand in the ratio

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \qquad (26.5)$$

Note the exact correspondence of these relations to the derivations for illumination from a point source, found in Section 18.12 and Fig. 18.12. Figure 26.6 shows graphically how a sound pulse is attenuated in *strength* (but not in waveform) as it travels outward from the source by action of distance.

The preceding derivation is based on a *point* source, that is, a source that is small relative to the wavelength produced. This type of source produces spherical waves. Line sources such as strings produce cylindrical waves. Large vibrating surfaces such as walls produce plane waves. The importance of these facts will become clear in the discussions on barriers and diffraction in Chapter 27.

The threshold of hearing, that is, the minimum sound power intensity (I) that a normal ear can detect, is 10^{-16} W/cm^2. (Actually, the ear responds to pressure, as explained below.) The maximum sound intensity that the ear can accept without damage is approximately 10^{-3} W/cm^2. This gives a range of 10^{13}, or 10 million million to 1 (10,000,000,000,000:1). Table 26.2 gives an idea of the physical significance of these numbers. Two problems arise immediately when dealing with quantities of this type; the numbers themselves are very small and the ratios are very large. Furthermore, the human ear responds logarithmically, not arithmetically to sound pressure (and intensity); that is, doubling

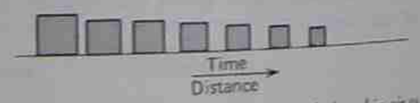

Fig. 26.6 Attenuation of a sound signal in air as it travels away from the source. The shape (information) remains constant when traveling in a nondispersive medium such as air. This is not the case with travel in solids, where different frequencies travel at different velocities, and therefore cause a wave-shape change with time and distance. Since velocity of propagation is constant, time and distance are linearly related and can therefore be plotted on the same axis.

TABLE 26.2 **Comparison of Decimal, Exponential, and Logarithmic Statements of Various Acoustic Intensities**

Intensity (W/cm^2)		Intensity Level—Logarithmic Notation	
Decimal Notation	Exponential Notation		Examples
0.001	10^{-3}	130 db	Painful
0.0001	10^{-4}	120 db	
0.00001	10^{-5}	110 db	75-piece orchestra
0.000001	10^{-6}	100 db	
0.0000001	10^{-7}	90 db	Shouting at 5 ft
0.000000001	10^{-9}	70 db	Speech at 3 ft
0.00000000001	10^{-11}	50 db	Average office
0.0000000000001	10^{-13}	30 db	Quiet unoccupied office
0.00000000000001	10^{-14}	20 db	Rural ambient
0.000000000000001	10^{-15}	10 db	
0.0000000000000001	10^{-16}	0 db	Threshold of hearing

the intensity of a sound does not double its loudness—the change is barely perceptible. To solve these problems it would be much more convenient if we were to construct a scale that:

1. Started at zero for the minimum sound (intensity or pressure) we can hear.
2. Used whole numbers rather than negative powers of 10.
3. Had some fixed relationships between an arithmetic difference and a loudness change; say, 10 units equals a doubling (or halving) of loudness. Thus, on such a scale, the difference between 20 and 30, 60 and 70, would always be a doubling of loudness.

Such a scale exists. It is the decibel scale.

26.8 Intensity Level (IL) and the Decibel (db)

The word "level" indicates a quantity relative to a base quantity. Intensity *level* is the ratio between a given intensity and a base intensity. If we express intensity level as

$$IL = 10 \log \frac{I}{I_0} \qquad (26.6)$$

where

IL = intensity level, db
I = intensity, W/cm^2
I_0 = base (i.e., 10^{-16} W/cm^2, the threshold of hearing)
log = logarithm to base 10

then we have established a scale that satisfies the three conditions set forth above. The quantity IL, intensity level, is dimensionless, since it indicates simply a ratio between two numbers. It is measured in decibels (db) for convenience in expressing the large numbers involved. Table 26.2 shows the great convenience of using the logarithmic decibel scale as compared to either decimal notation or exponential notation. Table 26.3 gives a short listing of subjective loudness changes expressed in decibels. Note that *10 db indicates a doubling of loudness*, and 20 db is loudness doubled twice, that is, four times as loud. The *difference* (Δ) between any two intensity levels

TABLE 26.3 **Subjective Loudness Changes and Corresponding Intensity Level Changes**

Change in Level (db)	Subjective Change in Loudness
3	Barely perceptible
6*	Perceptible
7	Clearly perceptible
10	Twice or half as loud
20	Four times or one-quarter as loud

*Six decibels corresponds to the change encountered when distance to the source in a free field is doubled (halved).

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$$\Delta IL = IL_2 - IL_1 = 10 \log \frac{I_2}{I_0} - 10 \log \frac{I_1}{I_0}$$

Therefore,

$$\Delta IL = 10 \log \frac{I_2}{I_1} \text{ db} \qquad (26.7)$$

A few examples using decibel notation and logarithmic calculations should help the reader become familiar with this useful system.

EXAMPLE 26.1. Two sound sources produce intensity levels of 50 and 60 db, respectively, at a point. When these are functioning simultaneously, what is the total sound intensity level? (We assume identical frequency content and random phase; that is, the phase relationship between the two sources changes in a random manner.)

SOLUTION. Note that we are dealing with intensity level, not intensity, since intensity itself has little significance for us. The technique involved in adding two sound intensity levels has three steps:

1. Convert both to actual intensity.

$$IL = 10 \log \frac{I}{I_0}$$

so

$$60 = 10 \log \frac{I_1}{10^{-16}}$$

or

$$6.0 = \log \frac{I_1}{10^{-16}}$$

Then, using the definition of a base 10 logarithm:

$$10^6 = \frac{I_1}{10^{-16}}$$

$$I_1 = (10^{-16})\, 10^6 = 10^{-10} \text{ W/cm}^2$$

By similar calculation,

$$I_2 = 10^{-11} \text{ W/cm}^2$$

2. Add arithmetically.

$$I_1 + I_2 = 10^{-10} + 10^{-11}$$

$$= (10 \times 10^{-11}) + 10^{-11}$$

$$I_{\text{tot}} = 11 \times 10^{-11} \text{ W/cm}^2$$

3. Reconvert to decibels. To find the intensity level IL corresponding to the new total intensity $I_1 + I_2$, we simply apply equation 26.6:

$$IL_{\text{tot}} = 10 \log \frac{I_{\text{tot}}}{I_0}$$

$$= 10 \log \frac{11 \times 10^{-11}}{10^{-16}}$$

$$= 10(\log 11 + \log 10^5)$$

$$= 10(1.04 + 5)$$

$$= 60.4 \text{ db}$$

which is only a fraction larger than the original 60 db of the stronger sound.

EXAMPLE 26.2. Assume two noise signals of 60 db each. What is the combined strength in decibels?

SOLUTION. One method would be to calculate levels as in Example 26.1. A shorter method is to find the difference between the sum and either signal and to add it to either original signal. Using equation 26.7,

$$\Delta IL = IL_{\text{comb}} - IL_1 = 10 \log \frac{I_{\text{comb}}}{I_1}$$

$$= 10 \log \frac{2I_1}{I_1}$$

$$= 10 \log 2$$

$$= 10(0.30)$$

$$= 3 \text{ db}$$

This answer (which is independent of any particular level) gives us the extremely important fact that *doubling a signal intensity raises the intensity level by 3 db.* (In our case, the combined intensity level would obviously be 60 db + 3 db or 63 db). Similarly, quadrupling a signal's intensity raises the received level by 6 db. This is because

$$\Delta IL = 10 \log \frac{4I}{I}$$

$$= 10 \log 4$$

$$= 10(0.60)$$

$$= 6 \text{ db}$$

Therefore, quadrupling 60 db gives 66 db, or 60 db + 60 db = 63 db and 63 db + 63 db = 66 db. This technique is very useful when combining a large number of identical levels, as in the following example.

EXAMPLE 26.3. A factory will contain 20 identical machines, each of which generates a noise level of 80 db. What will be the combined noise level? (Ignore problems of frequency content, phase, and fields.)

SOLUTION

$$\Delta IL = IL_{\text{tot}} - IL_{\text{single}}$$

$$= 10 \log \frac{I_{\text{tot}}}{I_{\text{single}}}$$

$$= 10 \log \frac{20 I_{\text{single}}}{I_{\text{single}}}$$

$$= 10 \log 20$$

$$= 10(1.3) = 13 \text{ db}$$

Therefore the total noise level will be

$$IL_{\text{tot}} = 80 \text{ db} + 13 \text{ db} = 93 \text{ db}$$

A chart for combining decibel levels of two sources is given below in Fig. 26.7 which eliminates the somewhat lengthy procedure detailed in Example 26.1. Referring to Table 26.3, we note that the human ear is not responsive to fractional db changes; indeed even a 3-db change is barely perceptible. This being so, we recommend that the detailed calculation and the chart be reserved for situations where a high degree of accuracy is required. For everyday calculations, the following rules of thumb may be used to combine db levels of two sources:

1. When the difference between two sources is 1 db or less, add 3 db to the higher level to obtain the total.
2. When the difference is 2 to 3 db, add 2 db.
3. When the difference is 4 to 8 db, add 1 db.
4. When the difference is 9 db or more, ignore the lower source.

A comparison of addition by these rules of thumb and by an accurate method shows that at usual levels, the error involved is always less than 1%.

db Level		Sum	
Lower	Higher	Approximate	Accurate
60	60	63	63
60	62	64	64.4
60	64	65	65.5
60	66	67	67
60	68	69	68.7
60	70	70	70.5

Returning to the inverse square law expressed in equation 26.5, we are now in a position to determine the effect on sound intensity level of moving away from the sound source.

EXAMPLE 26.4. Given a sound source that produces sound intensity IL at a distance d_1 from the source (the reader can substitute any numbers desired, or follow the problem with symbols), what are the intensities at twice the distance? Four times?

SOLUTION. We know from equation 26.7 that

$$\Delta IL = \frac{I_2}{I_1}$$

and we also know from equation 26.5 that

$$\frac{I_1}{I_2} = \frac{d_2^2}{d_1^2}$$

therefore, since $d_2 = 2d_1$

$$\frac{I_2}{I_1} = \frac{(d_1)^2}{(2d_1)^2} = \frac{1}{4}$$

Substituting in equation 26.7, we have

$$\Delta IL = 10 \log \frac{I_2}{I_1}$$

$$= 10 \log \tfrac{1}{4}$$

$$= 10(-0.6)$$

$$= -6 \text{ db}$$

which tells us that sound intensity level (not pressure) is reduced by 6 db. Similarly, when distance is quadrupled, it is reduced by 12 db.

To summarize, then, *intensity level changes 3 db with every doubling or halving of power and changes 6 db with every doubling or halving of*

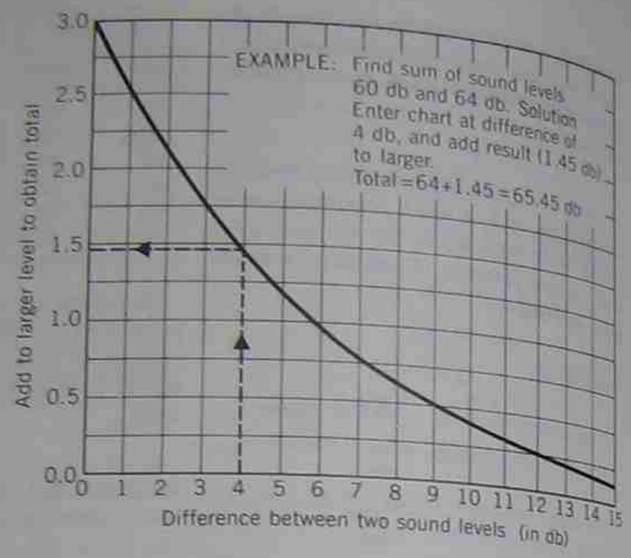

Fig. 26.7 Chart for adding two uncorrelated sound pressure levels when both are expressed in db. (reprinted by permission, from E. B. Magrab, Environmental Noise Control, *Wiley, New York 1975.)*

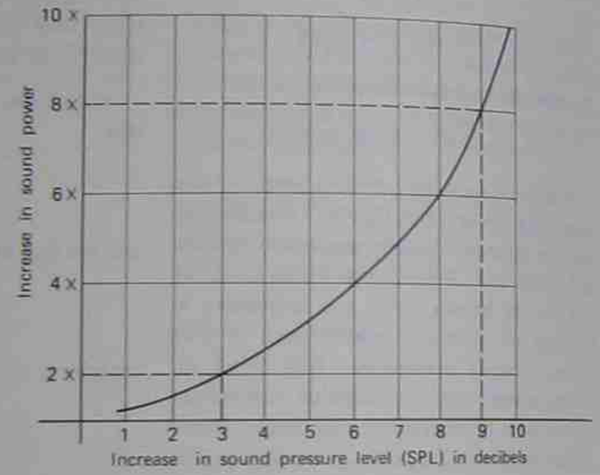

Fig. 26.8 Decibel level increase as a function of power (intensity) increase.

distance from a point source. Figures 26.7 through 26.9 illustrate these relationships.

The ear responds to sound pressure, not intensity. As explained below, sound *pressure level* (SPL) is equal numerically to *intensity level* (IL) (at least for normal temperature and pressure, i.e., for our use in architectural acoustics). Therefore, the foregoing examples and manipulations of intensity level are equally applicable to sound pressure level.

As explained in some detail in the following section, the combined effect of two sounds depends on their frequency content. In the examples above we assumed signals either of identical frequency and random phase or of very-wide-frequency spectrum—so wide that phase phenomena are not significant. In architectural acoustics work, such an assumption is generally valid.

26.9 Human Hearing

Refer to Fig. 26.10. The outer ear is funnel shaped and serves as a sound-gathering input terminal to the auditory system. Sound energy

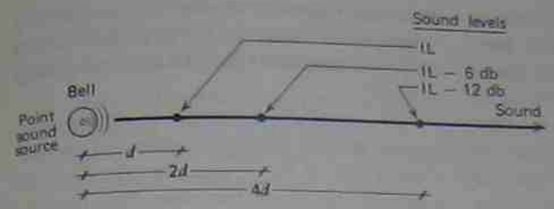

Fig. 26.9 Sound energy levels at varying distances from the source. Each doubling of distance reduces the level of 6 dB. These relationships hold true only in a free field.

travels through the auditory canal (outer ear) and sets in motion the components of the middle ear, comprising the eardrum, hammer, anvil, and stirrup. The stirrup acts as a piston to transmit vibrations into the fluid of the inner ear. This fluid motion causes movement of hair cells in the cochlea, which in turn stimulates nerves at their bases, which in turn transmit electrical impulses along the eighth cranial nerve, to the brain. These impulses we understand as sound.

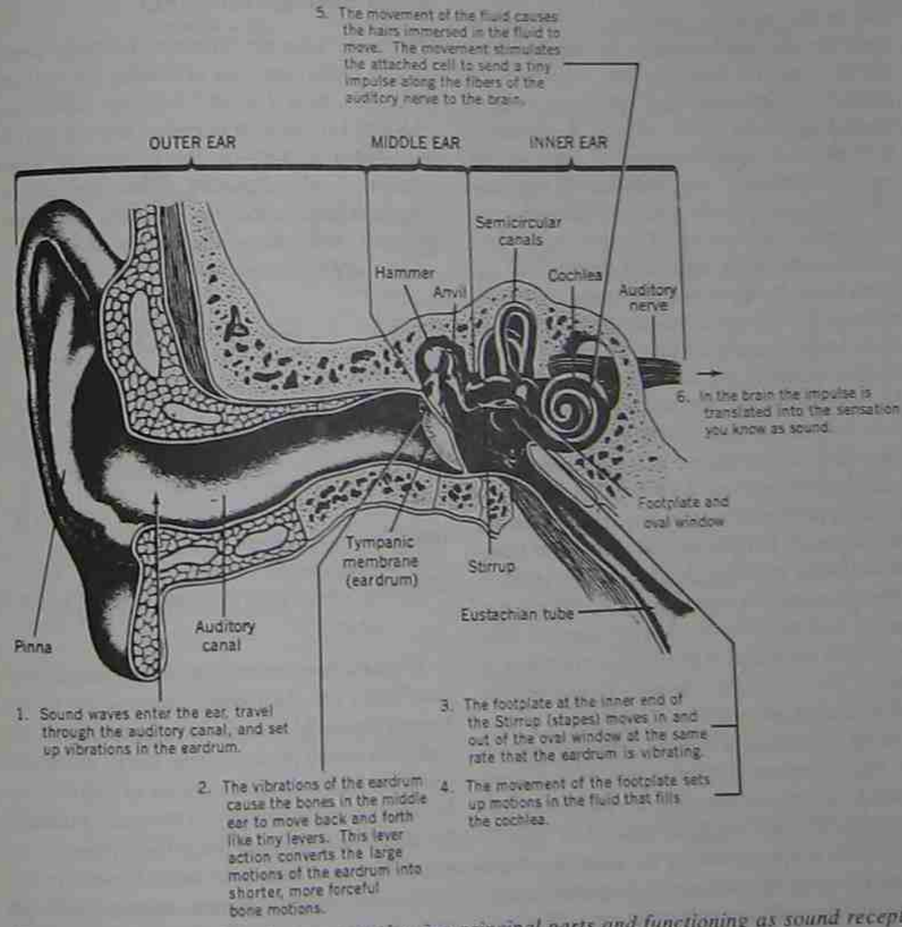

Fig. 26.10 Drawing of the human ear showing principal parts and functioning as sound receptor. [Drawing reproduced with permission from F. A. White, Our Acoustic Environment, *Wiley, New York, 1975. Notes from* Quieting: A Practical Guide to Noise Control *(1976).]*

Frequency recognition is accomplished in the cochlea, by the basilar membrane. This membrane resonates at one end at about 20 Hz and at the other at 20 kHz, giving the ear its frequency range. The ear hears and recognizes distinct frequencies, yet the hearing mechanism has the ability, apparently as directed by the brain, either to hear individual frequencies *or* to combine them into a single sound. Thus when we hear a string quartet we can, *at will*, hear either the entire quartet or each instrument individually. With concentration (vision helps in this), a "trained" ear can pick out a single instrument in an orchestra of 120 pieces, even if there is more than one such instrument in the group. Conductors do this regularly. Similarly, the ear can perform the selection known as the "cocktail party effect," that is, pick out one voice in background noise that may be 20 db louder than the wanted signal. In effect, the ear is attenuating the unwanted signals. Normally, however, the ear does precisely the opposite. It combines sounds that are clearly distinct from each other in frequency and phase. The three tones in a chord struck on a piano are different in frequency and, if played as a very rapid triplet, out of phase. Yet the ear combines them and hears a single sound, despite the fact that the maxima of the three tones do not occur simultaneously. In the preceding decibel calculations (Section 26.8), as well as those that will follow, it is assumed that the ear ignores phase differences and combines frequencies. This may not always be the case, particularly when the frequencies are very far apart. For this reason the type of information found in Table 26.4 (i.e., single-number representations of complex sounds) can be misleading and must be used with caution. This problem is discussed in the next section and in Section 26.12, which explains measurements and weighting networks.

At the threshold of hearing (approximately 0 db), the displacement of air molecules impinging on the eardrum, and the eardrum excursion, are approximately one angstrom unit (1 Å = 10^{-8} cm), which is approximately the diameter of an *atom*. Were the ear an order of magnitude more sensitive, it would hear thermal noise. The human ear is thus close to the practical limit of sensitivity. At the other end of the noise spectrum, the threshold of pain corresponds to a sound level of 130 db, and to an eardrum motion of approximately 0.25 mm. An astonishing range indeed!

As is obvious from the brief description of the hearing process above, movement of the eardrum is caused by air pressure. Therefore the quantities that interest us more than intensity (*power density*) are pressure, which is *force density*, and pressure level, which is the ratio of sound pressure to a base level, expressed in db

26.10 Sound Pressure and Sound Pressure Level (SPL)

The usual base or reference pressure corresponds to the threshold of hearing and is taken to be 20 μPa or 2×10^{-4} microbar (μbar) (see Table 27.15). As with intensity, this pressure is established as 0 db for the purpose of sound pressure *level* calculation. Since the ear responds logarithmically to intensity and since pressure varies as the square root of intensity, we can write the expression

$$\text{SPL} = 10 \log \frac{p^2}{p_0^2}$$

or

$$\text{SPL} = 20 \log \frac{p}{p_0} \qquad (26.8)$$

where

SPL = sound pressure level, db
p = pressure, Pa or μbar
p_0 = reference base pressure, (20 μPa or $2E^{-4}$ μbar)

Since for both intensity level and sound pressure level, the 0-db base corresponds to the hearing threshold, we can have equalized the db scales for sound pressure level (SPL) and intensity level (IL) *and the db values of the two can be used interchangeably*. Obviously, though, the actual intensity and the actual pressure corresponding to a particular decibel level are different—completely different, in magnitude and units. For instance, 70 db equals 10^{-9} W/cm intensity, and 0.063 Pa pressure. However, the important fact is that 70 db corresponds approximately to a particular noise level. We say "approximately" because assigning a single-number decibel level to a sound presents two difficulties:

1. The sound pressure level varies with time, except for a pure steady tone.
2. The different components of most common sounds vary in pressure level.

To overcome this problem two techniques are used. If a sound has a dominant frequency, that frequency's level can be used (see Fig. 26.11). This would be the case for a relatively constant sound such as a motor, or a fan or blower. Other sounds that vary widely in level and frequency can be plotted on an octave-band chart using maximum level for minimum percent of time (see Fig. 26.12). Where the position of the listener is not specified in the table, it is assumed to be at normal *close* distances, that is, 10 to 20 ft from a train, 3 to 5 ft from a radio, and the like.

26.11 Loudness Level: The Phon Scale

The human ear is not uniformly sensitive over its entire frequency range of 20 Hz to 20 kHz. The 120- to 130-db upper limit pain threshold

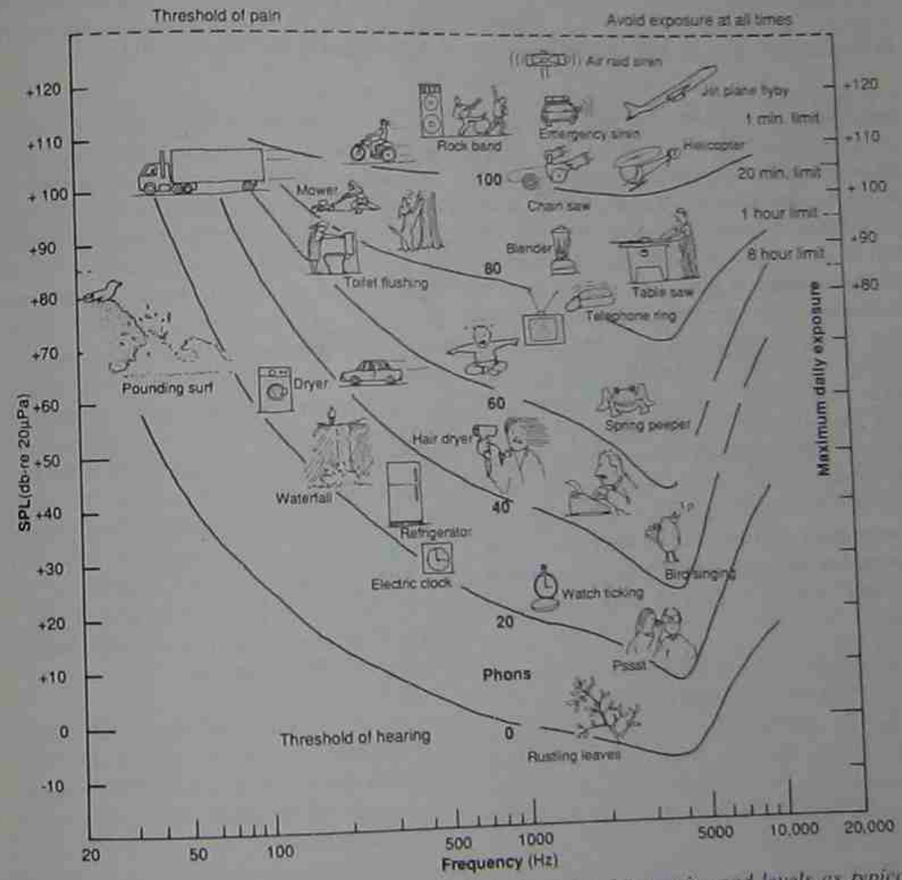

Fig. 26.11 Common sound sources plotted at their dominant frequencies and levels as typically heard by the observer. The equal loudness curves (see Section 26.11) show why certain sounds seem louder than others, despite the pressure levels that would indicate the contrary. [Reprinted with modification from Quieting: A Practical Guide to Noise Control *(1976).]*

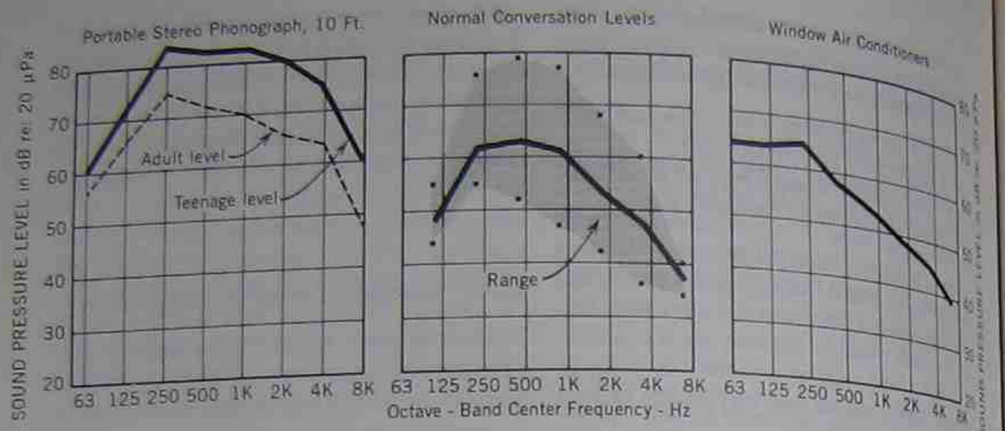

Fig. 26.12 *Curves of SPL of common noise sources plotted according to octave band frequency content. Values shown are averages of multiple measurements. [Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

occurs at all frequencies. However, at the lower limit, the 0-db threshold occurs only at 1000 Hz. The ear is in fact most sensitive at 3000 to 4000 Hz, at which frequencies the threshold is about −5 db. This nonlinear response exists throughout the ear's range. To determine the nature of this nonlinearity, a great number of tests were conducted with pure tones at different frequencies, in which listeners were asked to equate subjective loudness of signals. These tests resulted in a family of curves called *equal loudness level contours* or, alternatively, *Fletcher-Munson equal loudness contours* (after two of the principal researchers). These curves (see Fig. 26.13) are internationally recognized and standardized, and are used as the reference for normal hearing response. They are also used to "weight" measuring devices, as is explained in Section 26.12. Note that *by definition:*

1. All points on a single contour have the same *subjective* sensation of loudness.
2. The loudness level in *phons* (number shown in the center of each curve in Fig. 26.13) of the *entire* contour is defined by the db level of that contour at 1000 Hz.

The phon scale was constructed as a way of defining perceived sound (subjective loudness impression) in terms of the ear's nonlinear response. Assigning a single number—in a unit called the *phon*—to an equal loudness contour makes it possible to compare subjective loudness impressions of two sounds regardless of frequency or actual sound pressure level. Thus in Fig. 26.11, the subjective loudness of a whisper in the ear (20 phons) is the same as that of the distant pounding surf, despite the fact that the SPL of the former is 20 db and of the latter, 80 db. The 60-db differential is due to the ear's sharp drop in sensitivity at low frequencies. However, because the phon scale is nonlinear in terms of perceived loudness (a given phon differential does not correspond to the same perceived loudness change throughout the phon scale) and because phons cannot be combined arithmetically to give a resultant subjective loudness (60 phons plus 50 phons is not 110 phons), the scale has found only limited use.

The Fletcher–Munson contours demonstrate some interesting phenomena:

1. Sensitivity drops off sharply at low frequencies, particularly at low-db levels. (For this reason most high-fidelity amplifiers provide automatic bass boost at low-volume levels.)
2. Maximum sensitivity occurs between 3 and 4 kHz—precisely the frequencies that contain most information in human speech. (See Section 26.17 and Fig. 26.14.)

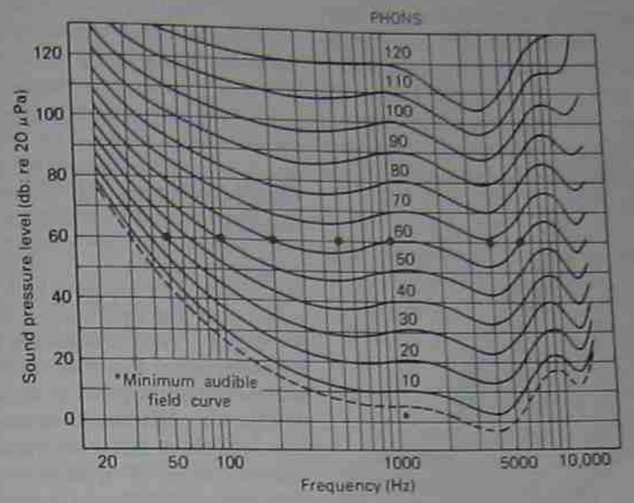

Fig. 26.13 *Standard equal loudness contours. These curves are accurate for a listener with normal binaural hearing, situated in the near field of a source producing pure tones directly ahead of the listener. The subjective loudness of the perceived sound of each contour is quantified in a unit called the* phon. *The phon value of each curve is shown in the center of the figure. Note that an SPL of 60 db corresponds to 30 phons at 50 Hz, 50 phons at 100 Hz, 63 phons at 500 Hz, 60 phons at 1 kHz, 68 phons at 4 kHz, and 60 phons at 6 kHz. This indicates the relative flatness of the ear's response in the central frequency-loudness range, and the sharp drop at low frequencies.*

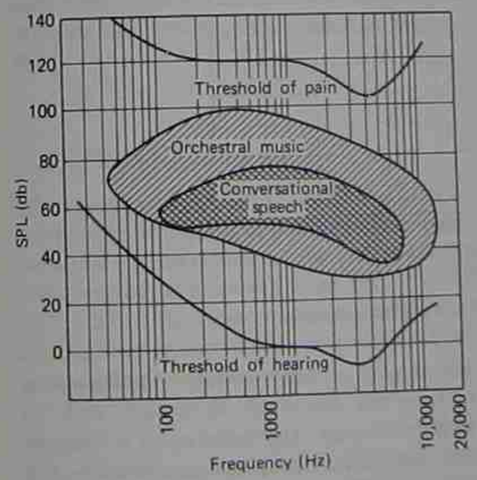

Fig. 26.14 *The positions of speech and wide-range music in the human ear's aural field are illustrated. Speech is in the nominally linear response area of the ear as is most music (see Fig. 26.13). Beyond these frequencies, the ear's action is effectively to attenuate the signal.*

3. In the normal listening range of 45 to 85 db, and the most used frequency range of 150 Hz to 6 kHz, the contour is substantially flat; that is, the ear's response is effectively linear. It is only at extremes of sound level and frequency that nonlinearity occurs.

26.12 Measurement of Sound Pressure Level

The need for a means of measuring sound levels is obvious. One such instrument is the integrating sound-level meter illustrated in Fig. 26.15*a*. To correlate meter readings with subjective loudness impressions, most such single-reading instruments are furnished with three weighing networks, the characteristics of which are given in Fig. 26.15*b*. The A network corresponds to the 40-phon contour and discriminates against low frequencies (see Fig. 26.13). The B network corresponds similarly to the 70-phon contour. The C network gives substantially flat uniform

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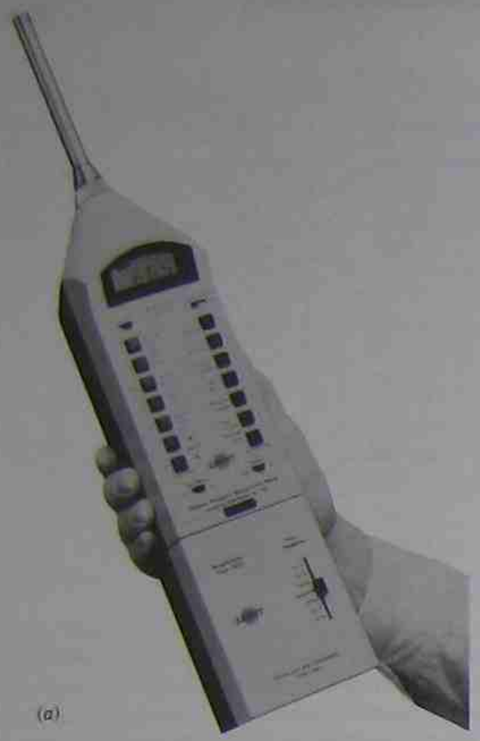
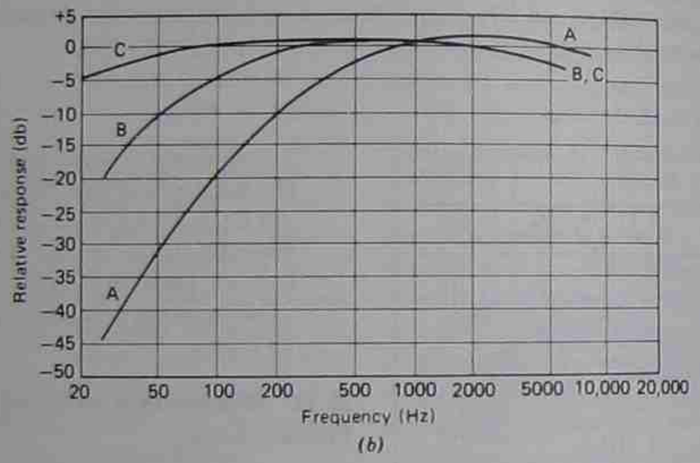


(a)

Fig. 26.15a *Modern precision sound level meter. This unit with its accessories will measure and record isolated nonrepetitive noise events in addition to continuous, fluctuating and impulsive sounds, and will give both instantaneous sound level and equivalent continuous sound level L_{eq}. The latter is important when sound at a location varies with time, and an equivalent level for design purposes is required. The unit takes level and duration into account and displays L_{eq} directly. It is arranged to measure dbA or linear (dbC), fast, or slow time constant. It adapts with filter networks to read octave or 1/3-octave bands, and reads out digitally. It also has peak-hold settings, which measure maximum sound during a time exposure. (Courtesy of Brüel and Kjaer.)*



(b)

Fig. 26.15b *Internationally standardized A, B and C weighting curves.*

response. In practice it was found that the B and C networks did not correspond well to subjective loudness reports. This was because the loudness contours on which they were based were taken for pure tones, whereas most field measurements are of very complex sounds. The A network, however, did correspond well, and has therefore become the standard single-number measuring scale for loudness of sounds at any frequency and intensity. Measurements taken in this way should be labeled "dbA" to identify the scale. The sound meter is equipped with two different damping characteristics—fast and slow. The former will follow reasonably rapid fluctuations. The latter is more heavily damped and will give an average reading of sounds with rapid changes of more than 4 db. Extremely rapid noise pulses are impulse noises, requiring special instruments.

It is known that the ear "averages" sounds over a minimum period, and that sound impulses shorter than this period sound quieter than they would sound as steady-state noise. This minimum sound length i.e. the time required for the sound to achieve full loudness is taken to be between 50 and 200 milliseconds (1/20–1/5 s) and depends to an extent on the sounds frequency content. A figure of 70 ms (1/14 s) is frequently found in the literature. This figure becomes important when considering the effect of echoes (see Sections 26.23 through 26.25).

More accurate measurements of complex sounds than are possible with a standard meter are accomplished with sophisticated instruments that measure intensity in octave bands and plot the results as in Fig. 26.12. Such measurements are necessary for accurate application of sound absorption and attenuation materials whose characteristics are also nonlinear over the frequency spectrum. Single-number dbA readings are known as *overall* levels and are useful as preliminary data and for broad-spectrum design.

Table 26.4 shows a list of common noise levels as measured by the dbA scale. Such single-value numbers are useful to establish a mental-aural comparison base, and to use in maximum exposure calculations, as discussed in Section 26.21.

26.13 Sound Absorption

When sound energy impinges on a material, part is reflected and the remainder is absorbed, in the sense that it is not reflected. (Some of the energy is transmitted, as discussed in the next chapter; see Fig. 27.2.) Most materials are neither perfect reflectors nor perfect absorbers. The coefficient of absorption (α) is defined as

$$\alpha = \frac{I_a}{I_i} \tag{26.9}$$

where

I_a = sound power density (intensity) absorbed by the material, W/cm²
I_i = intensity impinging on the material, W/cm²
α = absorption coefficient (no units)

Thus α is a measure of absorption efficiency. When $\alpha = 1.0$ all the impinging energy is absorbed. Since open space has this characteristic, α has also been defined as the ratio between the absorption of a given material and that of an *open window* of the same area. Obviously, then, for an opening (open window, open door, etc.)

$$\alpha = 1.0$$

The total absorption (A) provided by a surface is proportional to its area and its absorption coefficient, that is,

$$A = S\alpha \tag{26.10}$$

where

A = total absorption, *sabins*
S = surface area, square feet or meters
α = coefficient of absorption

Since α is a ratio and thus unitless, and S is a unit of area, $S\alpha$ should be area as well. Instead, sound absorption units are called sabins in honor of W. C. Sabine, a pioneer in architectural acoustics. One sabin (m²) is the sound absorption equivalent to an open window one square meter in area. Similarly, one sabin (ft²) is equivalent to 1 square foot of open window. Obviously, 1 sabin (m²) equals 10.76 sabin (ft²). When not specified, a sabin (ft²) is intended.

Most rooms are constructed of several materials, each having a different absorption coefficient α. Thus to determine the total absorption of the room, it is necessary to sum the component absorptions, that is,

$$\Sigma S\alpha = S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n$$

or

$$\Sigma A = A_1 + A_2 + \cdots + A_n \tag{26.11}$$

where

$\Sigma S\alpha$ = total absorption in the room, sabins
S_1, S_2, etc. = area of each material
α_1, α_2, etc. = coefficient of each material
A_1, A_2, etc. = total absorption of each different material

If S is expressed in square feet, then A will be in sabins (ft²); if S is in square meters then A is sabins (m²).

TABLE 26.4 **Common Noise Levels**

Sound Pressure Level, SPL (dbA)	*Typical Sound*	*Subjective Impression*
150		(Short exposure can cause hearing loss)
140	Jet plane takeoff	
130	Artillery fire, riveting, machine gun	(Threshold of pain)
120	Siren at 100 ft, jet plane (passenger ramp), thunder, sonic boom	Deafening
110	Woodworking shop, hard-rock band, accelerating motorcycle	Sound can be felt (Threshold of discomfort)
100	Subway (steel wheels), loud street noise, power lawnmower, outboard motor	Very loud, conversation difficult; ear protection required for sustained occupancy
90	Noisy factory, truck unmuffled, train whistle, machine shop, kitchen blender, pneumatic jackhammer	
80	Printing press, subway (rubber wheels), noisy office, supermarket, average factory	(Intolerable for phone use)
70	Average street noise, quiet typewriter, freight train at 100 ft, average radio, department store	Loud, noisy; voice must be raised to be understood
60	Noisy home, hotel lobby, average office, restaurant, normal conversation	Usual background; normal conversation easily understood
50	General office, hospital, quiet radio, average home, bank, quiet street	
40	Private office, quiet home	Noticeably quiet
30	Quiet conversation, broadcast studio	
20	Empty auditorium, whisper	Very quiet
10	Rustling leaves, soundproof room, human breathing	
0 db		Intolerably quiet Threshold of audibility

The mechanics of absorption and the use of absorptive materials are discussed in Sections 27.3 and 27.4 in connection with noise reduction techniques. Absorption coefficients for common materials, acoustic materials, and auditorium furnishings are tabulated in Table 27.1. It is important to note that for most common materials, absorption (and therefore α) varies with frequency. Thus absorption calculations must be made individually for the frequencies being studied.

26.14 Reverberation

Reverberation is the persistence of sound after the source of sound has ceased a result of repeated reflections. Reverbation time (T_R) describes the period required for the sound level to decrease 60 db after the sound source has stopped producing sound. For rooms of usual size and shape, the reverberation time at a specific frequency may be found by the formula:

$$T_R = K \times \frac{V}{\Sigma A} \text{ seconds} \quad (26.12)$$

where

K = a constant, equal to 0.05 when measurements are in feet and 0.16 when in meters
V = room volume, ft³ (m³)
ΣA = total absorption, sabins (ft² or m²) at that frequency

(For spaces of unusual shapes, see Beranek, 1988; Embelton, 1971; Young, 1959.) Subjectively, reverberation is one of the most pronounced hearing reactions in an enclosed space. Simply, it is the ear's reaction to echoes, giving an impression of "liveness" or "deadness of the space."

"Liveness" and "deadness" are terms that describe the subjective impression of sound reflection in a space. A space with highly reflective surfaces, and therefore low absorption ($\bar{\alpha} < 0.2$), sound live. Conversely, a highly absorptive nonreflective environment ($\bar{\alpha} > 0.4$) sounds dead. ($\bar{\alpha}$ is the average absorption of the entire space, as explained in detail in the next section.) Since room absorption is related to total surface area, which in turn is related by room proportions to room volume, it is possible to relate all three factors in a single diagram. Figure 26.16 is drawn using room proportions of 1.5:2:1 for L:W:H, based on Fig. 26.34 for preferred room proportions. These proportions (1.5:2:1) are the average of the extremes of Fig. 26.34 (i.e., 1.5:2.4:1, 1.8:2.2:1 and 1.3:1.6:1). The maximum differential introduced by using average proportions is 2½%—well within engineering accuracy.

The ultimate dead space is one where there is no reflection at all—as is the case outdoors. Indoors, we receive an auditory cue in the form of reflected sound (feedback) which helps us regulate our sound power output (voice level). Outdoors, the absence of this cue, to which we are so accustomed by our largely indoor existence, automatically causes us to raise our output. This is the reason then that most people tend to speak loudly and even to shout when outdoors. Conversely, and correctly, a highly reflective indoor condition gives a large feedback signal, which usually results in a lowered vocal output.

In most room acoustics studies, reverberation times are calculated at 125, 500, 1000, and 2000 Hz. The midfrequency (500 to 1000 Hz) range is generally the reference used in specifying the reverberation time of a room when studying the speech characteristic of the space.

Reverberation can be considered as a mixture of previous and more recent sounds. The converse of reverberation or reverberance is articulation. An articulate environment keeps each sound event separate rather than running them together. Spaces for speech activities should be less reverberant—more articulate—than those designed for performance of music. See Sections 26.23 and 26.24 for reverberation criteria for speech and music rooms, respectively.

26.15 Sound Fields in an Enclosed Space

The inverse square law described in Section 26.7 holds true for the acoustic *far field*, which is the sound field sufficiently far from the source that intensity is proportional to pressure squared. This type of acoustic field is developed in open, obstruction-free circumstances. Propagation in an enclosed space is quite different. There, when a sound reaches a wall or other large (with respect to wavelength) obstruction, part of the sound energy is reflected and part absorbed. Thus the sound at any point in the room is a combination of direct sound from the source plus reflected sound from walls and other obstructions. If the reflections are so large that the sound level becomes uniform throughout the room, the field within the room is termed a *diffuse* one (no shadows), and intensity measurements with respect to a specific source are meaningless. Of course, if it is our intention to measure sound pressure level at a specific point, such as a seat in an auditorium, the type of acoustic field in the room is irrelevant.

Most rooms do not have such a high level of reflection that a diffuse field is created. Instead, there is a *near field* near the source, a *free field* beyond the near field, and a *reverberant field* near the walls (see Fig. 26.17). They can be recognized as follows:

ACOUSTICS

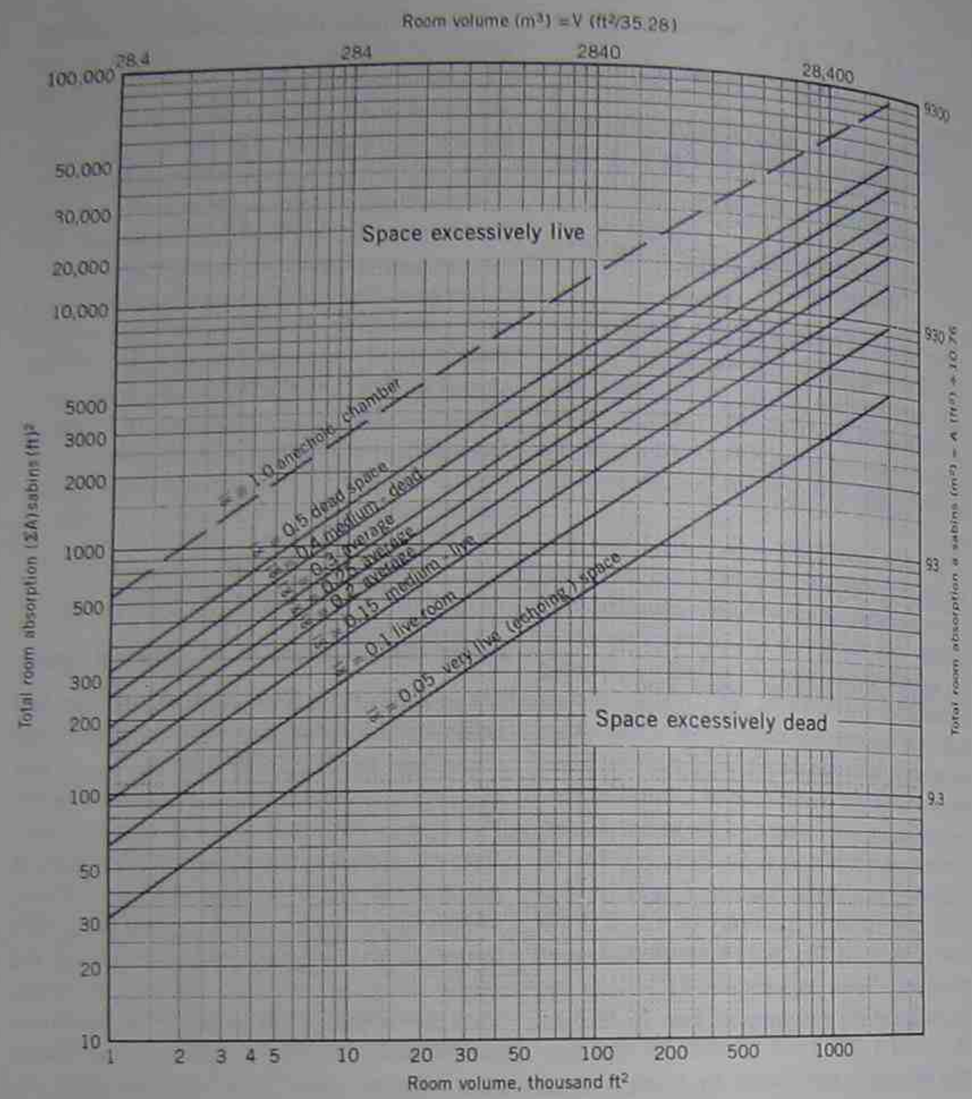


*Fig. 26.16 Chart indicating a room's "liveness" as a function of its volume and total Sabin absorption. The L-W-H room proportions chosen—*2H : 1.5H : H*—represent the average of the three extreme points of the recommended room proportion triangle in Fig. 26.34. For these proportions,* $S = 6.25V^{2/3}$ *and therefore* $A = S\bar{\alpha} = 6.25\bar{\alpha}V^{2/3}$.

1. The near field is generally within one wavelength of the lowest frequency of sound produced by the source. Within this distance SPL measurements vary widely and are not meaningful. (The maximum wavelength for the human male voice is about 11 ft.)

2. Near large obstructions such as walls, the *reverberant field* is dominant and approaches a diffuse condition. In well-designed music auditoriums the reverberant (diffuse) field predominates and sound pressure level remains relatively constant beyond the free field area.

3. The *free* (far) *field* exists between the near and reverberant fields, and there intensity varies as pressure and inversely with distance squared. In this field, sound pressure level drops 6 db with each doubling of distance from the source, and it is in this field that meaningful SPL measurements can be made, with respect to a specific small source.

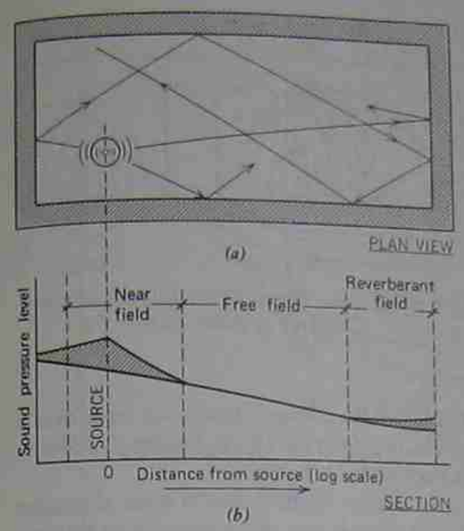


Fig. 26.17 Type of sound field in an enclosed space depends in large measure on reflections (reverberation) and absorption. In a typical room there is a near field adjacent to the sound, a free field beyond that, and a reverberant field adjacent to the walls. In a large hall or auditorium the reverberant field dominates and level remains approximately constant.

Since it is desirable to be able to predict the sound level (SPL) in a space during the design stage, and also because of the difficulty of SPL measurement in rooms with various types of sound field, as explained above, it is useful to have equations that relate sound *power* level (PWL) to sound *pressure* level. Sound power level is supplied by manufacturers with each item of equipment, at either octave or ⅓-octave points.

To avoid confusion, it will be helpful to the reader to think of sound pressure level (SPL) as the resultant "noise" or sound in an enclosed space, resulting from a source in that space, and affected by the characteristics of the space and the position of the listener. It is thus an end effect. The sound power level (PWL) is a measure of the amount of sound generated by a source, independent of its environment. In free space the two quantities are simply related by the inverse square law, whereas in enclosed spaces the room characteristics come into play. Roughly speaking, an analogy to lighting can be drawn: SPL corresponds to room illumination, that is, footcandles, and PWL corresponds to the lumen output of the source. The basic relationship between sound pressure level and sound power level for a single, small, non-directive source in a room large enough to have both free and reverberant fields is:

English units:

$$SPL = PWL + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{R} \right) + 10.5 \tag{26.13}$$

Metric units:

$$SPL = PWL + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{R} \right) + 0.2 \tag{26.14}$$

where Q is a directivity factor and

SPL = sound pressure level, db
PWL = sound power level, db
r = distance from source, ft (m)
R = room constant, ft² (m²)

The factor R can be calculated from

$$R = \frac{S\bar{\alpha}}{1 - \bar{\alpha}}$$

where

S = total room surface area, m²
$\bar{\alpha}$ = average absorption coefficient of all materials in the room

that is,

$$\bar{\alpha} = \frac{\Sigma A \text{ (total room absorption)}}{S \text{ (total room surface area)}} \tag{26.15}$$

or

$$\bar{\alpha} = \frac{S_1\alpha_1 + S_2\alpha_2 + \cdots + S_n\alpha_n}{S_1 + S_2 + \cdots + S_n} \tag{26.16}$$

The directional constant Q is either inherent in the sound source, and as such will be part of the given data, or can be obtained from Fig. 26.18

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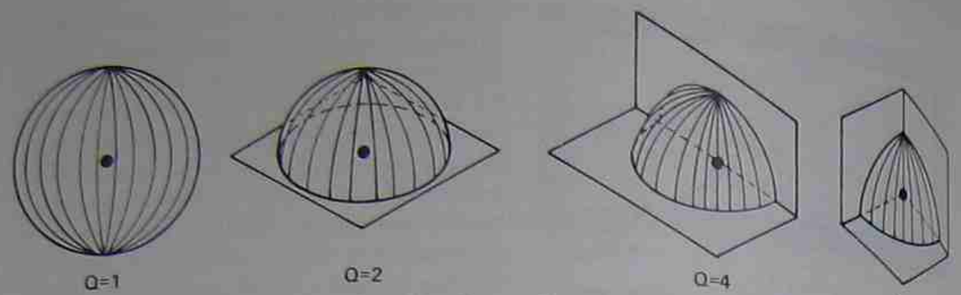


Fig. 26.18 Diagrams illustrating directivity factors for either inherently directive sources or nondirective sources placed adjacent to large reflecting surfaces. (Courtesy of Barry Blower Co.)

for a nondirectional source made directional by adjacent reflecting surfaces.

Thus for a source suspended or supported at least ½ wavelength (at its lowest frequency) from the ceiling or floor, $Q = 1$; a source near the floor and distant from the walls uses $Q = 2$; and so on. In a space containing more than one sound source, the sound pressure levels can be combined as explained in Section 26.8. In the two extreme cases [i.e., rooms with only far (direct) field and rooms with only reverberant (diffuse) fields, (corresponding to dead and live rooms, respectively)] for a nondirectional source located on the floor and away from walls ($Q = 2$), equations 26.13 and 26.14 reduce to:

Dead room, direct field:

English units:

$$\text{SPL} = \text{PWL} - 20 \log r + Q - 0.6$$
$$= \text{PWL} - 20 \log r + 1.4 \qquad (26.17)$$

Metric units:

$$\text{SPL} = \text{PWL} - 20 \log r + Q - 10.9$$
$$= \text{PWL} - 20 \log r - 8.9 \qquad (26.18)$$

Live room, diffuse-reverberent field:

English units:

$$\text{SPL} = \text{PWL} - 10 \log \Sigma A + 16.3 \qquad (26.19)$$

Metric units:

$$\text{SPL} = \text{PWL} - 10 \log \Sigma A + 6.0 \qquad (26.20)$$

To understand the application of these equations, and the effect of absorptive material in a space, see Example 27.1 in Section 27.7, Noise Reduction by Absorption.

To understand the effect of room absorption on the development of the reverberant field in a large space, refer to Fig. 26.19. The field is plotted from equation 26.13, for a room 80 ft × 120 ft × 30 ft high, using average absorptions $\bar{\alpha}$ ranging from 0.05 to 0.7, that is, from very live to very dead. Note particularly that the addition of sufficient absorbent material can entirely prevent the development of a reverberant (diffuse) field. This is particularly important in noisy industrial interiors where the building materials commonly employed are generally nonabsorbent, and the noise sources are both numerous and loud. For further discussion, see Sections 27.2 through 27.8.

26.16 Other Factors in Hearing

(a) Masking. When two separate sources of sound are perceived simultaneously, the perception of each is made more difficult by the presence of the other. This effect is known as masking, and is defined as the number of decibels by which the threshold of audibility of a sound is raised by the presence of another sound. Masking is greatest when two sounds are close in frequency or frequency content, since the ear has greater difficulty separating them. Also, a low frequency will more effectively mask a high frequency than the reverse, for the same decibel levels. With broad-frequency

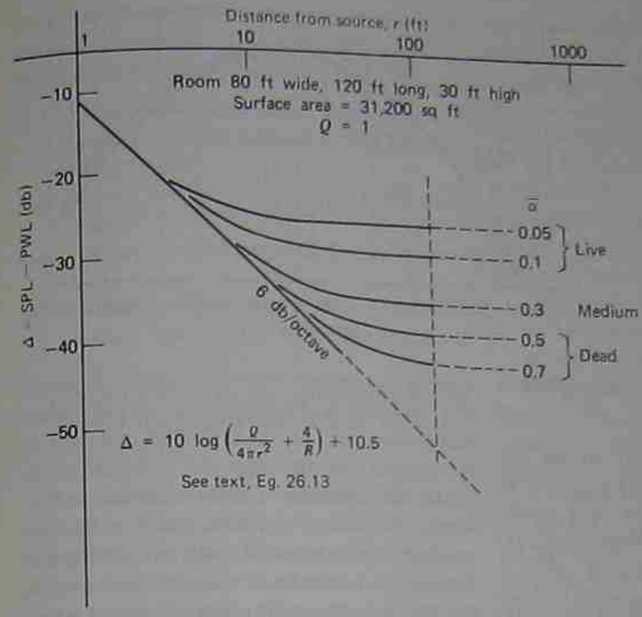


Fig. 26.19 Curves show that development of reverberant field (constant SPL, or flat curve) is dependent on the room's absorption characteristics. In a live room ($\bar{\alpha} = 0.1$) the reverberant field begins 20 ft from the source. In a dead room ($\bar{\alpha} = 0.5$) it begins at 120 ft from the source, that is, at the back wall. Effectively, then, there is no reverberant field in such a room. Slope of asymptote is 6 dB per octave, that is, inverse square attenuation.

sounds the masking effect is difficult to predict, since it depends in part on how "hard" the listener is listening. Masking is an extremely important technique in noise control where background noise levels are deliberately manipulated to mask unwanted sounds (see Section 27.22). The background noises used for this purpose are of the broadband continuous variety, such as "pink" noise, which are themselves noninformation bearing. They serve to obliterate lower level, information-bearing sounds that would cause annoyance and are therefore particularly useful in open (landscaped) office plans. Frequently, mechanical equipment noise such as from air diffusers and fans can be utilized to good advantage as masking noise.

(b) Directivity. The exact mechanism by which the binaural aspect of hearing detects direction is not entirely understood. It is clear, however, that in enclosed space, reverberation will blur most directivity and "stereo" information will be almost completely dependent on high frequencies in the near field.

SOUND SOURCES

26.17 Speech

As can be seen from Fig. 26.14, the ear's sensitivity is maximum in the speech frequency and normal energy range. Speech sounds vary in time length between 30 and 300 ms and the ear normally perceives them individually and clearly. Speech is comprised of *phonemes*, which are individual and distinctive sounds that to an extent vary from language to language. That is, certain ones exist in one language and not in another. Since certain phonemes carry more information than others, it is these that good architectural acoustics must be particularly careful to preserve intact, to preserve intelligibility. In English, consonants carry much more information than vowels, as can readily be demonstrated by writing a sentence first without consonants and then without vowels:

Most speech energy is concentrated in the 100- to 600-Hz range.

o ee ee i oeae i e 100–600 e ae

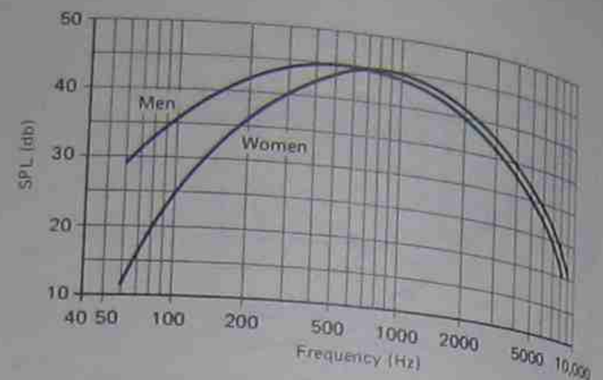


Fig. 26.20 Frequency distribution of typical male and female voices. [From Brüel and Kjaer (1963).]

Mst spch nrgy s cnentrtd n th 100–600 Hrtz rng.

The male voice centers its energy around 500 Hz; the female about 900 Hz (see Fig. 26.20). It is, however, in the high frequencies that consonants have most of their energy. Phonemes such as *s* and *sh* have most of their energy above 2 kHz and both are particularly important in conveying intelligence.

Normal speech averages between 40 and 50 dbA sound pressure level at 3 to 4 ft, with a dynamic range of from about 30 db for soft speech to about 65 db for loud speech at the same distance. Extremes of speech are 10 db for a soft whisper and 80 db for a shout, but in both these instances intelligibility is sharply reduced because of lack of consonant power. Indeed, in shouting, emphasis is necessarily on vowels, so that it is generally accepted that 70-db SPL is about the upper limit of fully intelligible human speech. (Singers who frequently exceed 90 db do so at great loss of intelligibility.) Another result of the high-frequency content of consonants, and therefore intelligibility, is its directiveness. The higher the frequency, the greater the sound's directivity and the less its diffraction (ability to be heard beyond a barrier). Therefore, intelligibility of speech is greatest directly in front of the speaker and least behind him. High-frequency tones are most easily absorbed and least diffracted.

26.18 Other Sounds

Music is much broader and complex than speech in frequency and dynamic range. It has no direct parallel to intelligibility. "Reception" of music is a combination of physiological and psychological phenomena. As such, it is beyond most of the purposes of this study but is briefly examined in our discussion of room acoustics, auditoriums, and halls. *Noise* is variously defined as unwanted sound, sound with no intelligence content, and broadband sound, depending on the listener and the situation. All three definitions are correct at various times and situations. For our purpose we must assume that any sound can be referred to as noise.

NOISE CRITERIA

26.19 Negative Effects of Noise

Although noise effects and their control are the subject of Chapter 27, noise criteria and their background are discussed here as part of our overall study of hearing and sound sources. There are two basic approaches to the negative effects of noise, a pyschological-practical one and a purely physiological one. The latter is concerned with the physical impact of noise on the body including hearing loss and other deleterious conditions (see Section 26.22). The former is concerned with noise levels that cause annoyance and disturbance to daily activities including work, relaxation, and rest, and is discussed in the following sections.

26.20 Noise and Annoyance

Research has developed accurate data on loudness. The concept of annoyance, however, being primarily subjective and psychological, is much more elusive. Tests have shown that *in general*, annoyance as a result of noise is:

1. Proportional to the loudness of the noise.
2. Greater for high-frequency than low-frequency noise.
3. Greater for intermittent than continuous noise.
4. Greater for pure-tone than for broad-band noise.
5. Greater for moving or unlocatable (reverberant) noise than for a fixed-location sound.
6. Much greater for an information bearing noise (neighbor's radio) than for a nonsense noise.

To establish criteria for *acceptable background noise* (i.e., noise whose annoyance level is acceptable), certain of these effects must be neglected for the sake of simplicity. [They can be and are considered in construction design and in establishing levels of masking noise (see Chapter 27)]. We thus ignore:

Factor 3, since design is based on continuous sounds.

Factor 4, since broadband noise is assumed.

Factor 5, since the noise source is assumed to be fixed in location.

Factor 6, since we can only consider noise level, not content.

Thus the particularly and special characteristics of noises such as a barking dog (3), a whistle (4), a single passing vehicle (5), and intelligible sounds (6) are not considered. In order to quantify the concept of acceptable background noise, it was necessary to remove it from the purely psychological arena and relate it to a physical phenomenon. This was done by studying the effect of the two remaining annoyance factors (1 and 2) on speech communication. This study resulted in two concepts: the Articulation Index (AI) and the Speech Interference Level (SIL). They are determined by reading a carefully selected set of phonetically balanced nonsense syllables to a test audience in the presence of different levels and compositions of background noise. The ratio of correct answers to total syllables is the Articulation Index. An Articulation Index (Beranek, 1949) in excess of 0.5 indicated a condition in which perfect intelligibility could be expected. A simplified version of the AI called the Speech Interference Level (SIL) was devised by Beranek. The SIL consists simply of the arithmetic average in decibels of the background-noise sound levels in three octave bands, 600 to 1200, 1200 to 2400, and 2400 to 4800 Hz, since it was found that correlation between intelligibility and the sound power in these three bands could be established.

Beranek developed the well-known and widely accepted noise criteria (NC) curves shown in Fig. 26.21. The NC curves take cognizance of the field-determined fact that most people prefer to speak at a level no greater than 22 phons above the background noise. By combining the SIL levels in decibels with this fact, the NC curves are derived, that is, they represent a loudness level 22 phons higher than the SIL in db. These contours represent then the maximum *continuous* background noise that will be considered acceptable in the environment specified and correspond fairly accurately to background noise level in commercial environments. A similar set of curves called noise rating (NR) curves, proposed by the International Standards Organization (ISO), finds considerable application outside the United States. They are less stringent than NC curves in the low frequencies and more stringent in the high frequencies.

In application, the octave-band spectrum of the noise being studied, over the range of 63 to 8000 Hz, is measured and plotted on an NC curve sheet. The lowest NC curve that is *not* exceeded by any portion of the plot is the NC rating of the noise. Thus specifying a maximum noise level of NC-30 for a space means that no portion of the sound pressure level curve of any continuous background noise in the area may cross the NC-30 contour. Conversely, a piece of equipment rated NC-35 has an octave-band spectrum completely below NC-35. A fan rating of NC-53 would indicate that at some point on its frequency-spectrum plot the fan exceeded NC-50 by 3 db (see Fig. 26.21).

The NC number of a noise varies between 5 and 10 db below the measured dbA. NR numbers correspond closely to NC numbers. The

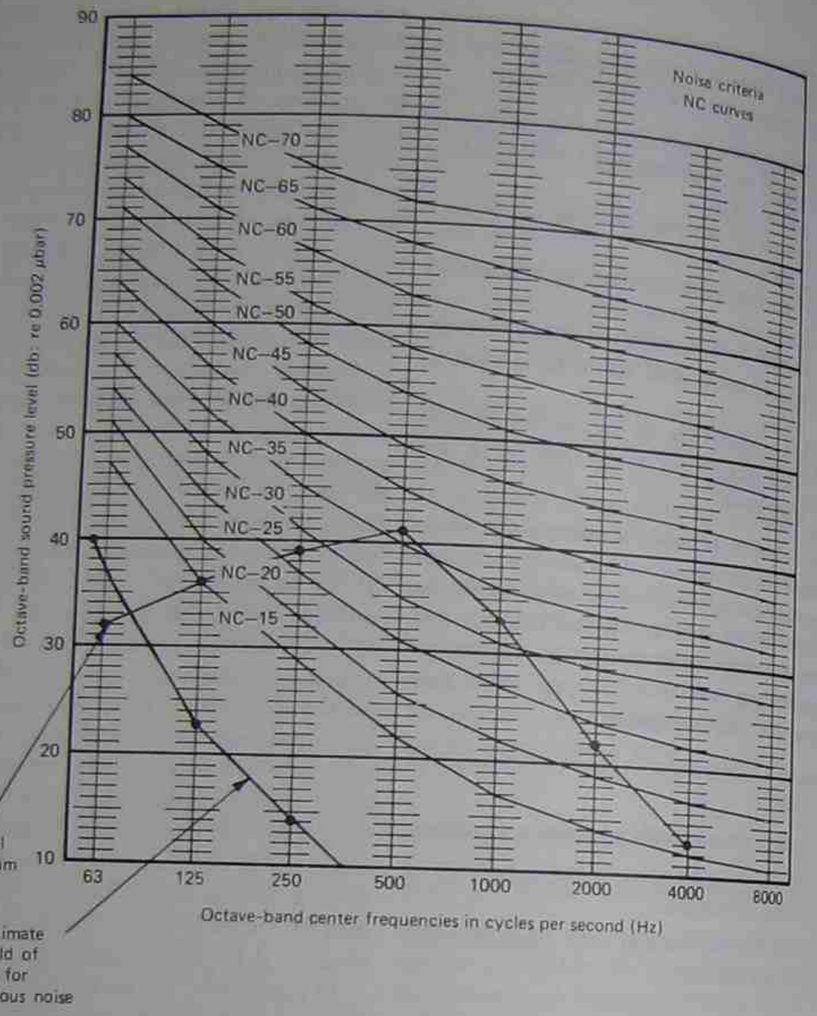


Fig. 26.21 *Noise criteria curves. Typical spectrum plotted would be rated NC-36, as it exceeds NC-35 at 500 Hz by 1 db. (See Table 27.8 for specific recommendations for interior spaces.)*

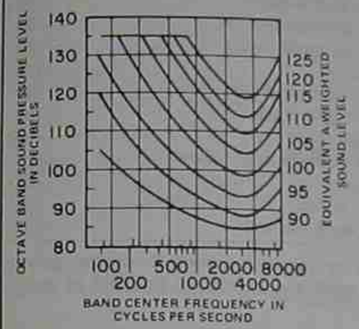
virtue of the NC curve system is that it is a single-number specification for an entire frequency spectrum. Its disadvantage is that it was derived for, and is primarily accurate for speech conversation against a continuous, non-intelligence-bearing noise. This is not the situation that is most troublesome in an office; indeed, continuous equipment noise may be *helpful* in masking unwanted speech interference, as mentioned above. See Sections 27.21 and 27.22, and Fig. 27.33. Nevertheless, NC curves remain the commonly used criteria for continuous *nonintentional* background noise acceptability.

26.21 High Noise Levels; Hearing Protection; OSHA

It has long been recognized that continuous exposure to high noise levels causes a degree of temporary deafness in a majority of people and that long periods of such exposure, even on an intermittent 8-h workday basis, appears to produce permanent hearing impairment. Many experts place the safe upper limit at 85 db. In addition, studies have indicated that continual exposure to noise levels as low as 75 to 85 dbA level can produce or contribute to numerous

§ 1910.95 Occupational noise exposure.

(a) Protection against the effects of noise exposure shall be provided when the sound levels exceed those shown in Table G-16 when measured on the A scale of a standard sound level meter at slow response. When noise levels are determined by octave band analysis, the equivalent A-weighted sound level may be determined as follows:



Equivalent sound level contours. Octave band sound pressure levels may be converted to the equivalent A-weighted sound level by plotting them on this graph and noting the A-weighted sound level corresponding to the point of highest penetration into the sound level contours. This equivalent A-weighted sound level, which may differ from the actual A-weighted sound level of the noise, is used to determine exposure limits from Table G-16.

[1910.95 amended at 39 FR 19468, June 3, 1974]

(b)(1) When employees are subjected to sound exceeding those listed in Table G-16, feasible administrative or engineering controls shall be utilized. If such controls fail to reduce sound levels within the levels of Table G-16, personal protective equipment shall be provided and used to reduce sound levels within the levels of the table.

(2) If the variations in noise level involve maxima at intervals of 1 second or less, it is to be considered continuous.

(3) In all cases where the sound levels exceed the values shown herein, a continuing, effective hearing conservation program shall be administered.

TABLE G-16—PERMISSIBLE NOISE EXPOSURES[1]

Duration per day, hours	Sound level dBA slow response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

[1] When the daily noise exposure is composed of two or more periods of noise exposure of different levels, their combined effect should be considered, rather than the individual effect of each. If the sum of the following fractions: $C_1/T_1+C_2/T_2+\cdots C_n/T_n$ exceeds unity, then, the mixed exposure should be considered to exceed the limit value. Cn indicates the total time of exposure at a specified noise level, and Tn indicates the total time of exposure permitted at that level.

[1910.95 Table G-16 amended at 39 FR 19468, June 3, 1974]

Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level.

Fig. 26.22 *The standard for exposure to noise in the workplace. (From OSHA Rev., July 1988.)*

physical and psychological ailments including headache, digestive problems, tachycardia, high blood pressure, anxiety, and nervousness—an almost complete catalog of human illnesses. Since continuous noises are most severe in industry, regulatory legislation in the United States has been most stringent and effective in this area. In 1969 the Walsh-Healy Public Contracts Act was passed, and thereafter its provision for maximum permissible exposure to noise levels was incorporated into the Occupational Safety and Health Act. Both the act and the associated regulatory agents, the Occupational Safety and Health Administration, are known as OSHA. The relevant provisions of this act are reproduced in Fig. 26.22. To avoid complex regulations, limitations of exposure are given in terms of single-number dbA values. Since workers rarely remain in a single acoustic environment for 8 h, their total daily exposure, or *time-*

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Fig. 26.23 This small (5½ in. × 2¾ in.) multifunction noise meter can be worn by the user throughout the workday. It measures noise dose, time-weighted average (TWA) noise level, and other noise levels, in addition to functioning as a normal sound-level meter. It can also be connected to a printer to provide timed histograms for statistical noise analyses. (Courtesy of Quest Electronics.)

weighted average (TWA) exposure can be calculated from timed dbA measurements using formulas and tables given in the OSHA code and then compared to permissible levels. Alternatively, one of the newer dose meters (see Fig. 26.23) can be used, which automatically integrates the noise to which a person is exposed over a given time period and reads out the TWA exposure directly.

Typical industrial noise levels are given in Table 26.5. When these levels are exceeded, management must take steps to reduce the exposure, either by reducing the noise or by providing hearing protectors. Typical characteristics of a few types are given in Fig. 26.24.

TABLE 26.5 Typical Industrial Noise Levels*

Equipment	dbA
Printing press plant (medium size automatic)	86
Heavy diesel-propelled vehicle (about 25 ft away)	92
Heavy-duty grinder	93
Air compressor	94
Plastic chipper	96
Cutoff saw	97
Multiple spot welder	98
Turbine condenser	98
15 cu ft air compressor	100
Drive gear	103
Banging of steel plate	104
Magnetic drill press	106
Air chisel	106
Positive displacement blower	107
Air hammer	107
Vacuum pump	108
Jolt squeeze hammer	122

*These are approximate values for typical generic equipment types and should not be used as design values.

OSHA does not deal extensively with impulse noises, except to state that they shall not exceed 140-dB peak sound pressure level. The area of impulse noise is quite different from continuous noise, since apprehended levels depend on duration, and specification is difficult. Much work has been done in this area by the military for obvious reasons. The interested reader is referred to the literature since this subject is substantially outside the area of architectural acoustics.

ROOM ACOUSTICS

26.22 Sound in Enclosures

When a continuous sound is generated in an enclosure, fields are set up as described in Section 26.15. When the sound is not a continuous tone or noise but a series of discrete sounds, following one upon the other and containing information as in speech or music, the room must be designed to maintain and enhance the information's intelligibility. That is what is meant by design of room acoustics.

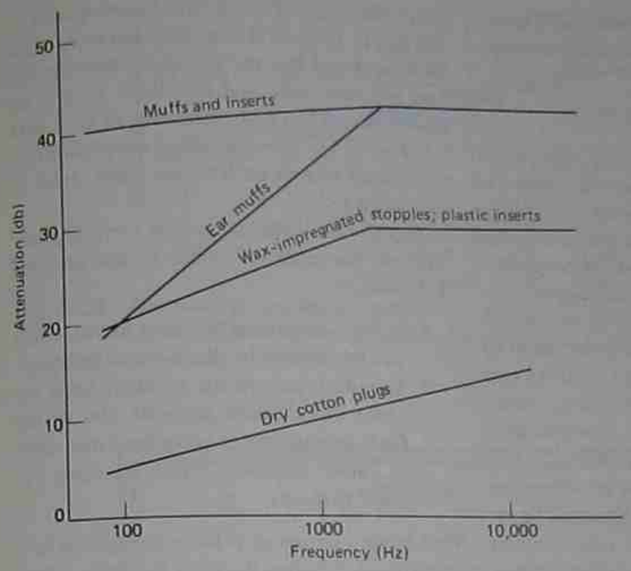


Fig. 26.24 Sound attenuation characteristics of various types of ear protectors. [From Quieting: A Practical Guide to Noise Control *(1976).]*

The generated sound radiates out from the source until it strikes a room boundary or other large surface. Before reaching this surface the sound intensity is attenuated by distance (inverse square law) and by absorption in the air. This latter is appreciable only in large rooms, and at frequencies above 2000 Hz. [For detailed data on air absorption, see Magrab (1975). In the absence of exact data, assume a figure of 0.40 sabin (m^2)/100 m^3 and see Table 27.1.) When the sound reaches the wall, it is partially reflected and partially absorbed. A small portion is transmitted into adjoining spaces. The energy transmitted is usually so small that it has little effect on the space within which the sound originates although, as discussed in Chapter 27, it may be very important in the surrounding spaces.

The ratio between the energy absorbed and the energy reflected will significantly affect what one hears within the space. Specifically, if little energy is absorbed and much is reflected, two effects will be noticeable. Intermittent sounds will be mixed together (which may make speech *less* intelligible or music *more* pleasant), and steady sounds will accumulate into a reverberant field, making the space "noisy." Conversely, if much energy is absorbed and little reflected, the room will sound quiet to speech and "dead" to music. At this point it may be helpful to the reader to review the technicalities of absorption and reverberation as discussed in Sections 26.13 through 26.15 above.

26.23 Criteria for Speech Rooms

The overriding criterion for speech is intelligibility. Since speech consists of short disconnected sounds 30 to 300 ms in length (see Section 26.17), among which are high-frequency, low-energy phonemes, the ideal room must assure the ear's undistorted reception of these phonemes. This requires keeping reverberation to a minimum. We can obtain a good approximation of the subjective feeling of liveness of a room, for purposes of *speech*, from the relation

$$T_R = 0.3 \log \frac{V}{10} \qquad (26.21)$$

where

T_R = optimum reverberation time in seconds, for speech

V = room volume, m^3

For instance, a typical classroom might have a volume of 150 m^3 (5300 ft^3). Optimum reverberation time is

$$T = 0.3 \log 15 = 0.35 \text{ s}$$

Reverberation times longer than this would sound live, shorter ones dead and flat. Indeed an increase of 20% in reverberation time would make the room excessively live and boomy and would negatively affect speech intelligibility. Figure 26.25 gives optimum mid-frequency reverberation times as a function of room size and use, since experience has shown these figures to be a good indication of the space's reverberation characteristic over the entire frequency band. For good speech intelligibility, reverberation time should remain flat down to 100 Hz.

Figure 26.26 gives *maximum* reverberation time figures for speech, in large rooms. The reflected sounds associated with reverberation have either a salutary or a deleterious effect. The ear cannot distinguish between sounds that arrive within a maximum of 50 ms (1/20 s) of each other. (Some authorities use 40 ms, i.e., 1/25 s.) Sounds arriving within this time *reinforce* the direct path signal and appear to come from the source. Sounds arriving after this time are apprehended as a fuzzy echo or elongation of the sound, reducing intelligibility and directiveness.

Since the range of 40 to 50 ms corresponds at 344 m/s to 13.76 to 17.2 m, a speech room must be so arranged that the difference between the first reflection path and the direct path is not greater than 17 m and preferably 14 m or less (see Fig. 26.27). For more detail concerning this and related factors on reflected paths, refer to Section 26.25.

Too *low* a reverberation time (very high absorption, minimum reflection) is also undesirable because:

1. It limits the size of the room to that which can be covered by direct sound only.
2. It is disturbing to the speaker, since absence of reflection prevents him or her from gauging proper voice level and tends to cause excessive effort (shouting, as when outdoors).

Thus proper design of a room for speech is a compromise between the need for some reflection and the desire to minimize reflection to preserve intelligibility.

26.24 Criteria for Music Performance

Adequate design for a music space requires recognition of the following:

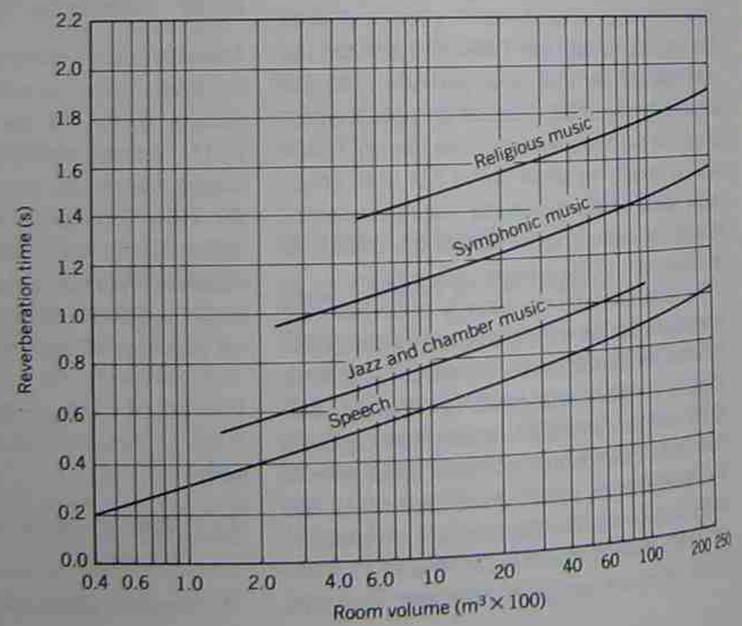


Fig. 26.25 *Optimum reverberation times for the frequency range 500 to 1000 Hz. (Reprinted by permission from E. B. Magrab,* Environmental Noise Control, *Wiley, New York, 1975, p. 206.)*

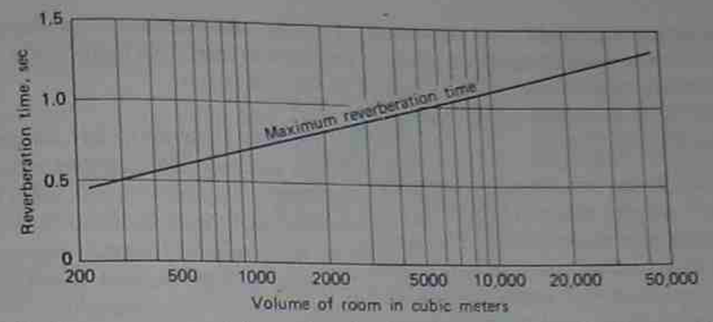


Fig. 26.26 *Maximum recommended reverberation time for speech in auditoriums and lecture halls. [From P. V. Brüel,* Sound Insulation and Room Acoustics, *Chapman & Hall, London, 1951, as reprinted in Brüel and Kjaer (1963).]*

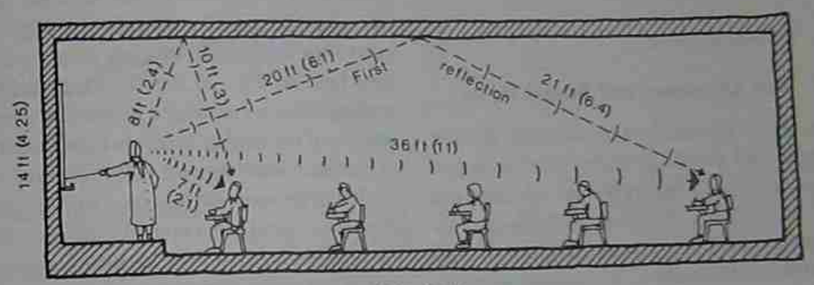


Fig. 26.27 *Sound paths in a typical medium-sized lecture room. Note that for both extremes of listener position, the maximum path-length difference between direct and first reflection is 11 ft. Thus signal is reinforced, and intelligibility should be excellent if room absorption is provided to limit reverberation time to about 1/2 s maximum (see Fig. 26.26). Numbers in parentheses are dimensions in meters.*

1. Large-volume spaces require direct-path sound reinforcement by reflection.

2. Relatively long reverberation time is needed to enhance the music—the exact amount depending on the type of music (see Fig. 26.25). Designers should keep in mind that recommendations vary as much as 100% between respected sources. In addition to an optimum reverberation time in the central 500-Hz to 1-kHz range, the reverberations at other frequencies should exhibit a slight drop in the higher frequencies to compensate for the sharp drop in ear sensitivity. Thus T_R at 100 Hz should be, according to most researchers, between 25 and 50% longer than T_R at the center frequencies. As a matter of interest, concert halls judged to be excellent by musical experts have a center frequency reverberation time between 1.6 and 1.8 s.

3. Directivity declines if the reinforcing signal is excessively delayed. With large ensembles, directivity gives the sense of depth and instrument location necessary for proper appreciation. This is often referred to as clarity or definition in music. With a solo instrument this problem is diminished.

4. Brilliance of tone is primarily a function of high-frequency content. Since these frequencies are most readily absorbed, a good direct path must exist between sound source and listener. Since our eyes and ears are close together, a

good sound path exists when a good vision path exists. At the other end of the spectrum, lack of sufficient bass expresses itself as a loss of "fullness," which is often caused by resonant absorption (see Section 27.3).

The actual design of music performance space is a very complex procedure involving extensive calculations of absorption, reverberation time and ray diagramming, and juggling of materials, dimensions, and wall angles. Simulation techniques and acoustic models are also employed. Most modern design also uses movable reflector panels and other active variables. After construction is completed, extensive tests are conducted and field adjustments are made.

26.25 Ray Diagrams and Sound Paths

Ideally, every listener in a lecture hall, theater, or concert hall should hear the speaker or performer with the same degree of loudness and clarity. Since this is obviously impossible by direct-path sound, the essential design task is to plan methods for reinforcing desirable reflections and minimizing and controlling undesirable ones. Normally only the first reflection is considered in ray diagraming, since it is strongest. Second and subsequent reflections are usually attenuated to the point that they need not be considered except for the special situations of flutter, echoes, and standing waves discussed below.

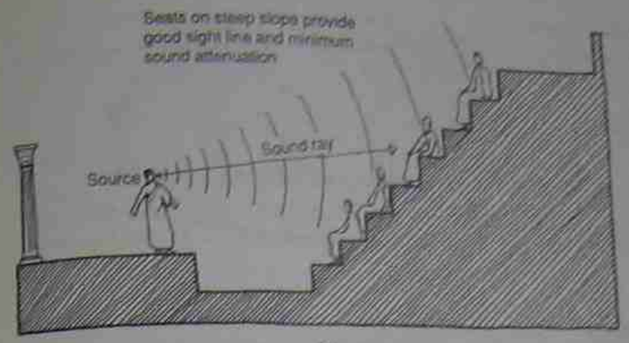
(a) Specular Reflection. Specular reflection occurs when sound reflects off a hard polished surface. This characteristic can be used to good advantage to create an effective image source. In ancient Greek and Roman theaters, seats were arranged on a steep, conical surface around the performers. The virtue of the arrangement (see Fig. 26.28*a*) is that the sound power travels to each location with minimal attenuation. The same effect can be accomplished by placing the sound source above the seats. This is not practical physically, but it can be accomplished effectively by the use of a reflecting panel (see Fig. 26.28*b*). Panel dimension must be at least one wavelength at the lowest frequency under consideration. Figure 26.29 is a conversion chart from frequency to wavelength in feet and meters.

(b) Ray Diagrams. Ray diagramming is a design procedure for analyzing reflected sound distribution throughout a hall, using the first reflection only. Figure 26.30 shows a ray diagram. The rays are drawn normal (perpendicular) to the spherically propagating sound waves. Specular reflection is assumed. That is, the angles between the reflecting panel and the incident and reflected rays are always equal. Thus, in addition to the direct sound, each listener is receiving reflected sound energy. It is as though there were additional sound sources, the real one and numerous image sources. Figure 26.30 shows the application of a ray diagram to a lecture hall. In Fig. 26.30*a* the stage height and seating slope are arranged to provide good sight lines, and the ceiling height is established by reverberation requirements esthetics, cost, and so on. It can be seen that less than half the ceiling is providing useful reflection. By dividing the ceiling into two panels (Fig. 26.30*b*), people in the rear of the room perceive the direct source plus two image sources, and the useful reflecting area is increased by 50%. In Fig. 26.30*c*, the shape has been further refined to include a lighting slot and a loudspeaker grille.

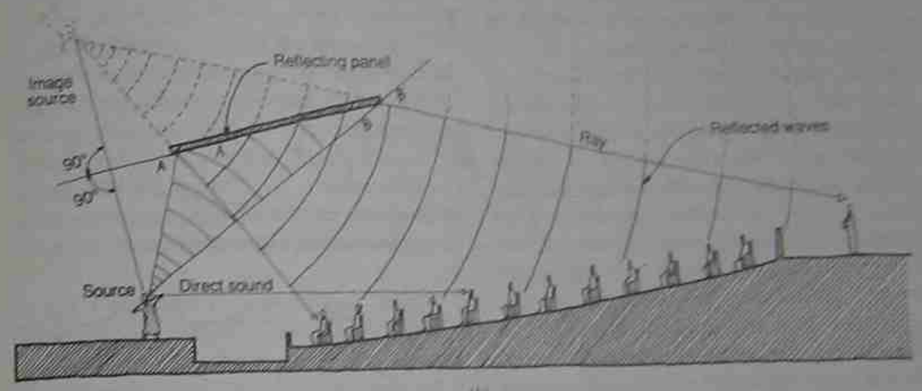
Although they are a useful design tool, ray diagrams have certain restrictions. For example, the hall is three dimensional and the diagram is two dimensional, that is, sectional. To properly ray diagram, depth (width) must also be considered, and this unduly complicates the diagram. Also, design must always be a compromise between ray diagrams for various "speaking positions" on the stage. Thus a paraboloid may be a perfect shape for one source position but will be very poor for other positions.

(c) Echoes. As explained in Section 26.23, a clear echo is caused when reflected sound of *sufficient intensity* reaches a listener more than 50 ms after he has heard the direct sound. Echoes, even if not distinctly discernible, are undesirable in rooms. They are annoying and make speech less intelligible. The relative annoyance is dependent on the time delay and loudness relative to the direct sound, which, in turn, are dependent on the size, position, shape, and absorption of the reflecting surface.

Typical echo-producing surfaces in an auditorium are the back wall and the ceiling above the proscenium. Figure 26.31 shows these problems and suggests remedies. Note that the energy that produced the echoes can be redirected to places where it becomes useful reinforcement. If echo control by absorption alone were used on the ceiling and back wall, that energy would be wasted. The rear wall, since its area cannot be reduced too far, may have to be made more sound absorptive to reduce the loudness of the reflected sound.



(*a*)



(*b*)

Fig. 26.28 Use of an angled reflector panel (b) creates an image source that stands in approximately the same relation to the audience as the performer in the classic Greek theater (a).

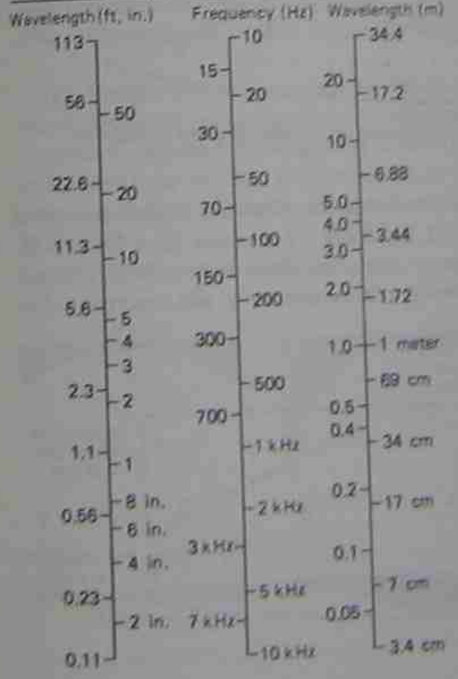


Fig. 26.29 Nomograph for determining wavelength in feet or meters, given frequency in hertz, or vice versa. Speed of sound is taken as 344 m/s and 1128 ft/s. To use, hold a straightedge horizontally across the nomograph, and read the figures directly.

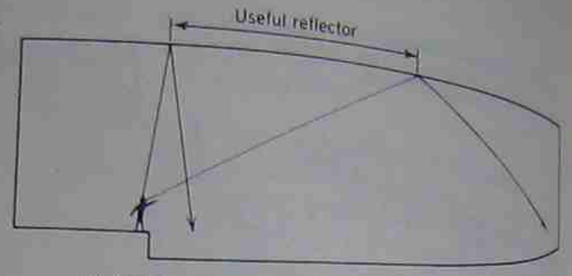
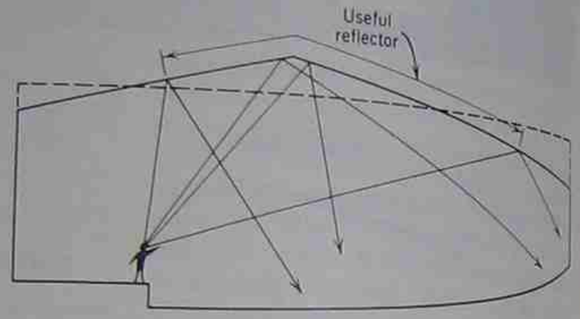
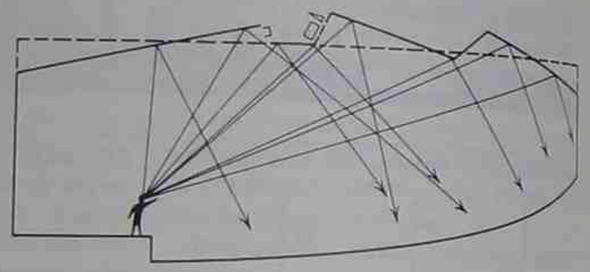


Fig. 26.30 Section through a typical lecture room showing use of ray diagrams.

(a) Flat ceiling



(b) Two panel ceiling increases useful reflecting area



(c) Multifaceted ceiling incorporates lights and loudspeakers

(d) Flutter. A flutter, perceived as a buzzing or clicking sound, is comprised of repeated echoes traversing back and forth between two nonabsorbing parallel (flat or concave) surfaces. Flutters often occur between shallow domes and hard, flat floors. The remedy for a flutter is either to change the shape of the reflectors or their parallel relationship, or to add absorption. The

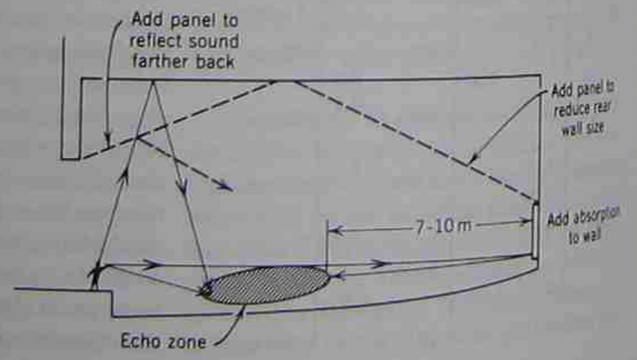


Fig. 26.31 Auditorium section showing the causes and remedies for two typical echoes.

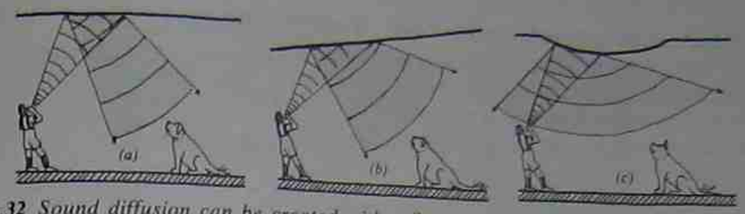


Fig. 26.32 Sound diffusion can be created with reflectors of different shapes, ranging from the horizontal flat (a), *inclined flat* (b), *or convex* (c). *Diffusion improves from* (a) *to* (c).

solution chosen will depend on reverberation requirements, cost, or esthetics.

(e) Diffusion. This is the converse of focusing and occurs primarily when sound is reflected from convex surfaces. A degree of diffusion is also provided by flat horizontal and inclined reflectors (see Fig. 26.32). In a diffuse sound field the sound level remains relatively constant throughout the space; an extremely desirable property for musical performances.

(f) Focusing. Concave domes, vaults, or walls will focus reflected sound into certain areas of rooms. This has several disadvantages. For example, it will deprive some listeners of useful sound reflections and cause hot spots at other audience positions (see Fig. 26.33*a*).

(g) Creep. This describes the reflection of sound along a curved surface from a source near the surface. Although the sound can be heart at points along the surface, it is unaudible away from the surface. Creep is illustrated in Fig. 26.33*b*.

(h) Standing Waves. Standing waves and flutters are very similar in principle and cause, but are heard quite differently. When an impulse (such as a hand clap) is the energy source, a flutter will occur between two highly reflective parallel walls. It is perceived as a slowly decaying buzz. When a steady, pure tone is the source, a standing wave will occur, but only when the parallel walls are spaced apart at some integral multiple of a half-wavelength.

When the parallel walls are exactly one-half wavelength apart, the tone will sound very loud near the walls and very quiet halfway between them. This is because at the center, the reflected waves traveling in one direction are exactly one-half wavelength away from those traveling in the other, and thus equal *but opposite in pressure*, which results in total cancellation. In other rooms standing waves are noted as points of quiet and maximum sound in the room. Standing waves are important only in rooms small with respect to the wavelengths generated (smallest room dimension <30 ft for music or <15 ft for speech).

Another effect of standing waves, *resonance*, is the accentuation of the particular frequency

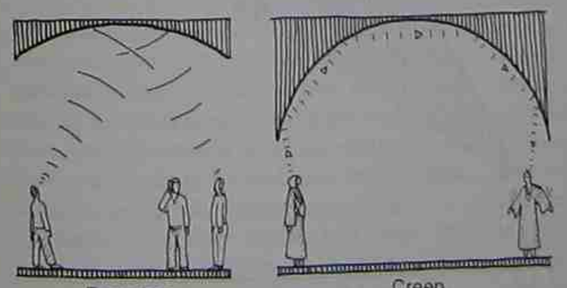


Fig. 26.33 Two undesirable phenomena in room acoustics.

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that will cause a standing wave in a room of that dimension. Thus, if one speaks (or plays a musical instrument) standing near a wall of a room, about 8 ft by 8 ft, one will notice an abnormal and sometimes unpleasant loudness in the sound at about 280 Hz.

Thus, when a musician plays a scale, one note may seem far louder than the adjacent ones, and listeners in one section of the room will hear a quality of sound different from that heard by those in other sections. This effect *must* be avoided for music performance but is merely an annoyance in rooms designed for speech use. This is one of the reasons that one finds music rehearsal rooms, broadcast studios, and so on with nonparallel walls and undulating ceilings. These irregularities prevent most of the undesirable effects described above from occurring. However, since rooms with nonparallel walls and undulating ceilings are for most applications unacceptable, and since standing waves and other resonant phenomena are related to room geometry, it is possible to calculate room proportions that will minimize these effects. Figure 26.34 shows such room proportions, which are applicable to bass frequencies (i.e., below 100 Hz). These are the problematic frequencies, since at higher frequencies (and in large rooms) many standing waves occur and the total effect is much less disturbing and frequently hardly noticeable.

26.26 Auditorium Design

This is a general term used to describe a space where people sit and listen to speech or music. Acoustical design of an auditorium includes room acoustics, noise control, and sound system design. Noise control is covered in Chapter 27. The first step in the acoustical and architectural design must be determining the program. If the program for the auditorium includes activities that need different acoustical environments, it must be decided early whether the acoustics will be a compromise between the program extremes or adjustable for various activities. Acoustical environments can be altered by changing volume, moving reflecting surfaces, and adding or subtracting sound-absorbing treatment. Figure 26.35 illustrates several examples of acoustical adjustability.

Factors that influence the acoustical design include audience size, range of performance activities, and sophistication of the potential audience. A small school auditorium and a professional theater will have widely divergent demands from both audience and performers.

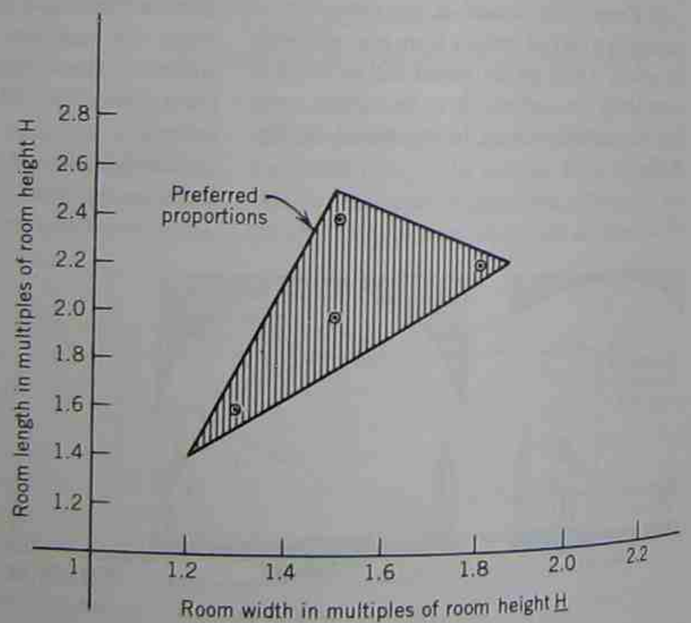


Fig. 26.34 *Triangular figure contains the room proportions recommended, for avoidance of disturbing low-frequency acoustic phenomena such as flutter, standing waves, and resonances, particularly at frequencies below 100 Hz. The points shown at the three apexes were averaged to obtain the center, average proportion of* 2H : 1.5H : H. *See also Fig. 26.16 for application of these proportions.*

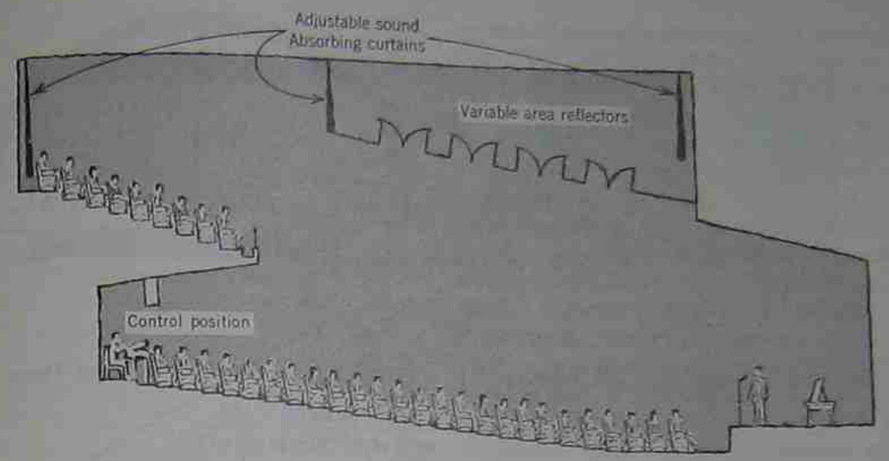


Fig. 26.35 *Adjustable acoustic elements in an auditorium.*

The audience size determines the basic floor area of an auditorium. Once this area has been fixed, the volume of the room is developed according to reverberation requirements of the space.

Figure 26.36 shows a typical auditorium in plan and section. The shape of wall and ceiling surfaces is developed to give proper distribution of sound and eliminate focusing or echoes. Essential characteristics of the design include:

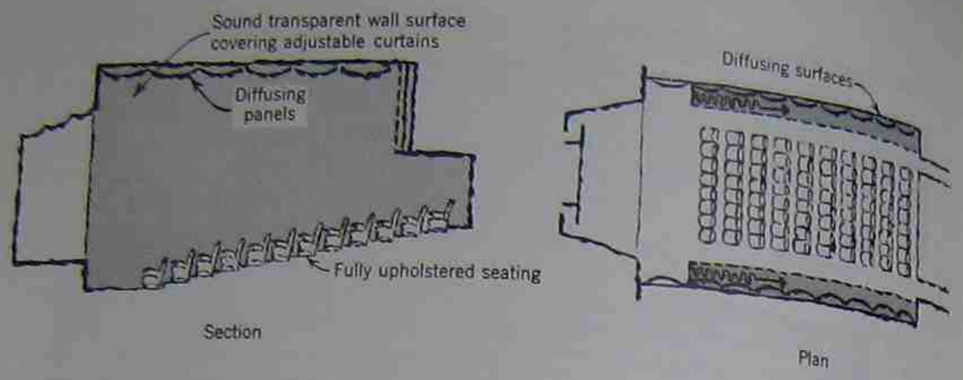
1. Ceiling and side walls at the front of the auditorium distribute sound to the audience. These surfaces must be close enough to the performers to minimize time delays between direct sound and reflected sound.
2. Ceiling and side walls provide diffusion.

Acoustics must be considered in selection of materials used in an auditorium. All auditoriums use both sound-reflecting and sound-absorbing materials. Since the largest area of sound-absorbing material in any auditorium is the audience, the difference in acoustical characteristics that occur without an audience may be minimized by using fully upholstered seating.

Chairs with fully upholstered seats and backs, covered in an open-weave material, will have absorption characteristics closely approximating an audience. Using the auditorium in Figure 26.36 as an example, the reverberation characteristics of an auditorium with various materials may be examined. In the first example, the room use is assumed to be for music performance. The only sound absorption is that provided by the audience and seating. In the second set of calculations absorptive curtains were installed along the rear wall and a portion of the side wall. This configuration might be used for lectures in a room that is adjustable between speech and music configurations. A third configuration might use permanent sound-absorbing treatment installed on the ceiling and rear and side walls. Because of its low reverberation time, this configuration would be appropriate only for movies and lectures, not for music activities.

These simple examples indicate the effect of changes in the amount of absorption on the characteristics of a room. Adjustable treatments permit the characteristics of the room to be modified to any point between the extremes to meet the program acoustic requirements of a multipurpose hall.

Existing spaces may require remedial treatment to eliminate unwanted phenomena such as focusing and echoes, as shown in Fig. 26.37. In the first example, the surface of the dome was covered with sound-absorbing material to eliminate focusing; in the second, sound-absorbing treatment was applied to a curved rear wall to



Simplified Calculations of Midfrequency (500 and 1000 Hz) Average Reverberation Times

$$\text{reverberation time } (RT) = \frac{0.05 \times \text{volume (cu ft)}}{\text{total absorption (sabins)}}$$

volume = 155,500 cu ft

	More Reverberant Condition (curtains retracted)			*Less Reverberant Condition (curtains exposed)*		
	Area	*a*	*Absorption*	*Area (sq ft =)*	*a*	*Absorption*
Seating and stage (with audience and performers)	3323	.92	3060	3323	.92	3060
Wall area				3600		
Concrete block	8000	.2	1600		.2	720
Concrete block (balance covered by curtains)						
Curtains				4400	.45	1970
Lower rear wall	450	.88	396	450	.88	396
Permanent sound-absorbing treatment						
			5056			6146
Total absorption More reverberant condition				Total absorption Less reverberant condition		

$$RT = \frac{0.05 \times 155{,}500}{5056} = 1.5 \text{ s}$$

$$RT = \frac{0.05 \times 155{,}500}{6146} = 1.2 \text{ s}$$

Fig. 26.36 *Auditorium with surface treatments for control of reflections and reverberation.*

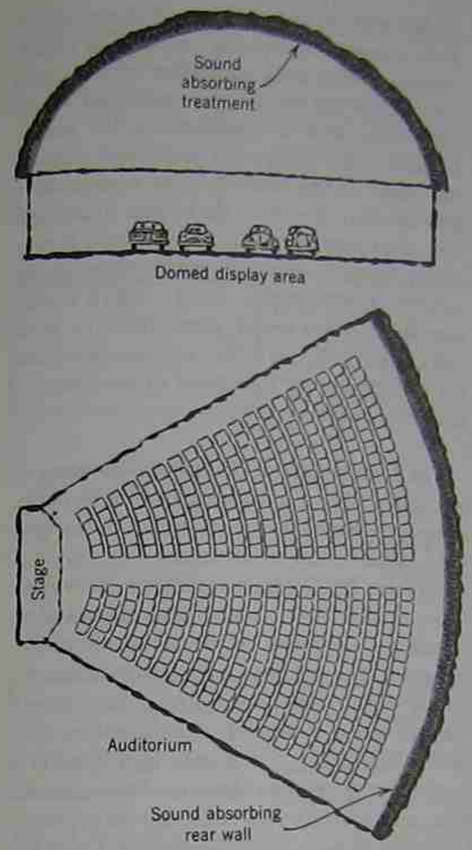


Fig. 26.37 *Sound-absorbing treatment used to eliminate focusing from dome and curved auditorium wall.*

eliminate an echo. Such treatment also will affect the reverberation characteristics.

SOUND REINFORCEMENT SYSTEMS

26.27 Objectives and Criteria

The purpose of a sound reinforcement system is just what the name indicates—to reinforce the sound, which would otherwise be inadequate. Thus an ideal sound system will give the listener the same loudness, quality, directivity, and intelligibility as if the source of sound were immediately adjacent to him—a distance of 2 to 3 ft for speech and farther for music, depending on type and number of instruments. This situation must obtain for every position in the space except that a variation of ±3 db for loudness is tolerable. The other factors should remain constant. Of these factors, loudness and intelligibility have been discussed at length and should be well understood. By quality we mean that frequency response should be linear so that reproduced sound bears the same relation between its frequency components as the original sound. (Quality is then field-adjusted by "voicing" or "equalization," as discussed below.)

Directivity is the characteristic whereby the sound appears to be coming from the originating source, that is, the loudspeakers should be directionally "invisible," and the listener must have the impression of actually hearing the source. It should be emphasized that sound systems cannot correct poor acoustic design completely, although they can improve a bad situation.

Generally, sound systems will be required in spaces larger than 50,000 ft^3 (~1400 m^3). In terms of population, this volume translates as 550 persons in lecture rooms (15 ft average ceiling height and 6 ft^2 per person) and 325 persons in theaters (20 ft average ceiling height and 7.5 ft^2 per person). In such a room (50,000 ft^3) a normal speaking voice can maintain a volume level of only 55 to 60 db, depending on room design and voice strength. With background noise at NC 30 (see Table 27.8), the speaker will be heard; at higher noise levels intelligibility will suffer.

26.28 Components and Specifications

All sound systems consist of three basic elements: input devices, amplifier(s), and loudspeaker systems.

(a) Input. Input is usually a microphone, a radio source, or some form of prerecorded material.

(b) Amplifier and Controls. Amplifiers must be rated to deliver sufficient power to produce intensity levels of 80 db for speech, 95 db for light music, and 105 db for symphonic music.

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This assumes a *maximum* background noise level of 60 dbA. Thus 80-db speech intensity will be 20 db higher, or four times as loud as the noise level. If noise level is *known* to be below 60 db maximum, amplifier and loudspeaker power ratings can be reduced accordingly. The amplifier should carry technical specifications for signal-to-noise ratio, linearity, and distortion. Exact figures here depend on application and are left to the acoustics specialist or sound engineer to supply.

In addition to the usual volume, tone mixing, and input–output selector controls, the amplifier *must* contain special equalization controls for signal shaping. These are highly critical filter networks which by selective amplification and attenuation of portions of the overall audio frequency spectrum, *voice* or *equalize* a system after installation. Equalization is a sine qua non of a good sound system; without it the system will howl, sound rough, give insufficient and poorly distributed gain and sound level, and generally sound poor. Essentially, voicing tailors the system to the acoustic properties of the space. A system not equipped for equalization is not a professional system, and results will verify it. Furthermore, the specification must provide for the services of a competent sound engineer to perform the equalization after installation and construction is complete.

Another control frequently required in theater systems is a delay mechanism or circuit that can introduce a time delay into a signal being fed to a loudspeaker. Figure 26.38 shows a sound system that covers a majority of an auditorium from a central-loudspeaker cluster. The underbalcony seating areas are hidden from the central cluster and receive the reinforced sound from distributed loudspeakers in the underbalcony soffit. To provide directional realism, the signal to the underbalcony loudspeakers must be delayed to allow the weaker signal from the central speakers to arrive first. Delay is necessary because electrical signals travel at the speed of light, whereas sound is much slower (one-millionth the speed, approximately). With this arrangement, sound will seem to come from the source, and the directivity so necessary to realism is maintained.

(c) Loudspeakers. These are the heart of any sound system and obviously must be of the same high quality as the remainder of the system. Indeed, system economies will show up much more quickly in loudspeaker performance than in any other component. Selection of speakers is a complex, technical task not within our scope. Nevertheless, a few general remarks are in order. The best systems use central-speaker arrays consisting of high-quality, sectional (multicell), directional, high-frequency horns, and large-cone woofers. These assemblies are frequently very large, and the architect should be aware of the dimensions that must be accommodated. Smaller units with folded horns can be used, at a sacrifice in low-frequency response. If only speech is to be reproduced, these will perform adequately. Distributed systems

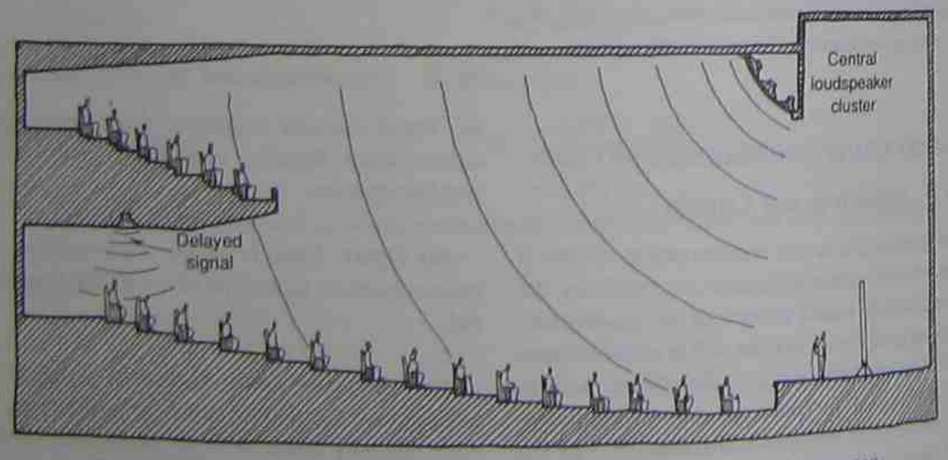

Fig. 26.38 Loudspeaker system using delayed signal to under-balcony area.

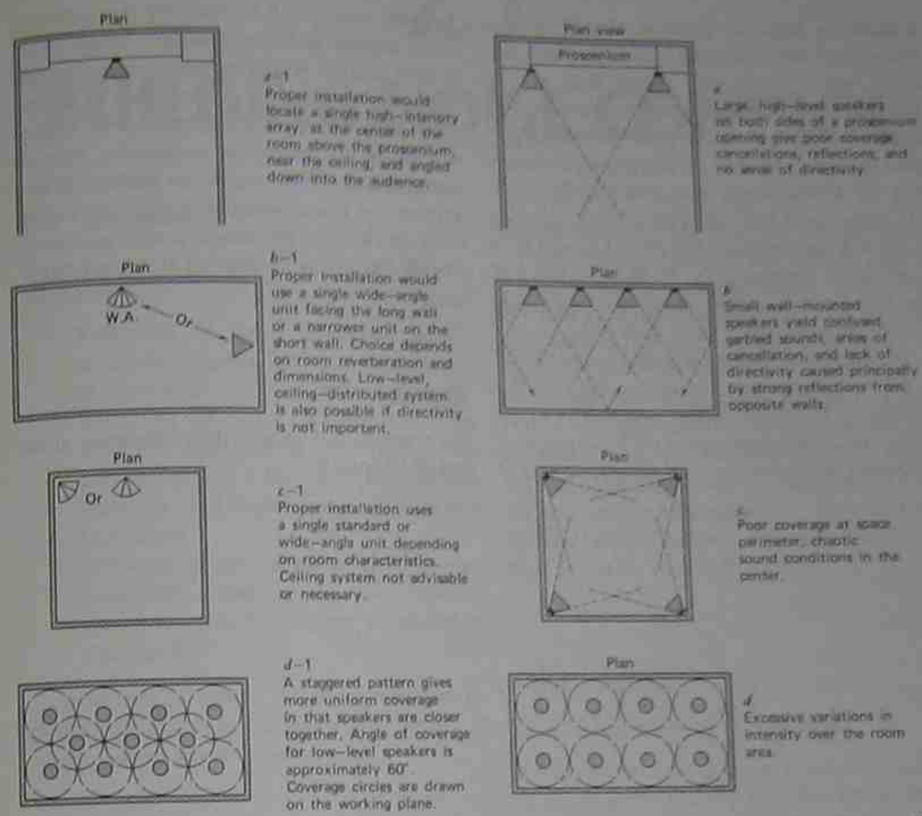

Fig. 26.39 *Poor layouts* (a) *to* (d) *and good layouts* (a-*1*) *to* (d-*1*). *Wide-angle speakers are available to fit most needs. Ceiling speakers give effective coverage on a 60° cone. Working plane is taken to be 4 ft AFF for seated audience and 6 ft AFF for standing listeners.*

use small (4 to 12 in. diameter) low-level speakers, ceiling mounted, and firing directly down.

26.29 Loudspeaker Considerations

Loudspeaker system design and placement must be coordinated with the architectural design. The two principal types of loudspeaker system are central and distributed. The loudspeakers in a central system are a carefully designed array of directional high-frequency units combined with less directional low-frequency units, placed above and slightly in front of the primary speaking position. In most theaters, this location is just above the proscenium on the centerline of the room. Located in this position, the system provides directional realism and is simple in its design.

The distributed loudspeaker system consists of a series of low-level loudspeakers located overhead throughout the space. Each loudspeaker covers a small area, in a manner similar to downlights. This type of system is used in low-ceilinged areas where a central-loudspeaker cluster could not provide proper coverage. It also can be used for public address functions if directional realism is not essential, in spaces such as exhibition areas, airline terminals, and offices. In addition, distributed loudspeaker systems provide flexibility for use in spaces where source and listener locations vary according to the use of the space, since loudspeakers can easily be switched to provide proper coverage. In

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general, a listening position should receive sound from only one loudspeaker. Systems that cover seating areas with signals from several scattered loudspeakers usually increase the loudness of the sound but tend to produce garbled speech. This rule is the principal reason that the arrangements shown in Fig. 26.39*a–d* will guarantee a bad job. The common practice of placing one loudspeaker on either side of a proscenium opening (Fig. 26.39*a*), or rows of speakers on one or both sides of a room (Fig. 26.39*b*), is particularly to be deplored.

Essential parameters for location and design of the control position create problems for the architect. The sound system operator must be within the coverage pattern of the loudspeakers. For proper operation, he or she should be able to hear the sound as it is heard by the audience. Some current auditorium designs locate sound system controls within the audience seating pattern (see Fig. 26.35). Others place a control room with a completely open wall or a large window at the rear of the auditorium. Monitor loudspeakers and earphones are inadequate substitutes for actual listening within the auditorium. In churches the simple control equipment can be located at the rear of the congregation area.

REFERENCES

See complete list of acoustics references at the end of Chapter 27.

27
BUILDING NOISE CONTROL

27.1 Introduction

Noise control in buildings is comprised of three components:

1. Reduction of noise generation at the source by proper selection and installation of equipment.
2. Reduction of noise transmission from point to point (along the transmission path) by proper selection of construction materials and appropriate construction techniques.
3. Reduction of noise at the receiver through acoustical treatment of the relevant spaces to meet NC criteria developed in Chapter 26.

Assurance of speech privacy is achieved by manipulation of all of the above plus the use of masking noise where necessary.

NOISE REDUCTION

27.2 Principles of Noise Reduction

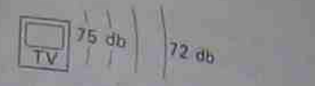
Noise reduction is essentially the science of converting acoustical energy into another, less disturbing form of energy—heat. Since the amounts of energy involved are minute—130 db corresponds to 1/1000 of a watt or 0.003 Btu/h—the heat produced is completely negligible. This energy conversion is accomplished by absorption of the sound energy by the room contents and wall coverings, and by the structure itself. The former controls noise levels *within* a space and the latter noise transmission between spaces. The reasons for this will become clear as our discussion proceeds. Noise control treatment of a room will affect the reverberant noise level *within* that room but will have minimal effect on the noise level in adjoining spaces. Refer to Fig. 27.1 for a graphic presentation of this fundamental fact. The best that can be accomplished with acoustic room treatment is elimination of the reverberant field, that is, to make the intensity at the room boundaries what it would have been in free space, as in Fig. 27.1*d*. (Even this is extremely difficult; the actual field at the wall would be above 72 db, except in a completely anechoic chamber.) Adding further wall or other acoustic absorbent as in Fig. 27.1*e* does nothing in the room itself and has minimal effect on the overall transmission loss, since the transmission loss in the acoustic material itself is very low, as can be seen in Fig. 27.2*b*.

ABSORPTION

27.3 Mechanics of Absorption

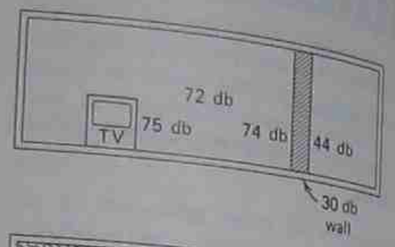
We have already learned in Sections 26.13 and 26.14 the definition of sound absorption and its relevance to room reverberation characteristics. At this point it is appropriate to reexamine absorption as an acoustic phenomenon so that we may understand the application of absorptive material. Refer to Fig. 27.2*a*. In an untreated room of normal construction, when the sound waves strike the walls or ceiling, a small portion is transmitted, a small portion is absorbed, and most of the sound is reflected. The exact proportions obviously depend on the nature of construction. When acoustical treatment is applied to the room surfaces as in Fig. 27.2*c*, some of the energy in the sound waves is dissipated before the sound reaches the wall. The transmitted portion is slightly reduced, but the reflection is greatly reduced. The difference between the two situations is shown graphically in Fig. 27.3. Refer back to Fig. 26.19, where the result of adding absorptive material to a room is shown in greater detail. The difference between a room with average absorption of 0.1 and the same

(a) TV set in free space produces 75-db sound level, which drops 6 db for each doubling of distance. Attenuation by inverse square law (see Section 26.7).

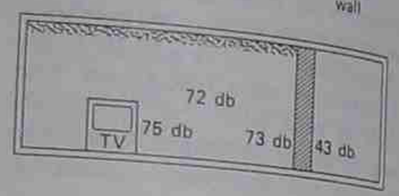


69 db

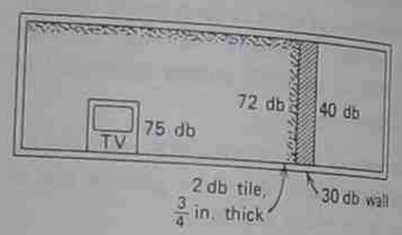
(b) TV still produces 75 db. In the free field, sound drops to 72 db but builds up to 74 db at the wall due to reverberant field reinforcement (see Figs. 26.16 and 26.18). Wall attenuation is 30 db. Sound on other side of the wall is 74 − 30 = 44 db.



(c) Acoustic tile ceiling acts to reduce room reverberant field. Free field is extended. Level at wall is 73 db. Level in second space is 73 − 30 = 43 db.



(d) Entire room is acoustically treated, effectively eliminating reverberant field. Room is "dead." Level on second side of wall is 72 db less acoustic tile loss, less wall loss (that is, 72 − 2 − 30 = 40 db).



(e) Add another 2¼ in. of acoustic wall treatment. Room is "dead." Level at wall 72 db. Level in second space = 72 − 4 − 30 = 38 db.

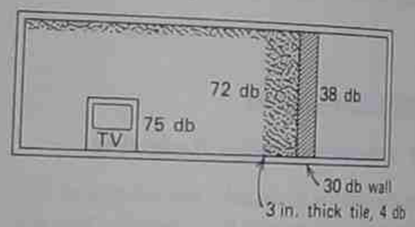


Fig. 27.1 Action of acoustic absorbent material.

room with $\bar{\alpha}$ of 0.7 is 15 db, which is a reduction in *loudness* of approximately 1.5 times (see Table 26.3). We will now examine the acoustic materials themselves and the effect of varying type, quantity, thickness, and installation methods.

27.4 Absorptive Materials

There are three families of devices for sound absorption—fibrous materials, panel resonators, and volume resonators. All types absorb sound by changing sound energy into heat energy. Only fibrous materials and panel resonators are used commonly in buildings. Volume resonators, also known as Helmholtz resonators, after their originator, are used principally as enclosures for absorbing a narrow band of frequencies. The following discussion refers to fibrous absorbers—the other two types are discussed separately in Section 27.8.

Fibrous or porous materials absorb acoustic energy by the frictional drag produced by moving the air in small spaces within the material. The absorption provided by a specific material depends on its thickness, density, porosity, and

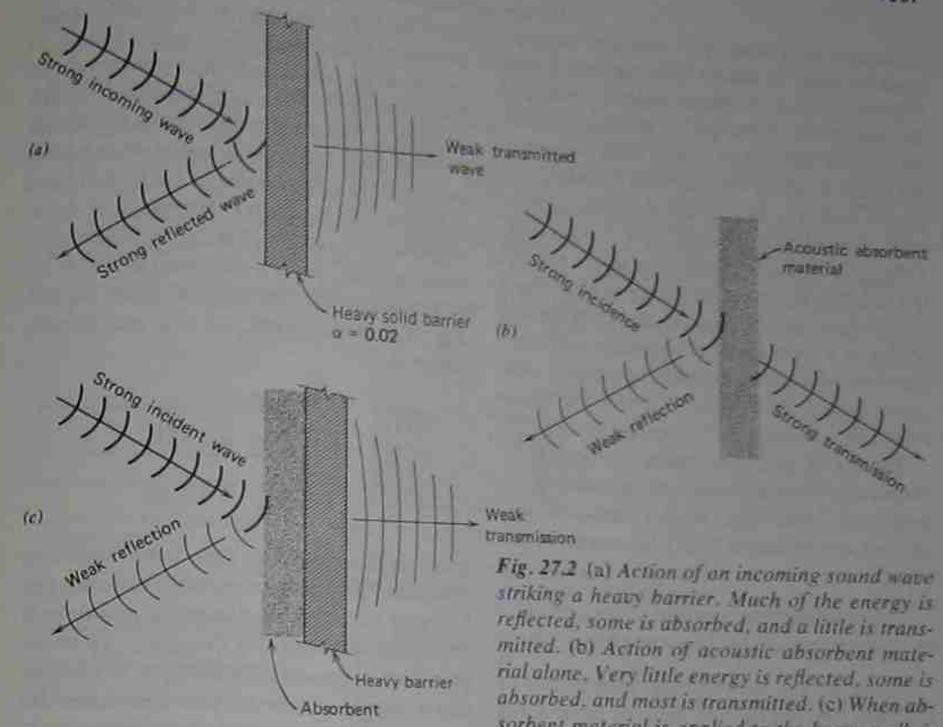


Fig. 27.2 (a) Action of an incoming sound wave striking a heavy barrier. Much of the energy is reflected, some is absorbed, and a little is transmitted. (b) Action of acoustic absorbent material alone. Very little energy is reflected, some is absorbed, and most is transmitted. (c) When absorbent material is applied to the heavy wall, it "traps" sound, preventing reflection, while wall mass acts to reduce transmission.

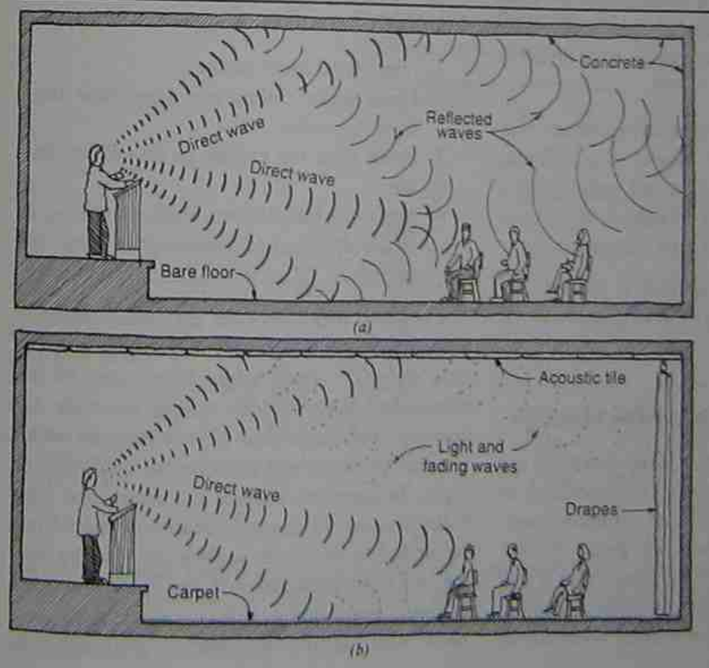


Fig. 27.3 In the untreated space (a) reverberant (reflected) sound constitutes a large portion of received sound in much of the room. These reflections are largely eliminated in (b) by wall and ceiling absorption. Note that direct wave is completely unaffected.

resistance to airflow. For example, materials must be thick to absorb low-frequency sounds effectively. Since the action depends on absorbing energy by "pumping" air through the material, the air paths *must extend from one side to the other*. A fibrous material with sealed pores is almost useless as an acoustic absorbent. (Therefore, painting will generally ruin a porous absorber.) A simple test is to blow smoke through the material. If the smoke passes through freely and the material is porous, fibrous, and thick, it should be a good sound absorbent. Absorbency increases with increasing material porosity up to approximately 70% porosity; above that figure absorbency remains fairly constant.

Table 27.1 gives absorption coefficients for fibrous absorbent materials and for building materials and furnishings. Several important conclusions can be drawn from examination of this table.

1. For absorbent materials, absorption is normally higher at high frequencies than at low.

2. Absorption is not always proportional to thickness, but depends on the type material being used and the method of installation (see Fig. 27.4). It is clear from this figure that beyond a nominal thickness, little is to be gained by adding thickness except at very low frequencies, or when installed discontinuously, as in item 3, below.

3. It is possible to obtain an α greater than 1.0 by using very thick blocks. See "Sound blocks" in Table 27.1. These are installed at a distance from each other. Edge absorption is very large, particularly at high frequencies.

4. Installation methods have a pronounced effect as discussed in the following section.

27.5 Installation of Absorptive Materials

Coefficient ratings for absorptive materials are always given with mountings corresponding to ASTM requirements. The most common standardized mounting methods are given in Fig. 27.5. Installation of absorbent directly on a wall or ceiling is the least effective means, since exposure to sound energy is minimal. When an air gap is left between the porous layer and the rigid surface, the combination acts almost as well, at midfrequencies, as a layer of absorbent equivalent in thickness to the air plus porous material (see Fig. 27.6). One problem with this technique is that at the $\lambda/2$ node of a standing wave there is a severe drop in absorption, as can be seen from Fig. 27.6*c*. Thus, at 1000 Hz, one-half wavelength is approximately 7 in. At that distance, or drops severely, but is a maximum at $\lambda/4$ or 3½ in. For ceiling tile hung at 16 in. below the slab (Fig. 27.5, method E405), the drop in absorption occurs at

$$\lambda/2 = 16 \text{ in.}$$

$$\lambda = 32 \text{ in.} = 2.67 \text{ ft}$$

$$f = \frac{1128}{2.67} = 422 \text{ Hz}$$

which is midfrequency. This factor should be considered in applying absorptive material; that is, avoid a spacing corresponding to a drop in absorption at a sensitive frequency. To obtain good low-frequency absorption, it is essential that a deep air space be provided behind the porous absorbent material, and that walls be treated in addition to the ceiling.

In increasing order of effectiveness, absorbent material can be applied:

1. Directly to room surface.
2. Hung below ceiling and supported away from the walls.
3. Hung from the ceiling as louvres or baffles.
4. Made up into shapes such as cubes, or tetrahedrons, and suspended from the ceiling.

The last two techniques are extremely effective because they expose a very large surface of porous material—much larger than could be accomplished with wall or ceiling covering. Of course, these suspended objects become architectural elements and must be handled accordingly. In contrast, surface coverings are relatively neutral. In general, treatment should not be limited to one room surface such as the ceiling. All three principal surfaces in the direction of sound propagation, that is, ceiling, floor, and back wall, should be treated *approximately*

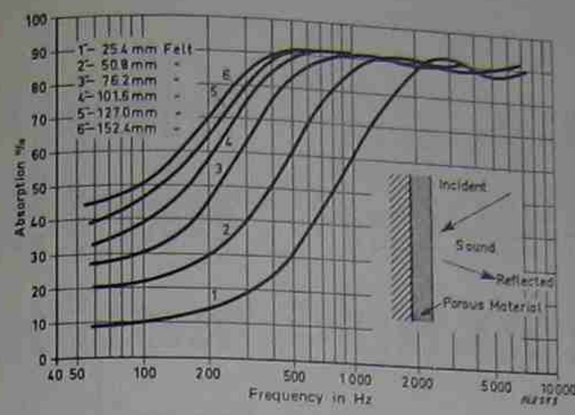


Fig. 27.4 Variation of absorption coefficient with thickness of felt absorbent. Note particularly that beyond 1 kHz, all thicknesses give the same α, whereas at low frequencies the absorption is proportional to thickness. Furthermore, it requires a very heavy layer to give appreciable absorption at low frequency. [Courtesy of Brüel and Kjaer (1951), as reprinted in Brüel and Kjaer (1963).]

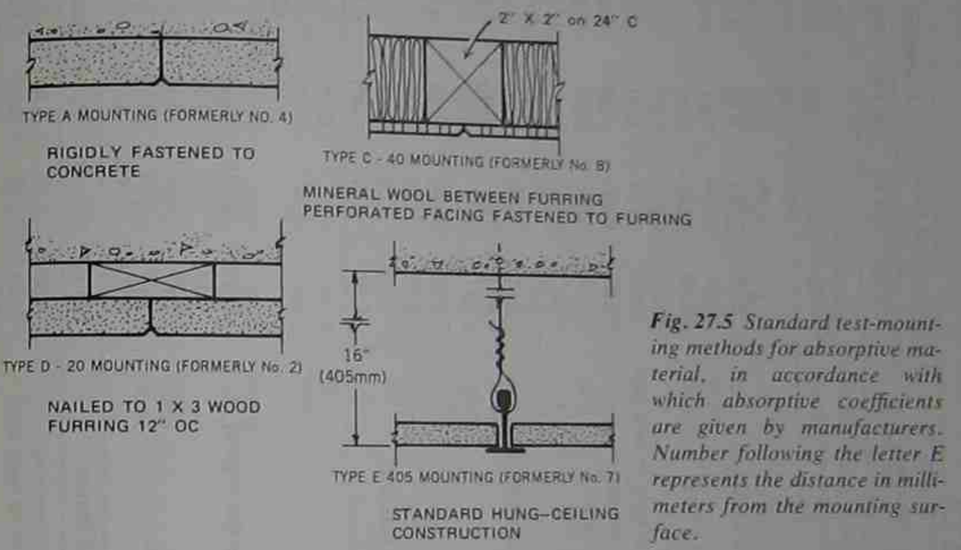


Fig. 27.5 Standard test-mounting methods for absorptive material, in accordance with which absorptive coefficients are given by manufacturers. Number following the letter E represents the distance in millimeters from the mounting surface.

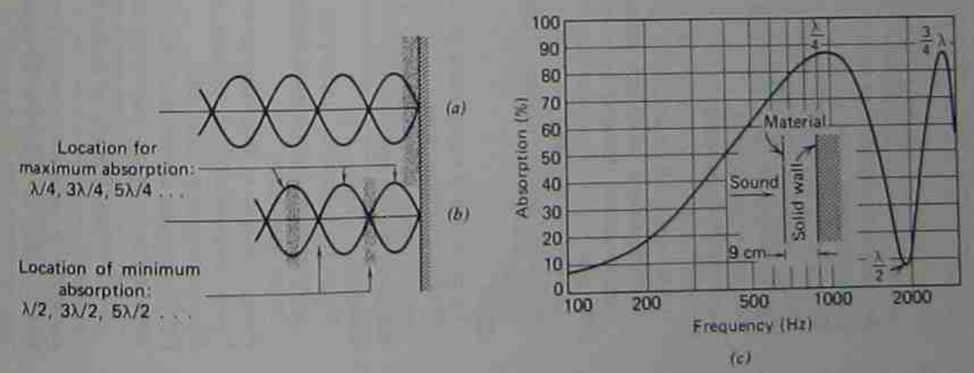


Fig. 27.6 Sound waves striking a surface of large mass will create standing waves at certain frequencies, depending on room dimension (a). *If insulation is placed at the nodes of these waves* (b), *attenuation is drastically reduced* (c). *[Illustration* (c) *from Brüel and Kjaer (1951), as reprinted in Brüel and Kjaer (1963).]*

TABLE 27.1 **Coefficients of Absorption[a]—α**

General Building Materials and Furnishings[b]	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*NRC[c]*
	Absorption Coefficients						
Air, sabins per 1000 ft³ at 50% rh				0.9	2.3	7.2	—
Brick, unglazed	0.03	0.03	0.03	0.04	0.05	0.07	0.005
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03	0.00
Carpet, heavy, on concrete	0.02	0.06	0.14	0.37	0.60	0.65	0.29
Carpet, heavy, on 40-oz hairfelt or foam rubber	0.08	0.24	0.57	0.69	0.71	0.73	0.55
Concrete block, coarse	0.36	0.44	0.31	0.29	0.39	0.25	0.35
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08	0.05
Fabrics							
Light velour, 10 oz/yd², hung straight, in contact with wall	0.03	0.04	0.11	0.17	0.24	0.35	0.15
Medium velour, 14 oz/yd², draped to half area	0.07	0.31	0.49	0.75	0.70	0.60	0.55
Heavy velour, 18 oz/yd², draped to half area	0.14	0.35	0.55	0.72	0.70	0.65	0.60
Floors							
Concrete or terrazzo	0.01	0.01	0.015	0.02	0.02	0.02	0.00
Linoleum, asphalt, rubber, or cork tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02	0.05
Wood	0.15	0.11	0.10	0.07	0.06	0.07	0.10
Glass							
Large panes of heavy plate glass	0.18	0.06	0.04	0.03	0.02	0.02	0.05
Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04	0.15
Gypsum board, ½ in. nailed to 2 × 4's 16 in. o.c.	0.10	0.08	0.05	0.03	0.03	0.03	0.05
Marble or glazed tile	0.01	0.01	0.01	0.01	0.02	0.02	0.00
Openings							
Stage, depending on furnishings			0.25–0.75				
Deep balcony, upholstered seats			0.50–1.00				
Grilles, ventilating			0.15–0.50				
Plaster, gypsum or lime, smooth finish on tile or brick	0.013	0.015	0.02	0.03	0.04	0.05	0.05
Plaster, gypsum or lime, on lath	0.14	0.10	0.06	0.05	0.04	0.03	0.05
Plywood paneling, ⅜ in. thick	0.28	0.22	0.17	0.09	0.10	0.11	0.15
Rough wood as tongue and groove cedar	0.24	0.19	0.14	0.08	0.13	0.10	0.14
Water surface, as in a swimming pool	0.008	0.008	0.013	0.015	0.020	0.025	0.00

Absorption of Seats and Audience[d]	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*NRC[c]*
Audience, in upholstered seats, per ft² of floor area	0.60	0.74	0.88	0.96	0.93	0.85	—
Unoccupied cloth upholstered seats, per ft² of floor area	0.49	0.66	0.80	0.88	0.82	0.70	—
Wooden pews, occupied, per ft² of floor area	0.57	0.61	0.75	0.86	0.91	0.86	—
Students in tablet-arm chairs, per ft² of floor area	0.30	0.42	0.50	0.46	0.50	0.46	—

Acoustic Absorptive Materials	*Mtg.[e]*	*125 Hz*	*250 Hz*	*500 Hz*	*1000 Hz*	*2000 Hz*	*4000 Hz*	*NRC[c]*
		Absorption Coefficients						
Armstrong[f]								
High-performance vinyl-faced fiberglass ceiling panels:								
1 in. thick	E405	0.82	0.86	0.72	0.96	0.96	0.77	0.90
1.5 in. thick	E405	0.79	0.98	0.83	1.03	0.98	0.80	0.95
Painted nubby glass cloth panels								
¾ in. thick	E405	0.81	0.94	0.65	0.87	1.00	0.96	0.85
1 in. thick	E405	0.78	0.92	0.79	1.00	1.03	1.10	0.95
Random fissured ⅝ in. thick panels								
Perforated	E405	0.66	0.76	0.68	0.80	0.89	0.80	0.75
Nonperforated	E405	0.44	0.29	0.28	0.77	0.83	0.76	0.55
Typical averages, mineral fiber tiles and panels								
¾ in. fissured	E405	0.47	0.50	0.52	0.76	0.86	0.81	0.65
¾ in. textured	E405	0.49	0.55	0.53	0.80	0.94	0.83	0.70
⅝ in. fissured	E405	0.28	0.33	0.66	0.73	0.74	0.75	0.60
⅝ in. textured	E405	0.29	0.35	0.66	0.63	0.44	0.34	0.50
⅝ in. perforated	E405	0.27	0.29	0.55	0.78	0.69	0.53	0.60
Gold Bond, National Gypsum[g] Quiet Touch ⅝-in. wall panel fabric-covered glass fiberboard on honeycomb core	A	0.00	0.07	0.37	0.78	0.91	0.94	0.55
	E60	0.29	0.65	0.91	0.89	0.87	0.92	0.85
	E405	0.61	0.70	0.65	0.81	0.96	0.96	0.80
Sound Touch ⅝-in. wall panel fabric-covered glass fiberboard on gypsumboard base	A	0.01	0.06	0.20	0.46	0.68	0.84	0.35
	E60	0.41	0.18	0.25	0.43	0.64	0.86	0.40
	E405	0.17	0.15	0.20	0.46	0.76	0.91	0.40
Tectum[h] Sound Blocks 3 in. thick × 15 in. square on 24-in. centers	A	0.36	0.53	1.81	2.65	2.75	2.73	

[a]Complete tables of coefficients of the various materials that normally constitute the interior finish of rooms may be found in books on architectural acoustics. This table will be useful in making simple calculations.

[b]Selected data courtesy of Owens-Corning Fiberglass.

[c]Noise reduction coefficient: the arithmetic average of the α values at 250, 500, 1000, and 2000 Hz.

[d]When the audience is randomly spaced, use an average of 5.0 sabins (ft²) per person.

[e]See Fig. 27.5.

[f]Courtesy of Armstrong World Industries.

[g]Courtesy of Gold Bond Building Products, Division of National Gypsum Co.

[h]Courtesy of Tectum, Inc.

[i]Figures are sabins (ft²) per unit.

equally for best results. The common practice of treating the ceiling only is generally inadvisable, since high frequencies are highly directive and may not reach the ceiling until the third reflection. See specific recommendations in Section 27.35.

27.6 Noise Reduction Coefficient

The last column in Table 27.1 is labeled NRC—noise reduction coefficient. This figure is the arithmetic average of the absorption coefficients at 250, 500, 1000, and 2000 Hz. The name is ill chosen inasmuch as it cannot be used as the words would seem to imply. It is useful as a single-number criterion for the *midband* effectiveness of a porous absorber. Obviously, if careful design is required or high- and low-end frequencies are of interest, NRC is nearly useless, and detailed calculations over the entire frequency range must be made. Similarly, two materials with the same NRC can perform quite differently, since the NRC is an average and few materials have a flat characteristic.

27.7 Noise Reduction by Absorption

The reader is referred back to Sections 26.13 through 26.15 and Fig. 26.19 for a review of the characteristics of absorption, reverberation, and fields in an enclosed space, as background material for a discussion of noise reduction by absorption. Equation 26.14 relates sound pressure level (SPL) and sound power level (PWL) as a function of distance from the source and room absorption. The following example shows the application of this equation and the result of adding absorption to the space.

EXAMPLE 27.1 An open blower is installed on the floor, away from the walls, in a large enclosed space that is 6 m long, 12 m wide, and 4 m high. The floor is concrete ($\alpha = 0.01$); walls and ceiling painted block ($\alpha = 0.07$). The sound power levels (PWL) supplied by the manufacturer are 90 db at 500 Hz and 87 db at 2000 Hz. Calculate the noise level SPL at distances of 5 m and 10 m from the blower outlet: (*a*) in the original room; (*b*) with double the absorption; (*c*) with quadruple the absorption.

SOLUTION

1. From Equation 6.14, we have the expression

$$SPL = PWL + 10 \log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right)$$

In our example, $Q = 2$ (see Fig. 26.18).

2. The first step is to calculate room factor R for the three situations of absorption.

$$R = \frac{S\bar{\alpha}}{1 - \bar{\alpha}}$$

$$S = 2(48) + 2(24) + 2(72) = 288 \text{ m}^2$$

from equation 26.16,

$\bar{\alpha}$ original

$$= \frac{3(48)(0.07) + 1(72)(0.07) + (72)(0.01)}{288}$$

$$= 0.055$$

$\bar{\alpha}_a = 0.055$ $R_a = 16.76$

$\bar{\alpha}_b = 2(0.055) = 0.11$ $R_b = 35.6$

$\bar{\alpha}_c = 4(0.055) = 0.22$ $R_c = 81.23$

3. Calculating SPL values and tabulating, we obtain

	500 Hz		2000 Hz	
SPL for:	5 m	10 m	5 m	10 m
Original room	83.9	83.8	80.9	80.8
Double $\bar{\alpha}$	80.8	80.6	77.8	77.6
Quadruple $\bar{\alpha}$	77.5	77.1	74.5	74.1

The results indicate the very important fact that *doubling the absorption decreases the noise level by only 3 db*. Therefore it requires a quadrupling of absorption to make the decrease noticeable (see Table 26.3). This is obviously an expensive procedure with diminishing returns.

If the entire space is considered to be a reverberant field, then from equation 26.19 the noise (sound) intensity level (IL) can be expressed as follows:

$$IL = PWL - 10 \log \Sigma A + 16.3 \text{ db} \quad (26.19)$$

where

ΣA = total absorption in room, sabins (ft²)

IL = intensity level, db

PWL = sound power level, db

Although increasing absorption decreases the noise level, the level never is reduced below the free field level for that distance from the source (see Fig. 27.1).

The amount of noise reduction provided by additional absorption may be determined by

$$\text{noise reduction} = IL_1 - IL_2$$

$$= 10 \log \Sigma A_2 - 10 \log \Sigma A_1$$

Therefore,

$$NR = 10 \log \frac{\Sigma A_2}{\Sigma A_1} \quad (27.1)$$

where

ΣA_1 = total absorption, initial condition

ΣA_2 = total absorption, final condition

From equation 27.1 it is obvious that doubling the absorption results in a noise reduction of 3 db, since $10 \log_{10} 2 = 3$ (db). It is of interest to work out a practical example using equations 26.19 and 27.1 and comparing the results with the more precise relation given in Equation 26.13.

EXAMPLE 27.2. Referring to Fig. 27.7, calculate the original noise level and the subsequent noise reduction by three steps of sound absorption treatment, assuming a completely reverberant field in the space, that is, SPL independent of location.

SOLUTION. *(a) Original Condition.* Painted concrete block chamber, $10 \times 10 \times 10$ ft.

Fan power level:

At 500 Hz = 88 db

At 2000 Hz = 78 db

Absorption	Area	α	Total Absorption ($\Sigma S\alpha$)
500 Hz	600 ft²	0.06	36 sabins (ft²)
2000 Hz	600 ft²	0.09	54 sabins (ft²)

Sound intensity level before treatment:

At 500 Hz:

IL = sound power $- 10 \log \Sigma S\alpha + 16.3$ db

$= 88$ db $- 10 \log 36 + 16.3$ db

$= 88$ db $- 15.6$ db $+ 16.3$ db

$= 88.7$ db

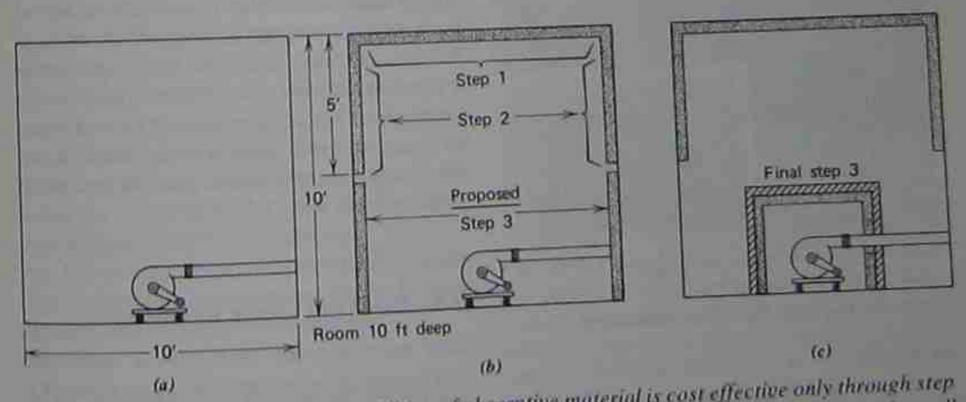


Fig. 27.7 Quieting the room (a) *by addition of absorptive material is cost effective only through step* 2 (b). *Further quieting would be accomplished locally* (c), *which might obviate the necessity for wall treatment (step 2). Ceiling treatment should remain.*

At 2000 Hz:

$$IL = 78 \text{ db} - 10 \log 54 + 16.3 \text{ db}$$
$$= 78 \text{ db} - 17.3 \text{ db} + 16.3 \text{ db}$$
$$= 77 \text{ db}$$

(b) Ceiling Treatment Only

At 500 Hz:

$$\alpha = 0.82$$
$$\text{additional absorption} = 100(0.82 - 0.06)$$
$$= 76 \text{ sabins}$$
$$NR = 10 \log \frac{76 + 36}{36}$$
$$= 4.9 \text{ db}$$

At 2000 Hz:

$$\alpha = 0.94$$
$$\Delta A = 100(0.94 - 0.09) = 85$$
$$NR = 10 \log \frac{85 + 54}{54}$$
$$= 4.1 \text{ db}$$

(c) Ceiling and Half-Wall Treated

At 500 Hz:

$$\text{added absorption} = 300(0.82 - 0.06)$$
$$= 228 \text{ sabins}$$
$$NR = 10 \log \frac{228 + 36}{36}$$
$$= 8.7 \text{ db}$$

At 2000 Hz:

$$\text{added absorption} = 300(0.94 - 0.09)$$
$$= 255 \text{ sabins}$$
$$NR = 10 \log \frac{255 + 54}{54}$$
$$= 7.5 \text{ db}$$

(d) Ceiling and Full-Wall Treatment

At 500 Hz:

$$\Delta A = 500(0.82 - 0.06)$$
$$= 380 \text{ sabins}$$
$$NR = 10 \log \frac{380 + 36}{36}$$
$$= 10.6 \text{ db}$$

At 2000 Hz:

$$\Delta A = 500(0.94 - 0.09)$$
$$= 425 \text{ sabins}$$
$$NR = 10 \log \frac{425 + 54}{54}$$
$$= 9.5 \text{ db}$$

Summary

	IL (SPL)	
	500 Hz	2000 Hz
Bare room	88.7	77
Ceiling treated	−4.9 db (−4.9)	−4.1 db (−4.2)
Half-wall treatment	−8.7 db (−8.7)	−7.5 db (−7.7)
Full-wall treatment	−10.6 db (−10.7)	−9.5 db (−9.6)

The numbers in parentheses are the SPL differences as calculated from equation 26.13, using $Q = 2$ and $r = 5$ ft.

We would conclude here that the third step is really not worthwhile, since only a negligible additional decibel of quieting is accomplished. This example is intended to indicate the law of diminishing returns in quieting by absorption. Starting with a live room, the initial application is effective. Beyond that, additional quieting by absorption is not economical, and the same outlay would be better applied in quieting the machine itself, probably with a machine enclosure as indicated in Fig. 27.7*c*.

27.8 Panel and Cavity Resonators

Panel resonators are built with a membrane such as thin plywood or linoleum in front of a sealed air space generally containing absorbent material. The panel is set in motion by the alternating pressure of the impinging sound wave.

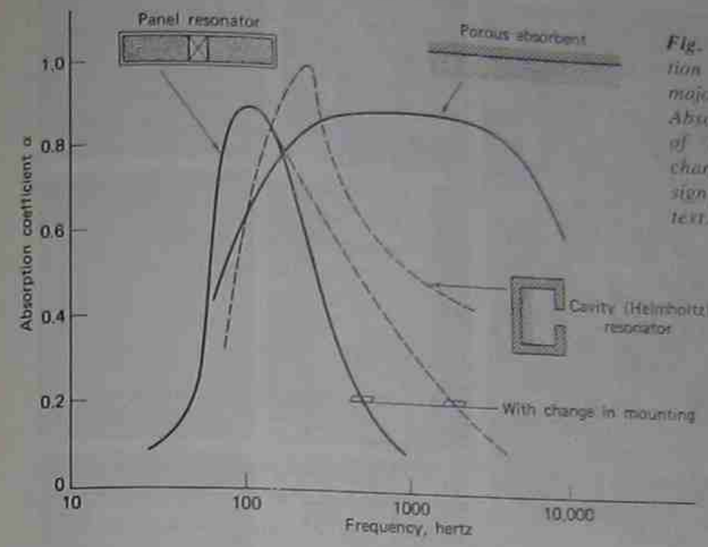


Fig. 27.8 Typical absorption curves for the three major types of absorbers. Absorption characteristic of each type can be changed by varying design, as discussed in the text.

The sound energy is converted into heat through internal viscous damping. Panel resonators are used where efficient low-frequency absorption is required and middle- and high-frequency absorption is unwanted or provided by another treatment (see Fig. 27.8). Panel resonators are often used in recording studios.

A *volume or cavity resonator* (Helmholtz resonator) is an air cavity within a massive enclosure, connected to the surroundings by a narrow neck opening. The impinging sound causes the air in the neck to vibrate, and the air mass behind causes the entire construction to resonate at a particular frequency. At that frequency absorption is very great—approaching unity, and dropping sharply above and below this frequency (see Fig. 27.8). By adjusting neck opening and cavity dimensions, the unit can be tuned to resonate at any desired frequency. This makes it extremely useful when a major single frequency is present, as with 120-Hz transformer hum. Such an installation is shown in Fig. 27.9 along with a typical concrete block resonator. Fibrous filler can be used in the block to increase high-frequency absorption.

27.9 Acoustically Transparent Surfaces

The soft porous material of which most absorbents are constructed is covered with perforated

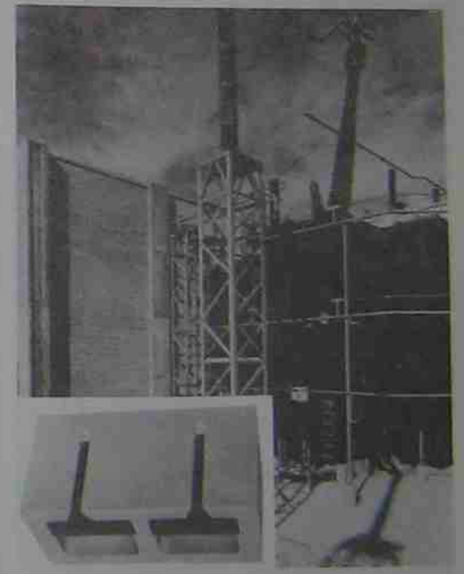


Fig. 27.9 Typical application of cavity resonators to absorb transformer hum in a large high-voltage substation. Wall is built of masonry units constructed to act as resonators (see insert). (This installation is made with SOUNDBLOX as manufactured by the Proudfoot Co., through whose courtesy photo is supplied.)

metal or wood panels, which act as physical protection and as stiffeners. These coverings are acoustically transparent except at higher frequencies. The frequency at which a noticeable reduction in absorption occurs can be estimated for circular holes as

$$f = \frac{40p}{d} \qquad (27.2)$$

where

f = frequency, Hz

p = percentage of open area

d = diameter of holes, in.

Thus for ¼-in. holes and 60% open area, which is a typical commercial construction,

$$f = \frac{40(6)}{0.25} = 9600 \text{ Hz}$$

which is very high and generally not of major concern. It is always preferable, given a fixed percentage of open area, to use small holes, rather than large ones since, as is obvious from the formula, this raises the frequency at which absorption drops. It is also desirable to stagger the holes as this improves absorption. An open-weave fabric is almost completely transparent to sound and can be used as a decorative cover on absorbent wall coverings (see Fig. 27.10).

27.10 Absorption Recommendations

To summarize the discussion above, absorption techniques are useful and effective:

1. To change room reverberation characteristics.
2. In spaces with distributed noise sources such as offices, schools, restaurants, and machine shops.
3. In spaces with hard surfaces and little absorptive content.
4. Where listeners are in the reverberant field. (No amount of absorptive material can reduce intensity levels in the direct field.)

Concentrated noise sources are better handled by individual equipment enclosures than by room treatment, since enclosures reduce direct field noise, which, as stated above, room surface treatment cannot do. In addition to ceiling tiles and wall panels, acoustic absorbent material can be applied in the form of a sprayed-on finish (acoustic plaster), suspended unit absorbers, carpets, draperies, and other surface treatments. See Table 27.2 for characteristics of the most common of these elements.

SOUND ISOLATION

27.11 Airborne and Structure-Borne Sound

In contradistinction to the preceding sections, which were concerned with the phenomenon of in-room sound reduction by absorption, the following sections will discuss the characteristics of sound *transmission* between enclosed spaces. The distinction is often made between airborne and structure-borne sound, although in reality they differ only in sound origin. *Airborne sound* originates in a space with any sound-producing source and although it changes to *structure-borne* sound when the sound wave strikes the room boundaries it is still referred to as airborne because it originated in the air. *Structure-borne* sound is generally understood as *direct impact* caused by a vibrating or impacting source directly contacting the structure. Hence a child crying in the adjoining apartment is contributing airborne sound; the same child bouncing a ball on the floor is creating structure-borne sound, in this case by impact. The building pumps that were installed without proper damping mounts create structure-borne sound by vibration.

In reality, all sound transmission is both airborne and structure-borne since, once having entered the structure, the sound travels along the structure and causes the structure to vibrate, generating airborne sound. Figure 27.11 should assist in understanding this action. In Fig. 27.11*a* the sound is airborne, originating in the air at one side of the partition. The incidence of sound energy *causes the partition to vibrate*, generating sound on the other side. Sound does not "pass through"—it causes the structure to become a secondary source. The partition vi-

Fig. 27.10 Acoustic ceiling tiles and wall panels are available in a wide variety of materials, designs, and finishes. Ceiling tiles: (a) *Pressed organic fiber and inorganic binder, textured finish;* (b), (c) *mineral fiberboard, carved pattern and vinyl paint finish;* (d) *random fissured rectangular fiberglass;* (e) *painted mineral fiberboard specially treated for high-humidity areas;* (f) *mineral fiberboard covered with brushed finish aluminum strips: 2 ft × 4 ft panel with routings between strips painted black. Wall panels:* (g) *Cloth-covered panel of wood fibers and inorganic binder;* (h) *perforated mineral fiberboard with cloth covering;* (i) *fiberglass panel covered with a variety of surfacing materials and finished in fabric. [Photos courtesy of Tectum* (a), (g), *and Armstrong World Industries* (b–f,h,i).*]*

TABLE 27.2 **Typical Recommended Acoustical Treatment**

Material Characteristics	*Acoustical Tile*	*Metal-Faced Acoustical Units*	*Acoustical Plaster*	*Acoustical Form Board*
Size and form	Square tiles 12 in. × 12 in.; some up to 48 in. × 96 in. Roof deck 2 ft × 8 ft—most common thicknesses, ⅝ and ¾ in.	12 in. × 24 in. up to 24 in. × 120 in. Thickness is controlled by acoustical pad backing. Either paper-wrapped mineral wool or cut or roll glass fiber. Units run 2 to 3 in. total thickness.	A plasterlike material of special fibrous or particulate aggregate, ½ to 1½ in. thick.	Sizes and thickness vary to fit structural requirements (floor and roof slabs only) 1 to 2½ in. for wall application.
Surface	Wide variety of perforated, textured, and sculptured surfaces with white, painted, vinyl, and glass cloth finishes.	Baked-enamel finish usually white, but available in color, perforated or slotted.	Fine-grain white texture, but may be spray painted.	"Shredded Wheat" or smooth pattern.
Method of installation	Adhesive, nailing, or stapling to wood furring; lay-in grids; concealed spline-grid.	Attached to metal supports nailed to wood furring or hung in a proprietary metal suspension system.	Trowel or spray.	According to structural design (floor and roof slabs only). Adhesive or mechanical application on walls.
Major area of application	All interior applications. Check specifications for application in high-humidity areas.	All interior applications. Check specifications for application in high-humidity areas.	Most interior applications. Especially useful for large curved surfaces. Not satisfactory in high humidity.	Floor and roof decks wherever applicable. Wall surfaces in most interior spaces.
Advantages	Provide widest range of finishes in high-absorption units. Mineral fiber tiles are rated incombustible. Lay-in units provide access to plenum above.	Incombustible. Easily maintained. Can be washed or painted; replacement units will match original job. Permits easy access to plenum.	Rapid, low-cost installation on large irregular or curved surface. Fine-grain texture. Incombustible—can be applied with (or as part of) fire protection.	Combines form board with thermal insulation and acoustical absorption.
Limitations	Allows transmission of sound over partition in hung ceiling unless selected for high-attenuation factor.	Allows transmission of sound over partition in hung ceiling unless backed by impervious layer.	Easily abused. Difficult to match finish in patching or repairing. Does not always perform as advertised. Performance limited to high-frequency absorption. Dusty in application.	Not advisable for high-humidity areas.

Material Characteristics	*Unit Sound Absorbers*	*Carpeting*	*Drapery*
Size and form	From 12 in. × 12 in. × 2 in. units to 24 in. × 48 in. plastic coated glass fiber baffles.	Sized or seamed to fit any floor or wall area.	Acoustically transparent fabrics ranging from opaque velours to transparent/translucent glass fibers.
Surface	12 in. × 12 in. units in smooth to rough surface. Baffles are vinyl wrapped.	Cut, looped, or combination to achieve any degree of "fuzzing."	Velveteen to bouclé (rough).
Method of installation	Units may be applied using special wall clips, pendents (ceiling only), or adhesive. Baffles are wire supported.	Tacking (floor only) or adhesive.	According to function and esthetics.
Major area of application	12 in. × 12 in. units are useful in all interior areas. Baffles in industrial areas.	Floors and walls.	Window or opaque wall areas and room dividers.
Advantages	Permit maximum flexibility. Hung units add sound absorption without requiring lowering lights or sprinkler heads.	Provides a relative degree of mid- and high-frequency absorption and luxurious appeal.	Provides a relative degree of overall sound absorption and luxurious appeal.
Limitations	Each application must be designed individually.	Acoustical absorption increases with pile height, pad, and fiber density.	Acoustical absorption increases with fabric density percent, fold when drawn, and air space behind.

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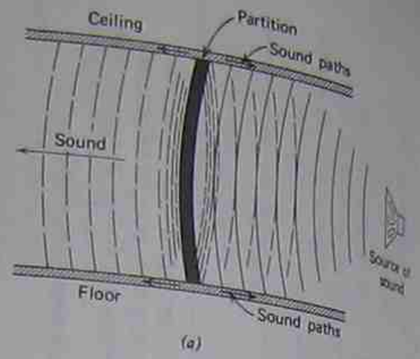
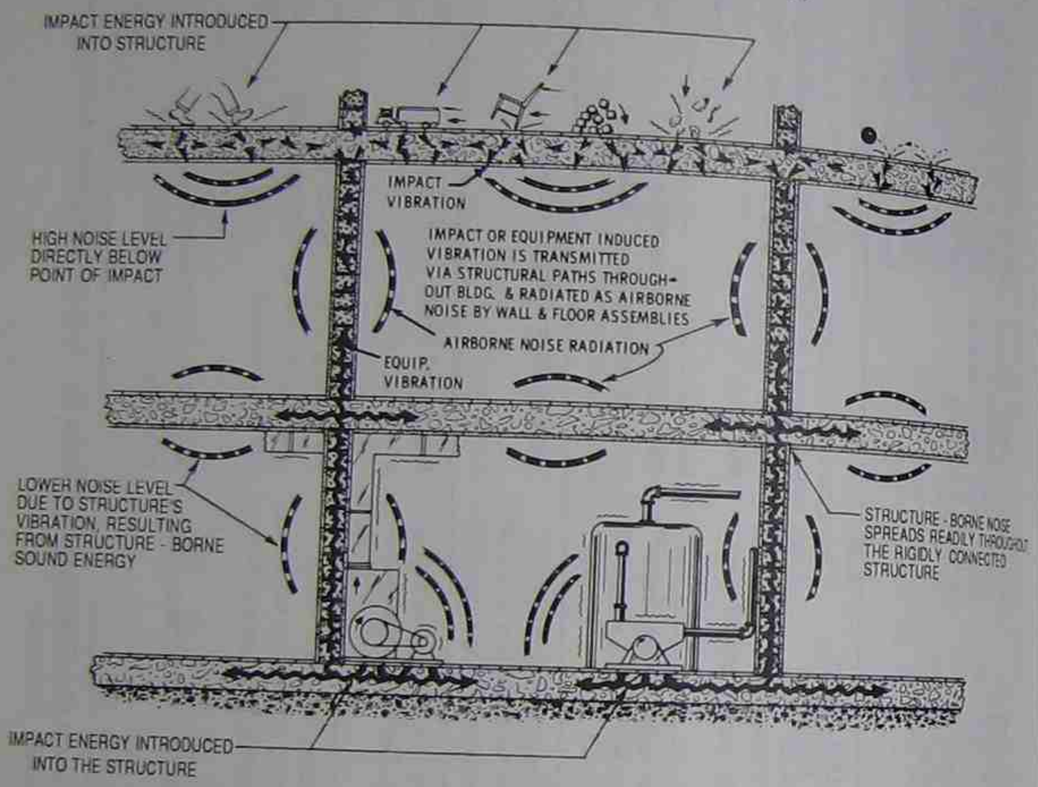
Fig. 27.11 (a) *Airborne sound is so called because it originates in the air.* (b) *Structure-borne sound originates from mechanical contact between structure and vibrating or impacting sources. As such its energy level is usually much higher than airborne sound.* (c) *Some techniques for controlling airborne sound. [Data from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

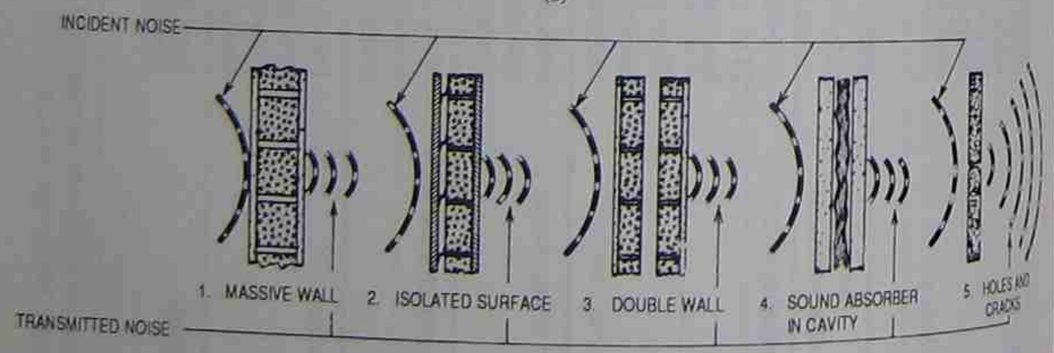


(a)



Transmission of Impact and Structure - Borne Noise.

(b)



Constructions 1-4 reduce transmitted noise; holes and cracks (5) can drastically reduce a wall's transmission loss and thereby its effectiveness as a sound barrier

(c)

brates primarily in the direction of the sound, that is, in the vertical plane. It also vibrates in other modes causing some sound energy to pass into the floor and ceiling, depending on the mode of attachment. This energy becomes structure-borne sound.

In Fig. 27.11*b* the process is similar, but reversed. Energy is introduced into the structure directly and efficiently by mechanical contact, that is, vibration and impact. Sound travels along the structure, as shown and by causing the structure to vibrate, creates airborne sound. In a structure with rigid wall-to-floor connections, these sounds are clearly heard throughout the structure. Airborne sound (originating in the air) is generally much less disturbing than structure borne, since its initial power is very low and it attenuates rapidly at boundaries. Structure-borne sound is generally at a much higher energy level initially and attenuates slowly as it travels through the structure, thereby causing disturbance over large sections of a building. This disturbance is magnified by the "sounding board effect."

We are all familiar with the fact that a tuning fork must be held up to the ear to be heard directly, but if its handle is placed on a table the sound is amplified. This action is not really amplification but an increase in the efficiency of energy transfer. In general, the efficiency of a radiator is proportional to the ratio of its surface dimensions to the sound wavelength. A tuning fork vibrating at concert A (440 Hz) of wavelength 2½ *feet* cannot couple its energy into the air. It is simply too small. By placing the instrument on a table whose dimensions are approximately one wavelength, we permit it to transfer its energy efficiently; hence the "amplification." The same effect can be extremely troublesome in structure-borne sound. A vibrating pump itself makes little sound. However, it transfers a large amount of energy into the structure, which will appear as audible sound at each partition, floor, and wall that is rigidly coupled to the structure. Soft (damping) connections prevent energy transfer, thereby greatly attenuating the transmission of sound energy into connecting efficient radiating surfaces; hence the desirability of such flexible connections.

Airborne sound changes direction easily (diffracts), with low frequencies being most flexible in this regard. Structure-borne sound travels much more rapidly than airborne sound (see Table 26.1) and with attenuation as low as 1 db per kilometer. Mass of the structure is an effective attenuator only in the direction of radiation. That is, a sound traveling along a massive structure will radiate little outward from the structure (although enough to be very annoying) because the large mass minimizes vibration in that direction. Thus in Fig. 27.11*b*, noise from impact on the floor above will be louder (for equal impact energy) than noise from machines below because the former generates sound directly downward while the latter introduces energy into the entire network of parallel paths.

The sections immediately following will deal with airborne sound and the means for controlling it (see Fig. 27.11*c*). Impact noise (structure-borne sound) is covered in Sections 27.23 to 27.25.

AIRBORNE SOUND

27.12 Transmission Loss (TL) and Noise Reduction (NR)

The transmission loss (TL) of a barrier is the ratio, expressed in decibels, of the acoustic energy reradiated by the barrier to the acoustic energy incident on it. This number is a figure of merit for the sound-isolating quality of the wall itself and is obtained from controlled laboratory tests. (In Europe transmission loss is referred to as sound reduction index, R.) However, the number that is of greater importance to the building designer is the actual noise reduction between two spaces separated by a barrier, that is, the action of the barrier in situ. This noise reduction is defined as the difference between the intensity levels in the two rooms, that is,

$$NR = IL_{\text{room 1}} - IL_{\text{room 2}} \qquad (27.3)$$

and is related to the TL of the barrier by the expression

$$NR = TL - 10 \log \frac{S}{A_R} \qquad (27.4)$$

where

NR = noise reduction, db

TL = barrier transmission loss, db

S = area of barrier wall, ft² (m²)

A_R = total absorption of *receiving* room, sabins, ft² (m²)

We see, therefore, that noise reduction and transmission loss are not equal but are related by the size of the dividing wall S and the absorption characteristic of the receiving room, A_R. A moment's thought will confirm the logic of this relation. When sound energy impinges on the wall, the wall in turn becomes the sound source, radiating into the receiving room. Therefore, the amount of sound energy transferred is proportional to the area S of the common wall between the two spaces.

The sound level in the receiving room is related to its own reverberance (absorption characteristic A) as we have seen repeatedly. (Refer back to equation 26.13, for example.) Thus if the receiving room is a reverberant, live space, A is low and NR is less than TL. Conversely, if the receiving room is dead, A is large and noise reduction can be greater than transmission loss, depending on the ratio of barrier wall size to room area (see Fig. 27.12). In lieu of calculating, the following rule of thumb can be used:

1. For a live receiving room,
$$NR = TL - 1 \text{ db}$$
2. For a medium receiving room,
$$NR = TL + 4 \text{ db}$$
3. For a dead receiving room,
$$NR = TL + 7 \text{ db}$$

The extreme case of "deadness" of the receiving room is one with no walls, that is, sound transmission from inside to the exterior. In such cases, NR exceeds TL by 10 to 15 db, depending on the size of the exterior opening and the point outside where IL is measured. To acquire facility with sound-isolation techniques, the reader must become familiar with the relationship of transmission loss to the barrier wall's physical characteristics, its mass, ridigity, material of construction, and method of construction and attachment. These considerations are the subject of the following sections.

Note: The reader is cautioned to be careful with the term *noise reduction* (NR), since a similar term—noise reduction coefficient (NRC)—also

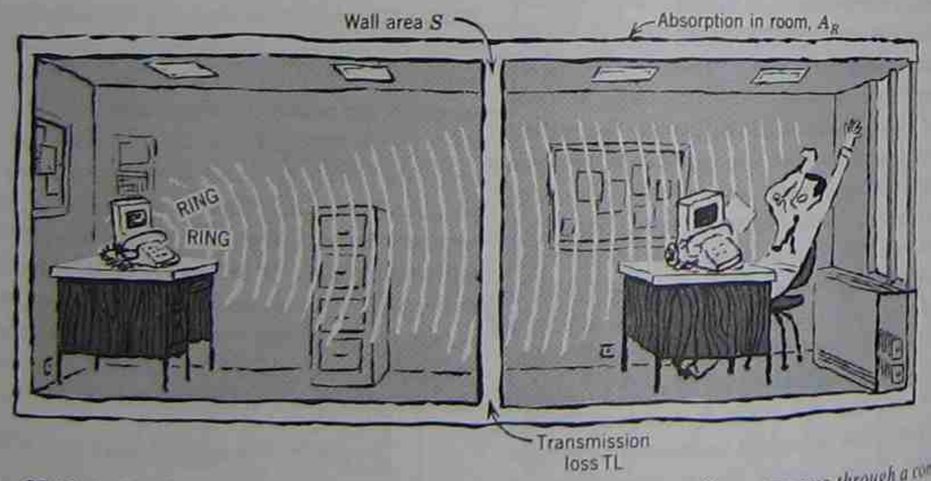


Fig. 27.12 A simple case of airborne sound transmission between adjacent rooms through a common barrier. With a sound source in one room, the transmitted sound level is dependent not only on the transmission loss of the barrier but also on the area of the barrier and the receiving-room absorption. The background noise level in the receiving room determines whether the transmitted sound will be heard. See Section 27.21 and Figs. 27.32, 27.33, and 27.35.

exists, which is completely unrelated. The latter, as pointed out in Section 27.6, is very poorly named.

27.13 Barrier Mass

Sound transmission requires that the barrier be set into vibration by the incident sound energy. Although this was stated above, we repeat it here to emphasize the fundamental importance of this simple statement. [We are of course referring to a barrier that is impervious to air (i.e., a solid barrier). Otherwise, the moving air molecules carrying the sound will simply pass through with minimal transmission loss.] The impinging energy acts as a force on the wall. Since $F = MA$, the larger the mass, the less it will vibrate. When other factors are taken into account, the resultant relationship is known in acoustics as the *mass law*. It states that for a nonporous, homogeneous structure of low stiffness, the sound transmission loss is proportional to the logarithm of surface mass (the weight of the wall per square foot of surface area) and to the frequency of vibration. Thus doubling the mass or frequency will, theoretically, cause an increase of 6 db in the transmission loss or, stated otherwise, the slope of TL versus the frequency times mass (fM) curve is 6 db (see Fig. 27.13). Table 27.3 lists the average transmission loss of some common barriers, confirming the overall operation of the mass law. Figure 27.13 is a graphic representation of mass law operation. With sound incident at 90°, maximum energy is imparted to the barrier and the entire mass resists, resulting in maximum transmission loss. In practice, however, sound is incident from 0 to 80° (called field or random incidence) reducing the mass effect, but keeping the slope at 6 db per octave. Due to nonhomogeneity, porousness, and stiffness, actual field results indi-

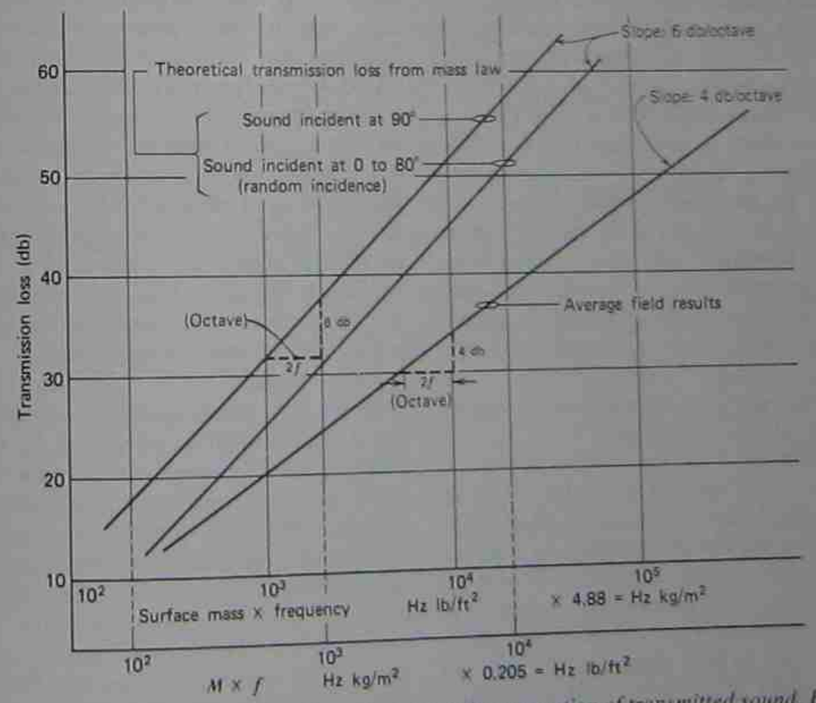


Fig. 27.13 Graphic representation of mass law action in attenuation of transmitted sound. Perpendicular (90°) sound incidence results in maximum transmission loss. Field or random incidence (0 to 80°) is approximately 6 db lower, but maintains the 6 db per octave slope. Field results are much lower due to flanking and stiffness effects, averaging 4 db per octave (frequency doubling).

ACOUSTICS

TABLE 27.3 **Typical Average[a] Transmission Loss**

Barrier Construction	*Surface Weight (lb/ft²)*	*Transmission Loss (db)*
3/32-in. plate glass	2.5	20
1/4-in. asbestos—cement sheet	3.0	21
2-in. plaster on wire lath	15	34
3-in. cinder block	25	39
4-in. concrete	50	45
8-in. brick, plastered	80	50
12-in. brick, plastered	120	53

[a]Over the frequency range of 150 to 3000 Hz.

cate transmission losses nearer 4 db per octave, as shown by the lower curve in the figure.

27.14 Stiffness and Resonance

The stiffness of a barrier is a function of its material composition and the rigidity of its mounting. The former is dependent on its internal cohesiveness, that is, its modulus of elasticity, and the latter depends on its boundary restraints—whether the barrier is tightly or loosely held. A homogeneous material of high Young's modulus (such as steel) has great cohesiveness between its molecules. As soon as one molecule is set in motion by the incident sound, the motion is passed to the next, and so on, making the material an excellent sound conductor. Homogeneous materials with low modulus of elasticity have high internal damping (motion of molecules is not transmitted well), and they are good sound insulators. Composite materials such as concrete and organic materials such as wood do not conform to these general rules.

The rigidity of mounting can be likened to a drumhead—the tighter it is stretched, the better it resounds. Ridigity (stiffness) in a panel barrier resists damping and assists vibrations, making it a poor noise transmission insulator. To recapitulate, stiffness, both internal and external, is an undesirable characteristic in sound isolation. A material such as lead, which has high mass and low modulus of elasticity, and resists rigid mounting, is an excellent sound attenuator.

The effects of stiffness and mass both vary with frequency, unfortunately in opposite directions. Stiffness acts to reduce transmission loss as frequency increases while, as we have seen, mass acts to increase it; the combined effect is shown in Fig. 27.14. Therefore, stiffness is most effective at low frequencies and mass at high frequencies. At very low frequencies the mass and stiffness effects negate each other, giving the resonance dips shown. Beyond approximately 200 Hz most common wall construction enters the mass law range and continues with it until the critical frequency. Deviations from a smooth 4 to 6 db per octave slope are due to the nonhomogeneous nature of most wall construction. At the critical frequency the phase of incident sound waves corresponds or "coincides" with the phase of vibration (shear wave) of the barrier in such a way as to pass a large portion of the incident energy. See insert on Fig. 27.14. This shows in Fig. 27.14 as the "coincidence dip." This effect is most pronounced in thin homogeneous partitions and light stiff ones.

Critical frequency f_c, as a function of panel thickness for common materials, is plotted in Fig. 27.15. To avoid a coincidence dip in the audible range, partitions can be either very heavy and/or very stiff, which greatly decreases the critical frequency, or heavy and limp (resilient), which greatly increases the critical frequency. In practical terms, cost effectiveness is heavily in favor of the latter alternative. Thus, for instance, the TL of a wood partition can be improved by grooving it to increase flexibility thereby increasing the critical frequency. The dramatic improvement in TL, resonances, and coincidence dip achieved by use of resilient mounting of a simple masonry partition is shown

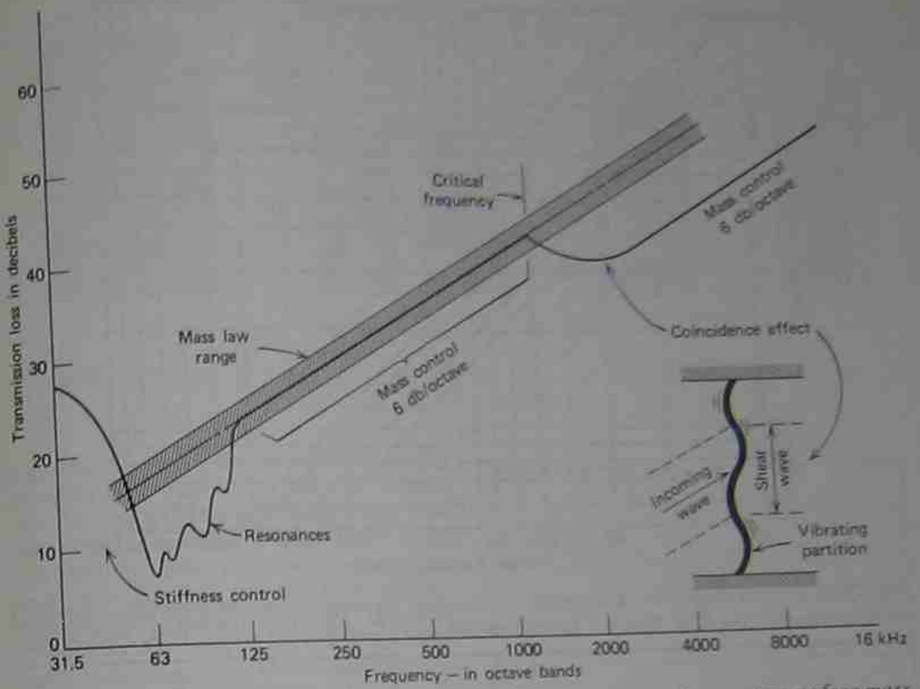


Fig. 27.14 Partition transmission loss as a function of frequency, assuming constant surface mass.

in Fig. 27.16. Both walls have the same weight—21 + lb/ft². The solid wall A has better attenuation below 200 Hz in the stiffness-controlled range. Above that frequency the resilient-mounted partition is 10 db better, which means that the transmitted noise is only one-half as loud. The sound transmission class (STC) (which is a figure of merit for partition sound transmission, as explained in Section 27.16) of wall A is 40; that of wall B is 51. Both show a coincidence dip at approximately 250 Hz (see Fig. 27.15) but that of wall B is shallow, that of A deep and wide. Furthermore, wall B is consistently better than mass law attenuation; wall A consistently worse (due to stiffness).

27.15 Compound Barriers (Cavity Walls)

Since the maximum theoretical increase in transmission loss with mass increase is 6 db per doubling of mass, it is apparent that this method of transmission loss improvement rapidly reaches the limits of practicality. Indeed as we have seen, actual single homogeneous walls fall below the mass law curve. This is because mass increase brings with it stiffness increase, which as we have seen acts to *reduce* transmission loss. If, however, a barrier is constructed of two separate layers without rigid interconnection, its performance is better than the calculated transmission loss based on mass alone. Note that even the nonrigid wire ties of wall B in Fig. 27.17 lower its STC by five points. At low frequencies, where stiffness controls the transmission loss (see Fig. 27.14), the cavity in C acts as a rigid connection between the layers, adding stiffness and increasing transmission loss. At higher frequencies, in the mass law range, the air in the cavity acts as a damping coupling to reduce stiffness. The net result is an improvement in performance throughout the frequency range.

Transmission loss for the entire cavity wall

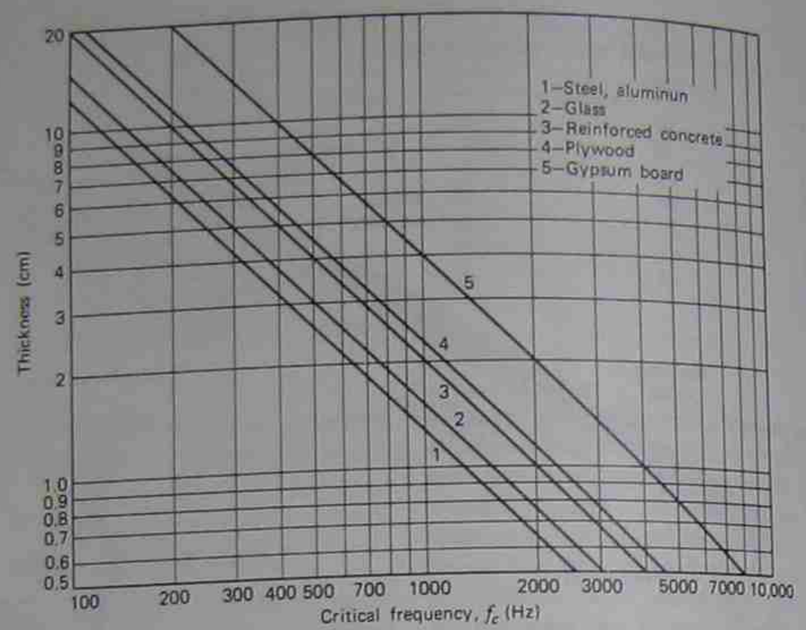


Fig. 27.15 Critical frequency as a function of thickness for several common materials. (Reprinted with permission from E. B. Magrab, Environmental Noise Control, *Wiley, New York, 1975, p. 262.)*

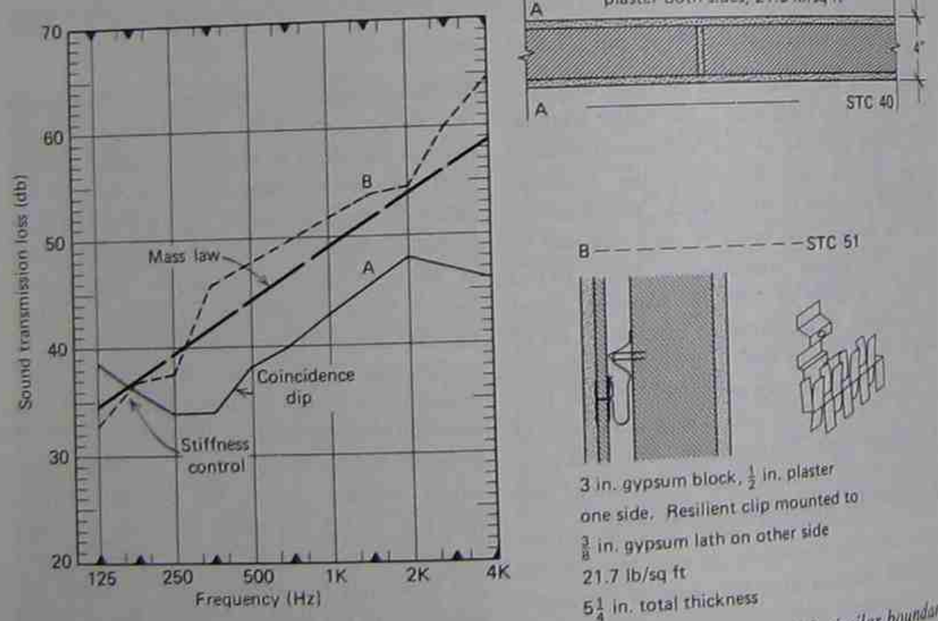


Fig. 27.16 Transmission loss characteristics of two equal-weight partitions with similar boundary constraints. The solid partition A is worse than the mass law due to stiffness. The resilient-mounted wall B performs better than the mass law and much better than wall A, except at the lowest frequencies. [Data extracted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

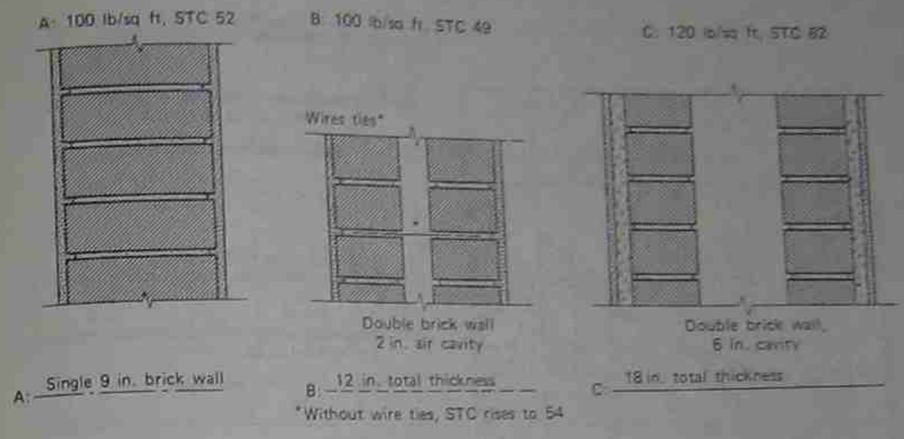
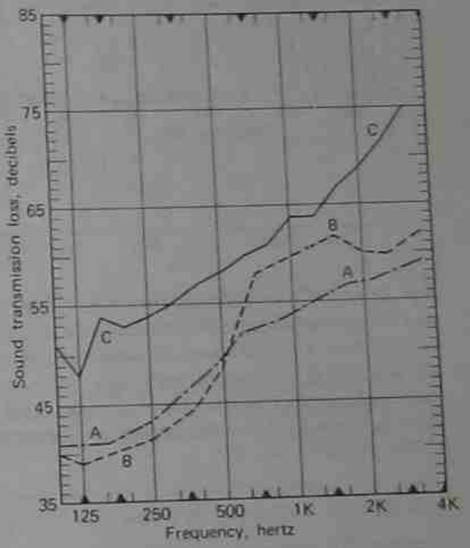


***Fig. 27.17** Transmission loss curves showing the effect of air space on heavy wall construction. All three walls are approximately the same mass. The 2-in. airspace in wall B is not significant until the higher frequencies, whereas the large, 6-in. airspace of wall C is effective throughout the frequency spectrum. [Data from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968), pp. W6, 22, 23.]*



increases with the width of the air space at the rate of approximately 5 db per doubling. Performance can be improved still further by filling the void with porous, sound-absorbent material. This acts to further decrease the stiffness of the compound structure *and* to absorb sound energy that reflects back and forth between the two inside surfaces. The performance of cavity walls is reduced by any rigid interconnections between leaves. Thus a common stud wall with frequent rigid interconnections acts little better than a single homogeneous wall. However, a stud wall with staggered studs exhibits much improved performance over a single-material wall or a common stud wall. The above effects are illustrated in Figs. 27.17 and 27.18 (see also Appendix F).

27.16 Average Transmission Loss (TL); Sound Transmission Class (STC)

Various attempts at using a single-number average transmission loss to describe a barrier's characteristics have been tried but with little success. Indeed these averages can be misleading, since they ignore both deficiencies and proficiencies at particular frequencies. Their use, therefore, in all but rough work is to be discouraged.

To avoid the shortcomings of averages and yet to benefit from the indisputable convenience of single-number ratings, a system of standard contours was developed, called sound transmission class (STC) contours. Actual test results for a given construction, measured in a series of sixteen ⅓-octave bands, are compared to the

ACOUSTICS

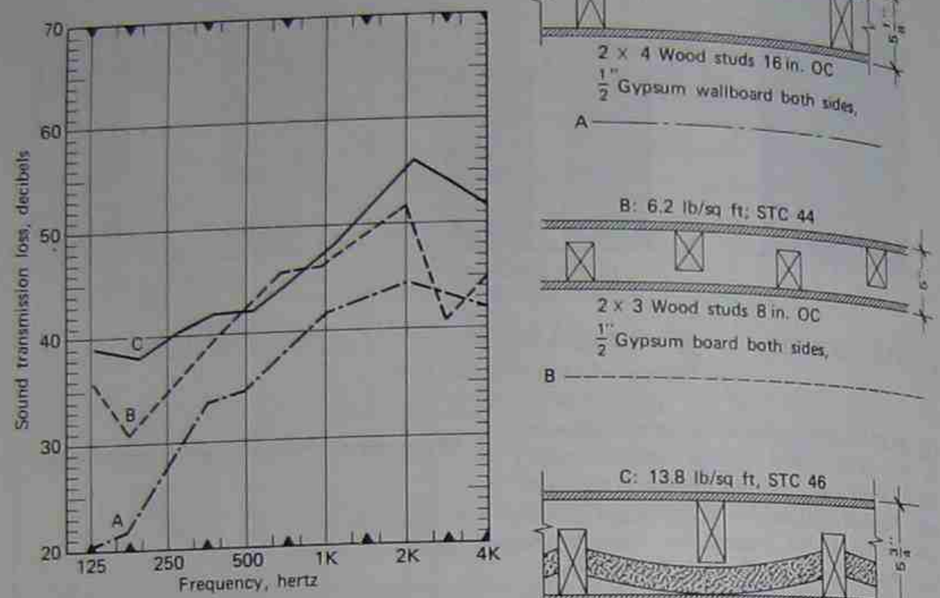
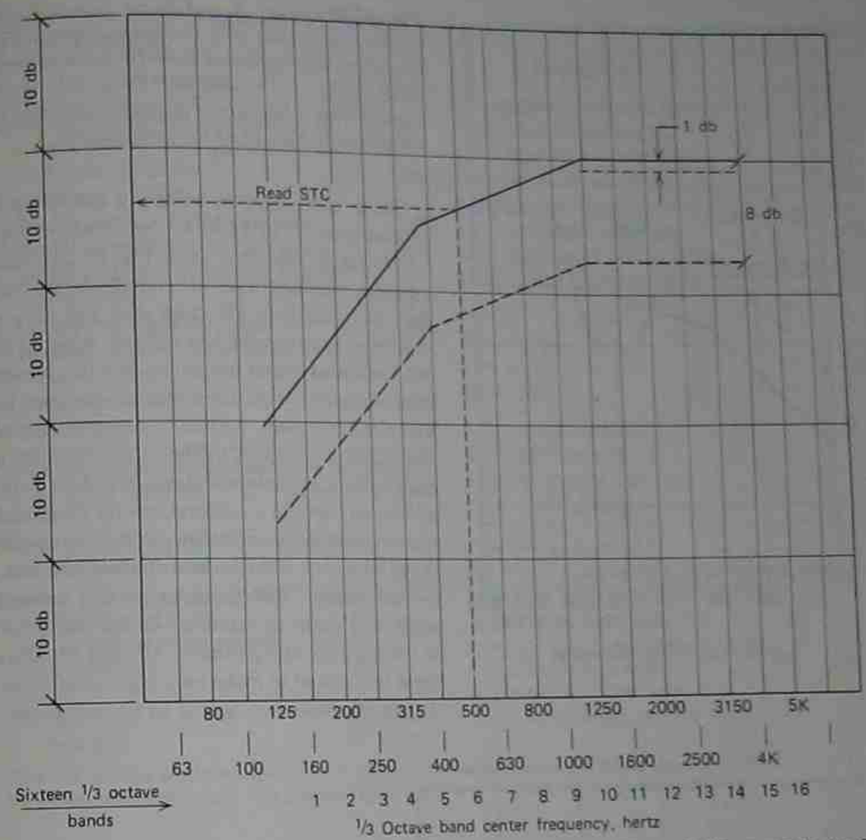


Fig. 27.18 *Transmission loss curves illustrating the effect on lightweight walls of stiffness reduction and addition of absorptive material in the cavity. Curve A is a standard stud wall as found in frame construction. Curve B shows the advantage of staggered studs over the entire frequency range. The dip at 3 kHz is a coincidence dip for a single leaf. Addition of absorption material C improves the attenuation characteristic at both ends and is particularly useful for its low end improvement. [Data from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968), pp. W20, 34, 37.]*

standard STC contours according to a fixed procedure, and the STC number for that barrier is derived. The technique is illustrated in Fig. 27.19. Figure 27.20 shows two *TL* curves and the STC ratings of each. The nine-frequency average *TL* for each is approximately 40. However, there is a major dip in transmission loss of curve *B*. The STC of *A* is 42 and of *B*, 33. Thus, the STC approach considers a flaw in performance that is ignored by average *TL*. Nevertheless, since STC fails to give credit for performance *above* the established requirements, octave-band transmission-loss data, rather than STC ratings, should be used in all critical work such as music rooms or mechanical rooms where certain particular frequencies may be dominant.

Figure 27.21 gives three standard STC contours that are of interest because they are used by the FHA to specify grades of construction. The criteria for their application are found in Section 27.33. An appreciation of the degree of speech sound isolation provided by walls with different STC ratings is given in Section 27.21 (see Table 27.7). Since the subjective reaction on the quiet side depends on the background noise level there, the table gives this reaction for two NC curve levels. To assist the designer, extensive sound transmission testing has been performed on most types of standard wall and partition construction and the results published. Table 27.4 and Appendix F give descriptions of construction with typical details, transmission loss data, STC ratings, and other pertinent data.



The STC is determined by comparison with a transparent overlay of Figure 27.19 on which the STC contour is drawn. The STC contour is shifted vertically, relative to the test curve, until some of the measured TL values for the test specimen fall below those of the STC contour (the solid line) and the following conditions are fulfilled:

1. The sum of the deficiencies (i.e., the deviations below the contour) shall not be greater than 32 db.
2. The maximum deficiency at a single test point shall not exceed 8 db [the broken (dashed) line beneath the STC contour].

When the contour is adjusted to the highest value (in integral db) that meets the above requirements, the sound transmission class for the specimen is the TL value corresponding to the intersection of the contour and the 500-Hz ordinate.

Fig. 27.19 *Overlay from which sound transmission class (STC) is determined graphically.*

27.17 Composite Walls and Leaks

It is frequently necessary to determine the transmission loss of a composite wall, that is, a wall with a window, door, vent opening, and the like. It should be clearly appreciated that the two materials are "in parallel," to borrow an electrical concept, and the behavior is similar to that situation. That is, the overall performance will be strongly affected by the poorer of the two, with some tempering of the degradation when the poorer barrier is much smaller in area than the other material. Figure 27.22 enables us to calculate situations of this type.

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Fig. 27.20 *Curves A and B are two different construction types with the same average TL. However, application of the STC curve criteria given in Fig. 27.19 yields an STC of only 33 for construction B because of its deep center dip, as compared to STC of 42 for construction A.*

Since an opening in a wall is effectively a second material of $TL = 0$, the curves of Fig. 27.22 can be replotted as in Fig. 27.23. Note carefully that the curves very rapidly flatten out; thus any wall with 1% open area will have a *maximum* transmission loss of 20 db, which is all but useless as sound insulation. For this reason it is absolutely imperative that all openings be completely sealed, particularly those around doors and windows. A hairline crack degrades a wall 6 db; a keyhole will degrade a door 3 db, and so on. Special considerations for doors and windows are discussed below. Care must also be taken with such common acoustic leaks as back-to-back electric outlets, pipes passing through walls, and medicine cabinets—in fact any break in the integrity of a partition. All such openings must be caulked to make an airtight joint if any degree of sound isolation is to be maintained.

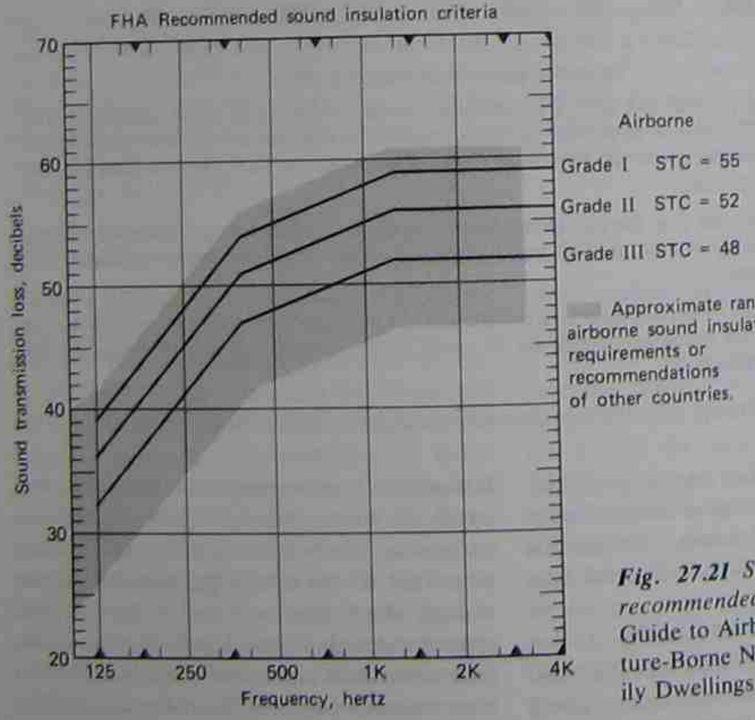


Fig. 27.21 *Sound insulation criteria recommended by the FHA. [From A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings (1968), pp. 10–11.]*

TABLE 27.4a **Improvements in STC Rating of Stud[a] Partitions[b]**

Description	*STC*[c]
Basic partition: single wood studs, 16 in. on centers, ½-in. gypsum board each side, air cavity	35
Add to basic partition	
Double gypsum board, one side	+2
Double gypsum board, both sides	+4
Single-thickness absorbent material in air cavity	+3
Double-thickness insulation	+6
Resilient channel supports for gypsum board	+5
Staggered studs	+9
Double studs	+13

[a]For application to metal stud partitions, use adders as in note *b*, but begin with STC = 40 for 3⅝-in. basic partition.

[b]When using two improvements add additional +2; for three improvements add +3.

EXAMPLE: Improvements to 35 STC basic partition:

Staggered wood studs	+9
Double gypsum board, one side	+2
Single insulation	+3
Adder	+3
Total	+17
Total STC	35 + 17 = 52

[c]The STC figures are conservative. Other sources list the same constructions with 1 to 5 points higher STC.

TABLE 27.4b **STC Ratings of Masonry Walls**

Description	*STC*[a]
4-in. lightweight[b] hollow block	36
4 in. dense hollow block	38
6-in. lightweight hollow block	41
6-in. dense hollow block	43
8-in. lightweight hollow block	46
8-in. dense hollow block	48
12-in. lightweight hollow block	51
12-in. dense hollow block	53
4-in. brick	41
6-in. brick	45
8-in. brick	49
12-in. brick	54
6-in. solid concrete	47
8-in. solid concrete	50
10-in. solid concrete	53
12-in. solid concrete	56

[a]See note c, Table 27.4a.

[b]All ratings of lightweight block assume sealing with paint. Note that this reduces absorption.

MODIFICATIONS

Add sand to cores of hollow blocks	+3
Add plaster to one side	+2
Add plaster to both sides	+4
Add furring strips, lath and plaster:	
1 side	+6
2 sides	+10
Add plaster via resilient mounting:	
1 side	+10
2 sides	+15

Examples 27.3 and 27.4 show how barriers of high *TL* are degraded by standard openings. To maintain the integrity of a barrier, special care must be taken in the design of windows and doors, as explained below.

EXAMPLE 27.3. Given a wall 9 ft × 18 ft with a transmission loss of 52 db at 1000 Hz, containing a 3 ft × 7 ft 6-in. hollow core door of 22-db transmission loss. Find the overall *TL* of the composite wall.

SOLUTION. Refer to Fig. 27.22.

$$TL_1 - TL_2 = 30 \text{ db}$$

$$\frac{S_2}{S_1} = \frac{3 \times 7\frac{1}{2}}{9 \times 18} \times 100 = 13.9\%$$

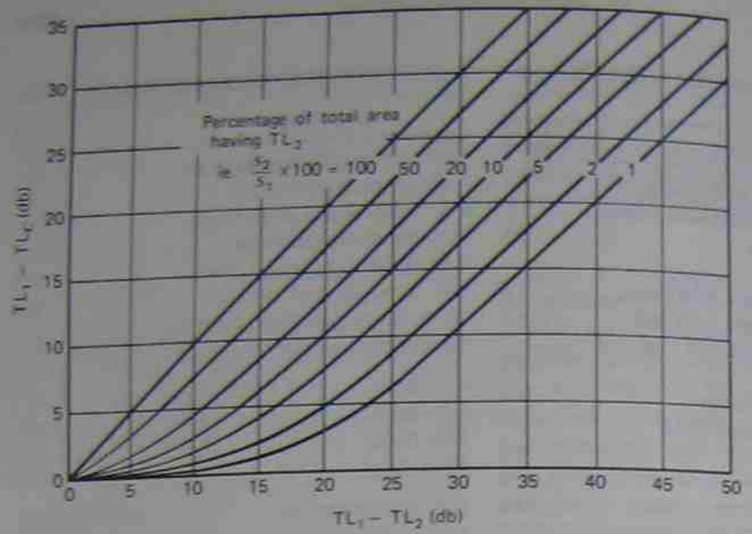
From curves:

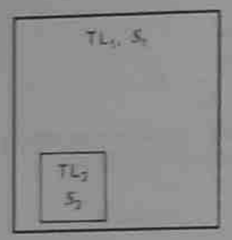
$$TL_1 - TL_c = 21.5$$

$$TL_c = 52 - 21.5 = 30.5 \text{ db}$$

That is, a door with an area of only 14% of the entire wall reduces the *TL* of the structure from 52 to 30.5 db—that is, from excellent to *very poor*.

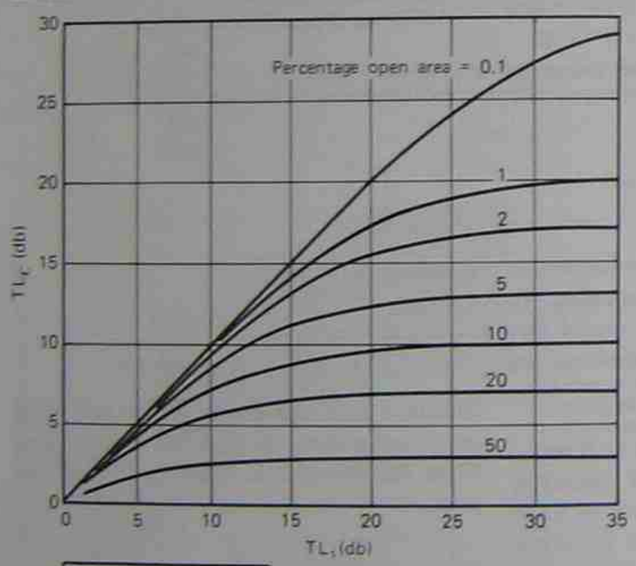
EXAMPLE 27.4. An exterior brick/frame wall having a *TL* of 54 at 1000 Hz, measuring 8 ft × 16 ft, is pierced by two wood frame windows, each of area 3 ft × 4 ft, with single ⅛-in. glass, and has a *TL* of 34 at 1000 Hz. Find the combined transmission loss.

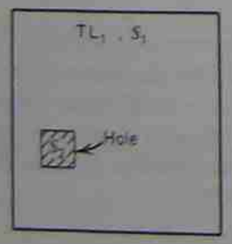




TL is transmission loss
S is area
TL_C is combined TL

Fig. 27.22 Transmission loss of a two-element composite barrier as a function of the relative transmission loss of the components. (From E. B. Magrab, Environmental Noise Control, Wiley, New York, 1975, p. 266, Fig. 7-45.)





TL is transmission loss
S is area
TL_C is combined TL
% open area
$= S_2/S_1 \times 100$

Fig. 27.23 Effect of a hole of a given percentage of the total area on a partition of TL, db. (From E. B. Magrab, Environmental Noise Control, Wiley, New York, 1975, p. 268, Fig. 7-47.)

SOLUTION

$$TL_1 - TL_2 = 54 - 34 = 20 \text{ db}$$

$$\frac{S_2}{S_1} = \frac{2 \times 3 \times 4}{8 \times 16} \times 100 = 18.75\%$$

From Fig. 27.22,

$$TL_1 - TL_c = 12.5 \text{ db}$$

$$TL_c = 41.5$$

Again the result is a reduction from an excellent wall to a poor one.

27.18 Doors and Windows

As can be appreciated from the preceding section, doors and windows in large measure determine the overall transmission loss of a wall. Since in almost every instance doors and windows are of lower acoustic rating than that of the wall in which they are mounted, particular care must be taken not to further degrade performance with leaks.

(a) Doors. Table 27.5 gives average *TL* figures for common wooden doors and for doors arranged in a sound lock, that is, two doors with a sufficient space between to allow door swing. As with all transmission loss averages, the number is usable only as an approximate figure of merit. STC is a better criterion; a frequency analysis is best. The important conclusions to be drawn from this table are:

1. Louvered doors and doors undercut to permit air movement are useless as sound barriers.
2. The most important step in sound-proofing doors is complete sealing around the opening. The door in the closed position should exert pressure on these gaskets, making the joints airtight.
3. Doors constructed of two leaves separated by a sound-absorbing material (e.g., steel sheets with fiber batting inside) are more effective than a single solid material door of the same weight.

Commercial products are available with STC rating up to 65 for application in sensitive locations.

(b) Windows. Windows are critically important to block exterior noise, and all the more so, since exterior wall construction is generally of high STC, making the window the deciding factor in the composite transmission loss. Sound leaks through cracks in operable windows will normally establish the windows' rating regardless of type of glazing. Fortunately, the attention now given to the sealing of windows for thermal purposes has had a salutary effect on their acoustic properties. As with doors, the importance of proper gasketing and sealing cannot be overstressed. Double glazing is effective only when the two panes are separated by a wide air gap (see Table 27.6). A narrow air gap acts as a stiff spring between the panes. The resultant TL

TABLE 27.5 **Average Sound Transmission Loss of Doors**

Construction	*Average TL (db)*	*STC*
Louvered door	10	15
Any door, 2-in. undercut	12	17
1¾ in. hollow core door, no gasketing	15	22
1¾ in. hollow core door, gaskets and drop closure	20	25
1¾ in. solid wood door, no gasketing	25	30
1¾ in. solid wood door, gaskets and drop closure	30	35
2 hollow core doors, gasketed all around with sound lock	38	45
2 solid core doors, gasketed all around, with sound lock	48	55
Special commercial construction, with lead lining and full sealing		45–65

TABLE 27.6 **Sound Transmission Class (STC) of Window Construction**

Window Construction	*STC*
Operable wood sash, ⅛-in. glass, unsealed	25
Operable wood sash, ¼-in. glass, unsealed	25
Operable wood sash, ¼-in. glass, gasketed	30
Operable wood sash, laminated glass, unsealed	28
Operable wood sash, double-glazed, ⅛-in. panes, ⅝-in. air space, gasketed	29
Fixed sash, double ⅛-in. panes, 3-in. air space, gasketed	44
Fixed sash, double ¼-in. panes, 4-in. air space, gasketed	48

is approximately that of a single pane of double weight.

In addition to a window's sound transmission characteristic when closed, it is important to consider the TL when open, because of ventilation and natural cooling requirements. The sound attenuation between the center of a room with a clear-through open window and a point some distance outside, is 5 to 15 db. This drops to ±3 db as the receiver–observer approaches the open element. By making the path from inside to outside indirect, the "open" window attenuation can be increased to as much as 25 db, but with considerable reduction of airflow, hence ventilation. Several possible arrangements with approximate TL figures are given in Fig. 27.24. This principle can be applied advantageously when exterior noise reduction is important, but sealed windows are undesirable. Window opening style and placement can also have an effect on the amount of exterior noise admitted, as shown in Figs. 27.25 and 27.26.

27.19 Diffraction; Barriers

The physical process by which sound passes around obstructions and through very small openings is called diffraction. Simply stated, diffraction is a process whereby any point on a wave front establishes a new wave front when passing an obstacle. Thus, although much of a sound wave is blocked by a small opening, the portion that does get through establishes a new wave front [see Fig. 27.11c(5)]. The *amplitude* of the diffracted wave is determined by the relationship between the size of the opening and the

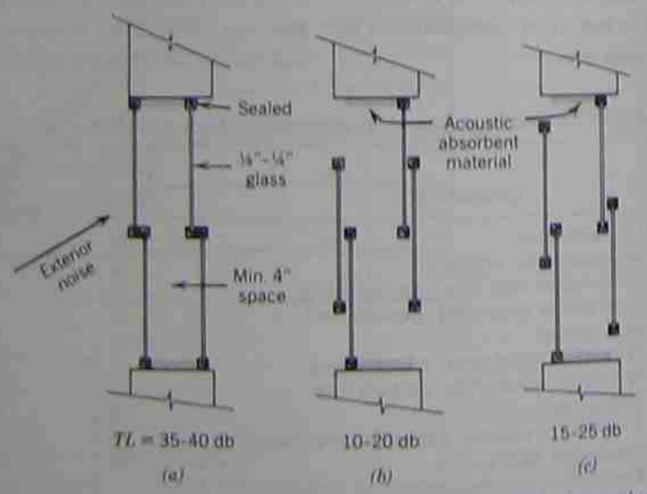


Fig. 27.24 *The degree of attenuation of external noise can be regulated when using pairs of double-hung (or horizontally sliding) windows with acoustic sealant and absorbent materials. Ventilation airflow varies inversely with transmission loss.*

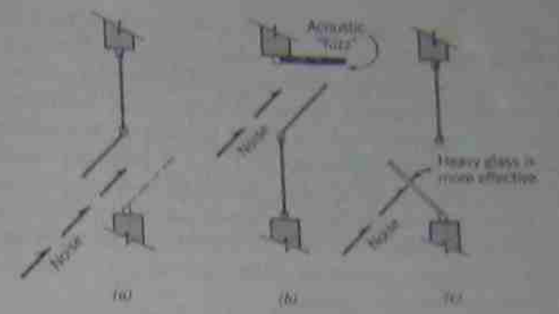


Fig. 27.25 *Alternative arrangements of the same basic "hopper" window design can yield results differing by up to 10 db. Design* (a) *is entirely open, and the noise path is unobstructed deep into the room. Design* (b) *is about 5 db better than* (a) *at frequencies above 1 kHz because of higher absorption and less diffraction. Lower frequencies diffract readily around the window leaf and are less affected by absorptive material. Design* (c) *can be 10 db better than* (a) *because it interposes a rigid barrier into the noise path, particularly at high frequencies. In this arrangement, the glass thickness is important.*

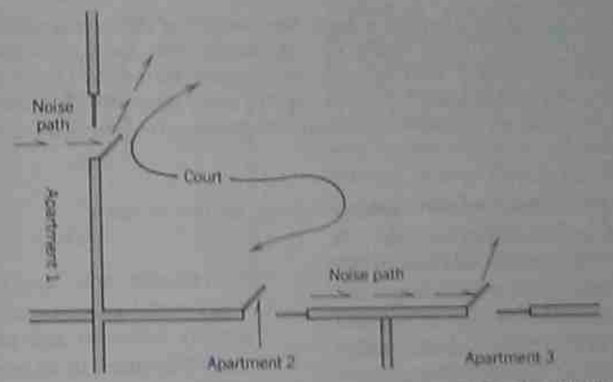


Fig. 27.26 *Noise transfer between contiguous corner spaces, as in apartments 1 and 2, can be particularly severe if windows are improperly designed. Swinging windows, as shown, are preferable to double-hung or hopper, because they act to reflect sound away from the adjacent space. Similarly, adjacent spaces on the same wall, as for apartments 2 and 3, can benefit from this type of swinging arrangement, which is preferable to sliding or double-hung designs.*

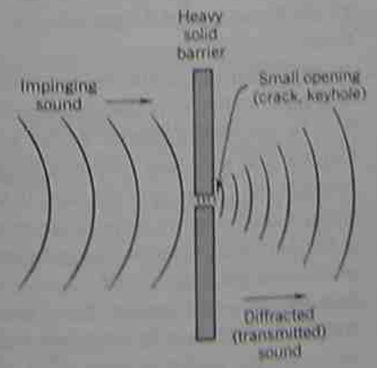


Fig. 27.27 *Sound passes through small openings by diffraction. The intensity of the transmitted sound is proportional both to frequency and to the size of the opening. It is always less than the intensity of the impinging sound [see also Fig. 27.11c(5)].*

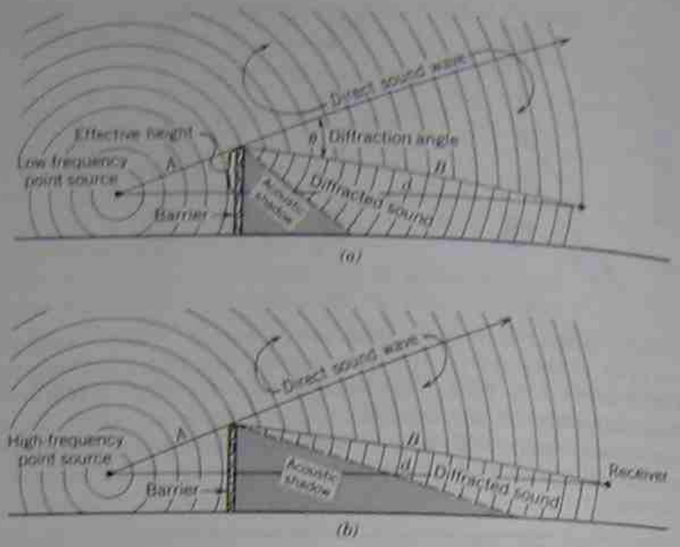


Fig. 27.28 *Comparison of the effect of a barrier on sources of different frequencies. The low-frequency sound* (a) *diffracts more readily over the barrier than the high-frequency sound* (b) *because of its longer wavelength. Thus the lower the frequency, the smaller the "acoustic shadow" and the lower the barrier attenuation. Of course, the "shadow" is not sharply defined; it represents increasing attenuation as the observer approaches the barrier. See Fig. 27.29, for evaluation of barrier attenuation.*

wavelength. For a small hole, short wavelengths (high frequencies) are attenuated less than long wavelengths (low frequencies). See Fig. 27.27.

When sound encounters a finite-length barrier, it diffracts around and over it, approximately as shown in Fig. 27.28. The attenuation of the diffracted sound depends on frequency, type of source, and the dimensions of the barrier. For a point source, with only a single *practical* path around the obstruction (barrier) the noise reduction to db can be calculated from Maekawa's equation:

$$NR = 20 \log \left[\frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} \right] + 5 \text{ db} \quad (27.5)$$

where

$N = (F/565)(A + B - d)$

NR = noise reduction, db

F = frequency, Hz

$A + B$ = shortest path length around the barrier, ft (over or around)

d = straight-line distance, source-to-receiver, ft

Note that this equation:

1. Is applicable only to exterior barriers where sound passing over the barrier is partially diffracted and partially attenuated by distance. In an interior situation, sound passing over a partial height barrier (see Fig. 27.35) strikes the ceiling and is reflected down, increasing the received sound and effectively reducing barrier attenuation. Maximum exterior barrier attenuation is 24 db as compared to about 15 db for a partial height interior partition.
2. Assumes that the barrier is very long (or very high) so that only one sound path exists. In practice, a barrier whose length (height) is at least four times the distance between the source and the wall is sufficient, if *the barrier is close to the source*. If the barrier is close to the receiver, it must be longer (higher) still.
3. Assumes a point source. Line sources (such as traffic) show 20 to 25% less attenuation for the same barrier.

The equation will, however, give reliable, usable results when the dimensions of the source are small with respect to the barrier, as is the case for speech; individual motors, fans, engines, and other mechanical devices; and individual motor vehicles. The chart in Fig. 3.19 relates barrier dimensions and position to traffic noise reduction. Note that there frequency is not a variable, since the chart has been plotted for an average attenuation at 220 Hz, which is traffic center frequency.

It should be apparent that the best location for a barrier is either very close to the source or very close to the receiver. The worst position for attenuation is halfway between. All effective barriers are assumed to be opaque and to have a minimum surface density of 5 lb/ft² (~ 20 kg/m²). The inherent TL of the barrier need not be very high; a massively thick barrier has only marginally higher attenuation than one with the minimum surface weight specified above. Absorptive material placed on the source side of a barrier will reduce the noise reflected back toward the source but will not effectively increase the barrier's attenuation with respect to the receiver. Although maximum noise reduction of an *exterior* barrier is about 24 db, in practice it rarely exceeds 20 db. Figure 27.29 is a nomograph based on equation 27.5.

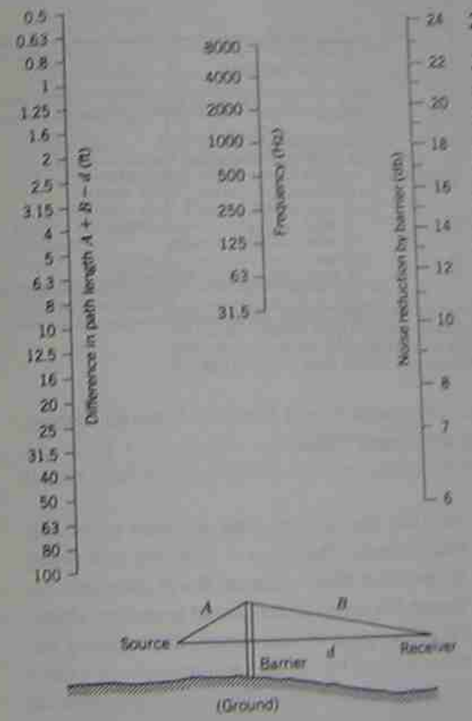


Fig. 27.29 *This nomograph to estimate the noise reduction afforded by a barrier is based on Equation 27.5 and assumes a point (small) source and only a single path around the barrier. The dimensions* A, B, *and* d *are taken from the insert sketch.* A *plus* B *represent the shortest path around the barrier—which may be over or around it. (Reprinted with permission from B. Fader,* Industrial Noise Control, *Wiley, New York, 1981, pp. 148–149.)*

27.20 Flanking

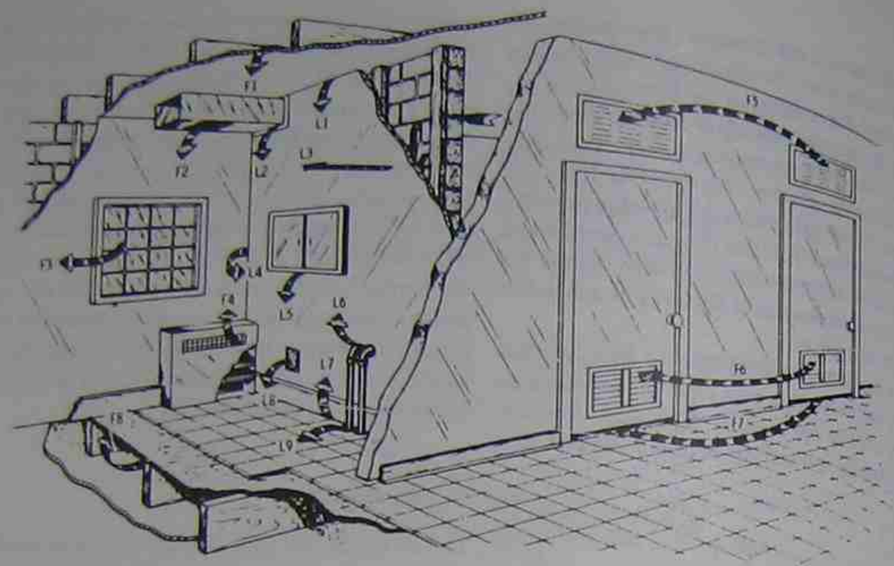
Just as sound will pass through the acoustically weakest part of a composite wall, so it will also find parallel or flanking paths, that is, an acoustic short-circuit. Proper design of window locations to avoid flanking paths has already been shown in Fig. 27.26. The same situation obtains with respect to doors and any other openings between spaces. Thus in Fig. 27.30 a high STC wall between the two spaces is in large measure defeated by flanking paths F5, F6, and F7. In other spaces the most common flanking path is via the plenum, as in Fig. 27.30, path F1, and Fig. 27.31*b* and *d*. Ductwork with registers or grilles in various rooms acts as an excellent intercom system unless completely lined with sound-absorptive material (see Section 27.29). Even then, low-frequency sound is only minimally attenuated, and special measures must be employed if good transmission loss is required. This subject is discussed further below, under, Mechanical System Noise Control.

27.21 Noise Reduction and Background Noise

Referring back to Section 27.12, we saw that

$$IL_2 = IL_1 - NR \quad (27.3)$$

where NR is noise reduction and IL_2 and IL_1 are sound intensity levels in the receiving and source rooms, respectively. If the resulting IL_2 is below the background noise level, it will not be a source of annoyance; conversely, if it is



FLANKING NOISE PATHS

F1 OPEN PLENUMS OVER WALLS, FALSE CEILINGS
F2 UNBAFFLED DUCT RUNS
F3 OUTDOOR PATH, WINDOW TO WINDOW
F4 CONTINUOUS UNBAFFLED INDUCTOR UNITS
F5 HALL PATH, OPEN VENTS
F6 HALL PATH, LOUVERED DOORS
F7 HALL PATH, OPENINGS UNDER DOORS
F8 OPEN TROUGHS IN FLOOR-CEILING STRUCTURE

NOISE LEAKS

L1 POOR SEAL AT CEILING EDGES
L2 POOR SEAL AROUND DUCT PENETRATIONS
L3 POOR MORTAR JOINTS, POROUS MASONRY BLK
L4 POOR SEAL AT SIDEWALL, FILLER PANEL ETC.
L5 BACK TO BACK CABINETS, POOR WORKMANSHIP
L6 HOLES, GAPS AT WALL PENETRATIONS
L7 POOR SEAL AT FLOOR EDGES
L8 BACK TO BACK ELECTRICAL OUTLETS
L9 HOLES, GAPS AT FLOOR PENETRATIONS

OTHER POINTS TO CONSIDER, RE: LEAKS ARE (A) BATTEN STRIP A/O POST CONNECTIONS OF PREFABRICATED WALLS, (B) UNDER FLOOR PIPE OR SERVICE CHASES, (C) RECESSED, SPANNING LIGHT FIXTURES, (D) CEILING & FLOOR COVER PLATES OF MOVABLE WALLS, (E) UNSUPPORTED A/O UNBACKED WALL BOARD JOINTS (F) EDGES & BACKING OF BUILT-IN CABINETS & APPLIANCES, (G) PREFABRICATED, HOLLOW METAL, EXTERIOR CURTAIN WALLS.

Fig. 27.30 *Flanking transmission of airborne noise. [Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

greater than the background noise it will be heard and, depending onintensity and content, could be a source of disturbance. See Fig. 27.32 for a graphic representation of this idea.

With this in mind, we can also tabulate the performance of a sound barrier, in terms of receiving-room background levels (see Table 27.7). Stated otherwise, the apparent isolation provided by a barrier may be greater than the actual noise reduction. Figure 27.33 shows two conditions of adjacent spaces. Although the source room level is uniform and partitions on both sides of the source room are identical, the background noise in the two receiving rooms is different. In *A*, the background is NC-35; in *B*, it is NC-25. The occupant of room *A* hears nothing from the source room. The occupant of room *B* hears clearly. Occupant *A* probably will praise the partition while occupant *B* will complain. Although the levels of reradiated sound are identical in the two receiving rooms, the intruding signal is masked by the background noise in *A* but it is clearly audible in *B*. Thus the apparent noise reduction is substantially higher in *A* than in *B*. Section 27.22 investigates this phenomenon of speech privacy.

Sound isolation may be achieved very economically by careful planning. Storage and circulation can serve as buffers for noise-sensitive areas. Physical separation of noisy areas from quiet ones often eliminates the need for complicated and expensive compound barriers.

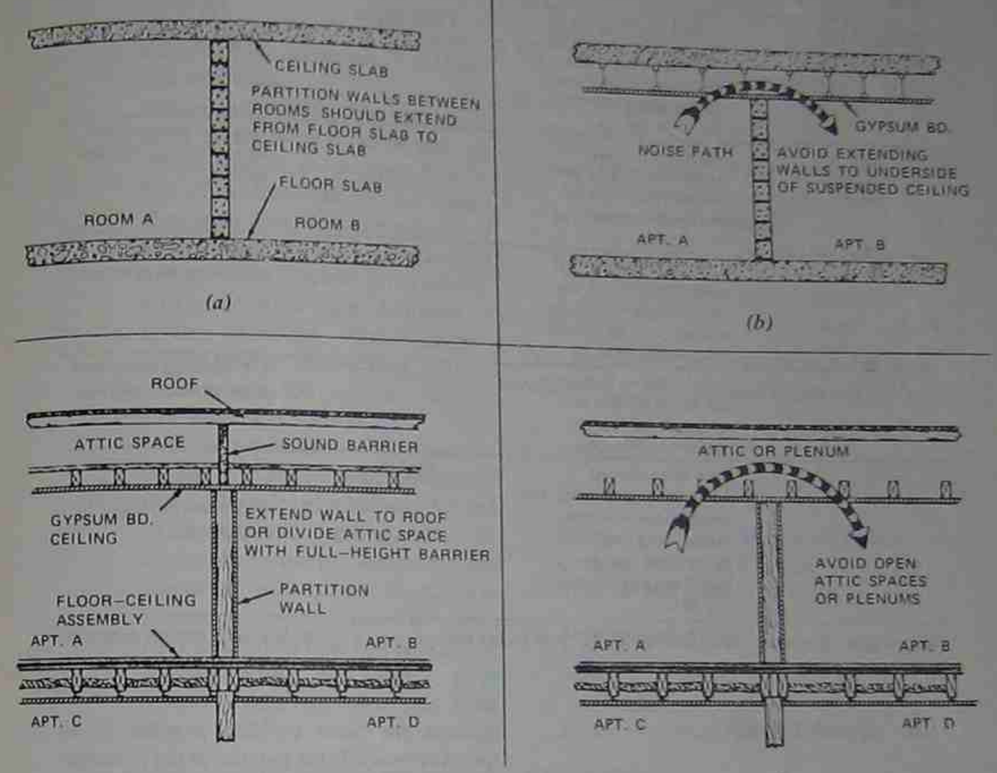


Fig. 27.31 *Construction techniques to avoid flanking paths. [Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

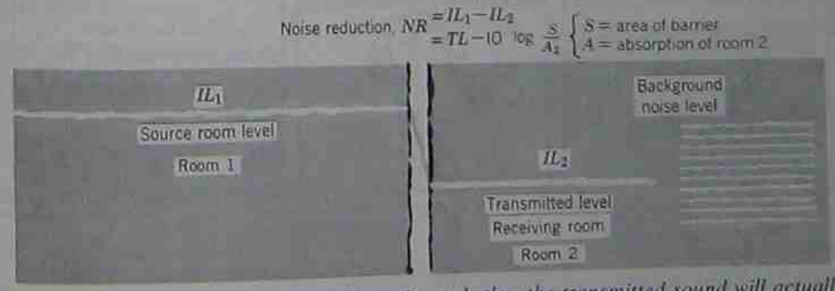


Fig. 27.32 *The background noise level determines whether the transmitted sound will actually be heard.*

TABLE 27.7 **Relations Between Barrier STC Rating and Hearing Condition on the Receiving Side**

Barrier STC[a]	*Hearing Condition*	*Description*	*Application*
25	Normal speech can be understood quite easily and distinctly through the wall	Poor	Space divider
30	Loud speech can be understood fairly well. Normal speech can be heard but not easily understood	Fair	Room divider where concentration not essential
35	Loud speech can be heard, but is not easily intelligible. Normal speech can be heard only faintly, if at all	Good	Suitable for offices next to quiet spaces
42–45	Loud speech can be faintly heard but not understood. Normal speech is inaudible	Very good	For dividing noisy and quiet areas; party wall between apartments
46–50	Very loud sounds, such as loud singing, brass musical instruments, or a radio at full volume can be heard only faintly or not at all.	Excellent	Music room, practice room, sound studio, bedrooms adjacent to noisy areas

[a]Assuming a background noise level of NC-25. With higher background, (e.g., NC-35), STC can be degraded one step.

27.22 Speech Privacy

The subject of speech privacy received considerable additional study and emphasis with the advent of open-plan offices (office landscaping), although the same problem prevails in all spaces. Essentially the purpose of the investigations was to determine the factors affecting speech privacy and to quantify them with a degree of accuracy sufficient for design purposes.

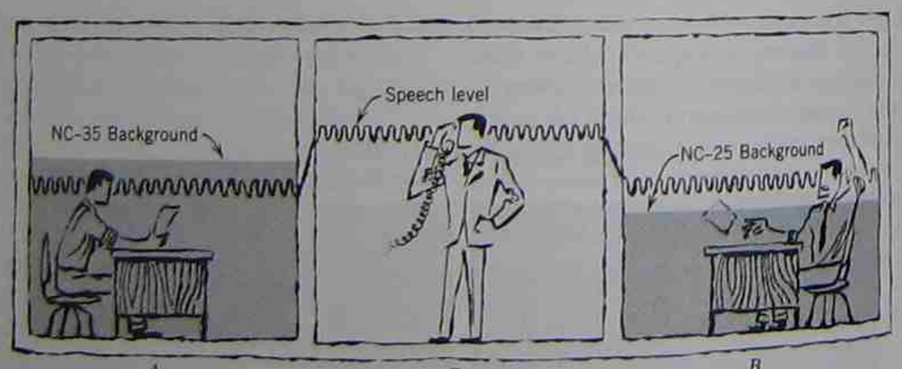


Fig. 27.33 The occupant in room A with background noise NC-35 (≈45 dbA) is unaware of the noise that is to disturbing to occupant B, whose NC-25 (≈36 dbA) is insufficient to mask C's loud speech.

These studies indicate that there are six factors involved, which can be subsumed under two headings:

1. Speech rating (source room, No. 1)
   - *a*. Speech effort—a measure of the loudness of speech.
   - *b*. Source room factor—gives the approximate effect of room absorption, on speech level in source room. Scale in Fig. 27.34 drawn for average normal absorption. For live rooms raise factor by two points; for dead rooms lower it by two points. Factors $a + b$ give approximate source room voice level.
   - *c*. Privacy allowance—What is the measure of privacy required?
2. Isolation rating (receiving room, No. 2)
   - *d*. STC—rating of the barrier.
   - *e*. Noise reduction factor A_2/S is an indication of receiving-room absorption, that is, the difference between *NR* and *TL*; A_2 is area of receiving room; *S* the area of the barrier between rooms. Absorption is assumed to be average. For live rooms lower this factor two points; for a dead room raise two points.
   - *f*. Recommended background noise level—in receiving room from Table 27.8.

An analysis sheet for enclosed spaces is provided in Fig. 27.34. See also Cavanaugh et al. (1962) and Young (1965). The two examples of this analysis that follow should clarify its use. The reader should follow the analysis with Fig. 27.34 in hand. The numbered steps in the examples correspond to the numbers in the figure.

EXAMPLE 27.5

(*a*) Source room:

General clerical office, 40 × 60 × 9 ft, average $\bar{\alpha}$
16-ft partition, STC 40

(*b*) Receiving room:

Conference rooms, 16 × 24 ft, medium-dead room
Background noise level, 40 dbA (NC-30), from Table 27.8

Privacy analysis (see Fig. 27.34)

(*a*) 1. Speech effort: raised	66
2. Area $A_1 > 1000$ ft^2	0
3. Privacy—normal	9
Speech rating:	75
(*b*) 4. STC (given)	40
5. A_2/S	3
[(16 × 24)/(16 × 9) = 2.6, corresponding to 2.0; add 1.0 for higher than average $\bar{\alpha}$	
6. Noise level	40
Isolation rating:	83
$a - b =$	−8

Therefore the STC rating of the partition can be reduced to 32 without affecting speech privacy.

EXAMPLE 27.6

(*a*) Source Room:

Drafting room 20 × 30 ft, medium-live
Common wall 12 × 8 ft high
STC: 26 (half glass, with door)

(*b*) Receiving room:

Supervisor's office, 12 ×14 ×8 ft, average absorption
Background noise level, 35 dbA

Privacy analysis:

(*a*) Speech effort—conversational	60
Source room factor, 2 + 1	3
Privacy—confidential	13
Speech rating:	76
(*b*) STC	26
A_2/S	2
[(12 × 14)(12 × 8) = 1.8, corresponds to 1.6; use 2.0, since system uses whole numbers only.]	
Noise level	35
Isolation rating:	63
$a - b =$	13

or strong dissatisfaction

The suggested corrections here are to increase STC to 36 by gasketing the door and increasing background noise level in the receiving room to

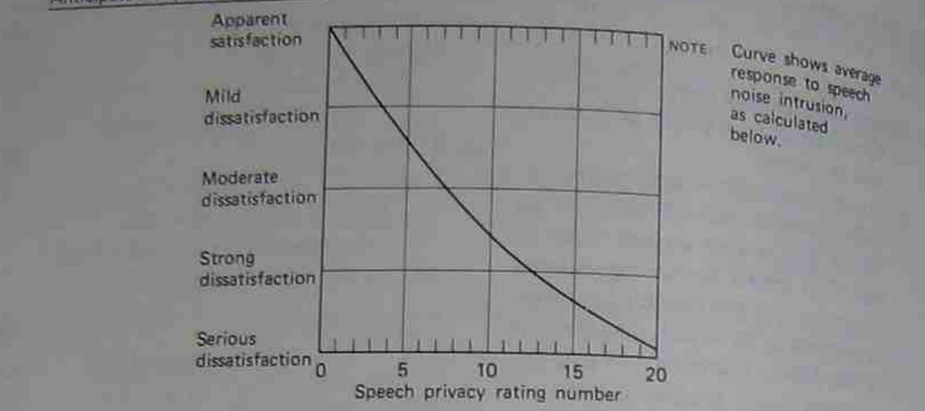


Fig. 27.34 *Speech privacy analysis sheet. [Based on Cavanaugh et al. (1962).]*

40 dbA (NC-30). This should result in a satisfactory condition. If still unsatisfactory, the glazing could be doubled.

A form similar to Fig. 27.34 is available for open plan offices. We have not included it because these spaces require critically accurate design best left to an acoustics expert. In these open spaces where partial height partitions can provide a *maximum* of 15 db isolation, masking noise of fairly high level must be introduced. Too high a level will result in the noise itself being disturbing; too low a level results in speech interference, extreme dissatisfaction, and impediments to work. Since in such areas, control of background noises is extremely difficult, success depends in large measure on proper physical placement of noise sources and grouping of common acoustic need areas. The indiscriminate reliance on noise generators is to be discouraged (see Fig. 27.35). Generally

TABLE 27.8 Recommended Category Classification and Suggested Noise Criteria Range for Steady Background Noise

Type of Space (and Acoustical Requirements)	*NC Curve*	*Equivalent[a] dBA*
Concert halls, opera houses, and recital halls (for listening to faint musical sounds).	10–20	20–30
Broadcast and recording studios (distant microphone pickup used).	15–20	25–30
Large auditoriums, large drama theatres and houses of worship (for excellent listening conditions).	20–25	30–35
Broadcast, television, and recording studios (close microphone pickup only).	20–25	30–35
Small auditoriums, small theatres, small churches, music rehearsal rooms, large meeting and conference rooms (for good listening), or executive offices and conference rooms for 50 people (no amplification).	25–30	35–40
Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, and so forth (for sleeping, resting, relaxing).	25–35	35–45
Private or semiprivate offices, small conference rooms, classrooms, libraries, and so forth (for good listening conditions).	30–35	40–45
Living rooms and similar spaces in dwellings (for conversing or listening to radio and TV).	35–45	45–55
Large offices, reception areas, retail shops and stores, cafeterias, restaurants, and so forth (for moderately good listening conditions).	35–50	45–60
Lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas (for fair listening conditions).	40–45	50–55
Light maintenance shops, office and computer equipment rooms, kitchens, and laundries (for moderately fair listening conditions).	45–60	55–70
Shops, garages, power-plant control rooms, and so forth (for just acceptable speech and telephone communication). Levels above PNC-60 are not recommended for any office or communication situation.	–	–
For work spaces where speech or telephone communication is not required, but where there must be no risk of hearing damage.	–	–

[a]For information only.

Source: Extracted with permission from E. B. Magrab, *Environmental Noise Control*, Wiley, New York, 1975.

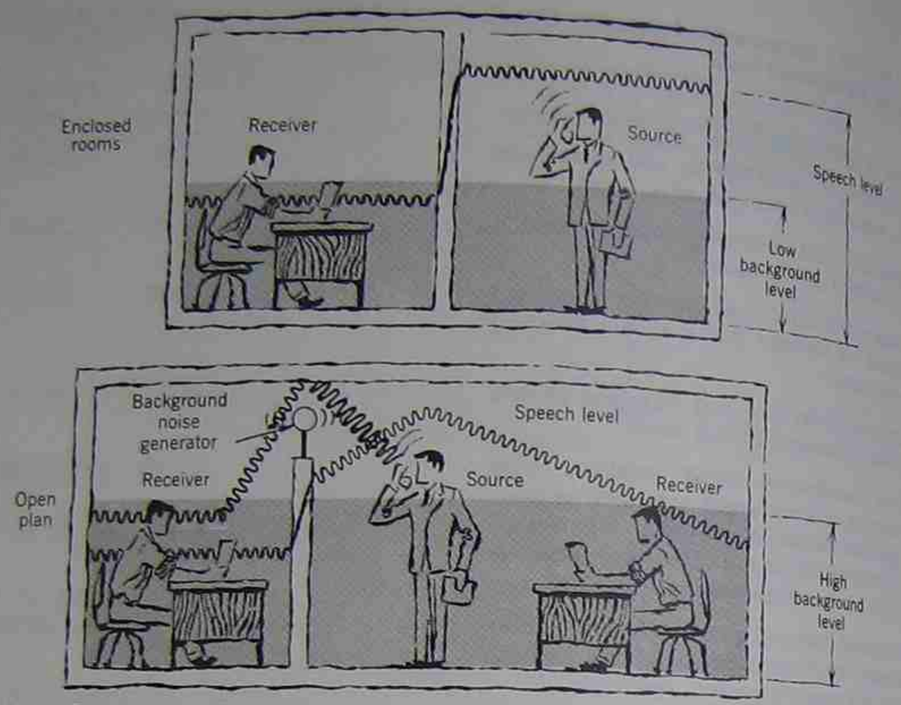


Fig. 27.35 *The open-plan background noise level must be high enough to mask adjacent speech but not so loud that it constitutes a disturbance itself. Received noise is a combination of partition-transmitted and ceiling reflected noise.*

speaking, open areas should use barriers at least 5 ft high × 8 ft wide of very high absorbency, and acoustic ceilings no higher than 9 ft with a minimum absorption coefficient of 0.7, backed by a plenum at least 30 in. deep. The partial height barriers must be set so that the listener is shielded from line-of-sight noise, either direct or on first reflection. Obviously the taller the barrier, the better.

It was found, when introducing background noise to provide masking, that a noise with a frequency spectrum conforming in shape to an NC curve was neither pleasant nor unnoticed (neutral), but instead sounded emphasized at both ends; that is, it rumbled and hissed. Similarly, it was found that neither white noise (a signal with equal energy per frequency band width) nor pink noise (a signal with equal energy per octave) were satisfactory. Instead, a signal with a drooping energy per octave characteristic was found to provide the greatest masking satisfaction in field tests, and is now generally used, although older installations still use pink noise.

STRUCTURE-BORNE SOUND

27.23 Structure-Borne Impact Noise

As stated in Section 27.11, structure-borne noise is at least as serious a problem as airborne noise because:

1. There is no air cushion between the source and the structure. Thus high-intensity energy is introduced into the structure, through which it travels with minimum attenuation and at great speed.

2. Sound, once introduced into the structure, is attenuated well only by discontinuities in the structure. Since the structure must have integrity to carry the loads, discontinuities of the type that will stop noise are complex and expensive.

3. The entire structure constitutes a network of parallel paths for sound. Therefore, partial solutions are useless, since sound will find flanking paths. The entire structure must be soundproofed to yield good results.

4. Unlike the case of airborne noise, additional mass does not usually alleviate floor-borne noise, particularly in long spans where the floor acts as a diaphragm.

5. The increasing use of exposed structural ceiling eliminates the attenuation that can be introduced into a plenum above a hung ceiling. This is particularly bad, since most structure-borne noise is carried by floor structures (rather than walls), which radiate sound up and down.

The discussion that follows will be limited to impact noise. Refer to Section 27.27 for a brief treatment of vibration that is felt rather than heard, and is in effect a very low-frequency noise. Many of the recommendations and techniques that will minimize impact noise will also reduce vibration.

27.24 Control of Impact Noise

Impact noise problems can be controlled in two ways—by preventing or minimizing the impact, and by attenuating it once it has occurred. Since we are concerned with structure, the latter problem is discussed first. The former problem is covered in Section 27.26. Impact on floors is more serious than wall impact because the latter will be partially attenuated at the wall/floor joint, whereas the former is introduced directly into the building framework.

The discussion below addresses each of the solutions shown in Fig. 27.36.

(a) Cushion the Impact. See Fig. 27.36*a*. This obvious solution will frequently eliminate all but severe problems. The resilient materials in common use are floor tiles of vinyl, rubber, and cork, or carpeting on pads, in ascending order of impact insulation. See Section 27.25 and Appendix G for quantitative data on impact isolation.

(b) Float the Floor. See Fig. 27.36*b*. Since the key to elimination of structure-borne sound is *isolation*, separating the impacted floor from the structure floor by a resilient element is extremely effective. This element can be rubber or mineral wool pads, or blankets, or special spring metal sleepers. The effectiveness depends on the mass of the floating floor, compliance of the resilient support, and degree of isolation of the floating floor. This last element is extremely important, since flanking paths via end contacts with walls can short-circuit the floating element's sound impedance and defeat the system. With floating floors it is important that:

1. Mass of the floating floor be large enough to properly spread the loads. Otherwise, the pad will compress and deform sufficiently to transmit the impact.
2. Total construction must be airtight. Airtight is soundtight.
3. Particular care be exercised where partitions rest on the floating floor (see Fig. 27.37).
4. Short-circuits at walls or by penetrations be avoided; see Fig. 27.11*b*. Details of proper construction techniques are given in *A Guide to Airborne, Impact and Structure-Borne Noise Control in Multi-family Dwellings* (see References.)

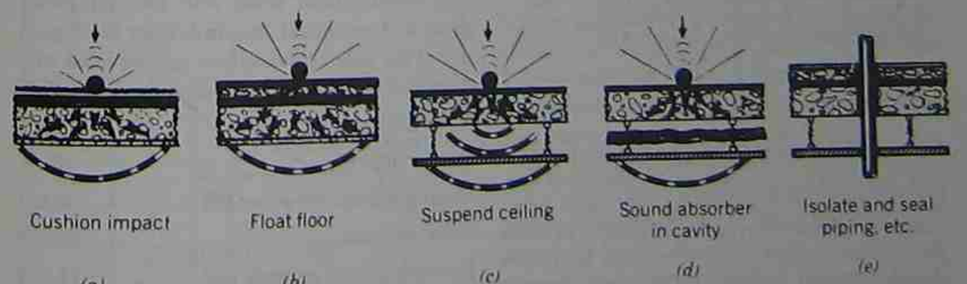


Fig. 27.36 *Methods of controlling impact sound transmission through floors. [Reprinted from* Quieting: A Practical Guide to Noise Control *(1976), p. 50.]*

ACOUSTICS

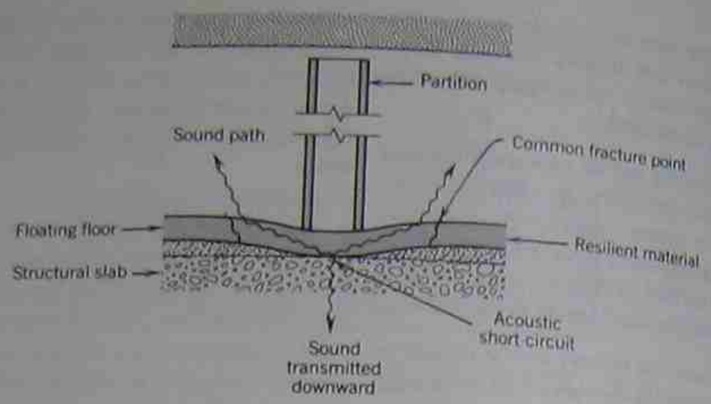


Fig. 27.37 *Caution must be exercised when supporting partitions on floating floors to prevent structural failures or short-circuiting of the floating element, as illustrated. [Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

5. Construction throughout be consistent. Mixed construction types invite flanking noise paths. (See Fig. 27.38).

(c) Suspend the Ceiling—and Use Absorber in Cavity. See Fig. 27.36(*c,d*). As stated, the most disturbing noise is radiated down from the ceiling. A flexibly suspended ceiling with an acoustic absorbent layer suspended in it can be very effective if not flanked by paths leading into the walls and from there reradiating into the space below. It is imperative that the entire floor slab above be decoupled from the walls below by resilient separators.

(d) Isolate All Piping. See Fig. 27.36*e*. All rigid structures such as piping must be isolated so as not to form a flanking path, and caulked with resilient sealing so as not to constitute an air-sound leak.

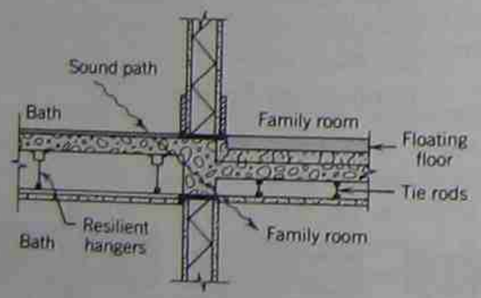


Fig. 27.38 *Flanking paths in mixed-construction type floors. FHA does not recommend mixing construction types unless provisions (e.g., expansion joints or breaks in all structural paths between each space) have been made to prevent flanking. [From* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

27.25 Impact Isolation Class (IIC)

This is a single-number, impact isolation rating for floor construction, similar in intent and derivation to STC wall ratings. Tests are made with a standard tapping machine and the noise levels measured in ⅓-octave bands. These are plotted and compared to a standard contour, exactly as with sound transmission class. Details of typical floor constructions along with IIC ratings are given in Appendix G. Resilient floor finishes on any of the floor constructions not provided with them will add to the IIC ratings approximately as follows:

1/16-in. vinyl tile	0
1/8-in. linoleum or rubber tile	4 ± 1
1/4-in. cork tile	10 ± 2
Low-pile carpet on fiber pad	12 ± 2
Low-pile carpet on foam rubber pad	18 ± 3
High-pile carpet on foam rubber pad	24 ± 3

MECHANICAL SYSTEM NOISE CONTROL

27.26 Mechanical Noise Sources

Mechanical devices obviously make noise. And, generally, the more power they consume, the more noise they make. In many of today's buildings, 40% of the total cost is spent on mechanical systems. These systems are located throughout a building.

In most buildings, the primary sources of mechanical noise are the components of the air conditioning and air-handling systems such as fans, compressors, cooling towers, condensers, ductwork, dampers, mixing boxes, induction units, and diffusers. The curve of Fig. 27.39 depicts typical air-handling system noise and indicates the portions of the spectrum produced by each group of components.

Pumps are another source of mechanical noise. Pump noise is frequently transmitted along pipes to remote points.

Elevators, escalators, and freight elevators also introduce mechanical noise into buildings. Escalators and freight elevators pose few problems, since they are localized in a specific area and have low operation speeds. However, elevator car operation is rapid, and it affects large areas. In addition, the motors and controls are located on or above the prime upper floors of a building. Motor, shaftway, and other equipment noise must be properly controlled to prevent annoyance to building tenants located near the shaftways or mechanical penthouses. Vibration isolation of these major components is a specialized problem beyond the scope of this text.

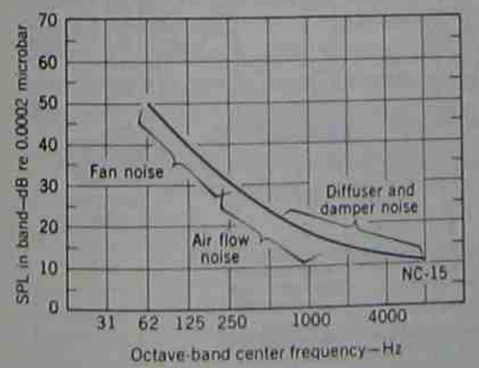


Fig. 27.39 *Frequency spectrum of noise of HVAC system components.*

27.27 Quieting of Machines

Machines cause noise by vibration. This noise is imparted directly to the surrounding air and by vibrational contact to the surrounding structure. Therefore, there are three ways to reduce this noise:

1. Reduce the vibration itself.
2. Reduce the airborne noise by decoupling the vibration from efficient radiating sources.
3. Decouple the vibrating source from the structure.

Refer to Fig. 27.40: Items 1, 3, and 4 reduce vibration; items 4, 5, 6, and 7 reduce and decouple the vibration from the radiating cabinet; and items 2 and 8 decouple the vibrating source from the structure. Once the noise becomes airborne or structure borne, the isolation techniques studied above are employed.

Vibration reduction takes two forms, damping and isolation. Damping is accomplished by rigidly coupling the vibrating source to a large mass, frequently called an inertia block. Much of the energy is absorbed and dissipated as friction; the remainder results in lower-amplitude vibration (see Fig. 27.41). *Isolation* is accomplished by supporting the vibrating mass on resilient supports. These take many forms and are used in tandem. Thus machines are supported on fibrous, rubber, or spring steel vibration isolators, and the entire mass can be supported on a floating floor, which in turn rests on resilient vibration isolators as in Fig. 27.41. Large machines are supported on special commercial "sandwiches" of asbestos, lead, cork, and other strong resilient materials. Piping is supported on cork pads and hung on resilient hangers.

The extensive use of emergency electric generators has caused a serious noise and vibration problem due to the large mass and extremely high noise levels. For such units, complete enclosures are frequently the best approach. Flexible joints in all pipes and ducts connected to vibrating machines are mandatory. This in-

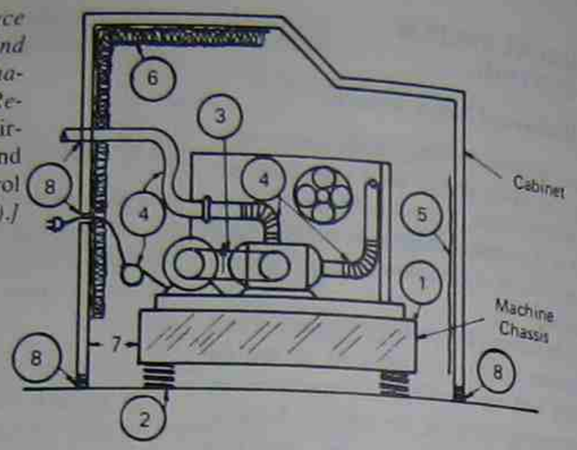


Fig. 27.40 Techniques to reduce the generation of airborne and structure-borne noise in machines and appliances. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

1. Install motors, pumps, fans, etc. on most massive part of the machine.
2. Install such components on resilient mounts or vibration isolators.
3. Use belt drive or roller drive systems in place of gear trains.
4. Use flexible hoses and wiring instead of rigid piping and stiff wiring.
5. Apply vibration damping materials to surfaces undergoing most vibration.
6. Install acoustical lining to reduce noise buildup inside machine.
7. Minimize mechanical contact between the cabinet and the machine chassis.
8. Seal openings at the base and other parts of the cabinet to prevent noise leakage.

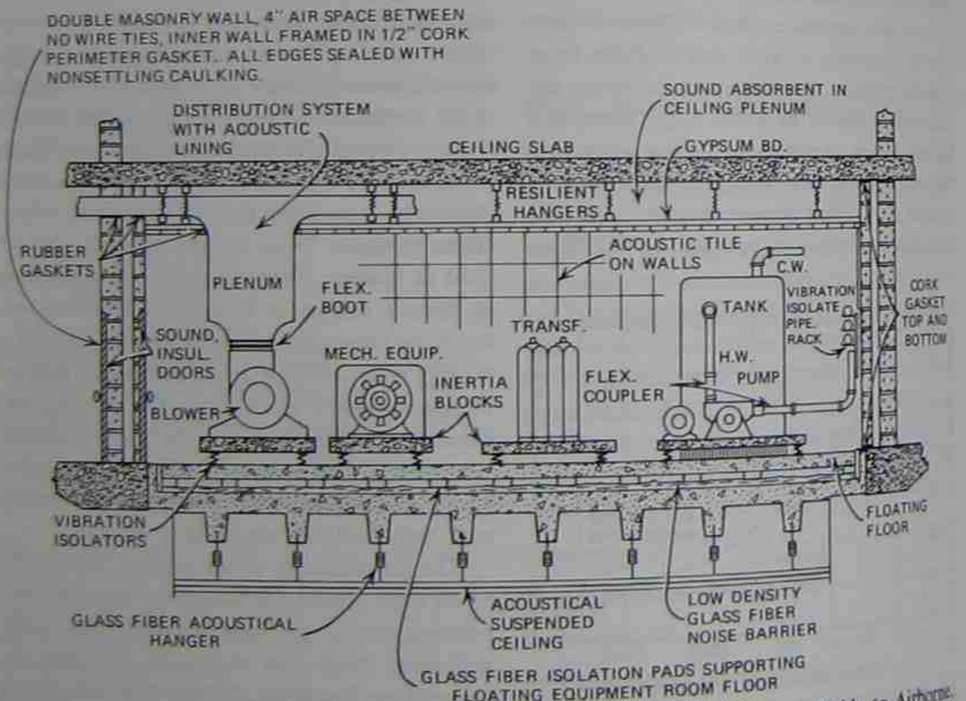


Fig. 27.41 Soundproofing a mechanical equipment room. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).]*

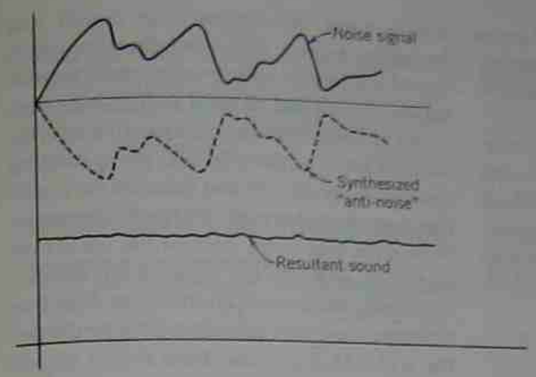


Fig. 27.42 Silencing of noise by introduction of a synthesized noise signal exactly out of phase with the original signal. The resultant sound is effectively zero: that is, silence.

cludes flexible conduit connectors to all motors, transformers, and lighting fixtures using ballasts.

27.28 Active Noise Cancellation

Since noise is a phenomenon consisting of acoustic wave energy being transmitted at certain frequencies, it is theoretically possible to *eliminate* (not mask) noise by simultaneous transmission of identical wave energy exactly out of phase with the noise. The sum of the two energy waves is zero—hence silence (see Fig. 27.42). The problem with this simple solution always has been (and still is) that even with the fastest computers, it still takes a finite amount of time to analyze the noise waveform, synthesize the antinoise, and inject it into the acoustic environment. Since the out-of-phase generated signal lags behind the noise, it cannot completely cancel it. Worse still, if the original noise is of random (i.e., nonpredictable) waveform, it will have changed in content during the synthesizing time lag so that the result of the combined waves is far from silent. Obviously, the faster the noise analysis and antinoise synthesis is accomplished, the more effective will be the partial silencing. Fortunately, however, most mechanical noise is repetitive or periodic because it is caused by repetitive actions—the pulsing of pistons in engines and compressors, the rotation of rotors and fan blades, the noise caused by mechanically produced fluid movement, the hum of transformers, and so on. That being so, it is a fairly simple (though expensive) procedure to determine the periodicity of the noise, analyze it, synthesize the antiphase waveform, and inject the "antinoise" into the *next* cycle, thus eliminating the time lag and effectively canceling the noise and creating silence. A block diagram of such a system is shown in Fig. 27.43.

A particularly important application of active noise cancellation, and one already in use, is in the area of hearing conservation for people exposed to high noise levels at work. Here the out-of-phase noise is introduced into earphones in headsets. This allows the wearer to hear random noise such as speech clearly, while repetitive cyclic noise from engines and the like is can-

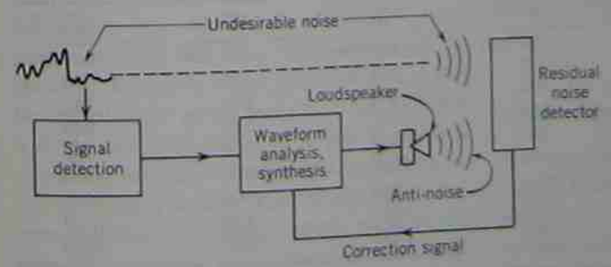


Fig. 27.43 Block diagram of active noise cancellation. The noise signal is detected, its periodicity determined and its waveform analyzed, and an out-of-phase noise is synthesized and injected into the acoustic environment. A residual noise detector provides a feedback signal, which acts to improve noise cancellation.

celed. Another important application of active noise cancellation is in the area of vibration control, since vibration is no more than very low frequency noise.

Active noise canceling systems are commercially available and are coming into increasing use at this writing. Their principal drawback presently is their high cost, but as with most high-tech equipment, costs will probably drop with increasing commercial acceptance.

27.29 Duct System Noise Reduction

Design of quiet duct system operation entails more than specification of duct lining. Air turbulence generates noise. Turbulence and noise levels increase as the velocity of airflow increases. Table 27.9 gives recommended design velocities for various distances from the terminal devices. Velocities should be as low as possible, since sound increases exponentially with velocity. Allowable velocities increase as the distance from the terminal device becomes greater. Return velocities may be slightly higher than supply.

Sound travels as easily against as with the airflow in ductwork. Therefore, both supply and return systems must be lined to control transmission of fan noise. Maximum noise reduction occurs at bends in the ducts. For maximum noise reduction in short runs, a pair of 90° bends often is designed into a system, since lining is not effective in runs shorter than 50 to 60 ft.

Other design approaches that are part of a quiet system include smooth transitions at changes of duct size and large radius bends with turning vanes. Attenuation drops rapidly with increasing size of duct, and therefore ducts should not be deliberately oversized. Crosstalk between rooms and between ducts can be minimized by using lined ducts, separating adjacent ducts as much as possible, and gluing damping material on the outside and lining on the inside. Damping material is particularly effective in preventing the thin metal walls of the ducts from resonating. Mufflers and silencers are effective in reducing fan noise. The pressure drop they introduce must be compensated for in the fan. The *ASHRAE Guide and Data Book*'s chapter on noise control in fans, plenums, housings, and ducts should be consulted for their recommendations. Figure 27.44 shows some of the ways by which cross-talk and flanking noises can be reduced. Figure 27.45 shows some of the techniques employed for quieting duct noise. Active noise cancellation is particularly useful in duct systems since it does not reduce air flow as do liners, baffles, and other mechanical silencing devices.

The increased use of variable air volume (VAV) systems has introduced some noise problems which should not be neglected. VAV system noise can be minimized by following a few basic design rules. Maintain minimum system static pressure since fan noise increases exponentially with static pressure. Select the air volume modulating device at the fan with care as it can be a noise source. Since outlet air volume control involves duct area restriction with attendant velocity increase and resultant noise, the design must include some sort of downstream silencing equipment. Ceiling diffuser acoustic characteristics must be coordinated with design air velocity and with any requirement for masking noise. Finally, avoid the use of throttling dampers on ceiling diffusers since a partially closed damper can generate very high noise levels.

TABLE 27.9 **Air Speeds in Ducts to Yield NC-15 or NC-25 Background Levels**[a]

	Supply		Return	
Location	*NC-15*	*NC-25*	*NC-15*	*NC-25*
Slot speed at min. ½ in. opening	250 fpm	350 fpm	300 fpm	420 fpm
10 ft of duct before opening	300	420	350	490
Next 20 ft	400	560	450	630
Next 20 ft	500	700	570	800
Next 20 ft	640	900	700	980
Next 20 ft	800	1120	900	1260
Next 20 ft	1000	1400	1100	1540
Next 20 ft	1300	1820	1450	2030
Next 20 ft	1600	2240	1800	2520

[a]Ducts with 1- to 2-in. inside duct lining, all duct sizes.

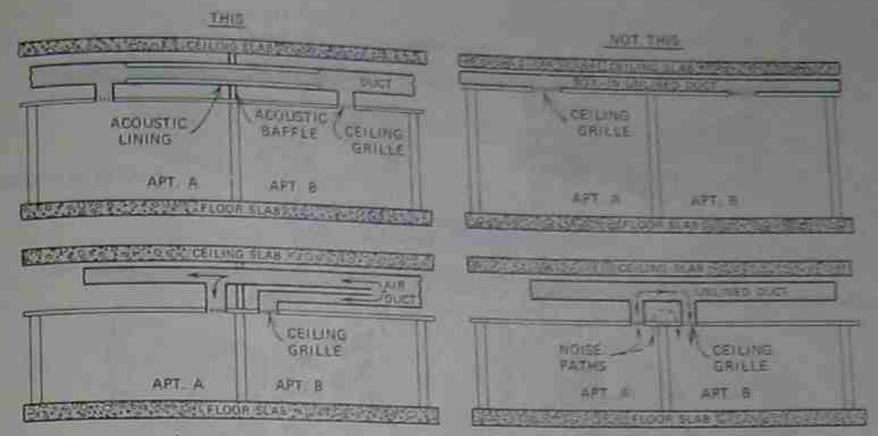


Fig. 27.44 Since ducts are extremely efficient sound transmission paths, considerable precaution must be taken to avoid crosstalk and ventilation, combustion, and equipment noise. Avoid running ducts as a common supply or return between rooms unless they are properly baffled and lined with sound-absorbing material. The common practice, in wood frame structures, of using troughs between joists as a common return duct between dwellings results in very serious noise transmission problems. Caulk or seal around ducts at all points of penetrations through partitions. Use double-wall ducts, acoustical lining, flexible boots, and resilient hangers where required. Dwelling units should be serviced by separate supply and return ducts, which branch off a main duct system. (Reprinted from A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968).)*

Pumps, as with all rotating equipment, are sources of vibration and noise and should be treated as described in Section 27.27. Figure 27.46 shows a typical pump installation with appropriate noise reduction measures. For at least a distance of 100 pipe diameters beyond the pump, resilient pipe hangers should be used. With centrifugal pumps as with fan and blowers, machine sound concentrates in narrow bands and, if extremely disturbing, can be attenuated with resonant filters. Reciprocating pumps are more difficult to control as the pulsations are more vibration than noise. Flexible connections in the piping and U-joints in the piping will absorb much of this vibration.

27.30 Piping System Noise Reduction

As with airflow, noise increases exponentially with velocity. Piping is not a major noise source normally, since the radiating diameter is small, although flow velocities much in excess of 8 fps, where the pipe is in contact with the structure, can create noise problems, particularly when passing through NC-15 to NC-25 areas (see Table 27.8). Domestic water system mains should be limited to 50 psi in other than tall buildings and pressure in branches to 35 psi. In high-rise structures pressure-reducing valves will be required in high-pressure mains to meet these recommendations. Obviously piping must be designed to prevent water hammer, and noise sources must be located away from quiet areas.

27.31 Electrical Equipment Noise

Electrical equipment is generally overlooked as a noise source and this is unwise. Most electrical noise is 120-Hz hum. This can be very disturbing because it is so low a frequency and, as we have noted repeatedly, low-frequency noise is diffi-

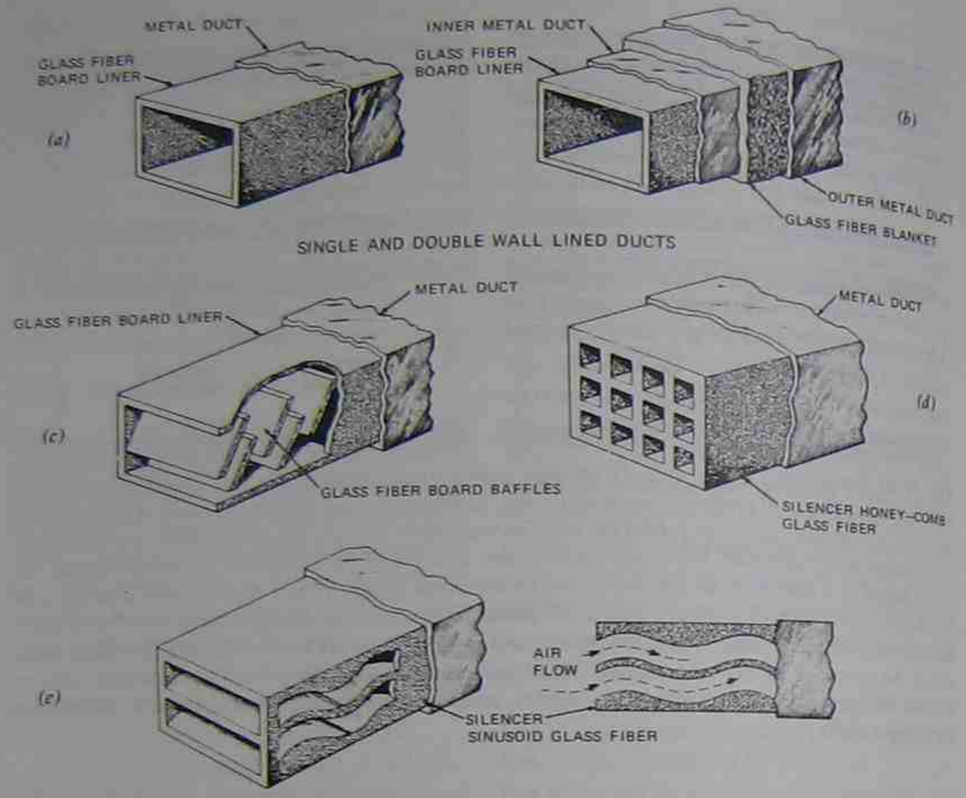


Fig. 27.45 *Unlined duct has negligible sound attenuation and acts as an excellent speaking tube. Inside lining* (a) *gives 2 to 3 db attenuation per foot in the range 1 to 2 kHz, dropping rapidly above and below those frequencies, and giving negligible low-frequency attenuation.* (b) *Double lining gives higher attenuation and reduces crosstalk between ducts. Duct silencers and baffles* (c–e) *give high broadband attenuation: a maximum of 10 to 12 db/ft in the range 1 to 2 kHz, and lower above and below. They are useful to reduce fan noise in short runs but cause considerable pressure drop. [Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968), Fig. 8-66.]*

cult to attenuate passively. Transformer noise levels are dictated by NEMA and ANSI standards. For a premium price lower noise units are obtainable. Table 27.10 lists maximum noise levels for dry-type units. Most manufacturers warranty noise levels below these. Oil- and silicone-filled units are normally quieter than dry-type transformers, as are units designed for lower temperature rise. Transformer noise can be minimized by these steps:

1. Mount unit on vibration isolators.
2. If transformer is wall hung, use resilient hanging. If it is floor mounted, place on as massive a slab as possible.
3. Locate the unit so that reflections do not amplify the sound. Sound-absorbent material on the walls behind the units is not useful at 120 Hz. Only cavity resonators will absorb appreciable amounts of sound at that frequency.
4. Use only flexible conduit connections.
5. Avoid locating transformers adjacent to, or immediately outside, quiet areas. A common error in this regard is placing a transformer pad immediately below the window of an NC 15–25 area.

The second major source of 120-Hz hum is conventional, core-and-coil discharge light fixture ballasts. (Electronic ballasts are practically noiseless.) This includes fluorescent plus all the HID sources. Table 27.11 lists the recommended application of conventional fluorescent ballasts. HID ballasts were not a problem until recently when metal–halide, and sodium lamps moved from their former noisy industrial surroundings into quiet office spaces. These ballasts can be very noisy, and care must be exercised in their placement. With all ballasts, the method of mounting has a marked effect on the radiated noise. As pointed out earlier, when a small vibrating source is coupled rigidly to a larger body, noise is amplified because of increased source-to-air coupling. Since fluorescent ballasts for linear lamps are necessarily closely coupled to large metal fixtures for heat dissipation purposes, the sound radiation is much amplified. A large number of fluorescent fixtures mounted in a plenum can create a serious problem. Solution of the problem lies in use of absorptive material in plenums, flexible con-

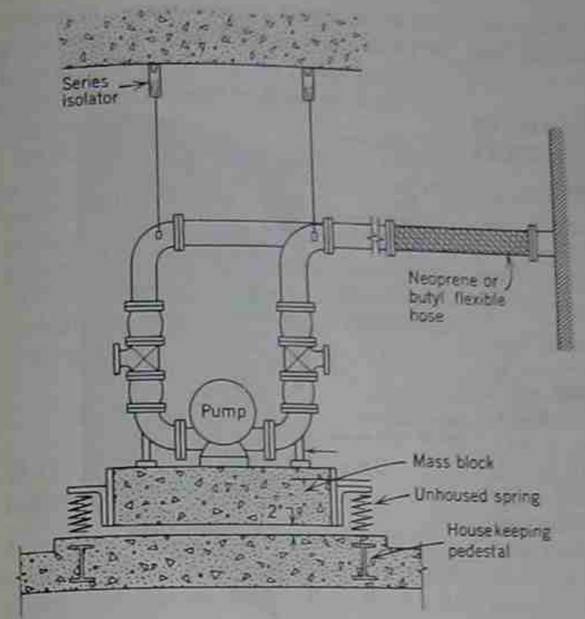


Fig. 27.46 *Typical pump installation with appropriate isolation and damping measures.*

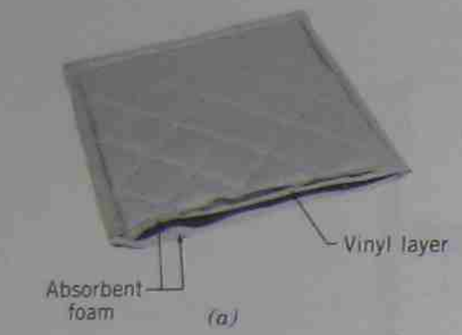
TABLE 27.10 **Maximum Sound Levels: Dry-Type Transformers**

kVA	*Decibels (NEMA Standard)*
0–9	40
10–50	45
51–150	50
151–300	55
301–500	60

TABLE 27.11 **Acoustic Criteria for Selection of Conventional Core-and-Coil Fluorescent Lamp Ballasts**

For an Installation in	*Use of Ballasts with This Rating Will Usually Be Satisfactory*
TV or radio station, church, synagogue	A
Offices, residence, night school	B
Library, reception or reading rooms, school study hall	C
Noisy office, doctor's or dentist's office, classroom	D

ACOUSTICS



(a)

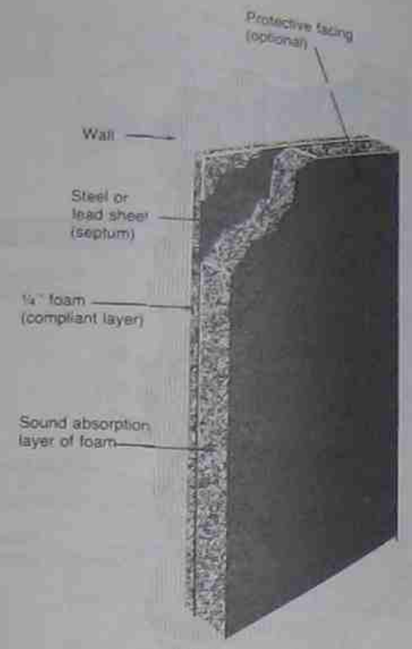
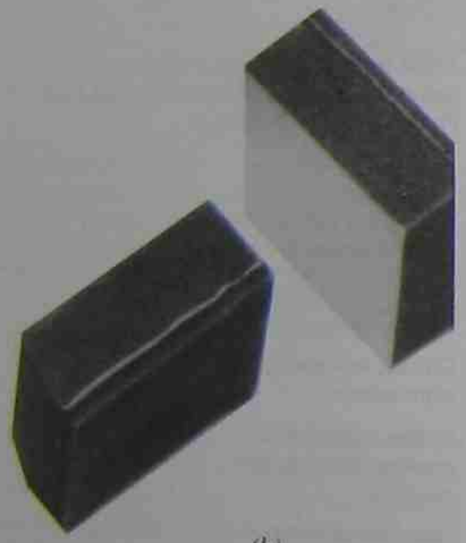


Fig. 27.47 (a) *Typical flexible nonmetallic composite acoustical barrier material which can be used as a free-hanging curtain or applied to a rigid surface. It consists of a layer of flexible vinyl sandwiched between two layers of fiberglass or other acoustic foam. It is most effective when applied with an airspace between it and any rigid support barrier. See Fig. 27.6 and Section 27.5. (Courtesy of EAR, division of Cabot Corp.)*



(b)

Fig. 27.47 (b) *Composite semirigid acoustical barrier material as used in enclosure panels or as an enclosure lining. The material comprises a thick (1- or 2-in.) foam layer installed facing the noise source, a 1-lb/ft² lead or steel layer (septum), and an outer ¼-in. foam layer, whose function is to isolate the inner foam and the metal from the supporting structure or wall when the material functions as an inner liner. See Fig. 27.47c.*

Foam/Metal/Foam

(c)

Fig. 27.47 (c) *Application of composite sound barrier material as an acoustic liner on a nonacoustic partition. [*(b, c) *Courtesy of United McGill Corporation.]*

duit connection to fixtures, and resilient fixture hanging. In severe cases ballasts can be remote-mounted. HID ballasts are inherently noisier than fluorescent but like ballasts for nonlinear fluorescent lamps are generally less troublesome, being coupled to small radiating bodies.

27.32 Noise Problems Due to Equipment Location

Roof-mounted HVAC units have proven themselves very economical and very noisy. The vibration, short duct runs, and sound reflections are serious problems that can be solved with vibration isolators, sound mufflers, and careful location of equipment. Roof-mounted cooling towers are a particular problem when located

adjacent to a taller building. That problem has led to a spate of lawsuits and noise control legislation in many cities. For this reason particular attention should be paid in design to all exterior equipment.

In high-rise buildings, problems are caused by the conflicts between the stringent noise requirements of the prime upper floor space and the near presence of elevator machine rooms, mechanical equipment rooms, and cooling towers. These problems are almost impossible to solve after construction and require the services of an acoustics expert during design.

27.33 Sound Isolation Enclosures and Barriers

In buildings with concentrated high-level noise sources such as certain types of machinery, it is always more desirable to reduce the noise at its source rather than attempt to treat the larger enclosing space. This is most effectively accomplished by enclosing the noise source with materials that will furnish a combination of reverberant noise reduction by absorption as explained in Section 27.7, and blocking of airborne sound with high transmission loss as detailed in Sections 27.12 to 27.17. These materials are available in the form of curtains, panels, and prefabricated partial and full enclosures, tailored to the specific characteristic of the noise source (see Fig. 27.47). These enclosures are not normally the responsibility of the building designer. It is, however, important to know that they will be used, as well as their characteristics, so that appropriate isolation can be designed into the building for the residual sound that is radiated from the enclosures.

The fundamental criteria of airborne sound insulation between dwelling units are, for grade II: (see Section 27.34 for grades)

Wall partitions	STC ≥ 52
Floor–ceiling assemblies	IIC ≥ 52

These apply where similar function spaces are contiguous, as bedroom to bedroom and living room to living room. Where this is not the case, the isolation must be revised up or down to meet the maximum sensitivity requirement.

RECOMMENDATIONS AND CRITERIA

Recommendations for background noise levels (NC criteria) are given in Table 27.8. Criteria for partition isolation (STC) and impact isolation (IIC) are given in the following sections and in Table 27.12.

27.34 Multioccupancy Residential STC/IIC Criteria

The most important and binding criteria for residential work in the United States are issued by the Department of Housing and Urban Development in conjunction with the Federal Housing Administration (HUD/FHA). The reader is referred to the latest issue of *A Guide to Airborne, Impact and Structure-Borne Noise Control* and to any subsequent HUD/FHA publications. Tables 27.13 and 27.14 give the essential data presented there in the current edition.

The recommendations are divided into grades I, II, and III. Grade II is the most important category and is applicable primarily in residential urban and suburban areas considered to have the "average" noise environment. The nighttime exterior noise levels might be about 40 to 45 dbA, and the permissible interior noise environment should not exceed NC 25–30 characteristics. Grade I is suburban, with a "quiet" noise environment characterized by a nighttime exterior noise level of about 35 to 40 dbA. *Grade I STC/IIC criteria are three points higher than those of grade II.*

Grade III recommendations are minimal and can be characterized as "noisy," with an average nighttime exterior noise level of about 55 dbA or higher. *Grade III STC/IIC recommendations are four points lower than those of grade II.*

27.35 Specific Occupancies

(a) Schools. School buildings house spaces of many kinds—classrooms, auditoriums, gym-

TABLE 27.12 **Recommended STC for Partitions; Specific Occupancies**

Type of Occupancy	Wall, Partition, or Panel Between: Room Being Considered	AND: Adjacent area	Sound Isolation Requirement: Background Level in Room Being Considered: Quiet	Normal
Normal school buildings without extraordinary or unusual activities or requirements	Classrooms	Adjacent classrooms	STC 42	STC 40
		Corridor or public areas	STC 40	STC 38
		Kitchen and dining areas	STC 50	STC 47
		Shops	STC 50	STC 47
		Recreation areas	STC 45	STC 42
		Music rooms	STC 55	STC 50
		Mechanical equipment rooms	STC 50	STC 45
		Toilet areas	STC 45	STC 42
	Music practice rooms	Adjacent practice rooms	STC 55	STC 50
		Corridor and public areas	STC 45	STC 42
Executive areas, doctors' suites; confidential privacy requirements	Office	Adjacent offices	STC 50	STC 45
		General office areas	STC 48	STC 45
		Corridor or lobby	STC 45	STC 42
		Washrooms and toilet areas	STC 50	STC 47
Normal office; normal privacy requirements	Office	Adjacent offices	STC 40	STC 38
		Corridor, lobby, exterior	STC 40	STC 38
		Washrooms, kitchen, dining	STC 42	STC 40
Any occupancy, using rooms for group meetings	Conference rooms	Other conference rooms	STC 45	STC 42
		Adjacent offices	STC 45	STC 42
		Corridor or lobby	STC 42	STC 40
		Exterior of building	STC 40	STC 38
		Kitchen and dining areas	STC 45	STC 42
Large offices, drafting areas, banking floors, etc.	Large general office areas	Corridors, lobby, exterior	STC 38	STC 35
		Data-processing area	STC 40	STC 38
		Kitchen and dining areas	STC 40	STC 38
Motels and urban hotels, hospitals and dormitories	Bedrooms	Adjacent bedrooms[a]	STC 52	STC 50
		Bathroom[a]	STC 50	STC 45
		Living rooms[a]	STC 45	STC 42
		Dining areas	STC 45	STC 42
		Corridor, lobby, or public spaces	STC 45	STC 42

[a]Separate occupancy.

Source: Courtesy of U.S. Gypsum.

nasiums, cafeterias, shop areas, and music suites—that pose acoustics problems.

1. *Auditoriums.* All auditoriums require a sound system for some of the activities accommodated (see Figs. 26.35 and 26.38). The most difficult aspect, architecturally, is integration of the loudspeaker system into the design. To provide proper sound reinforcement, loudspeakers must be located properly without obstructions. To accomplish this, the loudspeaker system should be incorporated in the earliest drawings.

TABLE 27.13 **Criteria for Airborne Sound Insulation of Wall Partitions Between Dwelling Units**

Partition Function Between Dwellings: Apt. A		Apt. B	Grade II STC
Bedroom	to	Bedroom	52
Living room	to	Bedroom[a]	54
Kitchen[b]	to	Bedroom[a]	55
Bathroom	to	Bedroom[a]	56
Corridor	to	Bedroom[a,c]	52
Living room	to	Living room	52
Kitchen[b]	to	Living room[a]	52
Bathroom	to	Living room	54
Corridor	to	Living room[a,c,d]	52
Kitchen	to	Kitchen[e]	50
Bathroom	to	Kitchen	52
Corridor	to	Kitchen[a,c,d]	52
Bathroom	to	Bathroom	50
Corridor	to	Bathroom[a,c]	48

[a]Whenever a partition wall might serve to separate several functional spaces, the highest criterion must prevail.

[b]Or dining or family or recreation room.

[c]It is assumed that there is no entrance door leading from corridor to living unit.

[d]Criterion applies to the partition. Doors in corridor partitions must have the rating of the partition, not vice versa.

[e]Double wall construction is recommended to minimize kitchen impact noises.

Source: Reprinted from *A Guide to Airborne, Impact, and Structure-borne Noise Control in Multifamily Dwellings* (1968). For Grade I, add 3 points; for Grade III, subtract 4 points.

In general, a school auditorium must be a multipurpose facility. It should be designed to meet speech requirements and also should be suitable for the school's music activities.

Often a modified gymnasium (gymnatorium) or cafeteria (cafetorium) functions as an auditorium. Obviously, acoustics compromises occur in such facilities. The large areas of sound-absorbing treatment in either kind of space make them unsuitable as auditoriums and most events that require speech amplification.

2. *Classrooms.* Typical classrooms are approximately 30 ft square with 10-ft ceilings. Adequate speech communication is easily achieved in a room of this size. Classroom acoustic design usually involves:

a. Locating sound-absorbing treatment to reduce classroom noise levels.
b. Ensuring adequate privacy between adjacent spaces.
c. Control of air-handling system noise.

Acoustic tile ceilings yield adequate sound absorption for most classrooms. An NRC of 0.7 is recommended (see Section 27.6).

Partition systems must produce sufficient isolation to prevent disturbance from activities in other classrooms and corridors. Such partitions should run full height from floor to ceiling slab or roof construction. If return air transfer ducts are needed, their noise reduction characteristics must be as good as the walls or doors that they penetrate (for NC data, see Table 27.8). Unit ventilators commonly used for classrooms produce approximately the required level of background noise.

3. *Music Suites.* School music programs usually range from individual instruction to band and choral concerts. The teaching spaces required for such a program include practice rooms, ensemble rooms, and large rehearsal spaces. Both room acoustics design and sound isolation are important in music suites. Privacy between adjacent spaces is critical, since simultaneous use is necessary.

4. *Dining Areas.* The activity in cafeterias or lunchrooms generates noise. The kitchen and serving areas should be separated from the eating spaces. Treat ceilings and wall areas in the cafeteria with sound-absorbing material. Unless the ceiling is completely treated with a highly efficient sound absorbing material, the environment will be unsatisfactory due to its high noise level. Minimum NRC should be 0.8.

5. *Gymnasiums.* Activities in gymnasiums create so much noise that even extensive treatment will not quiet these spaces. A quiet gymnasium probably would be unsatisfactory, since spectators are conditioned to consider the

TABLE 27.14 **Criteria for Airborne and Impact Sound Insulation of Floor–Ceiling Assemblies Between Dwelling Units**

Partition Function Between Dwellings			*Grade II*	
Apt. A		*Apt. B*	*STC*	*IIC*
Bedroom	above	Bedroom	52	52
Living room	above	Bedroom[a]	54	57
Kitchen[b]	above	Bedroom[a,c]	55	62
Family room	above	Bedroom[a,d]	56	62
Corridor	above	Bedroom[a]	52	62
Bedroom	above	Living room[e]	54	52
Living room	above	Living room	52	52
Kitchen	above	Living room[a,c]	52	57
Family room	above	Living room[a,d]	54	60
Corridor	above	Living room[a]	52	57
Bedroom	above	Kitchen[c,e]	55	50
Living room	above	Kitchen[c,e]	52	52
Kitchen	above	Kitchen[c]	50	52
Bathroom	above	Kitchen[a,c]	52	52
Family room	above	Kitchen[a,c,d]	52	58
Corridor	above	Kitchen[a,c]	48	52
Bedroom	above	Family room[e]	56	48
Living room	above	Family room[e]	54	50
Kitchen	above	Family room[e]	52	52
Bathroom	above	Bathroom[c]	50	50
Corridor	above	Corridor	48	48

[a]This arrangement requires greater impact sound insulation than the converse, where a sensitive area is above a less sensitive area.

[b]Or dining or family or recreation room.

[c]It is assumed that plumbing fixtures, appliances, and piping are installed with proper vibration isolation.

[d]The airborne STC criteria in this table apply as well to vertical partitions between these two spaces.

[e]This arrangement requires equivalent airborne sound insulation and perhaps less impact sound insulation than the converse.

Source: Reprinted from *A Guide to Airborne, Impact, and Structure-borne Noise Control in Multifamily Dwellings* (1968). For Grade I, add 3 points; for Grade II, subtract 4 points.

"noise" as an enjoyable aspect of athletic events. However, to provide a proper environment for normal sports activities, the ceiling area should be sound absorbing. In addition, if a sound amplification system is to be used, sound-absorbing wall treatment may be required to eliminate echoes that would reduce intelligibility of announcements. An NRC of 0.7 is suggested with sound-absorbent material to be ceiling mounted.

If a gymnasium will also serve as an auditorium, loudspeaker system placement needs special consideration. For example, the loudspeakers should be located above the source location for speeches and plays.

6. *Swimming Pools.* The acoustic environment of swimming pools is often chaotic. Most sound-absorbing materials disintegrate in the high-humidity conditions prevalent in pool areas. Use special sound-absorbing units that have moisture-resistant properties.

7. *Shops.* Metal, woodworking, and scenery shops in schools contain many noise sources—saws, planers, drill presses, and manual tools. Each generates high airborne and structure-borne noise levels. Consolidating noisy areas and maximizing the distance between them and quiet spaces are essential. Ceiling and wall absorptive treatment with an NRC of at least 0.75 is recommended.

(b) Churches. The basic activities of most churches combine speech and music. Thus, the church environment must be acoustically hospitable to both. The architectural plan also must respond to religious requirements including the relative positioning of pulpits, lecterns, the altar, and choir.

Successful church acoustics can be achieved by designing the overall environment for music and providing special assistance for speakers. Figure 27.48 illustrates a church that is adequately reverberant for music and includes a sound-reflecting canopy over the pulpit to direct the minister's voice to the congregation. In some larger churches, a loudspeaker located above the canopy further reinforces speech from the pulpit. The choir and organ communicate with the entire volume of the church and, therefore, benefit from the reverberant environment.

(c) Offices. Although office buildings contain public spaces, auditoriums, and restaurants, prime occupancy is in office areas. Most acoustics problems in office buildings relate to privacy—either between spaces within a single firm or between adjacent firms. Speech privacy has been discussed at length in Section 27.22, including consideration of open-plan offices. Mechanical equipment noise problems are discussed in Sections 27.27 to 27.32.

(d) Apartment Buildings. Large apartment buildings sometimes house thousands of residents. Privacy and freedom from annoyance are high on the list of tenant requirements. See HUD/FHA criteria in Section 27.34.

The performance of the partitions is compromised in many designs by careless planning of convenience outlets, medicine cabinets, and mechanical services. Moreover, direct-exhaust duct connections between apartments and back-to-back placement of medicine cabinets result in loss of privacy. Back-to-back convenience outlets must be avoided.

Installation of rugs or carpeting provides the best protection against footfall noise. Some leases now require that a tenant provide such impact-reducing floor covering over most of the floor area in his apartment. Good design also dictates that similar spaces in adjacent apartments be grouped—bedrooms next to bed-

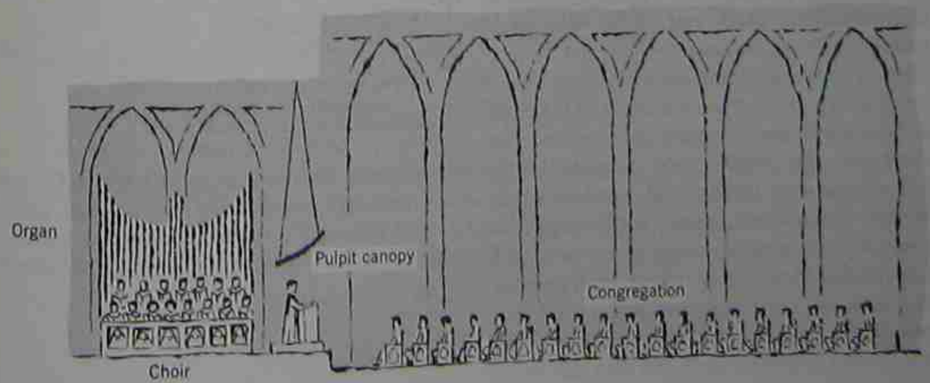


Fig. 27.48 Church with sound-reflecting pulpit canopy.

rooms, for example. Absorptive material in bedrooms should be ceiling mounted. An NRC of 0.6 is recommended.

Apartment house site selection seldom includes consideration of acoustics. Nevertheless, truck routes, superhighways, and airports can be annoying "neighbors." As mentioned above, cooling towers serving adjacent buildings must be considered during planning stages.

OUTDOOR ACOUSTIC CONSIDERATIONS

27.36 Sound Power and Pressure Levels in Free Space (Outdoors)

The equations of Section 26.15 are not applicable to outdoor propagation, in which the large reflective component of the indoor condition is absent. Although the propagation of sound outdoors may not appear to be of immediate importance in architectural acoustics, outdoor noise sources such as traffic, cooling tower, and aircraft are frequently loud enough to disturb activities within or immediately adjacent to a building. Conversely, the noise made by building equipment such as cooling towers, heat pumps, and even window air conditioners may be loud enough to disturb neighbors in a nearby building. For this reason it is desirable to have some basic understanding of outdoor sound propagation.

For preliminary evaluation of an outdoor noise problem, assuming a small nondirectional source on the ground, SPL can be determined from equations 26.13 and 26.14. For large sources such as cooling towers and traffic, which do not exhibit inverse square properties, sound level estimates are best made on the basis of experience and empirical data beyond the scope of this book (see Magrab, 1975; Schaudinischky, 1976). For small outdoor sources, the equipment power level can be estimated by measuring the sound power level at 5 ft and adding 15 db. Other factors, such as moisture in the air, the presence of trees, wind, and temperature gradients, will affect outdoor sound propagation to some extent, but they can be ignored except when great distances (i.e., over 1000 ft) are involved. Barriers, which are most effective outdoors, were discussed in Section 27.19.

27.37 Building Siting

As important as interior structural design is building siting vis-à-vis exterior noise sources. See also Section 3.5 and Figs. 3.18 and 3.19. Since this subject is somewhat beyond our scope, the discussion is brief. Buildings should be sited, with respect to noise sources:

1. To use natural terrain noise barriers (Fig. 27.49*a*).
2. With respect to trees as noise barriers, rely only on thick wooded areas (Fig. 27.49*b*).
3. To avoid naturally poor sites (Fig. 27.49*c*).
4. To avoid sound reflection from other buildings (Fig. 27.49*d*).

Factor 4 is also important in a multiwing building; in avoiding U shapes or other configurations where a central court becomes an echo chamber.

Where avoidance of an exterior noise source is impossible, quiet zones can be buffered from the noise by placing higher noise areas on the noisy side of the building. Thus, in a school, classrooms and offices can be buffered by a cafeteria and gym; in a residence, bedrooms by living rooms and corridors; in an office building, private offices by noisier clerical offices; and so on.

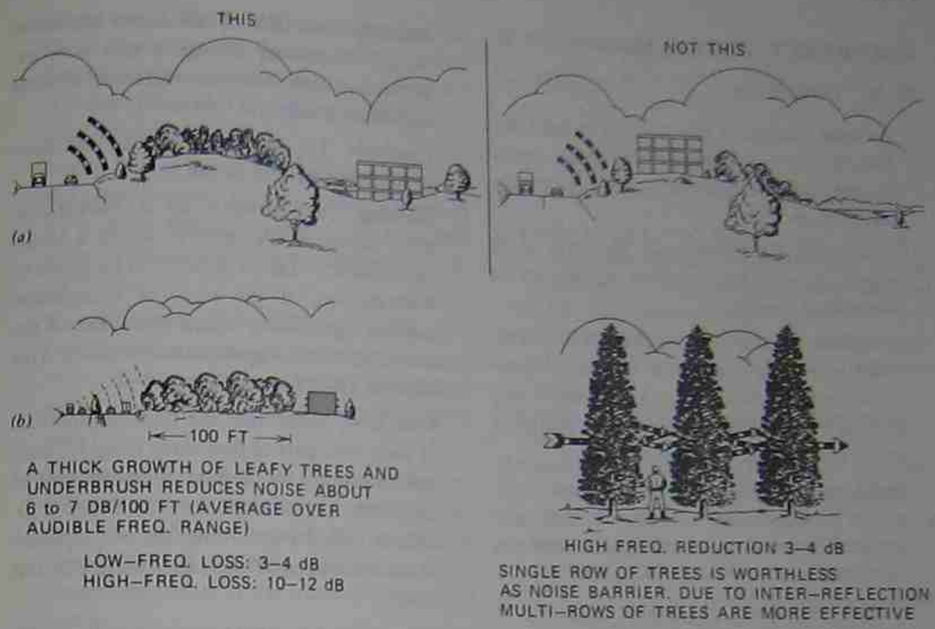


Fig. 27.49 (a) *Use of natural noise barriers.* (b) *Effectiveness of wooded areas as noise barriers. Noise reduction of trees.* (c) *An example of a poor building site.* (d) *Building sites near traffic arteries and other buildings. [Reprinted from* A Guide to Airborne, Impact, and Structure-Borne Noise Control in Multifamily Dwellings *(1968), p. 52.]*

ACOUSTICS

REFERENCE MATERIAL

27.38 Definitions

A-Scale. Identifies the filtering system that has characteristics that roughly match the response characteristics of the human ear. Referred to as dbA.

Absorption Coefficient (α). The ratio of the sound absorbed to the sound incident on the material or device.

Anechoic Room. An anechoic room provides a free field acoustic testing environment like the out-of-doors. All the sound emanating from a source is essentially absorbed at the surfaces of the room.

Baffle or Barrier, Sound. A shielding structure or partition used to increase the effective length of a sound transmission path between two locations.

Critical Frequency. The lowest frequency at which the wavelength of a bending wave, traveling in a structure, is the same as the wavelength in air at that frequency.

Damping. Dissipation of structure-borne noise. For the most part, this is accomplished by using a material with a high internal energy-absorbing capacity (i.e., high internal damping).

Decibel (db). See "Sound Pressure Level."

Diffuse Sound Field. A sound field that at any given point is made up of sound waves of all angles of incidence.

Direct Field. The sound in a region in which all or most of the sound arrives directly from the source without reflection.

Flanking Transmission. The transmission of sound or noise from one room to another by indirect paths, rather than directly through an intervening partition.

Free Sound Field (Free Field). A field in a homogeneous, medium free from boundaries. In the free field, the sound pressure level decreases 6 db for a doubling of distance from a point source.

Impact Isolation Class (IIC). A single-figure rating that provides an estimate of the impact sound-isolating performance of a floor–ceiling assembly.

Intensity Level (IL). A measure of the acoustic power passing through a unit area expressed on a decibel scale referenced to some standard (usually 10^{-12} W/cm^2).

Loudness. The subjective human definition of the intensity of a sound.

Masking. The presence of a background noise increases the level to which a sound signal must be raised in order to be heard or distinguished. If the level of background noise is significantly higher than that of the sound signal, the signal cannot be heard. This effect is known as masking.

Mass Law. States that the transmission loss of walls (in a part of frequency range) is controlled entirely by the mass per unit area of the panel. Also that the transmission loss increases 6 db for each doubling of frequency or each doubling of the panel mass per unit area.

Noise. Any undesired sounds, usually of different frequencies, resulting in an objectionable or irritating sensation.

Noise Reduction (NR). (1) The reduction in sound pressure level caused by making some alteration to a sound source. (2) The difference in sound pressure level measured between two adjacent rooms caused by the transmission loss of the intervening wall.

Octave Band (OB). A range of frequency where the highest frequency of the band is double the lowest frequency of the band. The band is usually specified by the center frequency.

Phon. Loudness level, at a particular frequency, equal to the 1000-Hz decibel level of that equal-loudness contour.

Pink Noise. Wide frequency spectrum noise, whose amplitude drops 3 dB per octave with increasing frequency (equal energy per octave). Useful for masking.

Reverberation. The persistence or echoing of previously generated sound caused by reflection of acoustic waves from the surfaces of enclosed spaces.

Sabin. The unit of acoustic absorption. One sabin (ft^2) (m^2) is the absorption of 1 square foot (meter) of perfect sound-absorbing material.

Sound-Level Meter. An instrument for the direct measurement of sound pressure level. Sound-level meters may also incorporate octave-band filters for measuring sound directly in octave bands.

Sound Power Level (PWL). A measure of the total airborne acoustic power generated by a noise source, expressed on a decibel scale referenced to some standard (usually 10^{-12} W).

Sound Pressure Level (SPL). A measure of the air pressure change caused by a sound wave. Expressed on a decibel scale referenced to some standard (usually 0.0002 μbar).

Transmission Loss (TL). The reduction of airborne sound power that is caused by placing a wall or barrier between the reverberant sound field of a source and its receiver. Transmission loss is a property of the wall or barrier.

White Noise. Noise of wide frequency range in which the amplitude of the noise is essentially the same in all frequency bands (equal energy per frequency band).

27.39 Units and Conversions

See Table 27.15.

TABLE 27.15 **Acoustic Units and Conversions**

Units	*MKS*	*CGS*
Force	kilogram-meter/s^2 = newton	gram-cm/s^2 = dyne
Intensity	watts/meter^2	watts/cm^2
Pressure	newtons/meter^2 = pascals	dynes/cm^2 = microbars

	In Conversion:		
Quantity	*Multiply*	*By*	*To Obtain*
Force	newtons	10^5	dynes
	dynes	10^{-5}	newtons
Intensity	watts/cm^2	10^4	watts/m^2
	watts/m^2	10^{-4}	watts/cm^2
Pressure	pascals	10	microbars
	microbar	10^{-1}	pascals

NOTE. One atmosphere = 1 bar = 10^6 μbar.

27.40 Symbols

See Table 27.16.

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TABLE 27.16 **Symbols and Abbreviations Used Commonly in Acoustics**

A =	Total absorption, sabins; area in square inches or square feet
A_R =	Absorption in receiving room, sabins
$A_{1,2,\ldots}$ =	Total absorption of each different material in a space, sabins
c =	Velocity of sound, feet per second
d =	Distance from source, meters or feet
db =	Decibel
f =	Frequency of sound, hertz (cps)
I =	Intensity, watts per square centimeter
I_a =	Absorbed energy, watts per square centimeter
I_i =	Incident energy, watts per square centimeter
I_0 =	Reference intensity, 10^{-16} watt per square centimeter
IIC =	Impact insulation class, no units
IL =	Intensity level, decibels
NC =	Noise criterion, no units
NRC =	Noise reduction coefficient, no units
NR =	Noise reduction, decibels
p =	Pressure, pascals or microbars
p_0 =	Reference base pressure 2×10^{-5} Pa
P =	Acoustic power, watts
Pa =	Pascal, unit of pressure (SI)
PWL =	Sound pressure level, decibels
R =	Room constant, square feet
r =	Distance from source, meters or feet
S =	Surface area, square feet
SPL =	Sound pressure level, decibels
STC =	Sound transmission class, no units
T_R =	Reverberation time, seconds
TL =	Transmission loss, decibels
V =	Volume, cubic feet
W,P =	Sound power, watts
W_0 =	Reference base sound power 10^{-12} watt
a, α =	Absorption coefficient (no units)
$\bar{a}, \bar{\alpha}$ =	Average absorption coefficient (no units)
λ =	Wavelength, feet or meters
Σ =	Sum of, or total (no units)
$\Sigma S_\alpha = \Sigma A$ =	Total absorption, sabins
Δ =	Change in a quantity or difference between two quantities

NOTE. Where definitions are expressed in feet, centimeters or meters is also understood, with proper conversion factors, and vice versa.

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PART X
APPENDICES

The purpose of this part is to present extensive important reference and ancillary data in a separate, easily accessed section. The appendices are entitled:

A Climate Conditions for the United States, Canada, and Mexico

B Solar Data

C Annual Solar Performance

D Sunshading

E Economic Analysis

F Sound Transmission Data for Walls

G Sound Transmission and Impact Insulation Data for Floor/Ceiling Construction

H Options for Computation Assistance

I Metrication: SI Units; Conversions

J Building Automation: Intelligent Buildings

K ASHRAE Standards for Energy Efficient Building Design

A

CLIMATIC CONDITIONS FOR THE UNITED STATES, CANADA, AND MEXICO

Prepared by ASHRAE Technical Committee 4.2, Weather Data, from data compiled from official weather stations where hourly weather observations are made by trained observers.

Station Designations

AP = airport

CO = urban areas (influenced by surroundings)

No designation = semirural, similar to airport locations

S = solar data available from National Climatic Data Center

Winter Design Conditions

For United States: percentage of the three-month period, December through February.

For Canada: percentage for January.

Prevailing winter wind lists the direction from which the wind occurs most frequently with the 97.5% winter design dry-bulb temperature.

Summer Design Conditions

For United States: percentage of the four-month period, June through September.

For Canada: percentage for July.

Prevailing summer wind lists the direction from which the wind occurs most frequently with the 2.5% summer design dry-bulb temperature.

Other stations: Many more stations in each state or province are found in the *ASHRAE 1989 Handbook of Fundamentals*, Chapter 24.

Interpretations Between Stations. As a general rule, weather data from listed stations can be adjusted for nearby locations in these ways:

*Adjustment for elevation.** For lower elevations, which tend to be warmer, *increase* the design temperatures; for higher elevations, *decrease* the design temperatures:

Dry-bulb temperature: 1F° per 200 ft of elevation

Wet-bulb temperature: 1F° per 500 ft of elevation

Adjustment for air mass (at coastlines). Along the west coast, both dry-bulb and wet-bulb design temperatures increase with distance from the ocean. Along the Gulf coast, dry-bulb temperatures increase for the first 200 to 300 miles inland, while wet-bulb temperatures decrease slightly. (Beyond this 200- to 300-mile belt, both dry-bulb and wet-bulb values decrease.)

* Elevations for many locations are given in Appendix B, Table B.15.

TABLE A.1 **Outside Design Conditions: United States and Canada**

State and Station[a]	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
ALABAMA						
Auburn		22	93/76	21	78	
Birmingham AP	NNW	21	94/75	21	77	WNW
Huntsville AP	N	16	93/74	23	77	SW
Mobile AP	N	29	93/77	18	79	N
Montgomery AP	NW	25	95/76	21	79	W
ALASKA						
Anchorage AP	SE	−18	68/58	15	59	WNW
Fairbanks AP (S)	N	−47	78/60	24	62	S
Juneau AP	N	1	70/58	15	59	W
Nome AP	N	−27	62/55	10	56	W
ARIZONA						
Flagstaff AP	NE	4	82/55	31	60	SW
Phoenix AP (S)	E	34	107/71	27	75	W
Prescott AP		9	94/60	30	65	
Tuscon AP (S)	SE	32	102/66	26	71	WNW
Winslow AP	SW	10	95/60	32	65	WSW
Yuma AP	NNE	39	109/72	27	78	WSW
ARKANSAS						
Fayetteville AP	NE	12	94/73	23	76	SSW
Fort Smith AP	NW	17	98/76	24	79	SW
Little Rock AP (S)	N	20	96/77	22	79	SSW
Texarkana AP	WNW	23	96/77	21	79	SSW
CALIFORNIA						
Bakersfield AP	ENE	32	101/69	32	71	WNW
Barstow AP	WNW	29	104/68	37	71	W
Burbank AP	NW	39	91/68	25	70	S
Eureka/Arcata AP	E	33	65/59	11	60	NW
Fresno AP (S)	E	30	100/69	34	71	WNW
Long Beach AP	NW	43	80/68	22	69	WNW
Los Angeles AP (S)	E	43	80/68	15	69	WSW
Los Angeles CO (S)	NW	40	89/70	20	71	NW
Needles AP		33	110/71	27	75	
Oakland AP	E	36	80/63	19	64	WNW
Pomona CO	E	30	99/69	36	72	W
Redding AP		31	102/67	32	69	
Sacramento AP	NNW	32	98/70	36	71	SW
San Diego AP	NE	44	80/69	12	70	WNW
San Francisco AP	S	38	77/63	20	64	NW
San Francisco CO	W	40	71/62	14	62	W
San Luis Obispo	E	35	88/70	26	71	W
Santa Barbara AP	NE	36	77/66	24	67	SW
Santa Maria AP (S)	E	33	76/63	23	64	WNW
Santa Monica CO		43	80/68	16	69	
COLORADO						
Alamosa AP		−16	82/57	35	61	

TABLE A.1 Outside Design Conditions: United States and Canada (Continued)

State and Station[a]	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
Boulder		8	91/59	27	63	
Colorado Springs AP	N	2	88/57	30	62	S
Denver AP	S	1	91/59	28	63	SE
Fort Collins		−4	91/59	28	63	
Grand Junction AP (S)	ESE	7	94/59	29	63	WNW
Leadville		−4	81/51	30	55	
Pueblo AP	W	0	95/61	31	66	SE
CONNECTICUT						
Bridgeport AP	NNW	9	84/71	18	74	WSW
Hartford	N	7	88/73	22	75	SSW
New Haven AP	NNE	7	84/73	17	75	SW
DELAWARE						
Wilmington AP	WNW	14	89/74	20	76	WSW
DISTRICT OF COLUMBIA						
Washington National AP	WNW	17	91/74	18	77	S
FLORIDA						
Daytona Beach AP	NW	35	90/77	15	79	(—)
Fort Myers AP	NNE	44	92/78	18	79	W
Gainesville AP (S)	W	31	93/77	18	79	W
Jacksonville AP	NW	32	94/77	19	79	SW
Key West AP	NNE	57	90/78	9	79	SE
Miami AP (S)	NNW	47	90/77	15	79	SE
Miami Beach CO		48	89/77	10	79	
Orlando AP	NNW	38	93/76	17	78	SSW
Panama City, Tyndall AFB	N	33	90/77	14	80	WSW
Pensacola CO	NNE	29	93/77	14	79	SW
Tallahassee AP (S)	NW	30	92/76	19	78	NW
Tampa AP (S)	N	40	91/77	17	79	W
West Palm Beach AP	NW	45	91/78	16	79	ESE
GEORGIA						
Athens	NW	22	92/74	21	77	WNW
Atlanta AP (S)	NW	22	92/74	19	76	NW
Augusta AP	W	23	95/76	19	79	WSW
Columbus, Lawson AFB	NW	24	93/76	21	78	W
Macon AP	NW	25	93/76	22	78	WNW
Rome AP		22	93/76	23	78	
Savannah-Travis AP	WNW	27	93/77	20	79	SW
Valdosta-Moody AFB	WNW	31	94/77	20	79	W
HAWAII						
Hilo AP (S)	SW	62	83/72	15	74	NE
Honolulu AP	ENE	63	86/73	12	75	ENE
Wahiawa	WNW	59	85/72	14	74	E
IDAHO						
Boise AP (S)	SE	10	94/64	31	66	NW

TABLE A.1 Outside Design Conditions: United States and Canada (Continued)

State and Station	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
Lewiston AP	W	6	93/64	32	66	WNW
Moscow		0	87/62	32	64	
Pocatello AP	NE	−1	91/60	35	63	W
ILLINOIS						
Carbondale		7	93/77	21	79	
Champaign/Urbana	W	2	92/74	21	77	SSW
Chicago, O'Hare AP	WNW	−4	89/74	20	76	SW
Chicago CO		2	91/74	15	77	
Moline AP	WNW	−4	91/75	23	77	SW
Peoria AP	WNW	−4	89/74	22	76	SW
Rockford		−4	89/73	24	76	
Springfield AP	NW	2	92/74	21	77	SW
INDIANA						
Evansville AP	NW	9	93/75	22	78	SW
Fort Wayne AP	WSW	1	89/72	24	75	SW
Indianapolis AP (S)	WNW	2	90/74	22	76	SW
Lafayette		3	91/73	22	76	
Muncie		2	90/73	22	76	
South Bend AP	SW	1	89/73	22	75	SSW
Terre Haute AP	NNW	4	92/74	22	77	SSW
IOWA						
Ames (S)	NW	−6	90/74	23	76	
Burlington AP	NW	−3	91/75	22	77	SSW
Des Moines AP	N	−5	91/74	23	77	S
Dubuque	NW	−7	88/73	22	75	SSW
Iowa City	NW	−6	89/76	22	78	SSW
Mason City AP	NNW	−11	88/74	24	75	S
Sioux City AP	NW	−7	92/74	24	77	S
Waterloo		−10	89/75	23	77	S
KANSAS	N					
Dodge City AP (S)	WSW	5	97/69	25	73	SSW
Goodland AP	NNE	0	96/65	31	70	S
Manhattan, Fort Riley (S)	NNW	3	95/75	24	77	S
Topeka AP	NNW	4	96/75	24	78	S
Wichita AP		7	98/73	23	76	SSW
KENTUCKY						
Bowling Green AP	WNW	10	92/75	21	77	
Lexington AP (S)	NW	8	91/73	22	76	SW
Louisville AP		10	93/74	23	77	SW
LOUISIANA	N					
Alexandria AP	ENE	27	94/77	20	79	S
Baton Rouge AP	N	29	93/77	19	80	W
Lafayette AP	N	30	94/78	18	80	SW
Lake Charles AP (S)		31	93/77	17	79	SSW

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TABLE A.1 **Outside Design Conditions: United States and Canada (Continued)**

State and Station	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
Monroe AP	N	25	96/76	20	79	S
New Orleans AP	NNE	33	92/78	16	80	SSW
Shreveport AP (S)	N	25	96/76	20	79	S
MAINE						
Bangor, Dow AFB	WNW	−6	83/68	22	71	S
Caribou AP (S)	WSW	−13	81/67	21	69	SW
Portland (S)	W	−1	84/71	22	72	S
MARYLAND						
Baltimore AP	W	13	91/75	21	77	WSW
Baltimore CO	WNW	17	89/76	17	78	S
Cumberland	WNW	10	89/74	22	76	W
Frederick AP	N	12	91/75	22	77	WNW
Salisbury (S)		16	91/75	18	77	
MASSACHUSETTS						
Boston AP (S)	WNW	9	88/71	16	74	SW
Pittsfield AP	NW	−3	84/70	23	72	SW
Worcester AP	W	4	84/70	18	72	W
MICHIGAN						
Alpena AP	W	−6	85/70	27	72	SW
Detroit	W	6	88/72	20	74	SW
Escanaba		−7	83/69	17	71	
Flint AP	SW	1	87/72	25	74	SW
Grand Rapids AP	WNW	5	88/72	24	74	WSW
Muskegon AP	E	6	84/70	21	73	SW
Sault Ste. Marie AP (S)	E	−8	81/69	23	70	SW
Traverse City AP	SSW	1	86/71	22	73	SW
MINNESOTA						
Bemidji AP	N	−26	85/69	24	71	S
Duluth AP	WNW	−16	82/68	22	70	WSW
International Falls AP	N	−25	83/68	26	70	S
Minneapolis/St. Paul AP	NW	−12	89/73	22	75	S
Rochester AP	NW	−12	87/72	24	75	SSW
MISSISSIPPI						
Columbus AFB	N	20	93/77	22	79	W
Jackson AP	NNW	25	95/76	21	78	NW
Meridian AP	N	23	95/76	22	79	WSW
Vicksburg CO		26	95/78	21	80	
MISSOURI						
Columbia AP (S)	WNW	4	94/74	22	77	WSW
Kansas City AP	NW	6	96/74	20	77	S
St Louis AP	NW	6	94/75	21	77	WSW
St Louis CO	NW	8	94/75	18	77	S
Springfield AP	NNW	9	93/74	23	77	S
MONTANA						
Billings AP	NE	−10	91/64	31	66	SW
Bozeman		−14	87/60	32	62	

TABLE A.1 **Outside Design Conditions: United States and Canada (Continued)**

State and Station	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
Cut Bank AP		−20	85/61	35	62	
Glasgow AP (S)	E	−18	89/63	29	66	S
Great Falls AP (S)	SW	−15	88/60	28	62	WSW
Helena AP	N	−16	88/60	32	62	WNW
Kalispell AP		−7	87/61	34	63	
Lewistown AP	NW	−16	87/61	30	63	NW
Miles City AP	NW	−15	95/66	30	68	SE
Missoula AP	ESE	−6	88/61	36	63	NW
NEBRASKA						
Grand Island AP	NNW	−3	94/71	28	74	S
Lincoln CO (S)	N	−2	95/74	24	77	S
North Platte AP (S)	NW	−4	94/69	28	72	SSE
Omaha AP	NW	−3	91/75	22	77	S
Scottsbluff AP	NW	−3	92/65	31	68	SE
NEVADA						
Elko AP	E	−2	92/59	42	62	SW
Ely AP (S)	S	−4	87/56	39	59	SSW
Las Vegas AP (S)	ENE	28	106/65	30	70	SW
Lovelock AP		12	96/63	42	65	
Reno AP (S)	SSW	10	92/60	45	62	WNW
Tonopah AP	N	10	92/59	40	62	S
Winnemucca AP	SE	3	94/60	42	62	W
NEW HAMPSHIRE						
Berlin		−9	84/69	22	71	
Concord AP		−3	87/70	26	73	SW
Portsmouth, Pease AFB	NW	2	85/71	22	74	W
NEW JERSEY	W					
Atlantic City CO		13	89/74	18	77	WSW
Newark AP	NW	14	91/73	20	76	WSW
Trenton CO	WNW	14	88/74	19	76	SW
NEW MEXICO	W					
Albuquerque AP (S)		16	94/61	27	65	W
Farmington AP	N	6	93/62	30	65	SW
Las Cruces	ENE	20	96/64	30	68	SE
Los Alamos	SE	9	87/60	32	61	
Raton AP		1	89/60	34	64	
Roswell, Walker AFB		18	98/66	33	70	SSE
Silver City AP	N	10	94/60	30	64	
Tucumcari AP		13	97/66	28	69	SW
NEW YORK	NE					
Albany AP (S)		−1	88/72	23	74	S
Binghamton AP	WNW	1	83/69	20	72	WSW
Buffalo AP	WSW	6	85/70	21	73	SW
Ithaca (S)	W	0	85/71	24	73	SW
Massena AP	W	−8	83/69	20	72	
NYC—Central Park (S)		15	89/73	17	75	

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TABLE A.1 **Outside Design Conditions: United States and Canada (Continued)**

State and Station	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
NYC—Kennedy AP	WNW	15	87/72	16	75	SSW
Rochester AP	WSW	5	88/71	22	73	WSW
Syracuse AP	N	2	87/71	20	73	WNW
NORTH CAROLINA						
Asheville AP	NNW	14	87/72	21	74	NNW
Charlotte AP	NNW	22	93/74	20	76	SW
Greensboro AP (S)	NE	18	91/73	21	76	SW
Raleigh/Durham AP (S)	N	20	92/75	20	77	SW
Wilmington AP	N	26	91/78	18	80	SW
NORTH DAKOTA						
Bismarck AP (S)	WNW	−19	91/68	27	71	S
Fargo AP	SSE	−18	89/71	25	74	S
Minot AP	WSW	−20	89/67	25	70	S
Williston		−21	88/67	25	70	
OHIO						
Akron-Canton AP	SW	6	86/71	21	73	SW
Cincinnati CO	W	6	90/72	21	75	SW
Cleveland AP (S)	SW	5	88/72	22	74	N
Columbus AP (S)	W	5	90/73	24	75	SSW
Dayton AP	WNW	4	89/72	20	75	SW
Mansfield AP	W	5	87/72	22	74	SW
Toledo AP	WSW	1	88/73	25	75	SW
Youngstown AP	SW	4	86/71	23	73	SW
OKLAHOMA						
Norman	N	13	96/74	24	76	S
Oklahoma City AP (S)	N	13	97/74	23	77	SSW
Stillwater (S)	N	13	96/74	24	76	SSW
Tulsa AP	N	13	98/75	22	78	SSW
OREGON						
Astoria AP (S)	ESE	29	71/62	16	63	NNW
Bend		4	87/60	33	62	
Eugene AP	N	22	89/66	31	67	N
Medford AP (S)	S	23	94/67	35	68	WNW
Pendleton AP	NNW	5	93/64	29	65	WNW
Portland AP	ESE	23	85/67	23	67	NW
Portland CO		24	86/67	21	67	
Salem AP	N	23	88/66	31	68	N
PENNSYLVANIA						
Allentown AP	W	9	88/72	22	75	SW
Erie AP	SSW	9	85/72	18	74	WSW
Harrisburg AP	NW	11	91/74	21	76	WSW
Philadelphia AP	WNW	14	90/74	21	76	WSW
Pittsburgh AP	WSW	5	86/71	22	73	WSW
Pittsburgh CO		7	88/71	19	73	WSW
Scranton/Wilkes-Barre	SW	5	87/71	19	73	WSW
State College (S)	NNW	7	87/71	23	73	

TABLE A.1 **Outside Design Conditions: United States and Canada (Continued)**

State and Station	Winter: Prevailing Wind	Winter: Design Dry-Bulb (97.5%)	Summer: Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)	Summer: Mean Daily Range	Summer: Design Wet-Bulb (2.5%)	Summer: Prevailing Wind
RHODE ISLAND						
Newport (S)	WNW	9	85/72	16	75	SW
Providence AP	WNW	9	86/72	19	74	SW
SOUTH CAROLINA						
Anderson	NNE	23	92/74	21	76	SW
Charleston AFB (S)		27	91/78	18	80	
Charleston CO	W	28	92/78	13	80	SW
Columbia AP		24	95/75	22	78	
Spartanburg AP		22	91/74	20	76	
SOUTH DAKOTA						
Huron AP	NNW	−14	93/72	28	75	S
Pierre AP	NW	−10	95/71	29	74	SSE
Rapid City AP (S)	NNW	−7	92/65	28	69	SSE
Sioux Falls AP	NW	−11	91/72	24	75	S
TENNESSEE						
Bristol–Tri City AP	WNW	14	89/72	22	75	SW
Chattanooga AP	NNW	18	93/74	22	77	WSW
Knoxville AP	NE	19	92/73	21	76	W
Memphis AP	N	18	95/76	21	79	SW
Nashville AP (S)	NW	14	94/74	21	77	WSW
TEXAS						
Abilene AP	N	20	99/71	22	74	SSE
Amarillo AP	N	11	95/67	26	70	S
Austin AP	N	28	98/74	22	77	S
Brownsville AP (S)	NNW	39	93/77	18	79	SE
Bryan AP		29	96/76	20	78	
Corpus Christi AP	N	35	94/78	19	80	SSE
Dallas AP	N	22	100/75	20	78	S
Del Rio, Laughlin AFB		31	98/73	24	77	
El Paso AP (S)	N	24	98/64	27	68	S
Forth Worth AP (S)	NW	22	99/74	22	77	S
Galveston AP	N	36	89/79	10	80	S
Houston AP	NNW	32	94/77	18	79	S
Houston CO		33	95/77	18	79	
Laredo AFB	N	36	101/73	23	78	SE
Lubbock AP	NNE	15	96/69	26	72	SSE
Lufkin AP	NNW	29	97/76	20	79	S
Midland AP (S)	NE	21	98/69	26	72	SSE
Port Arthur AP	N	31	93/78	19	80	S
San Angelo, Goodfellow AFB	NNE	22	99/71	24	74	SSE
San Antonio AP (S)	N	30	97/73	19	76	SSE
Sherman Perrin AFB	N	20	98/75	22	77	S
Waco AP		26	99/75	22	78	
Wichita Falls AP	NNW	18	101/73	24	76	S
UTAH						
Cedar City AP	SE	5	91/60	32	63	SW

APPENDICES

TABLE A.1 **Outside Design Conditions: United States and Canada (Continued)**

	Winter	Summer				
State and Station	*Prevailing Wind*	*Design Dry-Bulb (97.5%)*	*Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)*	*Mean Daily Range*	*Design Wet-Bulb (2.5%)*	*Prevailing Wind*
Salt Lake City AP (S)	SSE	8	95/62	32	65	N
Vernal AP		0	89/60	32	63	
VERMONT						
Barre		−11	81/69	23	71	
Burlington AP (S)	E	−7	85/70	23	72	SSW
VIRGINIA						
Charlottesville	NE	18	91/74	23	76	SW
Norfolk AP	NW	22	91/76	18	78	SW
Richmond AP	N	17	92/76	21	78	SW
Roanoke AP	NW	16	91/72	23	74	SW
WASHINGTON						
Bellingham AP	NNE	15	77/65	19	65	WSW
Olympia AP	NE	22	83/65	32	66	NE
Seattle CO (S)	N	27	82/66	19	67	N
Seattle-Tacoma AP (S)	E	26	80/64	22	64	N
Spokane AP (S)	NE	2	90/63	28	64	SW
Walla Walla AP	W	7	94/66	27	67	W
Yakima AP	W	5	93/65	36	66	NW
WEST VIRGINIA						
Beckley	WNW	4	81/69	22	71	WNW
Charleston AP	SW	11	90/73	20	75	SW
Huntington CO	W	10	91/74	22	77	SW
Wheeling	WSW	5	86/71	21	73	WSW
WISCONSIN						
Ashland		−16	82/68	23	70	
Eau Claire AP		−11	89/73	23	75	
Green Bay AP	W	−9	85/72	23	74	SW
La Cross AP	NW	−9	88/73	22	75	S
Madison AP (S)	NW	−7	88/73	22	75	SW
Milwaukee AP	WNW	−4	87/73	21	74	SSW
WYOMING						
Casper AP	NE	−5	90/57	31	61	SW
Cheyenne AP	N	−1	86/58	30	62	WNW
Lander AP (S)	E	−11	88/61	32	63	NW
Laramie AP (S)		−6	81/56	28	60	
Rock Springs AP	WSW	−3	84/55	32	58	W
Sheridan AP	NW	−8	91/62	32	65	N
Province and Station						
ALBERTA						
Calgary AP	NNW	−23	81/61	25	63	SE
Edmonton AP	E	−25	82/65	23	66	SE
Medicine Hat AP		−24	90/65	28	68	
BRITISH COLUMBIA						
Dawson Creek		−33	79/63	26	64	

TABLE A.1 **Outside Design Conditions: United States and Canada (Continued)**

	Winter	Summer				
State and Station	*Prevailing Wind*	*Design Dry-Bulb (97.5%)*	*Design Dry-Bulb and Mean Coincident Wet-Bulb (2.5%)*	*Mean Daily Range*	*Design Wet-Bulb (2.5%)*	*Prevailing Wind*
Nanaimo (S)		20	80/65	21	66	
Prince George AP (S)	N	−28	80/62	26	64	N
Prince Rupert CO		2	63/57	12	58	
Vancouver AP (S)	E	19	77/66	17	67	WNW
Victoria CO		23	73/62	16	62	
MANITOBA						
Flin Flon		−37	81/66	19	68	
Winnipeg AP (S)	W	−27	86/71	22	73	S
NEW BRUNSWICK						
Fredericton AP (S)		−11	85/69	23	71	
Saint John AP		−8	77/65	19	68	
NEWFOUNDLAND						
Corner Brook		0	73/63	17	66	
St. John's AP (S)	N	7	75/65	18	67	WSW
NORTHWEST TERR.						
Fort Smith AP (S)	NW	−45	81/64	24	66	S
Inuvik (S)		−53	77/60	21	62	
Yellowknife AP	SSE	−46	77/61	16	63	S
NOVA SCOTIA						
Halifax AP (S)		5	76/65	16	67	
Sydney AP		3	80/68	19	70	
Yarmouth AP	NW	9	72/64	15	66	S
ONTARIO						
Kitchener		−2	85/72	23	74	
Ottawa AP (S)		−13	87/71	21	73	
Sudbury AP		−19	83/67	22	70	
Toronto AP (S)	N	−1	87/72	20	74	SW
PRINCE EDWARD ISLAND						
Charlottetown AP (S)		−4	78/68	16	70	
QUEBEC						
Chicoutimi		−22	83/68	20	70	
Montréal AP (S)		−10	85/72	17	74	
Québec AP		−14	84/70	20	72	
Sept Iles AP (S)		−21	73/61	17	65	
Val d'Or AP		−27	83/68	22	70	
SASKATCHEWAN						
Prince Albert AP		−35	84/66	25	68	
Regina AP		−29	88/68	26	70	
Saskatoon AP (S)		−31	86/66	26	68	
YUKON TERRITORY						
Whitehorse AP (S)	NW	−43	77/58	22	59	SE

*S = solar data available. U.S. solar data available from the National Climatic Data Center, Federal Building, Ashville, NC 28801. Canadian solar data available from The Canadian Climate Center, Atmospheric Environment Service, 4905 Dufferin St., Downsview, Ontario M3H 5T 4.

APPENDICES

TABLE A.2 **Outdoor Design Conditions: Mexico and Puerto Rico**

	Winter[a]	Summer[b]		
Country and Station	Design Dry-Bulb 97.5%	Design Dry-Bulb 2.5%	Mean Daily Range	Design Wet-Bulb 2.5%
MEXICO				
Guadalajara	42	91	29	67
Mérida	61	95	21	79
Mexico City	39	81	25	60
Monterrey	41	95	20	78
Vera Cruz	62	89	20	83
PUERTO RICO				
San Juan	68	88	11	80

[a]For the three-month winter period

[b]For the four-month summer period

B
SOLAR DATA

This appendix presents both *clear day* and *average day* data.

Solar Intensity and Solar Heat Gain Factors (Tables B.1–B.10). These are listed for five latitudes; solar heat gain factors occur through one layer of double-strength sheet (DSA) glass. The data are based on an "average cloudless" day at each latitude. Tables B.1 through B.10 are copyrighted by the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta, Ga., and are reprinted by permission from *ASHRAE 1989 Handbook of Fundamentals*.

Solar Position and Clear Day Global Irradiance (Insolation) (Tables B.11–B.14). These are listed for four latitudes. The data are presented in conventional units for the following tilt angles (degrees above horizontal): latitude −10°, latitude, latitude +10°, latitude +20°, and vertical. To convert to SI units: Btu/h-ft² × 3.152 = W/m².

Elevation, Latitude, Average Horizontal Insolation, Average Vertical Insolation, Average Temperature, and Heating Degree Days (Table B.15). These are listed in conventional units for January and July, as well as yearly totals, for a number of locations (Fig. B.1). To convert horizontal surface (HS) and vertical surface (VS) to SI units: Btu/h ft² × 3.152 = W/m². To convert average temperature (TA) to Celsius: (°F − 32)/1.8 = °C. To convert DD(F) to DD(C): DD(F) × 9/5 = DD(C) or DD(K).

TABLE B.1 Solar Intensity and Solar Heat Gain Factors[a] for 16° N Latitude (Conventional Units)[b]

Date	Solar Time am	Direct Normal Btu/ft² h	Solar Heat Gain Factors, Btu/ft² h: N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time pm
Jan 21	7	141	3	6	44	93	134	134	126	96	49	8	3	3	3	3	3	3	3	5
	8	262	14	15	53	147	210	240	233	189	114	25	14	14	14	14	14	14	14	4
	9	360	21	21	53	122	200	244	251	218	152	54	32	21	21	21	21	21	21	3
	10	431	28	28	51	87	162	210	239	233	178	102	51	28	28	28	28	28	28	2
	11	472	34	34	49	51	111	168	195	210	194	146	91	51	34	34	34	34	34	1
	12	487	37	37	46	34	72	133	164	179	184	164	118	71	39	39	39	39	39	12
HALF DAY TOTALS			170	172	736	861	1360	1800	1896	1820	1581	826	411	222	111	111	111	111	111	
Feb 21	7	142	9	17	84	138	168	172	150	103	36	8	8	8	8	8	8	8	8	5
	8	273	17	19	98	180	231	247	224	166	71	18	17	17	17	17	17	17	17	4
	9	372	23	24	84	153	219	242	231	188	110	30	23	23	23	23	23	23	23	3
	10	438	28	29	57	92	183	202	211	188	134	61	30	28	28	28	28	28	28	2
	11	468	32	32	32	51	83	136	167	172	149	102	49	32	32	32	32	32	32	1
	12	478	33	33	33	33	34	80	107	142	154	142	106	60	33	33	33	33	33	12
HALF DAY TOTALS			174	177	521	809	865	1033	1034	885	582	283	174	111	114	124	124	124	124	
Mar 21	7	101	5	33	124	172	192	183	143	82	15	10	10	10	10	10	10	10	10	6
	8	213	20	50	140	205	219	211	175	121	32	19	19	19	19	19	19	19	19	4
	9	306	28	53	109	179	218	219	195	138	57	27	26	26	26	26	26	26	26	3
	10	372	33	53	81	130	185	182	172	134	74	34	32	31	31	31	31	31	31	2
	11	410	34	53	58	83	87	114	125	116	89	35	35	34	34	34	34	34	34	1
	12	420	35	53	56	56	57	67	80	91	86	58	47	37	36	36	36	36	36	12
HALF DAY TOTALS			141	324	694	111	928	971	879	643	319	187	151	102	139	139	139	139	139	
Apr 21	6	19	3	4	12	14	14	12	8	3	1	1	1	1	1	1	1	1	1	6
	7	197	24	34	133	187	191	167	117	43	14	13	13	13	13	13	13	13	13	5
	8	298	37	39	172	218	221	204	150	68	24	22	22	22	22	22	22	22	22	4
	9	380	51	39	149	193	208	197	147	77	31	29	29	29	29	29	29	29	29	3
	10	293	55	34	102	142	138	111	120	73	33	34	33	33	33	33	33	33	33	2
	11	299	58	40	54	72	85	88	79	60	43	38	38	36	36	36	36	36	36	1
	12	301	59	39	39	40	40	41	43	43	43	43	43	41	40	39	39	39	39	12
HALF DAY TOTALS			179	401	674	819	922	851	633	332	174	159	157	136	151	151	151	151	151	
May 21	6	64	14	30	61	83	83	54	19	4	1	1	1	1	1	1	1	1	1	6
	7	193	50	120	168	191	181	150	93	34	16	16	16	16	16	16	16	16	16	5
	8	244	52	132	189	218	215	179	115	58	25	24	24	24	24	24	24	24	24	4
	9	264	49	114	171	198	197	167	109	45	32	30	30	30	30	30	30	30	30	3
	10	280	47	89	130	151	150	126	84	44	37	35	35	35	35	35	35	35	35	2
	11	288	47	83	99	97	83	70	52	41	40	39	38	38	38	38	38	38	38	1
	12	288	46	46	46	44	43	42	41	41	41	41	41	41	42	42	42	42	42	12
HALF DAY TOTALS			283	573	804	916	897	748	493	217	172	167	167	167	167	167	167	167	167	
Jun 21	6	31	20	39	52	55	51	39	20	6	4	4	4	4	4	4	4	4	4	6
	7	188	63	128	172	190	179	141	80	30	16	16	16	16	16	16	16	16	16	5
	8	238	66	142	184	217	207	167	99	31	25	25	25	25	25	25	25	25	25	4
	9	261	63	130	178	198	190	154	93	31	31	31	31	31	31	31	31	31	31	3
	10	273	59	104	140	154	145	115	70	39	37	36	36	36	36	36	36	36	36	2
	11	278	57	76	90	92	82	63	46	41	40	39	39	39	40	41	42	42	42	1
	12	281	57	55	50	45	43	42	41	41	41	41	41	42	42	43	43	43	43	12
HALF DAY TOTALS			556	648	850	929	876	700	430	194	174	171	171	171	172	173	174	175	176	
Jul 21	6	41	14	29	39	42	40	31	18	4	3	3	3	3	3	3	3	3	3	6
	7	184	51	118	164	185	179	145	88	33	16	16	16	16	16	16	16	16	16	5
	8	236	55	132	187	214	210	174	111	37	25	25	25	25	25	25	25	25	25	4
	9	259	52	117	170	196	193	163	106	44	32	31	31	31	31	31	31	31	31	3
	10	272	50	92	131	151	148	123	81	44	38	36	36	36	36	36	36	36	36	2
	11	278	49	66	81	88	83	69	52	42	41	40	39	39	39	40	40	42	42	1
	12	279	49	48	46	46	44	43	42	42	42	42	42	42	43	44	46	48	48	12
HALF DAY TOTALS			296	580	799	903	878	729	478	215	176	172	171	171	171	172	173	174	175	
Aug 21	6	11	2	7	10	12	12	10	6	2	1	1	1	1	1	1	1	1	1	6
	7	180	26	92	145	176	180	156	109	42	15	14	14	14	14	14	14	14	14	5
	8	240	35	100	168	209	219	196	145	65	23	23	23	23	23	23	23	23	23	4
	9	268	33	82	148	190	203	187	142	74	33	30	30	30	30	30	30	30	30	3
	10	279	37	58	104	140	155	147	117	71	39	36	35	35	35	35	35	35	35	2
	11	281	40	41	57	75	86	87	78	59	44	40	39	38	38	38	38	39	39	1
	12	287	41	41	41	42	42	42	42	43	44	45	44	43	42	41	41	41	41	12
HALF DAY TOTALS			191	410	666	831	891	817	624	339	180	167	163	164	161	161	161	161	164	
Sep 21	7	179	12	30	114	158	176	168	133	76	15	11	11	11	11	11	11	11	11	6
	8	251	21	49	134	196	227	224	186	119	36	20	20	20	20	20	20	20	20	5
	9	281	28	56	106	171	211	217	191	134	57	28	27	27	27	27	27	27	27	4
	10	295	32	54	81	118	161	178	168	132	76	35	33	32	32	32	32	32	32	3
	11	303	35	56	57	74	88	113	123	114	88	56	38	36	35	35	35	35	35	2
	12	304	36	36	37	38	39	49	69	86	93	86	69	48	39	38	37	36	36	1
HALF DAY TOTALS			146	324	471	722	885	931	842	622	319	192	159	148	145	144	144	144	144	
Oct 21	7	146	8	18	78	128	156	159	139	95	33	9	8	8	8	8	8	8	8	5
	8	229	17	20	95	174	223	237	215	159	74	19	17	17	17	17	17	17	17	4
	9	292	24	23	83	150	209	233	225	182	106	31	24	24	24	24	24	24	24	3
	10	307	29	30	54	92	158	197	205	183	130	60	31	29	29	29	29	29	29	2
	11	314	32	32	33	39	83	133	163	167	145	100	49	34	32	32	32	32	32	1
	12	316	33	33	33	34	35	60	105	139	150	138	104	60	33	34	33	33	33	12
HALF DAY TOTALS			127	141	318	592	836	986	996	853	563	283	175	136	128	127	127	127	127	
Nov 21	7	134	5	6	42	89	119	129	120	92	47	6	5	5	5	5	5	5	5	5
	8	233	15	15	55	143	206	233	228	185	111	25	15	15	15	15	15	15	15	4
	9	295	21	21	53	121	197	241	247	215	150	57	22	21	21	21	21	21	21	3
	10	312	28	28	28	67	141	206	230	220	176	100	31	28	28	28	28	28	28	2
	11	320	29	29	29	31	77	146	192	207	191	144	74	31	29	29	29	29	29	1
	12	322	30	30	30	30	32	72	131	181	196	181	127	72	32	30	30	30	30	12
HALF DAY TOTALS			112	111	197	436	749	983	1077	1001	767	420	210	128	112	112	112	112	112	
Dec 21	7	118	4	3	30	72	101	112	107	85	48	7	4	4	4	4	4	4	4	6
	8	225	13	14	61	132	198	225	231	193	124	33	13	13	13	13	13	13	13	5
	9	297	20	20	23	108	191	241	254	227	165	72	21	20	20	20	20	20	20	4
	10	315	25	25	25	36	144	208	239	233	192	117	35	25	25	25	25	25	25	3
	11	323	28	28	28	29	73	150	202	221	207	161	86	30	28	28	28	28	28	2
	12	325	29	29	29	29	30	77	149	197	212	196	149	76	30	29	29	29	29	1
HALF DAY TOTALS			104	105	119	402	710	971	1099	1050	836	484	228	125	105	104	104	104	104	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).

[b]Half-day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.2 Solar Intensity and Solar Heat Gain Factors[a] for 32° N Latitude (Conventional Units)[b]

Date	Solar Time am	Direct Normal Btu/ft² h	Solar Heat Gain Factors, Btu/ft² h: N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time pm
Jan 21	7	1	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	5
	8	253	9	9	29	103	160	184	184	174	135	74	9	9	9	9	9	9	9	4
	9	389	15	15	37	91	173	229	249	235	189	82	17	15	15	15	15	15	15	3
	10	495	20	20	41	63	119	209	249	250	212	116	20	20	20	20	20	20	20	2
	11	506	23	23	43	44	64	129	221	243	228	170	110	26	23	23	23	23	23	1
	12	510	24	24	44	44	45	64	174	228	240	228	174	88	25	24	24	24	24	12
HALF DAY TOTALS			78	79	197	384	578	816	1011	1064	952	572	364	172	80	78	78	78	78	
Feb 21	7	112	4	7	43	83	103	106	85	47	16	4	4	4	4	4	4	4	4	5
	8	265	13	14	85	169	215	228	214	170	97	17	13	13	13	13	13	13	13	4
	9	387	19	19	72	132	199	241	248	218	150	55	20	19	19	19	19	19	19	3
	10	505	24	24	55	83	151	212	241	233	189	112	31	24	24	24	24	24	24	2
	11	514	26	26	26	28	56	126	208	237	233	183	85	28	26	26	26	26	26	1
	12	516	27	27	27	27	29	74	155	204	222	204	155	74	29	27	27	27	27	12
HALF DAY TOTALS			100	101	201	441	715	978	1280	1355	1185	693	478	228	132	100	100	100	100	
Mar 21	7	181	10	37	155	213	218	175	142	88	24	9	9	9	9	9	9	9	9	5
	8	340	17	35	197	283	277	227	157	89	25	17	17	17	17	17	17	17	17	4
	9	390	23	35	64	151	218	237	223	177	107	30	23	23	23	23	23	23	23	3
	10	304	28	28	30	87	159	202	215	195	144	70	30	28	28	28	28	28	28	2
	11	311	31	31	31	54	83	143	179	188	170	128	58	34	31	31	31	31	31	1
	12	313	32	32	32	32	32	66	132	163	175	163	132	66	32	32	32	32	32	12
HALF DAY TOTALS			134	162	359	629	873	1011	1041	884	589	338	196	115	134	134	134	134	134	
Apr 21	6	66	9	33	54	65	66	56	36	18	5	3	3	3	3	3	3	3	3	6
	7	206	17	80	148	188	200	182	136	69	16	14	14	14	14	14	14	14	14	5
	8	315	25	61	184	230	227	189	127	59	22	22	22	22	22	22	22	22	22	4
	9	378	28	36	105	168	206	202	165	113	38	28	28	28	28	28	28	28	28	3
	10	390	32	34	52	108	155	197	192	161	87	39	32	32	32	32	32	32	32	2
	11	393	35	35	36	47	83	138	181	185	155	108	70	40	36	35	35	35	35	1
	12	397	36	36	36	37	38	53	82	106	117	106	82	53	38	37	36	36	36	12
HALF DAY TOTALS			161	296	550	793	952	992	889	661	360	228	177	137	153	153	153	153	153	
May 21	6	118	33	72	108	131	118	84	36	11	4	3	3	3	3	3	3	3	3	6
	7	211	36	111	170	202	204	174	118	62	19	18	18	18	18	18	18	18	18	5
	8	250	39	94	183	208	200	159	99	41	25	25	25	25	25	25	25	25	25	4
	9	269	37	81	138	171	168	135	90	41	32	31	31	31	31	31	31	31	31	3
	10	280	36	80	76	121	130	116	88	44	37	36	36	36	36	36	36	36	36	2
	11	285	39	39	42	59	83	99	102	80	48	41	40	39	39	40	41	42	42	1
	12	286	38	39	40	40	41	47	59	73	74	70	59	47	41	40	40	39	39	12
HALF DAY TOTALS			322	438	702	900	985	911	741	647	395	298	183	177	174	174	174	175	1088	
Jun 21	6	131	44	92	133	155	137	99	51	13	10	10	10	10	10	10	10	10	10	6
	7	210	47	122	174	204	201	168	108	35	20	20	20	20	20	20	20	20	20	5
	8	245	46	106	171	208	214	189	135	68	28	27	27	27	27	27	27	27	27	4
	9	264	43	74	137	178	193	180	139	77	33	32	32	32	32	32	32	32	32	3
	10	274	38	47	86	135	166	161	123	83	45	38	36	36	36	36	36	36	36	2
	11	279	40	41	47	64	82	91	89	73	56	45	41	40	39	39	39	39	39	1
	12	280	41	41	41	42	42	46	52	58	60	58	52	46	42	41	41	41	41	12
HALF DAY TOTALS			361	504	762	955	985	897	678	372	225	197	189	185	184	184	184	184	1123	
Jul 21	6	113	34	76	105	117	113	90	53	13	9	9	9	9	9	9	9	9	9	6
	7	203	38	111	167	198	198	169	114	41	20	19	19	19	19	19	19	19	19	5
	8	241	31	93	163	204	213	184	135	70	28	26	26	26	26	26	26	26	26	4
	9	261	34	64	129	173	195	186	150	90	37	32	32	32	32	32	32	32	32	3
	10	271	37	42	78	121	158	153	134	96	51	38	36	36	36	36	36	36	36	2
	11	277	39	40	43	60	83	98	99	83	66	47	41	40	40	40	40	40	40	1
	12	279	40	40	41	41	42	48	58	66	72	68	58	48	42	41	41	41	41	12
HALF DAY TOTALS			231	444	701	890	967	913	726	433	248	202	187	182	180	179	174	180	1088	
Aug 21	6	59	10	33	50	60	60	51	34	11	4	4	4	4	4	4	4	4	4	6
	7	190	19	79	141	179	195	173	128	63	17	15	15	15	15	15	15	15	15	5
	8	240	25	83	141	195	219	210	170	103	31	23	23	23	23	23	23	23	23	4
	9	263	30	59	104	166	200	206	181	127	57	31	29	29	29	29	29	29	29	3
	10	276	34	36	53	109	153	173	167	136	84	40	35	34	34	34	34	34	34	2
	11	283	36	37	39	50	84	118	137	137	104	69	41	38	36	36	36	36	36	1
	12	284	37	37	37	37	39	60	84	101	111	103	81	54	40	38	37	37	37	12
HALF DAY TOTALS			171	303	546	774	922	955	854	618	352	231	184	146	142	141	140	140	999	
Sep 21	7	163	10	33	96	139	159	156	128	80	33	10	10	10	10	10	10	10	10	6
	8	240	18	36	101	173	215	224	198	143	60	18	18	18	18	18	18	18	18	5
	9	272	24	36	64	146	202	227	218	177	107	31	24	24	24	24	24	24	24	4
	10	287	29	29	32	86	154	196	208	189	141	70	31	29	29	29	29	29	29	3
	11	294	32	32	32	36	81	139	174	182	163	118	59	34	32	32	32	32	32	2
	12	296	33	33	33	33	35	66	120	138	171	138	120	66	35	33	33	33	33	1
HALF DAY TOTALS			150	164	345	598	831	983	993	852	574	323	197	142	130	129	129	129	845	
Oct 21	7	99	4	7	43	74	92	86	61	30	8	4	4	4	4	4	4	4	4	6
	8	229	13	15	63	143	195	217	206	162	90	17	13	13	13	13	13	13	13	5
	9	273	20	20	33	120	193	234	239	208	144	54	21	20	20	20	20	20	20	4
	10	293	24	24	28	62	147	207	234	225	183	100	32	24	24	24	24	24	24	3
	11	303	27	27	27	29	56	132	201	231	207	160	85	29	27	27	27	27	27	2
	12	304	28	28	28	28	30	78	135	199	219	199	151	78	30	28	28	28	28	1
HALF DAY TOTALS			103	106	200	433	708	941	1038	972	915	641	336	155	104	103	103	103	879	
Nov 21	7	3	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	5
	8	196	9	9	29	103	156	184	184	177	140	77	9	9	9	9	9	9	9	4
	9	263	16	16	37	90	173	225	241	221	166	80	17	16	16	16	16	16	16	3
	10	289	20	20	21	41	134	206	243	246	209	138	45	21	20	20	20	20	20	2
	11	301	23	23	23	24	61	137	218	245	234	188	109	24	23	23	23	23	23	1
	12	304	24	24	24	24	25	81	171	224	243	224	171	81	25	24	24	24	24	12
HALF DAY TOTALS			80	81	108	282	561	841	998	995	858	544	281	113	87	80	80	80	706	
Dec 21	8	176	7	7	19	84	155	163	146	103	43	7	4	4	4	4	4	4	4	5
	9	257	14	14	15	71	182	218	218	178	97	15	14	14	14	14	14	14	14	4
	10	288	18	18	18	34	127	204	246	251	218	148	52	18	18	18	18	18	18	3
	11	301	21	21	21	22	63	137	222	252	243	197	116	24	21	21	21	21	21	2
	12	304	22	22	22	22	23	89	177	232	252	232	177	89	23	22	22	22	22	1
HALF DAY TOTALS			71	71	84	227	500	752	965	986	852	574	375	201	72	71	71	71	640	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).

[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.3 Solar Intensity and Solar Heat Gain Factors[a] for 40° N Latitude (Conventional Units)[b]

Date	Solar Time am	Direct Normal Btu/h ft²	Solar Heat Gain Factors, Btu/h ft²																	
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time pm
Jan 21	6	142	4	4	17	73	131	132	133	114	75	32	8	8	8	8	8	8	8	
	7	259	12	12	12	12	154	205	224	209	160	82	12	12	12	12	12	12	12	
	8	274	14	14	14	14	124	198	241	246	213	136	14	14	14	14	14	14	14	
	9	268	14	14	14	14	14	156	222	252	244	178	14	14	14	14	14	14	14	
	10	244	14	14	14	14	14	14	178	234	244	211	14	14	14	14	14	14	14	
	11	207	14	14	14	14	14	14	14	202	234	231	14	14	14	14	14	14	14	
	12	157	14	14	14	14	14	14	14	14	202	231	14	14	14	14	14	14	14	
	HALF DAY TOTALS		83	83	83	83	452	724	968	1049	1017	852	83	83	83	83	83	83	83	
Feb 21	7	57	4	4	21	69	121	121	97	42	14	14	14	14	14	14	14	14	14	
	8	218	12	12	12	129	183	206	199	150	82	12	12	12	12	12	12	12	12	
	9	235	14	14	14	14	105	186	224	241	216	137	14	14	14	14	14	14	14	
	10	228	14	14	14	14	14	151	211	246	243	201	14	14	14	14	14	14	14	
	11	198	14	14	14	14	14	14	180	219	244	231	14	14	14	14	14	14	14	
	12	157	14	14	14	14	14	14	14	170	222	241	14	14	14	14	14	14	14	
	HALF DAY TOTALS		82	82	82	82	344	618	818	1049	1017	852	82	82	82	82	82	82	82	
Mar 21	7	171	4	4	21	69	121	121	97	42	14	14	14	14	14	14	14	14	14	
	8	228	12	12	12	129	183	206	199	150	82	12	12	12	12	12	12	12	12	
	9	242	14	14	14	14	105	186	224	241	216	137	14	14	14	14	14	14	14	
	10	232	14	14	14	14	14	151	211	246	243	201	14	14	14	14	14	14	14	
	11	198	14	14	14	14	14	14	180	219	244	231	14	14	14	14	14	14	14	
	12	157	14	14	14	14	14	14	14	170	222	241	14	14	14	14	14	14	14	
	HALF DAY TOTALS		104	104	104	104	452	724	968	1049	1017	852	104	104	104	104	104	104	104	
Apr 21	6	98	12	46	52	63	63	58	52	42	12	12	12	12	12	12	12	12	12	
	7	206	12	12	12	85	135	160	141	77	12	12	12	12	12	12	12	12	12	
	8	232	12	12	12	129	180	224	224	169	124	12	12	12	12	12	12	12	12	
	9	234	12	12	12	14	156	202	219	201	156	82	12	12	12	12	12	12	12	
	10	208	12	12	12	12	14	152	187	193	171	121	12	12	12	12	12	12	12	
	11	162	12	12	12	12	12	14	130	160	166	146	12	12	12	12	12	12	12	
	12	103	12	12	12	12	12	12	82	108	142	134	12	12	12	12	12	12	12	
	HALF DAY TOTALS		154	205	581	756	957	1051	994	782	488	298	154	154	154	154	154	154	154	
May 21	5	3	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	
	6	144	8	40	128	145	141	115	75	18	10	8	8	8	8	8	8	8	8	
	7	218	28	102	185	202	200	164	111	34	10	8	8	8	8	8	8	8	8	
	8	250	27	73	149	196	220	204	154	61	24	8	8	8	8	8	8	8	8	
	9	267	31	42	103	164	197	200	175	121	52	8	8	8	8	8	8	8	8	
	10	277	34	8	42	105	148	168	161	153	83	8	8	8	8	8	8	8	8	
	11	283	36	36	36	40	80	113	130	137	105	36	36	36	36	36	36	36	36	
	12	284	37	37	37	37	40	82	104	111	104	82	41	37	37	37	37	37	37	
	HALF DAY TOTALS		219	404	599	693	1024	1025	881	705	436	247	206	181	181	181	181	181	181	
Jun 21	5	22	10	17	21	22	20	14	8	3	1	1	1	1	1	1	1	1	1	
	6	155	48	104	143	154	153	123	91	57	33	13	13	13	13	13	13	13	13	
	7	218	37	113	172	205	207	179	122	64	25	11	11	11	11	11	11	11	11	
	8	240	30	85	158	201	216	199	152	80	29	11	11	11	11	11	11	11	11	
	9	263	33	53	114	166	202	190	161	105	45	13	13	13	13	13	13	13	13	
	10	272	35	38	63	109	145	156	148	116	66	34	16	16	16	16	16	16	16	
	11	277	38	38	40	52	81	105	116	110	85	80	41	38	38	38	38	38	38	
	12	278	38	38	38	40	41	52	72	89	95	89	52	41	40	38	38	38	38	
	HALF DAY TOTALS		257	470	734	943	1038	999	818	523	313	236	204	192	188	187	187	187	187	
Jul 21	5	2	1	2	2	2	2	2	1	1	0	0	0	0	0	0	0	0	0	
	6	138	37	89	125	142	137	112	68	18	11	11	11	11	11	11	11	11	11	
	7	208	30	102	163	194	204	179	127	53	23	20	20	20	20	20	20	20	20	
	8	241	29	75	149	196	216	203	160	90	30	26	26	26	26	26	26	26	26	
	9	259	32	44	116	163	193	186	170	118	52	31	31	31	31	31	31	31	31	
	10	269	35	35	56	106	146	167	158	129	81	43	36	35	35	35	35	35	35	
	11	275	37	38	40	61	81	111	127	123	102	69	43	39	37	37	37	37	37	
	12	278	38	38	38	40	41	55	80	101	109	101	80	55	41	40	38	38	38	
	HALF DAY TOTALS		223	411	666	805	1008	1003	858	584	352	248	204	198	184	180	180	180	180	
Aug 21	6	83	12	44	69	83	82	71	48	17	6	5	5	5	5	5	5	5	5	
	7	193	17	71	135	177	191	177	135	70	27	16	16	16	16	16	16	16	16	
	8	233	24	47	126	185	216	214	180	118	41	23	23	23	23	23	23	23	23	
	9	260	29	31	82	153	197	212	196	153	80	31	29	28	28	28	28	28	28	
	10	272	32	33	40	93	150	182	187	165	116	56	34	32	32	32	32	32	32	
	11	278	35	35	36	43	81	126	156	160	141	99	52	37	35	35	35	35	35	
	12	280	35	35	35	36	39	63	106	138	149	138	106	63	38	36	35	35	35	
	HALF DAY TOTALS		164	273	498	743	928	1013	956	751	474	296	205	166	157	156	156	156	156	
Sep 21	7	149	9	23	84	125	146	144	121	77	25	9	9	9	9	9	9	9	9	
	8	230	15	39	87	160	205	219	199	148	71	18	17	17	17	17	17	17	17	
	9	263	22	25	47	131	194	227	226	190	124	41	23	22	22	22	22	22	22	
	10	280	27	27	28	71	148	200	221	209	165	93	30	27	27	27	27	27	27	
	11	287	29	29	29	33	74	147	192	207	191	146	77	33	29	29	29	29	29	
	12	290	30	30	30	30	32	75	142	185	200	185	142	75	32	30	30	30	30	
	HALF DAY TOTALS		139	142	293	534	787	980	1033	925	672	396	222	137	119	118	118	118	118	
Oct 21	7	48	2	3	20	36	45	47	42	30	12	2	2	2	2	2	2	2	2	
	8	204	11	12	49	123	173	195	188	151	89	18	11	11	11	11	11	11	11	
	9	257	17	17	23	104	180	225	235	209	151	64	18	17	17	17	17	17	17	
	10	280	21	21	22	50	139	205	238	235	196	125	38	22	21	21	21	21	21	
	11	291	24	24	24	25	71	156	212	236	224	178	101	28	24	24	24	24	24	
	12	294	25	25	25	25	27	85	165	216	234	216	165	85	27	25	25	25	25	
	HALF DAY TOTALS		88	89	152	351	623	878	1006	974	791	491	247	117	89	88	88	88	88	
Nov 21	8	136	5	5	18	89	108	128	129	110	72	23	6	5	5	5	5	5	5	
	9	232	12	12	13	73	151	201	219	204	156	80	13	12	12	12	12	12	12	
	10	268	16	16	16	31	122	196	237	242	209	141	50	17	16	16	16	16	16	
	11	283	18	18	19	20	61	154	218	248	240	194	116	28	19	19	19	19	19	
	12	288	20	20	20	20	21	89	176	231	250	231	176	89	21	20	20	20	20	
	HALF DAY TOTALS		63	63	75	198	443	721	887	914	798	551	269	101	63	63	63	63	63	
Dec 21	9	89	3	3	8	41	67	82	84	73	50	17	3	3	3	3	3	3	3	
	10	217	10	10	11	60	135	185	205	194	151	83	13	10	10	10	10	10	10	
	11	261	14	14	14	25	113	188	232	239	210	146	55	15	14	14	14	14	14	
	12	280	17	17	17	17	56	151	217	249	242	198	120	28	17	17	17	17	17	
	HALF DAY TOTALS		52	52	56	146	374	649	822	867	735	557	276	94	53	52	52	52	52	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.4 Solar Intensity and Solar Heat Gain Factors[a] for 48° N Latitude (Conventional Units)[b]

Date	Solar Time am	Direct Normal Btu/h ft²	Solar Heat Gain Factors, Btu/h ft²																	
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time pm
Jan 21	6	37	1	1	6	18	29	34	35	30	18	6	1	1	1	1	1	1	1	
	7	182	8	8	8	53	115	136	134	109	63	18	8	8	8	8	8	8	8	
	8	239	12	12	12	32	106	162	178	168	115	39	12	12	12	12	12	12	12	
	9	261	14	14	14	14	14	156	210	226	211	145	14	14	14	14	14	14	14	
	10	267	15	15	15	15	15	14	186	234	245	198	15	15	15	15	15	15	15	
	11	261	14	14	14	14	14	14	14	216	250	224	14	14	14	14	14	14	14	
	12	247	13	13	13	13	13	13	13	13	216	250	13	13	13	13	13	13	13	
	HALF DAY TOTALS		43	43	46	117	316	507	624	645	597	443	43	43	43	43	43	43	43	
Feb 21	7	4	0	0	0	1	3	3	3	3	2	1	0	0	0	0	0	0	0	
	8	180	8	8	8	30	103	148	151	120	70	16	8	8	8	8	8	8	8	
	9	247	13	13	13	13	90	158	211	227	196	120	13	13	13	13	13	13	13	
	10	275	17	17	17	17	17	90	158	211	245	206	17	17	17	17	17	17	17	
	11	288	19	19	19	19	19	19	91	158	211	243	19	19	19	19	19	19	19	
	12	292	20	20	20	20	20	20	20	91	158	211	20	20	20	20	20	20	20	
	HALF DAY TOTALS		68	68	68	105	274	454	615	714	676	484	68	68	68	68	68	68	68	
Mar 21	7	133	3	3	22	80	133	134	110	63	16	3	3	3	3	3	3	3	3	
	8	216	14	15	15	78	154	203	204	158	82	15	14	14	14	14	14	14	14	
	9	270	19	19	19	21	21	21	21	21	21	21	19	19	19	19	19	19	19	
	10	287	23	23	23	24	24	24	24	24	24	24	24	23	23	23	23	23	23	
	11	295	25	25	25	26	26	26	26	26	26	26	26	26	25	25	25	25	25	
	12	298	26	26	26	26	27	27	27	27	27	27	27	27	27	26	26	26	26	
	HALF DAY TOTALS		100	119	250	994	773	1012	1106	1054	967	845	773	773	773	773	773	773	773	
Apr 21	6	108	12	53	86	105	103	91	84	71	39	12	12	12	12	12	12	12	12	
	7	205	15	61	132	170	179	169	148	111	64	15	15	15	15	15	15	15	15	
	8	244	15	28	90	141	197	221	215	174	106	15	15	15	15	15	15	15	15	
	9	280	28	28	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
	10	286	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
	11	288	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
	12	288	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	
	HALF DAY TOTALS		147	242	461	724	937	1098	1061	895	652	372	147	147	147	147	147	147	147	
May 21	5	41	17	31	40	42	39	29	14	3	1	1	1	1	1	1	1	1	1	
	6	152	35	97	141	162	160	133	82	24	12	12	12	12	12	12	12	12	12	
	7	219	23	90	158	206	212	193	142	68	21	12	12	12	12	12	12	12	12	
	8	248	26	54	132	190	218	214	178	113	47	12	12	12	12	12	12	12	12	
	9	264	29	32	82	151	194	208	183	147	81	12	12	12	12	12	12	12	12	
	10	274	33	34	39	90	161	178	184	165	116	57	33	33	33	33	33	33	33	
	11	279	35	35	36	40	79	126	155	160	142	101	54	37	35	35	35	35	35	
	12	280	35	35	35	36	38	63	103	139	150	139	107	63	38	36	35	35	35	
	HALF DAY TOTALS		215	388	645	893	1063	1114	1005	749	483	316	225	184	174	173	173	174	1045	
Jun 21	5	37	35	61	76	80	72	53	24	6	5	5	5	5	5	5	5	6	12	
	6	172	46	110	155	175	169	138	84	22	14	14	14	14	14	14	14	16	51	
	7	220	29	101	165	204	211	187	135	60	23	21	21	21	21	21	21	21	101	
	8	246	29	64	139	191	215	206	168	101	34	23	23	23	23	23	23	23	152	
	9	261	31	36	91	153	190	199	180	133	66	33	31	31	31	31	31	31	195	
	10	269	34	36	45	94	143	184	171	143	100	50	34	34	34	34	34	34	225	
	11	274	36	36	38	44	79	118	142	145	126	88	48	38	36	36	36	36	246	
	12	275	37	37	37	38	40	80	96	124	134	124	96	80	40	38	37	37	252	
	HALF DAY TOTALS		257	459	722	955	1095	1102	955	678	436	299	228	197	188	188	188	191	1108	
Jul 21	5	43	18	33	42	45	41	30	13	5	5	5	5	5	5	5	5	6	14	
	6	156	37	96	138	159	158	129	82	34	13	13	13	13	13	13	13	14	61	
	7	211	25	90	156	196	207	186	134	66	22	20	20	20	20	20	20	20	93	
	8	240	27	56	132	187	214	209	174	110	38	26	26	26	26	26	26	26	142	
	9	256	30	34	83	149	191	204	187	143	77	33	30	30	30	30	30	30	184	
	10	266	34	35	41	90	143	174	180	158	117	56	36	34	34	34	34	34	217	
	11	271	36	36	37	42	79	124	151	156	135	89	54	38	36	36	36	36	237	
	12	272	36	36	36	37	39	63	104	136	146	136	104	63	39	37	36	36	244	
	HALF DAY TOTALS		223	395	646	886	1050	1092	983	730	474	313	229	190	181	179	179	180	1082	
Aug 21	6	99	13	51	81	98	100	87	50	22	7	7	7	7	7	7	7	7	16	
	7	190	17	61	128	172	190	179	141	79	19	15	15	15	15	15	15	15	61	
	8	232	22	34	110	174	211	216	188	132	53	23	22	22	22	22	22	22	134	
	9	254	27	28	63	139	192	216	198	169	102	34	27	27	27	27	27	27	179	
	10	266	30	30	33	78	145	188	203	188	144	78	33	30	30	30	30	30	193	
	11	272	32	32	32	36	78	137	173	187	171	126	68	33	32	32	32	32	213	
	12	274	33	33	33	33	36	71	125	163	189	187	128	71	36	33	33	33	223	
	HALF DAY TOTALS		177	231	459	709	929	1060	1040	862	587	398	231	183	151	149	149	149	889	
Sep 21	7	131	8	21	71	108	128	128	108	71	23	8	8	8	8	8	8	8	26	
	8	215	15	18	72	144	191	207	193	145	71	18	15	15	15	15	15	15	65	
	9	251	20	20	34	116	184	223	227	197	136	52	21	20	20	20	20	20	114	
	10	269	24	24	25	58	141	200	228	221	182	112	34	25	24	24	24	24	153	
	11	278	26	26	26	28	53	111	163	223	210	166	92	29	26	26	26	26	174	
	12	280	27	27	27	27	29	82	139	204	220	204	139	82	29	27	27	27	182	
	HALF DAY TOTALS		105	121	240	653	729	953	1040	963	737	483	243	131	106	105	105	105	814	
Oct 21	7	4	0	0	2	3	4	4	3	2	1	0	0	0	0	0	0	0	3	
	8	165	8	9	33	96	139	159	155	126	77	36	8	8	8	8	8	8	23	
	9	233	14	14	16	88	161	207	220	199	148	68	15	14	14	14	14	14	88	
	10	262	18	18	18	19	128	196	233	234	199	135	43	18	18	18	18	18	134	
	11	274	20	20	20	21	64	153	213	241	233	186	109	27	20	20	20	20	128	
	12	278	21	21	21	21	23	87	171	223	242	223	171	87	23	21	21	21	136	
	HALF DAY TOTALS		71	71	108	266	519	760	923	925	779	515	256	106	72	71	71	71	893	
Nov 21	8	56	1	1	4	18	29	34	35	30	20	9	1	1	1	1	1	2	4	
	9	179	8	8	9	52	115	156	171	161	125	67	10	8	8	8	8	8	35	
	10	233	12	12	12	22	104	172	212	218	191	133	69	13	12	12	12	12	53	
	11	255	15	15	15	15	53	142	204	234	228	186	114	26	15	15	15	15	77	
	12	261	15	15	15	15	17	83	168	223	240	222	168	83	17	15	15	15	85	
	HALF DAY TOTALS		44	44	47	117	310	535	713	760	686	502	255	85	44	44	44	44	304	
Dec 21	9	140	5	5	8	36	66	88	120	133	127	100	56	8	5	5	5	5	13	
	10	214	10	10	10	16	41	91	156	194	201	179	126	49	10	10	10	10	38	
	11	242	12	12	12	13	46	114	195	225	220	180	111	25	12	12	12	12	57	
	12	250	13	13	13	13	14	81	183	215	233	215	168	81	14	13	13	13	65	
	HALF DAY TOTALS		33	33	34	73	231	458	810	965	910	668	345	78	34	33	33	33	141	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.5 Solar Intensity and Solar Heat Gain Factors[a] for 64° N Latitude (Conventional Units)[b]

Date	Solar Time am	Direct Normal Btu/h-ft²	Solar Heat Gain Factors, Btu/h · ft²																		Solar Time pm
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR		
Jan 21	10	22	1	1	1	1	9	16	20	21	19	13	5	1	1	1	1	1	1		
	11	81	3	3	3	3	4	33	67	89	96	89	67	33	4	3	3	3	3		
	12	100	3	3	3	3	4	33	67	89	96	89	67	33	4	3	3	3	3		
	HALF DAY TOTALS		5	5	5	6	25	79	121	142	141	119	75	33	5	5	5	5	5		
Feb 21	9	18	1	1	1	10	15	17	17	14	9	2	1	1	1	1	1	1	1		
	9	134	5	5	6	43	89	118	128	119	90	45	6	5	5	5	5	5	5		
	10	190	9	8	8	18	87	144	176	180	157	108	38	9	8	8	8	8	11		
	11	215	10	10	10	11	44	122	177	202	197	160	97	20	10	10	10	10	15		
	12	222	11	11	11	11	12	73	147	194	210	194	147	73	12	11	11	11	18		
	HALF DAY TOTALS		29	30	33	89	244	446	578	617	560	411	212	66	30	29	29	29	36		
Mar 21	7	95	4	11	47	74	90	91	79	53	17	4	4	4	4	4	4	4	6		
	8	185	9	10	46	113	158	177	170	135	78	14	9	9	9	9	9	9	16		
	9	227	13	13	16	88	159	203	215	194	143	64	14	13	13	13	13	13	26		
	10	249	16	16	16	35	122	190	226	228	194	130	42	16	16	16	16	16	35		
	11	260	17	17	17	18	60	148	209	236	228	184	109	25	17	17	17	17	43		
	12	263	18	18	18	18	19	85	168	221	239	221	168	85	19	18	18	18	48		
	HALF DAY TOTALS		68	74	150	334	596	854	984	958	779	504	257	104	68	68	68	68	152		
Apr 21	5	27	8	18	24	27	26	20	12	2	1	1	1	1	1	1	1	1	2		
	6	133	12	59	102	127	132	118	84	33	8	8	8	8	8	8	8	8	22		
	7	194	14	41	113	163	189	185	153	96	25	13	13	13	13	13	13	13	41		
	8	228	17	19	79	153	201	217	201	153	79	19	17	17	17	17	17	17	53		
	9	248	21	21	32	111	180	219	225	197	138	55	22	21	21	21	21	21	61		
	10	260	23	23	24	51	134	194	225	221	185	118	38	24	23	23	23	23	66		
	11	266	24	24	24	26	68	148	202	225	214	171	99	29	24	24	24	24	68		
	12	268	25	25	25	25	27	83	159	208	224	208	159	83	27	25	25	25	69		
	HALF DAY TOTALS		131	218	410	671	943	1150	1186	1036	763	487	273	149	121	120	120	120	301		
May 21	4	51	30	44	51	51	43	28	8	3	3	3	3	3	3	3	3	3	10		
	5	132	48	95	125	135	125	96	50	11	9	9	9	9	9	9	9	9	30		
	6	185	28	97	150	181	183	158	109	40	15	15	15	15	15	15	15	15	46		
	7	218	21	63	138	189	211	201	161	94	24	19	19	19	19	19	19	19	58		
	8	239	23	28	97	167	209	220	198	146	68	25	23	23	23	23	23	23	68		
	9	252	26	27	45	122	183	215	215	184	123	46	27	26	26	26	26	26	74		
	10	261	28	28	30	61	135	188	212	205	167	102	36	28	28	28	28	28	77		
	11	265	30	30	30	32	72	141	188	207	195	154	87	33	30	30	30	30	82		
	12	267	30	30	30	30	33	78	146	189	204	189	146	78	33	30	30	30	84		
	HALF DAY TOTALS		247	425	680	950	1177	1291	1218	985	708	465	288	191	169	168	168	168	511		
Jun 21	4	93	53	83	96	94	78	50	14	7	7	7	7	7	7	7	7	7	21		
	5	154	62	114	148	158	145	110	55	14	12	12	12	12	12	12	12	12	36		
	6	194	36	107	162	191	192	163	110	39	18	17	17	17	17	17	17	17	51		
	7	221	24	71	145	193	213	200	158	89	25	22	22	22	22	22	22	22	66		
	8	239	25	33	104	170	208	216	192	139	62	27	25	25	25	25	25	25	75		
	9	251	28	29	51	124	181	210	208	175	115	43	29	28	28	28	28	28	83		
	10	258	30	30	32	65	134	183	204	195	157	94	36	30	30	30	30	30	89		
	11	262	32	32	32	34	72	137	180	196	184	144	82	35	32	32	32	32	94		
	12	263	32	32	32	32	35	76	138	179	193	179	138	76	35	32	32	32	96		
	HALF DAY TOTALS		322	533	801	1061	1253	1317	1195	946	679	455	296	211	192	190	191	191	563		
Jul 21	4	53	32	47	55	54	46	29	9	4	4	4	4	4	4	4	4	4	11		
	5	128	49	94	123	133	124	95	50	11	10	10	10	10	10	10	10	10	31		
	6	179	30	96	148	177	180	155	106	39	16	15	15	15	15	15	15	15	45		
	7	211	22	64	137	186	207	197	157	92	25	20	20	20	20	20	20	20	60		
	8	231	24	30	97	165	205	215	193	142	67	26	24	24	24	24	24	24	72		
	9	243	27	28	47	121	180	211	211	179	120	46	28	27	27	27	27	27	81		
	10	253	29	29	31	62	134	185	208	200	164	100	37	29	29	29	29	29	87		
	11	257	31	31	31	33	72	139	185	202	193	151	86	34	31	31	31	31	93		
	12	259	31	31	31	31	34	78	143	185	200	185	143	78	34	31	31	31	93		
	HALF DAY TOTALS		258	434	684	946	1163	1269	1193	965	697	462	292	198	177	175	175	175	503		
Aug 21	5	29	9	20	27	30	29	22	13	2	2	2	2	2	2	2	2	2	5		
	6	123	13	58	97	121	125	111	80	34	9	9	9	9	9	9	9	9	25		
	7	181	15	42	109	157	180	176	145	92	26	14	14	14	14	14	14	14	33		
	8	214	19	21	78	148	193	208	192	147	76	21	19	19	19	19	19	19	47		
	9	234	22	22	34	109	174	211	217	189	133	55	23	22	22	22	22	22	57		
	10	246	25	25	26	52	131	188	217	214	178	114	39	25	25	25	25	25	64		
	11	252	26	26	26	28	69	144	196	217	207	166	97	31	26	26	26	26	69		
	12	254	27	27	27	27	29	82	155	201	217	201	155	82	29	27	27	27	69		
	HALF DAY TOTALS		142	226	410	657	934	1109	1141	997	740	478	275	158	131	130	130	130	356		
Sep 21	7	77	4	10	39	62	74	75	65	44	15	4	4	4	4	4	4	4	8		
	8	163	10	10	43	103	143	160	154	123	71	14	10	10	10	10	10	10	31		
	9	206	14	14	17	83	148	189	200	181	133	61	15	14	14	14	14	14	47		
	10	229	16	16	17	35	116	179	213	214	183	123	41	17	16	16	16	16	50		
	11	240	18	18	18	19	59	141	198	224	216	174	104	26	18	18	18	18	56		
	12	244	19	19	19	19	21	82	160	209	227	209	160	82	21	19	19	19	59		
	HALF DAY TOTALS		71	77	142	307	547	787	910	891	731	480	249	106	72	71	71	71	224		
Oct 21	8	17	1	1	3	10	14	16	16	13	8	2	1	1	1	1	1	1	3		
	9	122	5	5	6	40	82	109	118	110	83	42	6	5	5	5	5	5	16		
	10	176	9	9	9	18	83	135	165	169	147	102	36	9	9	9	9	9	29		
	11	201	11	11	11	11	43	116	167	191	186	152	92	20	11	11	11	11	41		
	12	208	11	11	11	11	13	70	140	184	199	184	140	70	13	11	11	11	48		
	HALF DAY TOTALS		31	31	34	86	231	420	542	580	527	388	202	66	32	31	31	31	108		
Nov 21	10	23	1	1	1	1	10	17	21	22	20	14	5	1	1	1	1	1	6		
	11	79	3	3	3	3	15	44	65	75	74	61	37	8	3	3	3	3	8		
	12	97	4	4	4	4	4	32	66	87	93	87	66	32	4	4	4	4	11		
	HALF DAY TOTALS		5	5	5	6	26	79	120	141	140	117	74	23	6	5	5	5	15		
Dec 21	11	4	0	0	0	0	1	2	3	4	4	3	2	0	0	0	0	0	1		
	12	16	0	0	0	0	1	5	11	14	15	14	11	5	1	0	0	0	2		
	HALF DAY TOTALS		0	0	0	0	1	5	9	11	11	10	7	3	0	0	0	0	1		
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM	

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).

[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.6 Solar Intensity and Solar Heat Gain Factors[a] for 16° N Latitude (SI Units)[b]

Date	Solar Time am	Direct Normal W/m²	Solar Heat Gain Factors, W/m²																		Solar Time pm
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR		
Jan 21	7	445	17	19	158	291	390	424	397	303	155	19	17	17	17	17	17	17	43	5	
	8	827	45	48	174	463	563	557	514	396	193	76	45	45	45	45	45	45	249	4	
	9	948	67	67	102	384	630	670	591	440	193	76	45	45	45	45	45	45	249	3	
	10	1001	82	82	86	209	474	658	737	704	563	321	97	82	82	82	82	82	440	2	
	11	1025	92	92	92	96	242	467	614	865	812	682	230	96	92	92	92	92	545	1	
	12	1032	95	95	95	95	100	228	438	880	828	590	438	228	100	95	95	95	782	12	
	HALF DAY TOTALS		348	353	618	1453	2390	3111	3458	3217	2465	1344	866	401	350	348	348	348	2539		
Feb 21	7	575	24	55	265	435	532	544	474	328	113	20	24	24	24	24	24	24	80	5	
	8	862	53	60	304	567	729	778	706	525	244	56	53	53	53	53	53	53	319	4	
	9	963	74	77	202	482	676	763	723	592	347	96	74	74	74	74	74	74	549	3	
	10	1006	90	91	104	292	598	656	665	593	423	193	94	90	90	90	90	90	722	2	
	11	1027	99	99	102	118	262	428	525	542	471	323	154	105	99	99	99	99	831	1	
	12	1034	103	103	103	105	108	189	336	648	607	457	448	336	189	108	105	103	868	12	
	HALF DAY TOTALS		390	431	1013	1922	2730	3229	3265	2792	1836	906	547	417	393	390	390	390	2939		
Mar 21	7	634	36	167	393	544	606	578	458	290	97	33	33	33	33	33	33	33	128	5	
	8	857	63	157	442	648	752	741	615	390	111	63	63	63	63	63	63	63	390	4	
	9	943	84	110	543	565	689	709	622	435	180	86	82	82	82	82	82	82	606	3	
	10	983	98	103	191	379	519	573	543	424	240	107	100	98	98	98	98	98	778	2	
	11	1003	108	110	113	166	273	361	395	366	281	173	114	110	108	108	108	108	885	1	
	12	1008	111	111	112	114	117	149	216	273	295	273	216	149	117	114	112	111	919	12	
	HALF DAY TOTALS		443	712	1558	2383	2926	3076	3273	3028	2006	988	633	448	440	440	439	437	3253		
Apr 21	6	44	7	24	37	43	43	37	24	7	3	2	2	2	2	2	2	2	6	6	
	7	622	75	298	482	589	604	528	369	143	41	42	42	42	42	42	42	42	189	5	
	8	807	85	312	543	682	718	644	473	217	74	70	70	70	70	70	70	70	413	4	
	9	885	97	248	469	610	657	608	465	244	97	90	90	90	90	90	90	90	623	3	
	10	924	112	171	321	444	499	476	380	231	118	109	106	106	106	106	106	106	764	2	
	11	942	120	127	169	228	270	276	245	189	136	121	118	115	115	115	115	115	882	1	
	12	948	123	123	124	125	126	129	135	143	143	141	135	129	126	125	124	123	911	12	
	HALF DAY TOTALS		565	1272	2127	2711	2909	2844	2659	2111	1547	923	694	491	490	489	490	492	3333		
May 21	6	138	43	94	128	143	134	106	59	11	9	9	9	9	9	9	9	10	199	6	
	7	608	157	378	531	603	583	474	290	76	49	49	49	49	49	49	49	55	417	5	
	8	771	165	415	598	689	677	564	362	121	78	76	76	76	76	76	76	80	625	4	
	9	845	156	366	539	626	622	526	344	141	100	96	96	96	96	96	96	100	621	3	
	10	883	149	281	410	478	474	398	264	139	118	111	111	111	111	111	111	111	682	2	
	11	902	147	198	248	275	262	220	166	130	128	125	120	120	122	124	128	132	802	1	
	12	907	146	144	140	134	132	131	130	129	129	129	130	131	132	134	140	144	890	12	
	HALF DAY TOTALS		893	1813	2537	2891	2829	2360	1555	885	541	528	527	526	527	529	533	557	3338		
Jun 21	6	168	64	124	163	175	162	123	64	13	12	12	12	12	12	12	12	13	24	6	
	7	593	191	404	543	598	565	445	252	63	52	52	52	52	52	52	52	57	203	5	
	8	750	209	449	612	684	653	526	313	98	79	79	79	79	79	79	79	84	425	4	
	9	823	199	409	560	626	601	487	294	118	98	98	98	98	98	98	98	105	613	3	
	10	861	187	329	441	486	459	363	222	123	116	113	113	113	113	113	113	121	759	2	
	11	879	181	241	283	290	258	200	146	130	126	122	122	122	122	122	125	136	847	1	
	12	885	179	173	158	142	134	132	130	129	129	129	130	132	134	142	158	173	873	12	
	HALF DAY TOTALS		1122	2043	2683	2930	2763	2207	1357	612	548	540	540	540	542	543	555	599	3308		
Jul 21	6	128	43	90	122	134	127	99	55	11	9	9	9	9	9	9	9	10	17	6	
	7	579	161	373	518	585	564	456	277	74	51	51	51	51	51	51	51	55	194	5	
	8	743	173	415	590	676	661	549	349	110	79	78	78	78	78	78	78	83	419	4	
	9	818	165	371	537	618	610	513	334	138	102	99	99	99	99	99	99	104	611	3	
	10	857	157	289	413	475	467	389	257	155	118	113	113	113	113	113	113	120	759	2	
	11	876	154	207	255	277	262	218	164	133	128	125	122	122	122	125	128	133	848	1	
	12	882	154	151	143	138	135	134	133	132	132	132	133	134	135	138	145	151	875	12	
	HALF DAY TOTALS		933	1829	2521	2848	2770	2298	1507	680	554	541	539	539	540	542	547	575	3289		
Aug 21	6	136	7	21	31	37	36	31	20	6	2	2	2	2	2	2	2	4	5		
	7	569	81	289	458	553	567	493	343	131	48	45	45	45	45	45	45	47	167	5	
	8	757	94	315	531	660	691	617	451	206	79	74	74	74	74	74	74	74	404	4	
	9	838	104	258	467	598	640	589	448	235	103	95	95	95	95	95	95	95	608	3	
	10	879	118	183	328	443	490	464	368	224	122	114	110	110	110	110	110	110	746	2	
	11	899	127	136	180	235	271	273	240	185	138	127	124	120	120	120	120	124	860	1	
	12	905	129	130	130	131	132	134	139	143	145	143	139	134	132	131	130	130	889	12	
	HALF DAY TOTALS		601	1294	2099	2640	2810	2578	1969	1069	568	528	519	516	515	514	515	518	3258		
Sep 21	7	565	38	157	380	497	554	529	419	240	48	35	35	35	35	35	35	35	122	5	
	8	797	67	156	424	618	716	705	587	374	113	64	64	64	64	64	64	64	367	4	
	9	887	87	114	335	547	665	684	602	424	181	90	86	86	86	86	86	86	585	3	
	10	931	101	107	193	372	507	560	529	415	240	111	103	101	101	101	101	101	752	2	
	11	952	111	114	118	169	272	356	389	361	279	176	118	114	111	111	111	111	856	1	
	12	958	114	114	116	118	121	153	217	272	293	272	217	153	121	118	116	114	889	12	
	HALF DAY TOTALS		461	712	1500	2276	2791	2937	2658	1963	1007	605	501	406	457	455	454	454	3126		
Oct 21	7	524	25	56	249	404	492	502	437	300	105	27	25	25	25	25	25	25	79	5	
	8	816	55	64	299	548	702	747	677	502	234	59	55	55	55	55	55	55	313	4	
	9	920	76	80	204	473	659	741	711	573	336	97	78	78	78	78	78	78	537	3	
	10	968	92	94	108	291	499	621	647	577	412	189	97	92	92	92	92	92	707	2	
	11	991	102	105	122	161	320	515	528	459	315	154	106	102	102	102	102	102	814	1	
	12	997	105	105	105	107	111	189	330	437	474	437	330	189	111	107	105	105	850	12	
	HALF DAY TOTALS		402	844	1002	1889	2837	3110	3141	2689	1776	893	553	428	404	403	402	402	2872		
Nov 21	7	423	17	19	134	280	371	406	379	289	147	19	17	17	17	17	17	17	43	5	
	8	806	46	49	174	456	651	742	719	583	350	78	46	46	46	46	46	46	247	4	
	9	929	67	67	105	282	623	779	779	679	472	180	70	67	67	67	67	67	468	3	
	10	984	83	83	87	210	470	651	727	694	554	316	98	83	83	83	83	83	633	2	
	11	1009	92	92	92	98	243	462	607	654	603	453	234	98	92	92	92	92	740	1	
	12	1016	96	96	96	96	101	227	432	572	618	573	432	227	101	96	96	96	775	12	
	HALF DAY TOTALS		352	357	620	1438	2343	3101	3396	3139	2421	1324	864	424	355	352	352	352	3520		
Dec 21	7	372	13	14	93	228	318	354	339	268	150	21	13	13	13	13	13	13	31	5	
	8	803	42	43	129	418	625	734	728	609	390	105	42	42	42	42	42	42	219	4	
	9	936	63	63	78	341	604	761	800	716	520	226	66	63	63	63	63	63	436	3	
	10	993	78	78	81	178	331	474	638	698	654	508	270	94	87	87	87	87	704	2	
	11	1019	87	87	87	92	191	295	469	626	670	626	469	241	95	91	91	91	719	12	
	12	1026	91	91	91	91	95	241	3076	3468	3312	2638	1527	723	393	333	328	328	2361		
	HALF DAY TOTALS		328	330	501	1269	2241	3076	3468	3312	2638	1527	723	393	333	328	328	328	2361		
			N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM	

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).

[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.7 Solar Intensity and Solar Heat Gain Factors[a] for 32° N Latitude (SI Units)[b]

Date	Solar Time am	Direct Normal W/m²	Solar Heat Gain Factors, W/m² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Hor	Time pm
Jan 21	7	4	0	0	1	1	4	4	4	3	2	0	0	0	0	0	0	0	1	5
	8	640	28	29	93	130	305	597	596	502	326	88	29	28	28	28	28	28	68	4
	9	849	48	48	53	286	533	721	775	711	334	238	52	48	48	48	48	48	83	3
	10	931	63	63	64	129	427	659	784	788	670	444	144	64	63	63	63	63	91	2
	11	967	71	71	71	75	213	502	698	784	750	602	347	90	71	71	71	71	92	1
	12	977	74	74	74	74	79	277	548	718	775	718	548	277	79	74	74	74	93	12
	HALF DAY TOTALS		249	256	338	897	1797	2700	3201	3198	2692	1746	931	353	252	249	249	249	1246	249
Feb 21	7	332	13	23	148	258	323	336	299	212	83	14	13	13	13	13	13	13	13	11
	8	773	41	41	204	469	646	719	683	538	300	53	41	41	41	41	41	41	41	10
	9	905	60	60	101	386	627	764	783	680	471	174	63	60	60	60	60	60	61	9
	10	964	73	73	78	195	473	670	760	733	595	352	99	73	73	73	73	73	80	8
	11	990	83	83	83	88	240	491	658	717	670	519	275	89	83	83	83	83	93	7
	12	999	86	86	86	88	91	250	489	644	696	643	489	250	91	86	86	86	97	6
	HALF DAY TOTALS		314	324	635	1405	2318	3086	3408	3188	2461	1426	718	384	318	314	314	314	1614	314
Mar 21	7	583	30	116	332	483	556	545	447	278	83	29	29	29	29	29	29	29	29	5
	8	827	54	78	339	578	717	746	661	473	195	57	54	54	54	54	54	54	54	4
	9	914	74	77	203	475	662	746	716	578	339	95	74	74	74	74	74	74	74	3
	10	959	88	88	96	273	499	637	677	615	456	221	93	88	88	88	88	88	88	2
	11	980	96	96	98	108	258	447	564	592	529	380	185	101	96	96	96	96	96	1
	12	987	99	99	99	99	105	209	388	511	554	511	386	209	105	99	99	99	99	12
	HALF DAY TOTALS		393	512	1131	1985	2761	3258	3284	2801	1858	1030	609	429	394	393	393	393	1966	393
Apr 21	6	210	29	110	172	205	207	177	119	38	11	11	11	11	11	11	11	11	11	6
	7	649	51	253	462	593	631	575	428	204	49	45	45	45	45	45	45	45	45	5
	8	804	73	192	453	632	715	689	559	337	95	69	69	69	69	69	69	69	69	4
	9	876	89	113	324	532	649	669	591	418	183	92	87	87	87	87	87	87	87	3
	10	913	101	106	165	342	490	599	583	445	275	123	104	101	101	101	101	101	101	2
	11	932	109	109	115	149	263	371	426	415	340	222	128	113	109	109	109	109	109	1
	12	937	112	112	112	116	120	167	260	333	383	335	260	167	120	116	112	112	112	12
	HALF DAY TOTALS		508	932	1734	2500	3003	3129	2806	2033	1135	721	359	496	482	479	479	479	1916	479
May 21	6	374	104	244	340	381	367	295	175	39	26	26	26	26	26	26	26	26	26	6
	7	666	112	350	535	638	643	550	374	134	60	57	57	57	57	57	57	57	57	5
	8	787	93	295	519	655	694	629	470	229	86	80	80	80	80	80	80	80	80	4
	9	849	104	194	404	558	625	601	488	294	117	100	97	97	97	97	97	97	97	3
	10	882	114	127	240	383	473	491	435	313	170	117	110	110	110	110	110	110	110	2
	11	898	121	124	132	186	260	312	322	285	215	147	126	122	118	118	118	118	118	1
	12	904	121	123	125	127	130	148	186	220	223	220	186	148	130	127	125	125	125	12
	HALF DAY TOTALS		700	1382	2214	2840	3106	2943	2356	1409	788	627	577	558	551	550	548	550	2551	550
Jun 21	6	412	140	299	388	425	401	314	174	39	32	32	32	32	32	32	32	32	32	6
	7	662	148	384	556	644	634	529	342	109	62	62	62	62	62	62	62	62	62	5
	8	773	115	331	540	656	677	597	427	188	89	84	84	84	84	84	84	84	84	4
	9	831	110	234	431	583	609	567	440	244	111	101	101	101	101	101	101	101	101	3
	10	863	120	150	272	395	461	458	387	261	143	120	114	114	114	114	114	114	114	2
	11	880	126	130	148	202	258	288	280	237	177	135	128	125	122	122	122	122	122	1
	12	885	128	129	130	132	134	144	164	183	191	183	164	144	134	132	130	128	128	12
	HALF DAY TOTALS		824	1589	2403	2950	3108	2829	2137	1174	710	621	595	585	582	579	579	579	2586	579
Jul 21	6	358	106	240	332	370	355	285	168	39	27	27	27	27	27	27	27	27	27	6
	7	640	118	349	526	623	626	534	361	129	62	59	59	59	59	59	59	59	61	5
	8	761	98	300	515	645	680	613	456	221	89	82	82	82	82	82	82	82	82	4
	9	823	107	202	405	553	615	588	475	284	117	100	100	100	100	100	100	100	100	3
	10	856	118	133	247	383	467	481	424	303	167	120	113	113	113	113	113	113	113	2
	11	871	124	128	137	191	261	308	314	277	210	147	129	125	121	121	121	121	121	1
	12	879	126	127	128	130	133	150	184	214	226	214	184	150	133	130	128	127	127	12
	HALF DAY TOTALS		728	1402	2210	2809	3052	2877	2290	1365	783	637	591	574	568	566	565	568	2431	565
Aug 21	6	187	30	103	159	188	189	162	108	35	12	12	12	12	12	12	12	12	12	6
	7	599	59	250	444	565	598	542	402	192	53	49	49	49	49	49	49	49	49	5
	8	736	79	200	446	614	690	662	536	321	96	74	74	74	74	74	74	74	74	4
	9	830	95	124	328	523	632	648	570	402	179	98	93	93	93	93	93	93	93	3
	10	889	106	113	175	344	482	544	526	429	266	126	110	106	106	106	106	106	106	2
	11	889	115	117	122	157	264	365	414	401	328	217	131	119	115	115	115	115	115	1
	12	894	117	117	117	122	126	170	255	324	350	324	255	170	126	122	117	117	117	12
	HALF DAY TOTALS		539	957	1721	2443	2910	3014	2694	1950	1109	729	581	524	510	507	506	506	2152	506
Sep 21	7	314	32	109	302	437	502	492	405	252	62	30	30	30	30	30	30	30	30	5
	8	758	57	81	324	546	679	706	626	450	190	61	57	57	57	57	57	57	57	4
	9	857	77	82	201	459	637	717	688	557	330	99	77	77	77	77	77	77	77	3
	10	905	91	91	101	270	483	617	655	596	444	220	97	91	91	91	91	91	91	2
	11	928	100	100	102	113	257	437	549	578	516	373	187	106	100	100	100	100	100	1
	12	937	103	103	103	103	110	210	379	499	540	499	379	210	110	103	103	103	103	12
	HALF DAY TOTALS		409	518	1089	1888	2621	3097	3132	2689	1812	1025	620	446	411	408	408	408	1864	408
Oct 21	7	312	13	24	136	233	291	301	268	190	75	14	13	13	13	13	13	13	13	5
	8	724	42	46	200	450	616	684	649	511	285	54	42	42	42	42	42	42	42	4
	9	862	63	63	104	378	608	738	755	655	454	170	65	63	63	63	63	63	63	3
	10	923	77	77	81	197	465	652	737	711	577	342	101	77	77	77	77	77	77	2
	11	952	86	86	86	91	239	481	639	697	651	505	269	95	86	86	86	86	86	1
	12	960	89	89	89	89	95	247	478	626	677	626	278	247	95	89	89	89	89	12
	HALF DAY TOTALS		325	333	632	1365	2234	2968	3275	3067	2376	1390	714	394	328	325	325	325	1425	325
Nov 21	7	3	0	0	1	2	4	3	4	3	2	0	0	0	0	0	0	0	1	5
	8	619	29	29	93	323	493	581	579	488	316	86	29	29	29	29	29	29	29	4
	9	829	49	49	55	284	545	709	761	697	523	253	49	49	49	49	49	49	49	3
	10	912	64	64	65	131	423	650	772	775	659	437	142	65	64	64	64	64	64	2
	11	949	72	72	72	76	213	496	688	773	739	593	342	91	72	72	72	72	72	1
	12	959	75	75	75	75	80	274	541	708	766	708	541	274	80	75	75	75	75	12
	HALF DAY TOTALS		253	254	342	890	1769	2653	3143	3138	2643	1717	824	355	256	253	253	253	1102	253
Dec 21	8	556	22	22	59	265	426	515	523	452	305	98	33	22	22	22	22	22	22	4
	9	812	43	43	46	244	512	688	751	701	539	282	48	43	43	43	43	43	43	3
	10	908	57	57	57	106	402	642	777	792	683	466	163	59	57	57	57	57	57	2
	11	949	66	66	66	69	200	497	700	795	766	620	367	92	66	66	66	66	66	1
	12	960	69	69	69	69	73	281	559	733	794	733	559	281	71	69	69	69	69	12
	HALF DAY TOTALS		223	223	265	717	1577	2499	3043	3111	2687	1823	868	339	225	223	223	223	1000	223
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).

[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.8 Solar Intensity and Solar Heat Gain Factors[a] for 40° N Latitude (SI Units)[b]

Date	Solar Time am	Direct Normal W/m²	Solar Heat Gain Factors, W/m² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Hor	Time pm
Jan 21	8	645	17	17	55	223	330	417	420	338	196	46								
	9	855	37	37	41	332	691	848	847	694	394	94								
	10	935	51	51	51	97	548	827	906	798	494	166								
	11	968	62	62	62	62	246	704	903	876	566	240								
	12	978	66	66	66	66	66	294	763	906	596	260								
	HALF DAY TOTALS		194	194	231	638	1426	3104	3972	3704	2394	1014								
Feb 21	7	155	6	16	71	325	390	347	198	50	6	0								
	8	692	33	35	198	467	734	871	828	593	286	36								
	9	854	52	52	79	337	747	948	1008	846	486	124								
	10	926	65	65	67	111	490	868	1017	940	598	196								
	11	958	73	73	73	73	224	704	980	968	668	252								
	12	967	76	76	76	76	80	271	766	940	680	260								
	HALF DAY TOTALS		267	371	479	1140	2045	3888	5308	5202	3595	1402								
Mar 21	7	540	25	93	295	441	514	506	415	258	77	27								
	8	799	50	57	289	554	688	732	665	456	188	55								
	9	899	67	70	147	429	640	749	744	623	374	92								
	10	958	80	80	85	226	482	651	723	683	473	215								
	11	987	88	88	88	88	247	478	625	673	602	358								
	12	998	91	91	91	91	97	256	498	652	606	358								
	HALF DAY TOTALS		358	680	954	1777	2920	3981	4629	4593	3419	1615								
Apr 21	6	282	39	184	229	275	279	241	164	53	15	15								
	7	653	50	223	462	584	633	588	437	215	50	45								
	8	795	69	140	402	601	706	702	572	345	97	69								
	9	865	84	91	254	488	638	691	640	454	188	94								
	10	901	96	96	111	291	488	588	608	478	278	101								
	11	920	104	107	107	132	255	431	538	523	359	128								
	12	926	106	106	106	109	114	196	341	449	406	144								
	HALF DAY TOTALS		497	835	1180	2190	3026	3914	4490	4318	3148	1319								
May 21	5	3	1	2	3	5	6	7	8	7	4	1								
	6	453	113	254	403	458	440	364	223	70	19	19								
	7	681	90	320	526	638	674	590	432	214	60	60								
	8	783	88	230	471	629	698	651	519	302	102	80								
	9	844	99	111	330	514	626	635	551	362	147	99								
	10	875	107	114	171	332	467	529	513	409	209	107								
	11	891	115	115	121	152	256	351	409	400	261	127								
	12	896	117	117	117	123	126	171	224	289	299	151								
	HALF DAY TOTALS		879	253	2102	2816	3251	3232	2778	1967	1129	520								
Jun 21	5	68	32	54	68	79	83	86	77	51	19	19								
	6	488	150	329	450	501	474	390	233	73	19	19								
	7	681	118	355	543	649	674	562	385	145	34	34								
	8	776	95	321	513	625	643	564	400	202	60	60								
	9	829	105	180	359	524	607	601	497	312	142	105								
	10	859	112	121	197	343	457	500	468	345	187	112								
	11	874	119	123	128	198	254	332	365	347	230	119								
	12	879	121	121	121	123	131	167	221	260	249	121								
	HALF DAY TOTALS		799	1483	2314	2968	3272	3193	2780	2080	1284	646								
Jul 21	5	3	1	2	3	5	6	7	8	7	4	1								
	6	435	116	291	395	447	433	352	216	67	18	18								
	7	656	95	321	513	625	643	564	400	202	60	60								
	8	762	90	236	468	620	680	628	477	277	97	90								
	9	818	102	118	333	513	618	616	517	347	167	102								
	10	850	110	118	177	333	462	519	500	380	208	110								
	11	866	117	120	125	157	256	372	433	413	253	120								
	12	871	120	120	120	125	130	184	270	340	342	120								
	HALF DAY TOTALS		705	1296	2102	2782	3190	3184	2797	2142	1362	682								
Aug 21	6	255	38	137	214	258	259	223	142	48	10	10								
	7	603	53	223	426	557	602	557	402	192	49	49								
	8	747	73	149	397	611	681	621	474	268	74	74								
	9	819	89	97	259	481	621	632	534	362	162	89								
	10	857	102	105	128	294	472	574	557	441	246	102								
	11	876	109	109	113	115	238	463	581	577	403	167								
	12	882	112	112	112	112	115	238	463	581	577	403								
	HALF DAY TOTALS		518	861	1371	2359	3195	3695	3644	3000	1911	894								
Sep 21	7	472	28	87	265	395	468	441	311	144	34	34								
	8	723	52	81	275	513	688	733	646	411	131	52								
	9	830	71	71	98	229	468	631	631	469	221	71								
	10	882	84	84	84	98	241	463	631	602	377	141								
	11	906	92	92	92	92	95	237	466	631	602	377								
	12	914	95	95	95	95	101	257	498	674	643	402								
	HALF DAY TOTALS		374	447	817	1383	2404	3502	4262	4284	3211	1523								
Oct 21	7	153	6	10	84	113	142	142	104	42	10	10								
	8	644	35	37	155	387	545	611	545	367	161	35								
	9	811	54	54	73	329	567	710	686	488	223	54								
	10	884	67	67	67	157	428	644	686	488	223	67								
	11	917	76	76	76	80	223	488	686	488	223	67								
	12	927	78	78	78	78	84	247	544	774	686	488								
	HALF DAY TOTALS		277	282	670	1508	2967	4284	5104	4784	3511	1744								
Nov 21	8	430	17	17	55	217	339	364	264	104	26	26								
	9	733	34	34	42	211	494	681	681	494	211	34								
	10	846	52	52	52	96	352	686	852	686	352	96								
	11	894	60	60	60	60	192	494	852	852	686	352								
	12	908	63	63	63	63	69	211	494	852	852	686								
	HALF DAY TOTALS		197	198	215	603	1403	2712	3794	4104	3511	2211								
Dec 21	8	279	9	9	23	128	227	264	184	64	9	9								
	9	645	31	31	31	158	427	584	584	427	158	31								
	10	825	45	45	45	58	277	584	777	584	277	58								
	11	882	53	53	53	56	86	277	584	777	584	277								
	12	899	56	56	56	56	60	86	277	584	777	584								
	HALF DAY TOTALS		165	165	179	461	1180	2066	2994	3778	3778	2994								
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).

[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.9 Solar Intensity and Solar Heat Gain Factors[a] for 48° N Latitude (SI Units)[b]

Date	Solar Time am	Direct Normal W/m²	Solar Heat Gain Factors, W/m² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time pm
Jan 21	6	119	4	4	13	31	90	109	110	94	63	24	4	4	4	4	4	4	4	6
	7	488	24	24	26	168	371	505	551	533	406	217	30	24	24	24	24	24	24	5
	8	714	37	37	37	99	333	556	682	702	615	429	135	38	37	37	37	37	37	4
	9	847	45	45	45	47	166	457	606	733	734	598	367	83	45	45	45	45	45	3
	10	922	49	49	49	48	51	271	541	713	772	721	541	271	51	49	49	49	49	2
	11	947	50	50	50	48	48	51	271	541	713	772	721	541	271	51	48	48	48	1
	HALF DAY TOTALS		134	134	134	164	568	996	1788	2298	2668	2313	1816	817	287	136	134	134	134	
Feb 21	7	11	0	1	1	1	3	10	11	10	7	0	0	0	0	0	0	0	0	5
	8	568	24	25	114	338	679	737	534	428	259	51	24	24	24	24	24	24	24	4
	9	780	42	42	49	284	530	683	727	660	488	235	45	42	42	42	42	42	42	3
	10	889	54	54	55	130	415	641	764	768	673	434	137	55	54	54	54	54	54	2
	11	928	59	59	61	64	209	498	696	787	755	601	316	64	61	59	59	59	59	1
	12	908	61	61	61	61	68	280	551	728	790	728	551	280	68	61	61	61	61	
	HALF DAY TOTALS		214	216	311	884	1708	2715	3054	3051	2565	1877	825	326	216	214	214	214	214	
Mar 21	7	882	33	71	253	587	858	858	588	253	71	33	33	33	33	33	33	33	33	5
	8	944	44	88	239	686	844	901	651	408	251	69	44	44	44	44	44	44	44	4
	9	913	50	80	108	581	809	938	733	652	449	164	83	66	50	50	50	50	50	3
	10	806	72	72	72	181	660	856	749	728	596	363	156	72	72	72	72	72	72	2
	11	592	79	79	79	83	372	692	663	731	689	541	297	88	79	79	79	79	79	1
	12	439	81	81	81	81	86	281	509	666	720	666	509	261	86	81	81	81	81	
	HALF DAY TOTALS		917	872	790	1358	2446	3193	3473	3199	2620	1866	986	395	319	316	316	316	316	
Apr 21	6	340	33	37	271	530	839	595	468	264	56	45	45	45	45	45	45	45	45	6
	7	646	49	109	417	567	828	709	619	431	173	67	66	66	66	66	66	66	66	5
	8	779	64	99	150	566	690	709	619	431	173	67	66	66	66	66	66	66	66	4
	9	847	75	83	191	644	821	703	679	554	335	105	79	79	79	79	79	79	79	3
	10	884	90	90	91	284	466	810	660	613	472	251	91	90	90	90	90	90	90	2
	11	903	97	97	97	107	345	843	670	609	558	419	211	103	97	97	97	97	97	1
	12	909	99	99	99	99	106	324	814	543	587	543	414	224	106	99	99	99	99	
	HALF DAY TOTALS		863	765	1454	2281	3019	5465	5411	3821	1908	1169	711	492	445	442	442	442	442	
Mar 21	5	129	32	97	127	133	172	91	44	9	8	8	8	8	8	8	8	8	8	7
	6	511	112	305	443	512	554	418	367	75	38	38	38	38	38	38	38	38	38	6
	7	690	73	283	498	631	668	604	448	214	66	61	61	61	61	61	61	61	61	5
	8	782	83	170	418	590	689	611	563	358	139	79	79	79	79	79	79	79	79	4
	9	834	93	101	259	475	611	656	605	481	243	100	93	93	93	93	93	93	93	3
	10	864	103	106	124	281	418	561	579	513	366	179	109	103	103	103	103	103	103	2
	11	879	109	109	111	127	249	396	488	505	447	320	170	116	109	109	109	109	109	1
	12	884	111	111	111	114	120	198	336	439	474	439	336	198	120	114	111	111	111	
	HALF DAY TOTALS		879	1224	2035	2817	3360	3513	3176	2363	1525	997	709	579	556	546	546	546	539	
Jun 21	5	581	111	192	241	252	228	166	91	19	17	17	17	17	17	17	17	17	17	7
	6	564	140	344	488	552	534	434	266	70	66	66	66	66	66	66	66	66	66	6
	7	695	93	317	524	642	667	593	427	188	72	67	67	67	67	67	67	67	67	5
	8	771	96	301	440	604	678	651	539	320	107	84	84	84	84	84	84	84	84	4
	9	821	99	118	286	483	600	629	567	418	208	105	99	98	98	98	98	98	98	3
	10	849	108	113	142	296	450	534	540	465	319	157	114	108	108	108	108	108	108	2
	11	864	114	114	120	138	248	373	449	456	396	279	156	121	114	114	114	114	114	1
	12	868	116	116	116	120	126	189	303	391	423	391	303	189	126	120	116	116	116	
	HALF DAY TOTALS		811	1446	2379	3013	3454	3477	3013	2140	1376	942	718	620	597	593	593	593	585	
Jul 21	5	235	91	104	133	141	129	98	46	11	9	9	9	9	9	9	9	9	9	7
	6	492	116	302	436	501	492	407	259	71	40	40	40	40	40	40	40	40	40	6
	7	666	78	285	492	619	651	588	436	207	69	63	63	63	63	63	63	63	63	5
	8	771	96	176	418	590	675	660	547	348	119	81	81	81	81	81	81	81	81	4
	9	809	98	106	265	471	601	643	591	450	237	104	98	98	98	98	98	98	98	3
	10	839	106	109	130	283	453	550	566	500	356	177	112	106	106	106	106	106	106	2
	11	855	112	112	117	132	249	390	477	492	435	312	169	119	112	112	112	112	112	1
	12	859	114	114	114	117	124	198	329	428	462	428	329	199	124	117	114	114	114	
	HALF DAY TOTALS		701	1247	2039	2795	3311	3446	3101	2303	1496	993	721	598	570	565	565	565	550	
Aug 21	5	311	42	161	256	310	316	273	190	70	22	21	21	21	21	21	21	21	21	6
	6	599	53	193	403	543	598	565	444	250	59	49	49	49	49	49	49	49	49	5
	7	732	69	108	347	549	665	681	593	417	168	73	69	69	69	69	69	69	69	4
	8	801	84	90	198	437	607	683	655	534	323	108	84	84	84	84	84	84	84	3
	9	839	95	95	104	247	453	593	639	592	456	245	104	95	95	95	95	95	95	2
	10	858	102	102	102	113	247	433	553	589	539	406	215	110	102	102	102	102	102	1
	11	868	104	104	104	104	113	224	368	526	568	526	404	224	113	104	104	104	104	
	HALF DAY TOTALS		496	790	1449	2237	2929	3343	3282	2720	1852	1156	728	521	475	471	471	471	471	
Sep 21	7	414	24	66	224	342	401	401	343	224	66	24	23	23	23	23	23	23	23	5
	8	678	46	71	228	455	602	654	608	467	244	52	46	46	46	46	46	46	46	4
	9	792	63	63	107	366	581	702	716	621	430	163	66	63	63	63	63	63	63	3
	10	848	75	75	79	183	444	630	719	699	513	313	107	75	75	75	75	75	75	2
	11	876	82	82	82	88	230	476	639	704	664	524	292	93	82	82	82	82	82	1
	12	884	84	84	84	84	91	257	494	643	695	643	494	257	91	84	84	84	84	
	HALF DAY TOTALS		335	581	558	1467	2300	3007	3280	3039	2324	1429	766	412	334	331	331	331	331	
Oct 21	7	12	0	1	1	5	9	11	12	11	8	3	0	0	0	0	0	0	0	5
	8	522	25	27	111	304	439	501	489	398	242	51	25	25	25	25	25	25	25	4
	9	734	44	44	52	276	508	652	693	629	466	216	47	44	44	44	44	44	44	3
	10	835	56	56	58	122	403	618	736	739	628	418	136	58	56	56	56	56	56	2
	11	866	64	64	64	67	203	483	673	760	729	587	345	86	64	64	64	64	64	1
	12	878	66	66	66	66	71	274	538	704	763	704	538	274	71	66	66	66	66	
	HALF DAY TOTALS		222	225	340	818	1637	3461	2918	2918	2459	1619	808	334	226	223	223	223	223	
Nov 21	8	113	4	4	11	31	90	108	109	93	62	18	4	4	4	4	4	4	4	4
	9	561	25	25	27	165	361	492	540	509	394	211	31	25	25	25	25	25	25	3
	10	731	38	38	38	70	328	543	668	688	602	420	156	40	38	38	38	38	38	2
	11	804	46	46	46	48	165	448	645	739	720	587	358	83	46	46	46	46	46	1
	12	821	48	48	48	48	51	267	531	700	758	700	531	267	51	48	48	48	48	
	HALF DAY TOTALS		538	538	547	868	979	1752	2250	2396	2165	1583	804	368	140	138	138	138	138	
Dec 21	9	442	18	18	18	113	272	378	420	401	316	176	23	16	16	16	16	16	16	3
	10	616	30	30	30	51	286	493	613	636	563	398	156	32	30	30	30	30	30	2
	11	701	38	38	38	40	146	421	615	708	694	569	351	80	38	38	38	38	38	1
	12	789	41	41	41	41	44	256	514	679	734	679	514	256	44	41	41	41	41	
	HALF DAY TOTALS		105	105	107	211	731	1444	1924	2098	1944	1477	778	239	107	105	105	105	105	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.10 Solar Intensity and Solar Heat Gain Factors[a] for 64° N Latitude (SI Units)[b]

Date	Solar Time am	Direct Normal W/m²	Solar Heat Gain Factors, W/m² N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	HOR	Solar Time pm
Jan 21	10	69	2	2	2	4	29	51	61	66	58	41	16	2	2	2	2	2	2	2
	11	256	9	9	9	9	46	145	210	242	228	156	78	14	9	9	9	9	9	1
	12	316	11	11	11	11	52	184	311	380	385	311	184	52	11	11	11	11	11	
	HALF DAY TOTALS		16	16	16	18	85	330	582	693	660	514	295	72	17	16	16	16	16	
Feb 21	8	56	2	2	2	11	44	92	93	64	27	4	2	2	2	2	2	2	2	4
	9	433	14	14	18	134	280	373	405	375	285	143	58	14	14	14	14	14	14	3
	10	605	28	28	28	57	276	493	554	547	449	287	119	28	28	28	28	28	28	2
	11	679	32	32	32	34	139	386	558	638	622	508	307	64	32	32	32	32	32	1
	12	701	34	34	34	34	37	151	404	612	668	613	404	151	37	34	34	34	34	
	HALF DAY TOTALS		93	93	103	279	716	1408	1822	1947	1741	1284	668	259	93	93	93	93	93	
Mar 21	7	309	13	34	147	255	384	386	349	188	54	13	13	13	13	13	13	13	13	5
	8	583	39	91	247	397	498	559	538	427	246	64	39	39	39	39	39	39	39	4
	9	717	61	61	61	277	502	643	679	613	450	205	64	61	61	61	61	61	61	3
	10	788	69	69	93	111	386	598	714	718	603	410	155	69	69	69	69	69	69	2
	11	831	74	74	74	77	190	468	658	746	718	579	344	74	74	74	74	74	74	1
	12	831	76	76	76	76	81	269	535	686	754	686	535	269	81	76	76	76	76	
	HALF DAY TOTALS		333	534	673	1012	1879	2895	3589	3833	3497	2799	1831	758	455	383	383	383	383	
Apr 21	5	81	34	56	77	85	81	64	36	6	4	4	4	4	4	4	4	4	4	7
	6	419	38	147	330	400	414	371	268	111	26	24	24	24	24	24	24	24	24	6
	7	613	83	139	355	516	595	584	483	302	80	41	41	41	41	41	41	41	41	5
	8	720	54	90	249	483	653	681	634	484	270	80	54	54	54	54	54	54	54	4
	9	782	65	65	109	351	567	690	710	620	426	174	68	65	65	65	65	65	65	3
	10	820	72	72	76	161	422	613	704	698	582	375	159	72	72	72	72	72	72	2
	11	839	75	75	75	83	211	468	631	720	696	546	312	85	75	75	75	75	75	1
	12	846	79	79	79	79	85	263	505	655	708	655	505	263	85	79	79	79	79	
	HALF DAY TOTALS		413	687	1204	2115	2974	3618	3741	3268	2408	1337	801	472	382	378	378	378	378	
Mar 21	4	160	34	139	183	181	135	61	21	10	10	10	10	10	10	10	10	10	10	8
	5	418	112	298	395	423	395	302	158	34	29	29	29	29	29	29	29	29	29	7
	6	584	90	304	474	598	628	561	414	197	72	48	48	48	48	48	48	48	48	6
	7	688	65	199	436	596	661	634	507	297	93	68	68	68	68	68	68	68	68	5
	8	754	72	93	307	527	660	694	623	439	215	78	72	72	72	72	72	72	72	4
	9	796	82	85	193	364	577	678	679	559	380	147	85	82	82	82	82	82	82	3
	10	822	89	89	94	199	427	592	668	642	528	332	158	89	89	89	89	89	89	2
	11	836	93	93	93	100	228	446	594	647	644	507	288	93	93	93	93	93	93	1
	12	841	95	95	95	95	103	248	460	597	666	597	460	248	103	95	95	95	95	
	HALF DAY TOTALS		780	1341	2145	2998	3712	4073	3847	3108	2254	1447	908	485	385	385	385	385	385	
Jun 21	4	294	181	363	302	297	247	156	45	21	21	21	21	21	21	21	21	21	21	8
	5	685	195	360	466	458	458	348	175	44	39	39	39	39	39	39	39	39	39	7
	6	814	113	338	516	603	605	556	347	122	55	55	55	55	55	55	55	55	55	6
	7	698	54	225	457	610	672	632	498	282	90	64	64	64	64	64	64	64	64	5
	8	754	79	105	327	555	697	663	505	318	137	85	85	85	85	85	85	85	85	4
	9	791	89	93	181	393	573	662	655	532	343	157	93	93	93	93	93	93	93	3
	10	814	96	96	102	207	423	577	642	615	498	297	114	96	96	96	96	96	96	2
	11	827	100	100	100	108	228	451	568	619	581	426	238	100	100	100	100	100	100	1
	12	831	101	101	101	101	110	240	436	566	610	566	436	240	110	101	101	101	101	
	HALF DAY TOTALS		1016	1680	2124	2547	3951	4134	3769	2995	2142	1456	935	547	396	396	396	396	396	
Jul 21	4	168	101	149	173	172	144	93	25	13	12	12	12	12	12	12	12	12	12	8
	5	405	154	297	389	426	390	298	156	36	32	32	32	32	32	32	32	32	32	7
	6	564	94	303	467	560	567	488	335	124	71	63	63	63	63	63	63	63	63	6
	7	665	69	201	431	585	653	620	495	290	80	61	61	61	61	61	61	61	61	5
	8	730	75	94	307	520	648	660	509	349	146	58	58	58	58	58	58	58	58	4
	9	771	85	88	148	382	567	665	664	566	380	158	85	85	85	85	85	85	85	3
	10	791	92	92	98	196	422	583	655	611	458	307	116	92	92	92	92	92	92	2
	11	812	96	96	96	104	226	439	582	645	630	475	311	116	96	96	96	96	96	1
	12	816	98	98	98	98	107	240	453	596	646	596	453	240	107	98	98	98	98	
	HALF DAY TOTALS		814	1370	2157	2983	3669	4004	3763	3046	2198	1497	930	538	398	398	398	398	398	
Aug 21	5	92	28	62	85	94	89	71	40	9	4	4	4	4	4	4	4	4	4	8
	6	388	42	182	306	380	395	352	252	107	30	27	27	27	27	27	27	27	27	7
	7	570	68	152	344	494	567	555	458	289	81	65	65	65	65	65	65	65	65	6
	8	675	59	66	247	468	609	657	587	447	243	86	59	59	59	59	59	59	59	5
	9	737	70	70	107	345	549	666	683	597	420	175	70	70	70	70	70	70	70	4
	10	775	78	78	82	165	412	598	717	686	553	322	114	78	78	78	78	78	78	3
	11	798	83	83	83	89	216	456	617	684	633	469	208	83	83	83	83	83	83	2
	12	805	84	84	84	84	92	266	489	637	684	637	489	266	92	84	84	84	84	1
	HALF DAY TOTALS		647	914	1293	2073	2884	3498	3600	3147	2331	1509	866	500	360	360	360	360	360	
Sep 21	7	242	12	30	122	194	234	218	144	47	13	11	11	11	11	11	11	11	11	5
	8	513	30	33	136	324	411	505	484	387	225	65	30	30	30	30	30	30	30	4
	9	651	43	43	54	261	468	596	563	472	317	120	43	43	43	43	43	43	43	3
	10	723	52	52	53	111	366	545	623	596	480	268	52	52	52	52	52	52	52	2
	11	758	57	57	57	61	181	445	590	664	660	504	304	57	57	57	57	57	57	1
	12	769	59	59	59	59	65	260	504	660	713	660	504	260	65	59	59	59	59	
	HALF DAY TOTALS		224	341	448	968	1727	2484	2871	2810	2305	1613	1007	536	384	384	384	384	384	
Oct 21	8	54	3	7	10	30	45	52	51	42	28	13	7	3	3	3	3	3	3	4
	9	383	17	17	19	127	279	345	372	346	263	133	19	17	17	17	17	17	17	3
	10	556	28	28	28	58	311	487	528	503	385	321	115	28	28	28	28	28	28	2
	11	653	34	34	34	36	80	222	441	581	628	481	292	54	34	34	34	34	34	1
	12	693	36	36	36	36	36	128	367	528	603	528	367	128	36	36	36	36	36	
	HALF DAY TOTALS		98	98	109	273	728	1124	1711	1829	1661	1325	838	354	98	98	98	98	98	
Nov 21	10	372	9	9	9	10	11	55	87	99	62	43	17	9	9	9	9	9	9	3
	11	230	11	11	11	11	13	102	207	238	234	192	118	24	11	11	11	11	11	2
	12	307	17	17	17	19	81	348	378	444	440	374	295	369	234	16	17	17	17	1
	HALF DAY TOTALS		0	0	0	0	2	16	28	35	30	22	12	8	1	1	1	1	1	
Dec 21	11	12	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
	12	51	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	HALF DAY TOTALS		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
			N	NNW	NW	WNW	W	WSW	SW	SSW	S	SSE	SE	ESE	E	ENE	NE	NNE	HOR	PM

[a]Total solar heat gains for DSA glass (based on a ground reflectance of 0.20).
[b]Half day totals computed by Simpson's rule, time interval = 10 min.

TABLE B.11 **Solar Position and Clear Day Insolation, 32° N Latitude**

	Solar Time		Solar Position		Direct	Global Irradiance (Btu/h ft²)					
						South-Facing Elevation Angle					
Date	A.M.	P.M.	Alt	Azm	Normal	Horiz	22	32	42	52	90
Jan 21	7	5	1.4	65.2	1	0	0	0	0	1	1
	8	4	12.5	56.5	203	56	93	106	116	123	115
	9	3	22.5	46.0	269	118	175	193	206	212	181
	10	2	30.6	33.1	295	167	235	256	269	274	221
	11	1	36.1	17.5	306	198	273	295	308	312	245
	12		38.0	0.0	310	209	285	308	321	324	253
	Surface Daily Totals				2458	1288	1839	2008	2118	2166	1779
Feb 21	7	5	7.1	73.5	121	22	34	37	40	42	38
	8	4	19.0	64.4	247	95	127	136	140	141	108
	9	3	29.9	53.4	288	161	206	217	222	220	158
	10	2	39.1	39.4	306	212	266	278	283	279	193
	11	1	45.6	21.4	315	244	304	317	321	315	214
	12		48.0	0.0	317	255	316	330	334	328	222
	Surface Daily Totals				2872	1724	2188	2300	2345	2322	1644
Mar 21	7	5	12.7	81.9	185	54	60	60	59	56	32
	8	4	25.1	73.0	260	129	146	147	144	137	78
	9	3	36.8	62.1	290	194	222	224	220	209	119
	10	2	47.3	47.5	304	245	280	283	278	265	150
	11	1	55.0	26.8	311	277	317	321	315	300	170
	12		58.0	0.0	313	287	329	333	327	312	177
	Surface Daily Totals				3012	2084	2378	2403	2358	2246	1276
Apr 21	6	6	6.1	99.9	66	14	9	6	6	5	3
	7	5	18.8	92.2	206	86	78	71	62	51	10
	8	4	31.5	84.0	255	158	156	148	136	120	35
	9	3	43.9	74.2	278	220	225	217	203	183	68
	10	2	55.7	60.3	290	267	279	272	256	234	95
	11	1	65.4	37.5	295	297	313	306	290	265	112
	12		69.6	0.0	297	307	325	318	301	276	118
	Surface Daily Totals				3076	2390	2444	2356	2206	1994	764
May 21	6	6	10.4	107.2	119	36	21	13	13	12	7
	7	5	22.8	100.1	211	107	88	75	60	44	13
	8	4	35.4	92.9	250	175	159	145	127	105	15
	9	3	48.1	84.7	269	233	223	209	188	163	33
	10	2	60.6	73.3	280	277	273	259	237	208	56
	11	1	72.0	51.9	285	305	305	290	268	237	72
	12		78.0	0.0	286	315	315	301	278	247	77
	Surface Daily Totals				3112	2582	2454	2284	2064	1788	469
Jun 21	6	6	12.2	110.2	131	45	26	16	15	14	9
	7	5	24.3	103.4	210	115	91	76	59	41	14
	8	4	36.9	96.8	245	180	159	143	122	99	16
	9	3	49.6	89.4	264	236	221	204	181	153	19
	10	2	62.2	79.7	274	279	268	251	227	197	41
	11	1	74.2	60.9	279	306	299	282	257	224	56
	12		81.5	0.0	280	315	309	292	267	234	60
	Surface Daily Totals				3084	2634	2436	2234	1990	1690	370

TABLE B.11 **Solar Position and Clear Day Insolation, 32° N Latitude (Continued)**

	Solar Time		Solar Position		Direct	Global Irradiance (Btu/h ft²)					
						South-Facing Elevation Angle					
Date	A.M.	P.M.	Alt	Azm	Normal	Horiz	22	32	42	52	90
Jul 21	6	6	10.7	107.7	113	37	22	14	13	12	8
	7	5	23.1	100.6	203	107	87	75	60	44	14
	8	4	35.7	93.6	241	174	158	143	125	104	16
	9	3	48.4	85.5	261	230	220	205	185	159	31
	10	2	60.9	74.3	271	274	269	254	232	204	54
	11	1	72.4	53.3	277	302	300	285	262	232	69
	12		78.6	0.0	279	311	310	296	273	242	74
	Surface Daily Totals				3012	2558	2422	2250	2030	1754	458
Aug 21	6	6	6.5	100.5	59	14	9	7	6	6	4
	7	5	19.1	92.8	190	85	77	69	60	50	12
	8	4	31.8	84.7	240	156	152	144	132	116	33
	9	3	44.3	75.0	263	216	220	212	197	178	65
	10	2	56.1	61.3	276	262	272	264	249	226	91
	11	1	66.0	38.4	282	292	305	298	281	257	107
	12		70.3	0.0	284	302	317	309	292	268	113
	Surface Daily Totals				2902	2352	2388	2296	2144	1934	736
Sep 21	7	5	12.7	81.9	163	51	56	56	55	52	30
	8	4	25.1	73.0	240	124	140	141	138	131	75
	9	3	36.8	62.1	272	188	213	215	211	201	114
	10	2	47.3	47.5	287	237	270	273	268	255	145
	11	1	55.0	26.8	294	268	306	309	303	289	164
	12		58.0	0.0	296	278	318	321	315	300	171
	Surface Daily Totals				2808	2014	2288	2308	2264	2154	1226
Oct 21	7	5	6.8	73.1	99	19	29	32	34	36	32
	8	4	18.7	64.0	229	90	120	128	133	134	104
	9	3	29.5	53.0	273	155	198	208	213	212	153
	10	2	38.7	39.1	293	204	257	269	273	270	188
	11	1	45.1	21.1	302	236	294	307	311	306	209
	12		47.5	0.0	304	247	306	320	324	318	217
	Surface Daily Totals				2696	1654	2100	2208	2252	2232	1588
Nov 21	7	5	1.5	65.4	2	0	0	0	1	1	1
	8	4	12.7	56.6	196	55	91	104	113	119	111
	9	3	22.6	46.1	263	118	173	190	202	208	176
	10	2	30.8	33.2	289	166	233	252	265	270	217
	11	1	36.2	17.6	301	197	270	291	303	307	241
	12		38.2	0.0	304	207	282	304	316	320	249
	Surface Daily Totals				2406	1280	1816	1980	2084	2130	1742
Dec 21	8	4	10.3	53.8	176	41	77	90	101	108	107
	9	3	19.8	43.6	257	102	161	180	195	204	183
	10	2	27.6	31.2	288	150	221	244	259	267	226
	11	1	32.7	16.4	301	180	258	282	298	305	251
	12		34.6	0.0	304	190	271	295	311	318	259
	Surface Daily Totals				2348	1136	1704	1888	2016	2086	1794

NOTE: 1 Btu/h ft² = 3.152 W/m².

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TABLE B.12 **Solar Position and Clear Day Insolation, 40° N Latitude**

	Solar Time		Solar Position			Global Irradiance (Btu/h ft²)					
					Direct		South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Normal	Horiz	30	40	50	60	90
Jan 21	8	4	8.1	55.3	142	28	65	74	81	85	84
	9	3	16.8	44.0	239	83	155	171	182	187	171
	10	2	23.8	30.9	274	127	218	237	249	254	223
	11	1	28.4	16.0	289	154	257	277	290	293	253
	12		30.0	0.0	294	164	270	291	303	306	263
	Surface Daily Totals				2182	948	1660	1810	1906	1944	1726
Feb 21	7	5	4.8	72.7	69	10	19	21	23	24	22
	8	4	15.4	62.2	224	73	114	122	126	127	107
	9	3	25.0	50.2	274	132	195	205	209	208	167
	10	2	32.8	35.9	295	178	256	267	271	267	210
	11	1	38.1	18.9	305	206	293	306	310	304	236
	12		40.0	0.0	308	216	306	319	323	317	245
	Surface Daily Totals				2640	1414	2060	2162	2202	2176	1730
Mar 21	7	5	11.4	80.2	171	46	55	55	54	51	35
	8	4	22.5	69.6	250	114	140	141	138	131	89
	9	3	32.8	57.3	282	173	215	217	213	202	138
	10	2	41.6	41.9	297	218	273	276	271	258	176
	11	1	47.7	22.6	305	247	310	313	307	293	200
	12		50.0	0.0	307	257	322	326	320	305	208
	Surface Daily Totals				2916	1852	2308	2330	2284	2174	1484
Apr 21	6	6	7.4	98.9	89	20	11	8	7	7	4
	7	5	18.9	89.5	206	87	77	70	61	50	12
	8	4	30.3	79.3	252	152	153	145	133	117	53
	9	3	41.3	67.2	274	207	221	213	199	179	93
	10	2	51.2	51.4	286	250	275	267	252	229	126
	11	1	58.7	29.2	292	277	308	301	285	260	147
	12		61.6	0.0	293	287	320	313	296	271	154
	Surface Daily Totals				3092	2274	2412	2320	2168	1956	1022
May 21	5	7	1.9	114.7	1	0	0	0	0	0	0
	6	6	12.7	105.6	144	49	25	15	14	13	9
	7	5	24.0	96.6	216	114	89	76	60	44	13
	8	4	35.4	87.2	250	175	158	144	125	104	25
	9	3	46.8	76.0	267	227	221	206	186	160	60
	10	2	57.5	60.9	277	267	270	255	233	205	89
	11	1	66.2	37.1	283	293	301	287	264	234	108
	12		70.0	0.0	284	301	312	297	274	243	114
	Surface Daily Totals				3160	2552	2442	2264	2040	1760	724
Jun 21	5	7	4.2	117.3	22	4	3	3	2	2	1
	6	6	14.8	108.4	155	60	30	18	17	16	10
	7	5	26.0	99.7	216	123	92	77	59	40	14
	8	4	37.4	90.7	246	182	159	142	121	97	16
	9	3	48.8	80.2	263	233	219	202	179	151	47
	10	2	59.8	65.8	272	272	266	248	224	193	74
	11	1	69.2	41.9	277	296	296	278	253	221	92
	12		73.5	0.0	279	304	306	289	263	230	98
	Surface Daily Totals				3180	2648	2434	2224	1974	1670	610

TABLE B.12 **Solar Position and Clear Day Insolation, 40° N Latitude (Continued)**

	Solar Time		Solar Position			Global Irradiance (Btu/h ft²)					
					Direct		South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Normal	Horiz	30	40	50	60	90
Jul 21	5	7	2.3	115.2	2	0	0	0	0	0	0
	6	6	13.1	106.1	138	50	26	17	15	14	9
	7	5	24.3	97.2	208	114	89	75	60	44	14
	8	4	35.8	87.8	241	174	157	142	124	102	24
	9	3	47.2	76.7	259	225	218	203	182	157	58
	10	2	57.9	61.7	269	265	266	251	229	200	86
	11	1	66.7	37.9	275	290	296	281	258	228	104
	12		70.6	0.0	276	298	307	292	269	238	111
	Surface Daily Totals				3062	2534	2409	2230	2006	1728	702
Aug 21	6	6	7.9	99.5	81	21	12	9	8	7	5
	7	5	19.3	90.0	191	87	76	69	60	49	12
	8	4	30.7	79.9	237	150	150	141	129	113	50
	9	3	41.8	67.9	260	205	216	207	193	173	89
	10	2	51.7	52.1	272	246	267	259	244	221	120
	11	1	59.3	29.7	278	273	300	292	276	252	140
	12		62.3	0.0	280	282	311	303	287	262	147
	Surface Daily Totals				2916	2244	2354	2258	2104	1894	978
Sep 21	7	5	11.4	80.2	149	43	51	51	49	47	32
	8	4	22.5	69.6	230	109	133	134	131	124	84
	9	3	32.8	57.3	263	167	206	208	203	193	132
	10	2	41.6	41.9	280	211	262	265	260	247	168
	11	1	47.7	22.6	287	239	298	301	295	281	192
	12		50.0	0.0	290	249	310	313	307	292	200
	Surface Daily Totals				2708	1788	2210	2228	2182	2074	1416
Oct 21	7	5	4.5	72.3	48	7	14	15	17	17	16
	8	4	15.0	61.9	204	68	106	113	117	118	100
	9	3	24.5	49.8	257	126	185	195	200	198	160
	10	2	32.4	35.6	280	170	245	257	261	257	203
	11	1	37.6	18.7	291	199	283	295	299	294	229
	12		39.5	0.0	294	208	295	308	312	306	238
	Surface Daily Totals				2454	1348	1962	2060	2098	2074	1654
Nov 21	8	4	8.2	55.4	136	28	63	72	78	82	81
	9	3	17.0	44.1	232	82	152	167	178	183	167
	10	2	24.0	31.0	268	126	215	233	245	249	219
	11	1	28.6	16.1	283	153	254	273	285	288	248
	12		30.2	0.0	288	163	267	287	298	301	258
	Surface Daily Totals				2128	942	1636	1778	1870	1908	1686
Dec 21	8	4	5.5	53.0	89	14	39	45	50	54	56
	9	3	14.0	41.9	217	65	135	152	164	171	163
	10	2	20.7	29.4	261	107	200	221	235	242	221
	11	1	25.0	15.2	280	134	239	262	276	283	252
	12		26.6	0.0	285	143	253	275	290	296	263
	Surface Daily Totals				1978	782	1480	1634	1740	1796	1646

NOTE: 1 Btu/h ft² = 3.152 W/m².

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TABLE B.13 **Solar Position and Clear Day Insolation, 48° N Latitude**

	Solar Time		Solar Position			Global Irradiance (Btu/h ft²)					
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	38	48	58	68	90
Jan 21	8	4	3.5	54.6	37	4	17	19	21	22	22
	9	3	11.0	42.6	185	46	120	132	140	145	139
	10	2	16.9	29.4	239	83	190	206	216	220	206
	11	1	20.7	15.1	261	107	231	249	260	263	243
	12		22.0	0.0	267	115	245	264	275	278	255
	Surface Daily Totals				1710	596	1360	1478	1550	1578	1478
Feb 21	7	5	2.4	72.2	12	1	3	4	4	4	4
	8	4	11.6	60.5	188	49	95	102	105	106	96
	9	3	19.7	47.7	251	100	178	187	191	190	167
	10	2	26.2	33.3	278	139	240	251	255	251	217
	11	1	30.5	17.2	290	165	278	290	294	288	247
	12		32.0	0.0	293	173	291	304	307	301	258
	Surface Daily Totals				2330	1080	1880	1972	2024	1978	1720
Mar 21	7	5	10.0	78.7	153	37	49	49	47	45	35
	8	4	19.5	66.8	236	96	131	132	129	122	96
	9	3	28.2	53.4	270	147	205	207	203	193	152
	10	2	35.4	37.8	287	187	263	266	261	248	195
	11	1	40.3	19.8	295	212	300	303	297	283	223
	12		42.0	0.0	298	220	312	315	309	294	232
	Surface Daily Totals				2780	1578	2208	2228	2182	2074	1632
Apr 21	6	6	8.6	97.8	108	27	13	9	8	7	5
	7	5	18.6	86.7	205	85	76	68	59	48	21
	8	4	28.5	74.9	247	142	149	141	129	113	69
	9	3	37.8	61.2	268	191	216	208	194	174	115
	10	2	45.8	44.6	280	228	268	260	245	223	152
	11	1	51.5	24.0	286	252	301	294	278	254	177
	12		53.6	0.0	288	260	313	305	289	264	185
	Surface Daily Totals				3076	2106	2358	2266	2114	1902	1262
May 21	5	7	5.2	114.3	41	9	4	4	4	3	2
	6	6	14.7	103.7	162	61	27	16	15	13	10
	7	5	24.6	93.0	219	118	89	75	60	43	13
	8	4	34.7	81.6	248	171	156	142	123	101	45
	9	3	44.3	68.3	264	217	217	202	182	156	86
	10	2	53.0	51.3	274	252	265	251	229	200	120
	11	1	59.5	28.6	279	274	296	281	258	228	141
	12		62.0	0.0	280	281	306	292	269	238	149
	Surface Daily Totals				3254	2482	2418	2234	2010	1728	982
Jun 21	5	7	7.9	116.5	77	21	9	9	8	7	5
	6	6	17.2	106.2	172	74	33	19	18	16	12
	7	5	27.0	95.8	220	129	93	77	59	39	15
	8	4	37.1	84.6	246	181	157	140	119	95	55
	9	3	46.9	71.6	261	225	216	198	175	147	74
	10	2	55.8	54.8	269	259	262	244	220	189	105
	11	1	62.7	31.2	274	280	291	273	248	216	126
	12		65.5	0.0	275	287	301	283	258	225	133
	Surface Daily Totals				3312	2626	2420	2204	1950	1644	874

TABLE B.13 **Solar Position and Clear Day Insolation, 48° N Latitude (Continued)**

	Solar Time		Solar Position			Global Irradiance (Btu/h ft²)					
							South-Facing Elevation Angle				
Date	A.M.	P.M.	Alt	Azm	Direct Normal	Horiz	38	48	58	68	90
Jul 21	5	7	5.7	114.7	43	10	5	5	4	4	3
	6	6	15.2	104.1	156	62	28	18	16	15	11
	7	5	25.1	93.5	211	118	89	75	59	42	14
	8	4	35.1	82.1	240	171	154	140	121	99	43
	9	3	44.8	68.8	256	215	214	199	178	153	83
	10	2	53.5	51.9	266	250	261	246	224	195	116
	11	1	60.1	29.0	271	272	291	276	253	223	137
	12		62.6	0.0	272	279	301	286	263	232	144
	Surface Daily Totals				3158	2474	2386	2200	1974	1694	956
Aug 21	6	6	9.1	98.3	99	28	14	10	9	8	6
	7	5	19.1	87.2	190	85	75	67	58	47	20
	8	4	29.0	75.4	232	141	145	137	125	109	65
	9	3	38.4	61.8	254	189	210	201	187	168	110
	10	2	46.4	45.1	266	225	260	252	237	214	146
	11	1	52.2	24.3	272	248	293	285	268	244	169
	12		54.3	0.0	274	256	304	296	279	255	177
	Surface Daily Totals				2898	2086	2300	2200	2046	1836	1208
Sep 21	7	5	10.0	78.7	131	35	44	44	43	40	31
	8	4	19.5	66.8	215	92	124	124	121	115	90
	9	3	28.2	53.4	251	142	196	197	193	183	143
	10	2	35.4	37.8	269	181	251	254	248	236	185
	11	1	40.3	19.8	278	205	287	289	284	269	212
	12		42.0	0.0	280	213	299	302	296	281	221
	Surface Daily Totals				2568	1522	2102	2118	2070	1966	1546
Oct 21	7	5	2.0	71.9	4	0	1	1	1	1	1
	8	4	11.2	60.2	165	44	86	91	95	95	87
	9	3	19.3	47.4	233	94	167	176	180	178	157
	10	2	25.7	33.1	262	133	228	239	242	239	207
	11	1	30.0	17.1	274	157	266	277	281	276	237
	12		31.5	0.0	278	166	279	291	294	288	247
	Surface Daily Totals				2154	1022	1774	1860	1890	1866	1626
Nov 21	8	4	3.6	54.7	36	5	17	19	21	22	22
	9	3	11.2	42.7	179	46	117	129	137	141	135
	10	2	17.1	29.5	233	83	186	202	212	215	201
	11	1	20.9	15.1	255	107	227	245	255	258	238
	12		22.2	0.0	261	115	241	259	270	272	250
	Surface Daily Totals				1668	596	1336	1448	1518	1544	1442
Dec 21	9	3	8.0	40.9	140	27	87	98	105	110	109
	10	2	13.6	28.2	214	63	164	180	192	197	190
	11	1	17.3	14.4	242	86	207	226	239	244	231
	12		18.6	0.0	250	94	222	241	254	260	244
	Surface Daily Totals				1444	446	1136	1250	1326	1364	1304

NOTE: 1 Btu/h ft² = 3.152 W/m².

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APPENDICES

TABLE B.14 **Solar Position and Clear Day Insolation, 64° N Latitude**

Date	Solar Time A.M.	Solar Time P.M.	Solar Position Alt	Solar Position Azm	Direct Normal	Global Irradiance (Btu/h ft²) Horiz	South-Facing Elevation Angle 54	64	74	84	90
Jan 21	10	2	2.8	28.1	22	2	17	19	20	20	20
	11	1	5.2	14.1	81	12	72	77	80	81	81
	12		6.0	0.0	100	16	91	98	102	103	103
	Surface Daily Totals				306	45	268	290	302	306	304
Feb 21	8	4	3.4	58.7	35	4	17	19	19	19	19
	9	3	8.6	44.8	147	31	103	108	111	110	107
	10	2	12.6	30.3	199	55	170	178	181	178	173
	11	1	15.1	15.3	222	71	212	220	223	219	213
	12		16.0	0.0	228	77	225	235	237	232	226
	Surface Daily Totals				1432	400	1230	1286	1302	1282	1252
Mar 21	7	5	6.5	76.5	95	18	30	29	29	27	25
	8	4	12.7	62.6	185	54	101	102	99	94	89
	9	3	18.1	48.1	227	87	171	172	169	160	153
	10	2	22.3	32.7	249	112	227	229	224	213	203
	11	1	25.1	16.6	260	129	262	265	259	246	235
	12		26.0	0.0	263	134	274	277	271	258	246
	Surface Daily Totals				2296	932	1856	1870	1830	1736	1656
Apr 21	5	7	4.0	108.5	27	5	2	2	2	1	1
	6	6	10.4	95.1	133	37	15	9	8	7	6
	7	5	17.0	81.6	194	76	70	63	54	43	37
	8	4	23.3	67.5	228	112	136	128	116	102	91
	9	3	29.0	52.3	248	144	197	189	176	158	145
	10	2	33.5	36.0	260	169	246	239	224	203	188
	11	1	36.5	18.4	266	184	278	270	255	233	216
	12		37.6	0.0	268	190	289	281	266	243	225
	Surface Daily Totals				2982	1644	2176	2082	1936	1736	1594
May 21	4	8	5.8	125.1	51	11	5	4	4	3	3
	5	7	11.6	112.1	132	42	13	11	10	9	8
	6	6	17.9	99.1	185	79	29	16	14	12	11
	7	5	24.5	85.7	218	117	86	72	56	39	28
	8	4	30.9	71.5	239	152	148	133	115	94	80
	9	3	36.8	56.1	252	182	204	190	170	145	128
	10	2	41.6	38.9	261	205	249	235	213	186	167
	11	1	44.9	20.1	265	219	278	264	242	213	193
	12		46.0	0.0	267	224	288	274	251	222	201
	Surface Daily Totals				3470	2236	2312	2124	1898	1624	1436
Jun 21	3	9	4.2	139.4	21	4	2	2	2	2	1
	4	8	9.0	126.4	93	27	10	9	8	7	6
	5	7	14.7	113.6	154	60	16	15	13	11	10
	6	6	21.0	100.8	194	96	34	19	17	14	13
	7	5	27.5	87.5	221	132	91	74	55	36	23
	8	4	34.0	73.3	239	166	150	133	112	88	73
	9	3	39.9	57.8	251	195	204	187	164	137	119
	10	2	44.9	40.4	258	217	247	230	206	177	157
	11	1	48.3	20.9	262	231	275	258	233	202	181
	12		49.5	0.0	263	235	284	267	242	211	189
	Surface Daily Totals				3650	2488	2342	2118	1862	1558	1356

TABLE B.14 **Solar Position and Clear Day Insolation, 64° N Latitude (Continued)**

Date	Solar Time A.M.	Solar Time P.M.	Solar Position Alt	Solar Position Azm	Direct Normal	Global Irradiance (Btu/h ft²) Horiz	South-Facing Elevation Angle 54	64	74	84	90
Jul 21	4	8	6.4	125.3	53	13	6	5	5	4	4
	5	7	12.1	112.4	128	44	14	13	11	10	9
	6	6	18.4	99.4	179	81	30	17	16	13	12
	7	5	25.0	86.0	211	118	86	72	56	38	28
	8	4	31.4	71.8	231	152	146	131	113	91	77
	9	3	37.3	56.3	245	182	201	186	166	141	124
	10	2	42.2	39.2	253	204	245	230	208	181	162
	11	1	45.4	20.2	257	218	273	258	236	207	187
	12		46.6	0.0	259	223	282	267	245	216	195
	Surface Daily Totals				3372	2248	2280	2090	1864	1588	1400
Aug 21	5	7	4.6	108.8	29	6	3	3	2	2	2
	6	6	11.0	95.5	123	39	16	11	10	8	7
	7	5	17.6	81.9	181	77	69	61	52	42	35
	8	4	23.9	67.8	214	113	131	123	112	97	87
	9	3	29.6	52.6	234	144	190	182	169	150	138
	10	2	34.2	36.2	246	168	237	229	215	194	179
	11	1	37.2	18.5	252	183	268	260	244	222	205
	12		38.3	0.0	254	188	278	270	255	232	215
	Surface Daily Totals				2808	1646	2108	2008	1860	1662	1522
Sep 21	7	5	6.5	76.5	77	16	25	24	24	23	21
	8	4	12.7	62.6	163	51	92	92	90	85	81
	9	3	18.1	48.1	206	83	159	159	156	147	141
	10	2	22.3	32.7	229	108	212	213	209	198	189
	11	1	25.1	16.6	240	124	246	248	243	230	220
	12		26.0	0.0	244	129	258	260	254	241	230
	Surface Daily Totals				2074	892	1726	1736	1696	1608	1532
Oct 21	8	4	3.0	58.5	17	2	9	9	10	10	10
	9	3	8.1	44.6	122	26	86	91	93	92	90
	10	2	12.1	30.2	176	50	152	159	161	159	155
	11	1	14.6	15.2	201	65	193	201	203	200	195
	12		15.5	0.0	208	71	207	215	217	213	208
	Surface Daily Totals				1238	358	1088	1136	1152	1134	1106
Nov 21	10	2	3.0	28.1	23	3	18	20	21	21	21
	11	1	5.4	14.2	79	12	70	76	79	80	79
	12		6.2	0.0	97	17	89	96	100	101	100
	Surface Daily Totals				302	46	266	286	298	302	300
Dec 21	11	1	1.8	13.7	4	0	3	4	4	4	4
	12		2.6	0.0	16	2	14	15	16	17	17
	Surface Daily Totals				24	2	20	22	24	24	24

NOTE: 1 Btu/h ft² = 3.152 W/m².

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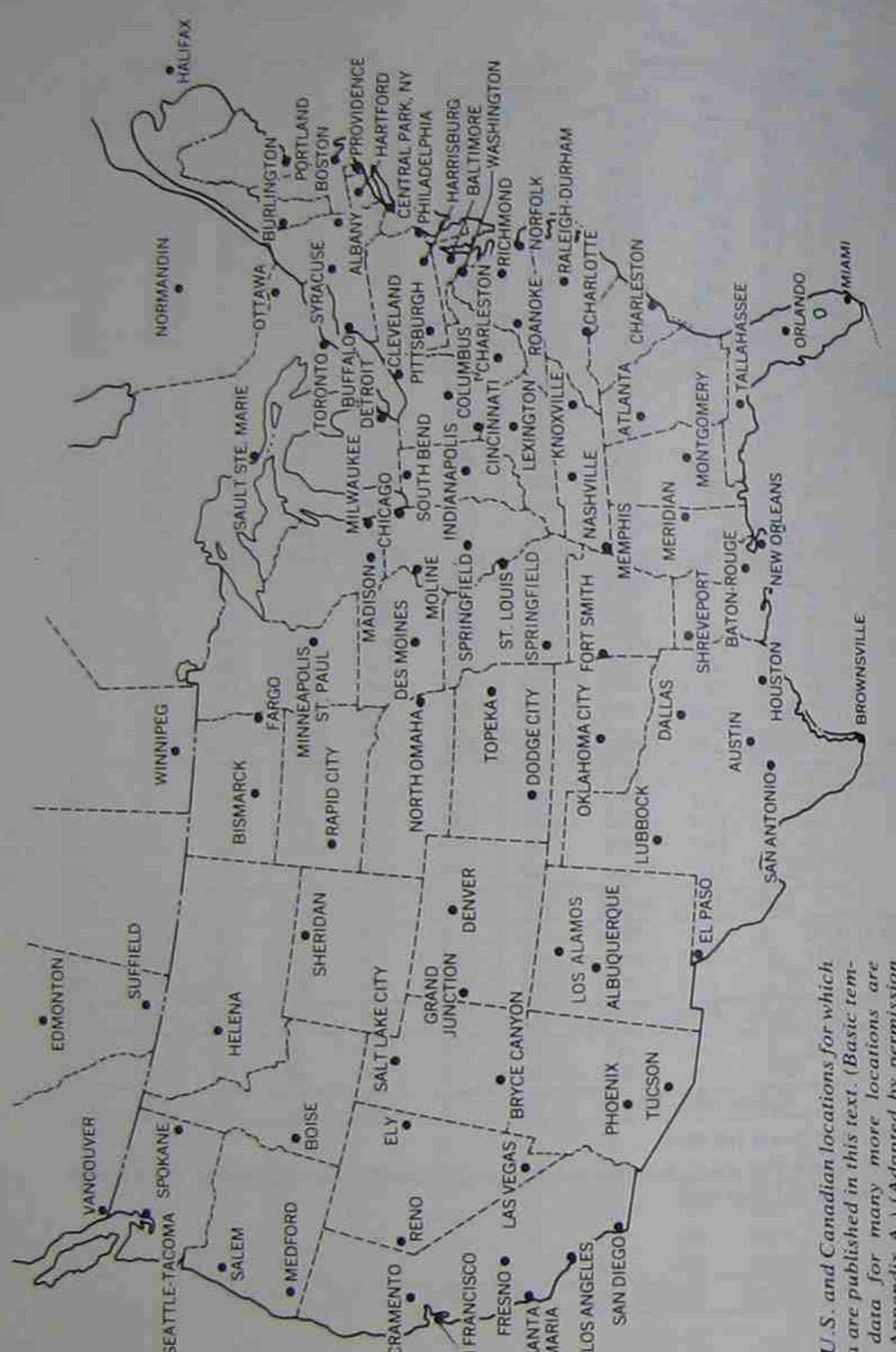

Fig. B.1 U.S. and Canadian locations for which solar data are published in this text. (Basic temperature data for many more locations are found in Appendix A.) (Adapted by permission from J. D. Balcomb et al., Passive Solar Design Handbook, Vol 3, © 1983, American Solar Energy Society, Inc., Boulder, Colo.)

TABLE B.15 Average Insolation, Temperature, and DD Data

Elevation in feet, latitude in degrees north latitude, HS (horizontal surface) and VS (vertical surface) in Btu/day ft², TA in degrees F, D50 through D65 in degree days F.

United States

MONTGOMERY, ALABAMA — Elev 203 Lat 32.3

	HS	VS	TA	D50	D55	D60	D65
Jan	752	896	48	148	256	394	556
Jul	1841	820	81	0	0	0	0
Yr	1390	946	65	445	866	1474	2269

PHOENIX, ARIZONA — Elev 1112 Lat 33.4

	HS	VS	TA	D50	D55	D60	D65
Jan	1021	1462	51	78	162	285	428
Jul	2486	964	91	0	0	0	0
Yr	1371	1326	70	187	459	919	1552

TUCSON, ARIZONA — Elev 2556 Lat 32.1

	HS	VS	TA	D50	D55	D60	D65
Jan	1099	1539	51	80	166	292	442
Jul	2341	922	86	0	0	0	0
Yr	1874	1307	68	214	525	1036	1752

FORT SMITH, ARKANSAS — Elev 463 Lat 35.3

	HS	VS	TA	D50	D55	D60	D65
Jan	744	996	39	346	497	651	806
Jul	2065	908	82	0	0	0	0
Yr	1406	1013	61	996	1622	2405	3336

FRESNO, CALIFORNIA — Elev 328 Lat 36.8

	HS	VS	TA	D50	D55	D60	D65
Jan	657	886	45	176	308	457	611
Jul	2685	1076	81	0	0	0	0
Yr	1714	1210	62	507	1021	1741	2650

LOS ANGELES, CALIFORNIA — Elev 105 Lat 33.9

	HS	VS	TA	D50	D55	D60	D65
Jan	926	1293	55	21	83	186	331
Jul	2307	942	69	0	1	5	19
Yr	1596	1157	62	64	299	849	1819

SACRAMENTO, CALIFORNIA — Elev 26 Lat 38.5

	HS	VS	TA	D50	D55	D60	D65
Jan	597	829	45	183	315	464	617
Jul	2688	1131	75	0	0	0	0
Yr	1646	1198	60	554	1097	1871	2843

SAN DIEGO, CALIFORNIA — Elev 30 Lat 32.7

	HS	VS	TA	D50	D55	D60	D65
Jan	976	1325	55	9	58	160	314
Jul	2186	902	70	0	0	1	6
Yr	1600	1151	63	23	170	623	1507

SAN FRANCISCO, CALIFORNIA — Elev 16 Lat 37.6

	HS	VS	TA	D50	D55	D60	D65
Jan	708	1023	48	82	210	363	518
Jul	2392	1034	63	0	2	21	93
Yr	1556	1156	57	202	705	1643	3042

SANTA MARIA, CALIFORNIA — Elev 236 Lat 34.9

	HS	VS	TA	D50	D55	D60	D65
Jan	854	1198	51	51	150	296	450
Jul	2341	965	62	0	3	30	112
Yr	1610	1172	57	155	624	1604	3053

DENVER, COLORADO — Elev 5331 Lat 39.7

	HS	VS	TA	D50	D55	D60	D65
Jan	840	1465	30	623	778	933	1088
Jul	2273	1053	73	0	0	0	0
Yr	1570	1334	50	2592	3588	4733	6016

GRAND JUNCTION, COLORADO — Elev 4839 Lat 39.1

	HS	VS	TA	D50	D55	D60	D65
Jan	791	1296	27	726	880	1035	1190
Jul	2465	1094	79	0	0	0	0
Yr	1661	1346	53	2514	3412	4434	5605

HARTFORD, CONNECTICUT — Elev 160 Lat 41.9

	HS	VS	TA	D50	D55	D60	D65
Jan	477	694	25	781	936	1091	1246
Jul	1649	861	73	0	0	0	0
Yr	1060	835	49	2971	3948	5075	6350

WASHINGTON, D.C. — Elev 289 Lat 38.9

	HS	VS	TA	D50	D55	D60	D65
Jan	572	793	32	555	710	865	1020
Jul	1817	883	75	0	0	0	0
Yr	1210	912	54	2004	2869	3864	5010

MIAMI, FLORIDA — Elev 7 Lat 25.8

	HS	VS	TA	D50	D55	D60	D65
Jan	1057	1121	67	1	4	18	53
Jul	1763	787	82	0	0	0	0
Yr	1474	941	76	3	14	55	206

ORLANDO, FLORIDA — Elev 118 Lat 28.5

	HS	VS	TA	D50	D55	D60	D65
Jan	999	1151	60	13	42	105	197
Jul	1801	795	81	0	0	0	0
Yr	1488	984	72	39	126	348	733

TALLAHASSEE, FLORIDA — Elev 69 Lat 30.4

	HS	VS	TA	D50	D55	D60	D65
Jan	877	1033	53	73	150	256	408
Jul	1748	786	81	0	0	0	0
Yr	1434	969	68	215	501	951	1563

ATLANTA, GEORGIA — Elev 1033 Lat 33.6

	HS	VS	TA	D50	D55	D60	D65
Jan	718	884	42	246	393	546	701
Jul	1812	821	78	0	0	0	0
Yr	1347	941	61	758	1362	2150	3095

BOISE, IDAHO — Elev 2867 Lat 43.6

	HS	VS	TA	D50	D55	D60	D65
Jan	485	770	29	651	806	961	1116
Jul	2613	1309	75	0	0	0	0
Yr	1499	1255	51	2420	3395	4536	5833

CHICAGO, ILLINOIS — Elev 623 Lat 41.8

	HS	VS	TA	D50	D55	D60	D65
Jan	507	756	24	797	952	1107	1262
Jul	1944	984	75	0	0	0	0
Yr	1217	960	51	2954	3881	4940	6127

MOLINE, ILLINOIS — Elev 594 Lat 41.4

	HS	VS	TA	D50	D55	D60	D65
Jan	535	803	22	884	1039	1194	1349
Jul	1939	974	75	0	0	0	0
Yr	1226	973	50	3191	4117	5178	6395

SPRINGFIELD, ILLINOIS — Elev 614 Lat 39.8

	HS	VS	TA	D50	D55	D60	D65
Jan	585	852	27	723	877	1032	1187
Jul	2058	984	76	0	0	0	0
Yr	1304	1003	53	2558	3434	4425	5558

TABLE B.15 Average Insolation, Temperature, and DD Data (Continued)

INDIANAPOLIS, INDIANA — Elev 807 Lat 39.7

	HS	VS	TA	D50	D55	D60	D65
Jan	496	668	28	685	840	995	1150
Jul	1806	891	75	0	0	0	0
Yr	1167	873	52	2511	3403	4421	5577

SOUTH BEND, INDIANA — Elev 774 Lat 41.7

	HS	VS	TA	D50	D55	D60	D65
Jan	416	566	24	806	961	1116	1271
Jul	1852	944	72	0	1	4	6
Yr	1140	864	49	3112	4084	5199	6462

DES MOINES, IOWA — Elev 965 Lat 41.5

	HS	VS	TA	D50	D55	D60	D65
Jan	581	912	19	949	1104	1259	1414
Jul	2097	1037	75	0	0	0	0
Yr	1314	1065	49	3491	4435	5510	6710

DODGE CITY, KANSAS — Elev 2582 Lat 37.8

	HS	VS	TA	D50	D55	D60	D65
Jan	827	1303	31	596	750	905	1060
Jul	2295	1013	79	0	0	0	0
Yr	1562	1232	55	2132	2980	3945	5046

TOPEKA, KANSAS — Elev 886 Lat 39.1

	HS	VS	TA	D50	D55	D60	D65
Jan	681	1033	28	683	837	992	1147
Jul	2128	993	78	0	0	0	0
Yr	1387	1036	54	2325	3175	4137	5243

LEXINGTON, KENTUCKY — Elev 988 Lat 38.0

	HS	VS	TA	D50	D55	D60	D65
Jan	546	714	33	531	685	840	995
Jul	1850	881	76	0	0	0	0
Yr	1221	892	55	1865	2686	3632	4729

BATON ROUGE, LOUISIANA — Elev 75 Lat 30.5

	HS	VS	TA	D50	D55	D60	D65
Jan	785	889	51	90	174	294	451
Jul	1746	786	82	0	0	0	0
Yr	1380	913	67	232	530	1006	1670

NEW ORLEANS, LOUISIANA — Elev 10 Lat 30.0

	HS	VS	TA	D50	D55	D60	D65
Jan	835	950	53	73	150	252	403
Jul	1813	801	82	0	0	0	0
Yr	1438	943	68	197	465	887	1465

SHREVEPORT, LOUISIANA — Elev 259 Lat 32.5

	HS	VS	TA	D50	D55	D60	D65
Jan	762	920	47	154	264	403	552
Jul	2014	864	83	0	0	0	0
Yr	1428	973	66	428	832	1415	2167

PORTLAND, MAINE — Elev 62 Lat 43.6

	HS	VS	TA	D50	D55	D60	D65
Jan	450	689	22	884	1039	1194	1349
Jul	1659	894	68	0	1	5	27
Yr	1052	857	45	3648	4758	6039	7498

DETROIT, MICHIGAN — Elev 627 Lat 42.4

	HS	VS	TA	D50	D55	D60	D65
Jan	417	585	26	760	915	1070	1225
Jul	1835	951	73	0	0	0	0
Yr	1122	869	50	2931	3890	4986	6228

SAULT STE. MARIE, MICHIGAN — Elev 725 Lat 46.5

	HS	VS	TA	D50	D55	D60	D65
Jan	325	492	14	1110	1265	1420	1575
Jul	1835	1045	64	1	7	33	96
Yr	1044	861	40	4969	6198	7607	9193

MINNEAPOLIS, MINNESOTA — Elev 837 Lat 44.9

	HS	VS	TA	D50	D55	D60	D65
Jan	464	768	12	1172	1327	1482	1637
Jul	1970	1071	72	0	1	5	11
Yr	1172	996	44	4584	5631	6824	8159

MERIDIAN, MISSISSIPPI — Elev 308 Lat 32.3

	HS	VS	TA	D50	D55	D60	D65
Jan	744	883	47	163	274	413	575
Jul	1823	815	81	0	0	0	0
Yr	1371	933	65	510	955	1582	2368

SAINT LOUIS, MISSOURI — Elev 564 Lat 38.7

	HS	VS	TA	D50	D55	D60	D65
Jan	627	898	31	581	735	890	1045
Jul	2049	959	79	0	0	0	0
Yr	1329	1006	56	1961	2762	3686	4750

SPRINGFIELD, MISSOURI — Elev 1270 Lat 37.2

	HS	VS	TA	D50	D55	D60	D65
Jan	684	956	33	534	686	840	995
Jul	2063	936	78	0	0	0	0
Yr	1364	1011	56	1848	2618	3522	4571

HELENA, MONTANA — Elev 3898 Lat 46.6

	HS	VS	TA	D50	D55	D60	D65
Jan	419	719	18	989	1144	1299	1454
Jul	2334	1312	68	1	3	12	33
Yr	1266	1134	43	4151	5342	6689	8190

NORTH OMAHA, NEBRASKA — Elev 1325 Lat 41.4

	HS	VS	TA	D50	D55	D60	D65
Jan	634	1034	20	924	1079	1234	1389
Jul	2106	1038	75	0	1	3	7
Yr	1323	1078	49	3369	4309	5381	6601

ELY, NEVADA — Elev 6253 Lat 39.3

	HS	VS	TA	D50	D55	D60	D65
Jan	819	1380	24	818	973	1128	1283
Jul	2447	1094	67	0	2	11	23
Yr	1675	1391	44	3716	4922	6291	7814

LAS VEGAS, NEVADA — Elev 2178 Lat 36.1

	HS	VS	TA	D50	D55	D60	D65
Jan	978	1553	44	216	346	493	645
Jul	2588	1039	90	0	0	0	0
Yr	1866	1431	66	631	1129	1788	2601

RENO, NEVADA — Elev 4400 Lat 39.5

	HS	VS	TA	D50	D55	D60	D65
Jan	800	1345	32	561	716	871	1026
Jul	2692	1167	69	0	1	5	17
Yr	1764	1439	49	2292	3345	4590	6022

ALBUQUERQUE, NEW MEXICO — Elev 5312 Lat 35.0

	HS	VS	TA	D50	D55	D60	D65
Jan	1016	1562	35	459	614	769	924
Jul	2489	995	79	0	0	0	0
Yr	1830	1379	57	1497	2292	3216	4292

LOS ALAMOS, NEW MEXICO — Elev 7380 Lat 35.9

	HS	VS	TA	D50	D55	D60	D65
Jan	893	1340	29	650	804	958	1113
Jul	2051	913	68	0	0	0	20
Yr	1579	1244	48	2822	3851	5043	6437

ALBANY, NEW YORK — Elev 292 Lat 42.7

	HS	VS	TA	D50	D55	D60	D65
Jan	456	674	22	884	1039	1194	1349
Jul	1725	908	72	0	1	3	9
Yr	1068	843	48	3424	4428	5586	6868

TABLE B.15 Average Insolation, Temperature, and DD Data (Continued)

BUFFALO, NEW YORK — Elev 705 Lat 42.9

	HS	VS	TA	D50	D55	D60	D65
Jan	349	465	24	815	970	1125	1280
Jul	1776	935	70	0	0	3	12
Yr	1037	780	47	3322	4363	5551	6927

NEW YORK, NEW YORK — Elev 187 Lat 40.8

	HS	VS	TA	D50	D55	D60	D65
Jan	500	708	32	552	707	862	1017
Jul	1688	861	77	0	0	0	0
Yr	1101	849	55	1931	2759	3737	4848

SYRACUSE, NEW YORK — Elev 407 Lat 43.1

	HS	VS	TA	D50	D55	D60	D65
Jan	385	538	24	818	973	1128	1283
Jul	1758	931	72	0	1	3	11
Yr	1037	791	48	3215	4218	5366	6678

CHARLOTTE, NORTH CAROLINA — Elev 768 Lat 35.2

	HS	VS	TA	D50	D55	D60	D65
Jan	719	944	42	255	402	555	710
Jul	1831	841	79	0	0	0	0
Yr	1346	981	61	828	1451	2257	3218

RALEIGH-DURHAM, NORTH CAROLINA — Elev 440 Lat 35.9

	HS	VS	TA	D50	D55	D60	D65
Jan	694	924	41	300	451	605	760
Jul	1776	832	78	0	0	0	0
Yr	1297	955	59	990	1659	2509	3514

BISMARCK, NORTH DAKOTA — Elev 1647 Lat 46.8

	HS	VS	TA	D50	D55	D60	D65
Jan	467	847	8	1296	1451	1606	1761
Jul	2184	1241	71	0	2	8	18
Yr	1251	1145	41	5235	6364	7627	9044

FARGO, NORTH DAKOTA — Elev 899 Lat 46.9

	HS	VS	TA	D50	D55	D60	D65
Jan	415	720	6	1367	1522	1677	1832
Jul	2120	1210	71	0	1	5	13
Yr	1206	1075	41	5485	6607	7858	9271

CINCINNATI, OHIO — Elev 889 Lat 39.1

	HS	VS	TA	D50	D55	D60	D65
Jan	500	659	31	587	741	896	1051
Jul	1771	869	76	0	0	0	0
Yr	1160	858	54	2117	2973	3951	5070

CLEVELAND, OHIO — Elev 804 Lat 41.4

	HS	VS	TA	D50	D55	D60	D65
Jan	388	507	27	716	871	1026	1181
Jul	1828	929	71	0	1	4	9
Yr	1093	808	50	2804	3768	4879	6154

COLUMBUS, OHIO — Elev 833 Lat 40.0

	HS	VS	TA	D50	D55	D60	D65
Jan	459	606	28	670	825	980	1135
Jul	1755	876	74	0	0	0	0
Yr	1128	834	52	2524	3438	4491	5702

OKLAHOMA CITY, OKLAHOMA — Elev 1302 Lat 35.4

	HS	VS	TA	D50	D55	D60	D65
Jan	801	1114	37	413	565	719	874
Jul	2128	925	82	0	0	0	0
Yr	1463	1073	60	1232	1903	2734	3695

MEDFORD, OREGON — Elev 1299 Lat 42.4

	HS	VS	TA	D50	D55	D60	D65
Jan	407	565	37	417	571	725	880
Jul	2475	1207	72	0	1	3	11
Yr	1356	1033	53	1576	2505	3621	4930

SALEM, OREGON — Elev 200 Lat 44.9

	HS	VS	TA	D50	D55	D60	D65
Jan	332	471	39	348	502	657	812
Jul	2142	1154	67	0	1	7	43
Yr	1130	897	52	1265	2220	3411	4852

HARRISBURG, PENNSYLVANIA — Elev 348 Lat 40.2

	HS	VS	TA	D50	D55	D60	D65
Jan	536	763	30	617	772	927	1082
Jul	1764	883	76	0	0	0	0
Yr	1152	887	53	2221	3093	4086	5224

PHILADELPHIA, PENNSYLVANIA — Elev 30 Lat 39.9

	HS	VS	TA	D50	D55	D60	D65
Jan	555	792	32	549	704	859	1014
Jul	1758	876	77	0	0	0	0
Yr	1170	905	55	1935	2775	3749	4865

PITTSBURGH, PENNSYLVANIA — Elev 1224 Lat 40.5

	HS	VS	TA	D50	D55	D60	D65
Jan	424	553	28	679	834	989	1144
Jul	1689	857	72	0	1	3	7
Yr	1071	793	50	2635	3574	4669	5930

PROVIDENCE, RHODE ISLAND — Elev 62 Lat 41.7

	HS	VS	TA	D50	D55	D60	D65
Jan	506	750	28	670	825	980	1135
Jul	1695	878	72	0	0	0	0
Yr	1114	884	50	2566	3543	4669	5972

CHARLESTON, SOUTH CAROLINA — Elev 39 Lat 32.9

	HS	VS	TA	D50	D55	D60	D65
Jan	744	904	49	120	222	360	521
Jul	1799	813	80	0	0	0	0
Yr	1346	940	65	360	756	1355	2146

RAPID CITY, SOUTH DAKOTA — Elev 3169 Lat 44.0

	HS	VS	TA	D50	D55	D60	D65
Jan	542	928	22	871	1026	1181	1336
Jul	2223	1161	73	1	2	8	13
Yr	1344	1177	47	3681	4749	5965	7324

KNOXVILLE, TENNESSEE — Elev 981 Lat 35.8

	HS	VS	TA	D50	D55	D60	D65
Jan	621	785	41	302	449	602	756
Jul	1804	839	78	0	0	0	0
Yr	1275	909	60	1018	1671	2504	3478

MEMPHIS, TENNESSEE — Elev 285 Lat 35.0

	HS	VS	TA	D50	D55	D60	D65
Jan	683	870	41	312	455	606	760
Jul	1972	879	82	0	0	0	0
Yr	1368	965	62	988	1588	2357	3227

NASHVILLE, TENNESSEE — Elev 591 Lat 36.1

	HS	VS	TA	D50	D55	D60	D65
Jan	580	721	38	369	519	673	828
Jul	1891	869	80	0	0	0	0
Yr	1272	891	59	1195	1874	2720	3696

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TABLE B.15 Average Insolation, Temperature, and DD Data (Continued)

AUSTIN, TEXAS — Elev 620 Lat 30.3

	HS	VS	TA	D50	D55	D60	D65
Jan	864	1008	50	116	207	333	483
Jul	2105	865	85	0	0	0	0
Yr	1478	974	68	289	602	1088	1737

BROWNSVILLE, TEXAS — Elev 20 Lat 25.9

	HS	VS	TA	D50	D55	D60	D65
Jan	913	923	60	18	51	116	225
Jul	2212	867	84	0	0	0	0
Yr	1550	917	74	44	127	325	650

DALLAS, TEXAS — Elev 489 Lat 32.8

	HS	VS	TA	D50	D55	D60	D65
Jan	821	1035	45	189	312	457	608
Jul	2122	890	86	0	0	0	0
Yr	1470	1014	66	505	943	1543	2290

EL PASO, TEXAS — Elev 3917 Lat 31.8

	HS	VS	TA	D50	D55	D60	D65
Jan	1125	1572	44	210	355	509	663
Jul	2450	934	82	0	0	0	0
Yr	1901	1327	63	561	1102	1810	2678

HOUSTON, TEXAS — Elev 108 Lat 30.0

	HS	VS	TA	D50	D55	D60	D65
Jan	772	852	52	71	150	263	416
Jul	1828	805	83	0	0	0	0
Yr	1353	884	69	161	409	825	1434

LUBBOCK, TEXAS — Elev 3241 Lat 33.6

	HS	VS	TA	D50	D55	D60	D65
Jan	1031	1497	39	343	494	648	803
Jul	2412	956	80	0	0	0	0
Yr	1768	1279	60	1069	1739	2582	3545

SAN ANTONIO, TEXAS — Elev 794 Lat 29.5

	HS	VS	TA	D50	D55	D60	D65
Jan	895	1026	51	93	179	302	451
Jul	2121	863	85	0	0	0	0
Yr	1501	973	69	213	490	941	1570

BRYCE CANYON, UTAH — Elev 7588 Lat 37.7

	HS	VS	TA	D50	D55	D60	D65
Jan	914	1511	20	936	1091	1246	1401
Jul	2424	1044	62	1	8	47	128
Yr	1742	1404	40	4693	6106	7675	9133

SALT LAKE CITY, UTAH — Elev 4226 Lat 40.8

	HS	VS	TA	D50	D55	D60	D65
Jan	639	1017	28	683	837	992	1147
Jul	2590	1186	77	0	0	0	0
Yr	1606	1301	51	2648	3612	4725	5983

BURLINGTON, VERMONT — Elev 341 Lat 44.5

	HS	VS	TA	D50	D55	D60	D65
Jan	385	572	17	1029	1184	1339	1494
Jul	1721	941	70	0	1	4	20
Yr	1023	815	44	4142	5230	6464	7876

NORFOLK, VIRGINIA — Elev 30 Lat 36.9

	HS	VS	TA	D50	D55	D60	D65
Jan	678	932	41	300	450	605	760
Jul	1853	868	78	0	0	0	0
Yr	1327	990	59	974	1646	2489	3488

RICHMOND, VIRGINIA — Elev 164 Lat 37.5

	HS	VS	TA	D50	D55	D60	D65
Jan	632	863	38	390	543	698	853
Jul	1774	849	78	0	0	0	0
Yr	1250	936	58	1296	2021	2909	3939

ROANOKE, VIRGINIA — Elev 1175 Lat 37.3

	HS	VS	TA	D50	D55	D60	D65
Jan	660	911	36	423	577	732	887
Jul	1796	854	75	0	0	0	0
Yr	1271	958	56	1486	2277	3211	4307

SEATTLE-TACOMA, WASHINGTON — Elev 400 Lat 47.4

	HS	VS	TA	D50	D55	D60	D65
Jan	262	378	38	367	521	676	831
Jul	2248	1299	65	0	2	16	80
Yr	1056	857	51	1386	2393	3662	5185

SPOKANE, WASHINGTON — Elev 2365 Lat 47.6

	HS	VS	TA	D50	D55	D60	D65
Jan	315	496	25	763	918	1073	1228
Jul	2357	1368	70	0	2	7	21
Yr	1227	1068	47	3061	4150	5411	6835

CHARLESTON, WEST VIRGINIA — Elev 951 Lat 38.4

	HS	VS	TA	D50	D55	D60	D65
Jan	498	638	35	483	636	791	946
Jul	1682	827	75	0	0	0	0
Yr	1125	822	55	1726	2540	3488	4590

MADISON, WISCONSIN — Elev 860 Lat 43.1

	HS	VS	TA	D50	D55	D60	D65
Jan	515	822	17	1029	1184	1339	1494
Jul	1934	1009	70	0	1	5	14
Yr	1193	978	45	4086	5143	6352	7730

MILWAUKEE, WISCONSIN — Elev 692 Lat 42.9

	HS	VS	TA	D50	D55	D60	D65
Jan	479	731	19	949	1104	1259	1414
Jul	1962	1017	70	0	1	4	15
Yr	1194	957	46	3774	4833	6045	7444

SHERIDAN, WYOMING — Elev 3966 Lat 44.8

	HS	VS	TA	D50	D55	D60	D65
Jan	517	900	21	899	1054	1209	1364
Jul	2329	1237	70	1	2	9	28
Yr	1333	1170	45	3860	4991	6279	7708

Canada

EDMONTON, ALBERTA — Elev 2220 Lat 53.6

	HS	VS	TA	D50	D55	D60	D65
Jan	324	746	4	1421	1574	1728	1883
Jul	1977	1378	62	1	7	38	117
Yr	1114	1205	36	6317	7563	9016	10650

SUFFIELD, ALBERTA — Elev 2549 Lat 50.3

	HS	VS	TA	D50	D55	D60	D65
Jan	433	937	7	1333	1486	1640	1794
Jul	2173	1377	67	0	2	11	49
Yr	1239	1269	40	5500	6637	7923	9393

VANCOUVER, BRITISH COLUMBIA — Elev 310 Lat 49.3

	HS	VS	TA	D50	D55	D60	D65
Jan	254	395	37	425	572	724	876
Jul	2021	1239	63	0	1	13	82
Yr	1060	916	50	1791	2781	4041	5588

WINNIPEG, MANITOBA — Elev 820 Lat 49.9

	HS	VS	TA	D50	D55	D60	D65
Jan	461	1011	0	1588	1740	1893	2047
Jul	2025	1264	67	0	2	9	45
Yr	1190	1199	36	6925	8062	9338	10790

TABLE B.15 Average Insolation, Temperature, and DD Data (Continued)

HALIFAX, NOVA SCOTIA — Elev 136 Lat 44.6

	HS	VS	TA	D50	D55	D60	D65
Jan	456	737	26	752	900	1051	1204
Jul	1694	929	65	0	1	8	57
Yr	1076	907	46	3457	4500	5746	7211

OTTAWA, ONTARIO — Elev 377 Lat 45.5

	HS	VS	TA	D50	D55	D60	D65
Jan	510	914	13	1169	1320	1473	1627
Jul	1875	1040	69	0	1	4	23
Yr	1158	1015	43	4912	5965	7158	8529

TORONTO, ONTARIO — Elev 443 Lat 43.7

	HS	VS	TA	D50	D55	D60	D65
Jan	487	777	22	891	1041	1194	1348
Jul	1958	1035	70	0	0	3	18
Yr	1171	948	46	3842	4853	6013	7343

NORMANDIN, QUEBEC — Elev 450 Lat 48.8

	HS	VS	TA	D50	D55	D60	D65
Jan	454	921	0	1564	1719	1873	2028
Jul	1707	1031	62	1	7	40	118
Yr	1092	1053	34	7037	8308	9762	11376

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APPENDICES

C

ANNUAL SOLAR PERFORMANCE

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This appendix lists 30 passive solar heating systems (3 water wall, 9 Trombé wall, 9 direct gain, and 9 sunspace) for the U.S. and Canadian locations shown in Fig. B.1. The *Passive Solar Heating Analysis* lists 94 systems, for about twice as many locations. The specifications for all 94 systems are listed here, so that the original source may be consulted if your passive system is not represented by one of those in this appendix.

TABLE C.1 **Characteristics of Selected Passive Solar Heating Systems**

Part A. ***Water Wall Systems***

Designation	Thermal Storage Capacity[a] (Btu/ft² F)	Wall Thickness (in.)	No. of Glazings	Wall Surface	Night Insulation
WW-A1	15.6	3	2	Normal	No
WW-A2	31.2	6	2	Normal	No
WW-A3[b]	46.8	9	2	Normal	No
WW-A4	62.4	12	2	Normal	No
WW-A5	93.6	18	2	Normal	No
WW-A6	124.8	24	2	Normal	No
WW-B1	46.8	9	1	Normal	No
WW-B2	46.8	9	3	Normal	No
WW-B3	46.8	9	1	Normal	Yes
WW-B4[b]	46.8	9	2	Normal	Yes
WW-B5	46.8	9	3	Normal	Yes
WW-C1	46.8	9	1	Selective	No
WW-C2[b]	46.8	9	2	Selective	No
WW-C3	46.8	9	1	Selective	Yes
WW-C4	46.8	9	2	Selective	Yes

Part B. ***Trombe Wall Systems: Vented***

Designation	Thermal Storage Capacity[c] (Btu/ft² F)	Wall Thickness[c] (in.)	pck[d] (Btu²/h-ft⁴-F²)	No. of Glazings	Wall Surface	Night Insulation
TW-A1[b]	15	6	30	2	Normal	No
TW-A2[b]	22.5	9	30	2	Normal	No
TW-A3[b]	30	12	30	2	Normal	No
TW-A4[b]	45	18	30	2	Normal	No
TW-B1	15	6	15	2	Normal	No
TW-B2	22.5	9	15	2	Normal	No
TW-B3[b]	30	12	15	2	Normal	No
TW-B4	45	18	15	2	Normal	No
TW-C1	15	6	7.5	2	Normal	No
TW-C2	22.5	9	7.5	2	Normal	No
TW-C3	30	12	7.5	2	Normal	No
TW-C4	45	18	7.5	2	Normal	No
TW-D1	30	12	30	1	Normal	No
TW-D2	30	12	30	3	Normal	No
TW-D3	30	12	30	1	Normal	Yes
TW-D4[b]	30	12	30	2	Normal	Yes
TW-D5	30	12	30	3	Normal	Yes
TW-E1	30	12	30	1	Selective	No
TW-E2[b]	30	12	30	2	Selective	No
TW-E3	30	12	30	1	Selective	Yes
TW-E4	30	12	30	2	Selective	Yes

Note: Vented systems may be made to perform as unvented systems by sealing both top and bottom vent openings.

TABLE C.1 **Characteristics of Selected Passive Solar Heating Systems (Continued)**

Part C. Trombe Wall Systems: Unvented

Designation	Thermal Storage Capacity[c] (Btu/ft² F)	Wall Thickness[c] (in.)	ρck[d] (Btu²/h-ft⁴-F²)	No. of Glazings	Wall Surface	Night Insulation
TW-F1	15	6	30	2	Normal	No
TW-F2	22.5	9	30	2	Normal	No
TW-F3[b]	30	12	30	2	Normal	No
TW-F4	45	18	30	2	Normal	No
TW-G1	15	6	15	2	Normal	No
TW-G2	22.5	9	15	2	Normal	No
TW-G3	30	12	15	2	Normal	No
TW-G4	45	18	15	2	Normal	No
TW-H1	15	6	7.5	2	Normal	No
TW-H2	22.5	9	7.5	2	Normal	No
TW-H3	30	12	7.5	2	Normal	No
TW-H4	45	18	7.5	2	Normal	No
TW-I1	30	12	30	1	Normal	No
TW-I2	30	12	30	3	Normal	No
TW-I3	30	12	30	1	Normal	Yes
TW-I4	30	12	30	2	Normal	Yes
TW-I5	30	12	30	3	Normal	Yes
TW-J1	30	12	30	1	Selective	No
TW-J2[b]	30	12	30	2	Selective	No
TW-J3	30	12	30	1	Selective	Yes
TW-J4	30	12	30	2	Selective	Yes

Part D. Direct-Gain Systems

Designation	Thermal Storage Capacity[c] (Btu/ft² F)	Mass Thickness[c] (in.)	Ratio of Mass to Glazing Area	No. of Glazings	Night Insulation
DG-B1[b]	30	2	6	2	No
DG-B2[b]	30	2	6	3	No
DG-B3[b]	30	2	6	2	Yes
DG-B1[b]	45	6	3	2	No
DG-B2[b]	45	6	3	3	No
DG-B3[b]	45	6	3	2	Yes
DG-C1[b]	60	4	6	2	No
DG-C2[b]	60	4	6	3	No
DG-C3[b]	60	4	6	2	Yes

TABLE C.1 **Characteristics of Selected Passive Solar Heating Systems (Continued)**

Part E. Sunspace Systems

Designation	Type[a]	Tilt (Degrees)	Common Wall	End Walls	Night Insulation
SS-A1[b]	Attached	50	Masonry	Opaque	No
SS-A2	Attached	50	Masonry	Opaque	Yes
SS-A3	Attached	50	Masonry	Glazed	No
SS-A4	Attached	50	Masonry	Glazed	Yes
SS-A5	Attached	50	Insulated	Opaque	No
SS-A6	Attached	50	Insulated	Opaque	Yes
SS-A7	Attached	50	Insulated	Glazed	No
SS-A8	Attached	50	Insulated	Glazed	Yes
SS-B1[b]	Attached	90/30	Masonry	Opaque	No
SS-B2[b]	Attached	90/30	Masonry	Opaque	Yes
SS-B3[b]	Attached	90/30	Masonry	Glazed	No
SS-B4	Attached	90/30	Masonry	Glazed	Yes
SS-B5	Attached	90/30	Insulated	Opaque	No
SS-B6	Attached	90/30	Insulated	Opaque	Yes
SS-B7	Attached	90/30	Insulated	Glazed	No
SS-B8	Attached	90/30	Insulated	Glazed	Yes
SS-C1[b]	Semi-enclosed	90	Masonry	Common	No
SS-C2[b]	Semi-enclosed	90	Masonry	Common	Yes
SS-C3	Semi-enclosed	90	Insulated	Common	No
SS-C4	Semi-enclosed	90	Insulated	Common	Yes
SS-D1	Semi-enclosed	50	Masonry	Common	No
SS-D2	Semi-enclosed	50	Masonry	Common	Yes
SS-D3	Semi-enclosed	50	Insulated	Common	No
SS-D4	Semi-enclosed	50	Insulated	Common	Yes
SS-E1[b]	Semi-enclosed	90/30	Masonry	Common	No
SS-E2[b]	Semi-enclosed	90/30	Masonry	Common	Yes
SS-E3[b]	Semi-enclosed	90/30	Insulated	Common	No
SS-E4	Semi-enclosed	90/30	Insulated	Common	Yes

[a]Per unit of projected area.

[b]Listed in this text.

[c]The thermal storage capacity is per unit of projected area, or, equivalently, the quantity ρcf. The wall thickness (t) is listed only as an appropriate guide by assuming that $\rho c = 30$ Btu/ft³-°F (ρ of 150 lb/ft³ and c of 0.2 Btu/lb-°F), typical of ordinary concrete.

[d]pck is the product of the density (lb/ft³), specific heat (Btu/lb-°F) and thermal conductivity (Btu/h-ft-°F); see Table C.2.

[e]See Fig. C.1 for additional description.

TABLE C.2 **Thermal Properties of Various Materials**

Material	*Source*[a]	*Density, ρ (lb/ft³)*	*Specific Heat, c (Btu/lb-°F)*	*Heat Capacity, ρc (Btu/ft³-°F)*	*Conductivity, k (Btu/h-°F-ft)*	*Diffusivity, k/ρc (ft²/h)*	*ρck (Btu²/h-ft⁴-°F²)*
Water	1	62.3	1.0	62.3			
Concrete	2, 3	144	0.21	30.3	0.89	0.029	27.0
Concrete block	2, 3						
Heavy weight		135	0.21	28.4	0.74	0.026	21.0
Medium weight		105	0.22	23.1	0.41	0.018	9.5
Light weight		85	0.23	19.6	0.27	0.014	5.3
Brick	1, 4						
Paving		135	0.19	25.7	0.75	0.029	19.3
Face		130	0.19	24.7	0.75	0.030	18.5
Building		120	0.19	22.8	0.42	0.018	9.6
Mortar or grout	1	116	0.20	23.2	0.42	0.018	9.7
Adobe	5	80	0.20	16.0	0.38	0.024	6.1
		100		20.0	0.75	0.038	15.0
Gypsum or plasterboard	1	50	0.26	13.0	0.097	0.058	9.8
Douglas fir plywood	1	34	0.29	9.9	0.067	0.007	0.7
Hardwood	1	45	0.30	13.5	0.092	0.007	1.2

Source: Reprinted by permission from *Passive Solar Heating Analysis*, © 1984, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga.

Note: Concrete and masonry products can be manufactured in a variety of densities. The values listed are for the most commonly available products. The thermal properties of concrete and concrete block vary with density. Empirical correlations between these properties are[2] $k = 0.05e^{0.02\rho}$ and [3] $c = 1/(3.934 + 0.006\rho)$.

[a]1. *ASHRAE Handbook: 1981 Fundamentals* (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga., 1981).

2. "Calculating the Steady State *U*-Value of Concrete Masonry Walls," Expanded Shale, Clay, and Slate Institute, 4905 Del Ray Avenue, Bethesda, Md.

3. David Whiting, Albert Litvin, and Stanley E. Goodwin, "Specific Heat of Selected Concretes," *Research and Development Bulletin RD058.01B*, Portland Cement Association, 5420 Old Orchard Road, Skokie, Ill.

4. "Brick Passive Solar Heating Systems. Material Properties—Part IV," *Technical Notes on Brick Construction 43D*, Brick Institute of America, 1750 Old Meadow Road, McLean, Va. September/October 1980.

5. Benjamin T. Rogers, private communication; and W. L. Sibbitt, measurements at Los Alamos National Laboratory. *Note that the thermal conductivity of adobe varies greatly with moisture content, which is part of the reason for the wide range quoted.*

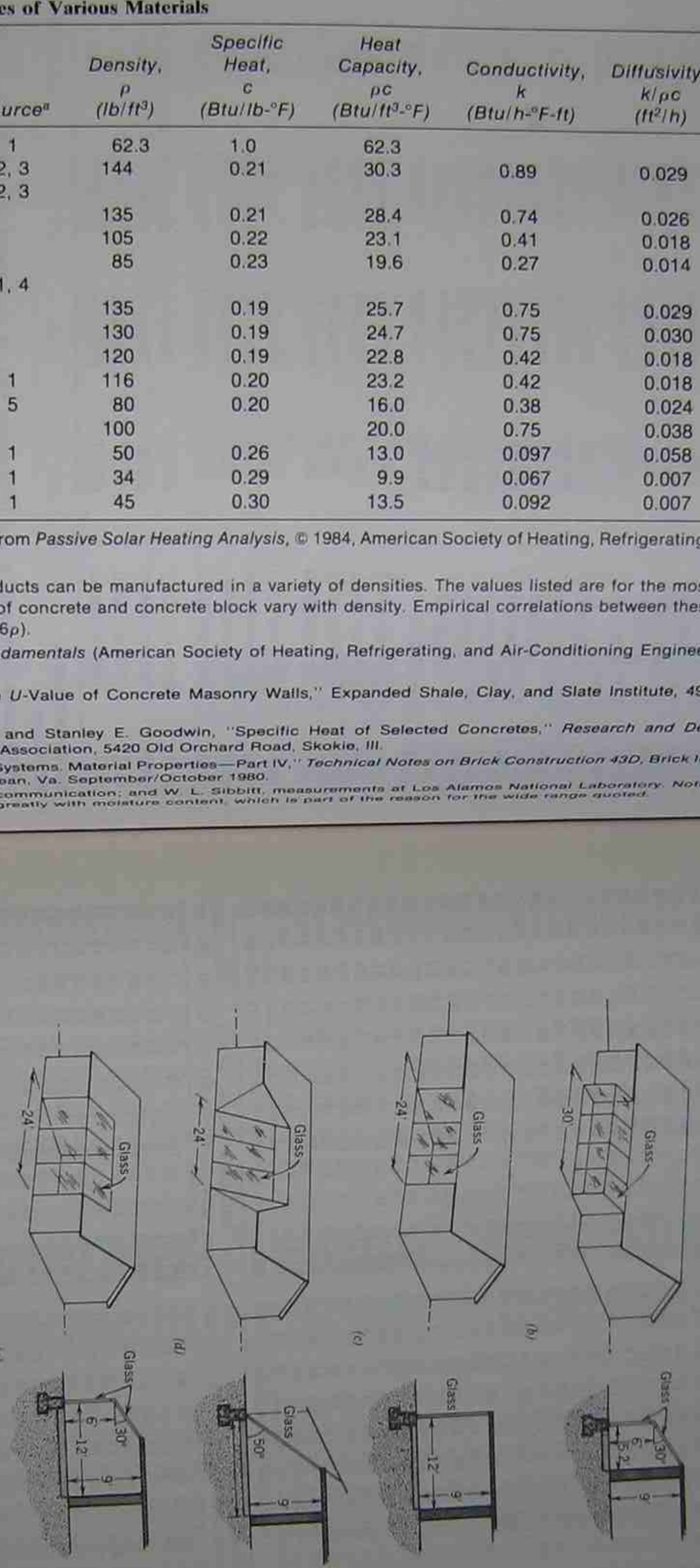


Fig. C.1 *Types of sunspaces, described in Table C.1, Part E.* (a) *and* (b) *Considered* attached *to the building;* (c), (d), *and* (e) *considered* semienclosed *by the building. The architectural detail at the sides of type* (d) *is insignificant; no shading of the sunspace by the building was accounted for in the performance estimates of Table C.2.* (*Reprinted by permission from J. D. Balcomb et al., Passive Solar Heating Analysis,* © *1989, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga.*)

TABLE C.3 Annual Passive Heating Performance: SSF

For each location, DD listed are DD65. For a description of SSF (Solar Savings Fraction) see Fig. 5.6, page 205; LCR (load–collector ratio) is described in Section 5.6. LCR units are Btu/DD-ft².

United States

MONTGOMERY, ALABAMA SSF (%)						2272 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	17	29	38	48	55	64	70	77
WWB4	18	36	48	60	68	78	83	89
WWC2	18	36	47	59	67	76	82	88
TWA1	17	24	29	35	40	46	51	57
TWA2	16	26	33	41	46	54	60	67
TWA3	15	26	34	43	49	58	63	70
TWA4	14	26	34	43	49	58	64	72
TWB3	14	24	31	39	45	54	60	67
TWD4	17	33	43	54	62	72	78	84
TWE2	18	34	44	55	63	72	78	84
TWF3	12	23	30	39	45	54	60	67
TWJ2	15	31	41	52	60	70	76	82
DGA1	12	21	28	34	39	45	49	53
DGA2	13	23	31	39	45	53	58	64
DGA3	15	27	37	47	55	64	70	77
DGB1	12	22	29	37	43	51	56	62
DGB2	13	24	32	41	49	58	65	71
DGB3	15	28	38	49	57	68	75	82
DGC1	14	25	34	43	50	60	66	72
DGC2	15	27	36	47	55	66	72	79
DGC3	18	32	42	55	64	75	81	87
SSA1	21	32	40	48	55	63	68	75
SSB1	17	28	35	42	48	56	62	68
SSB2	21	35	44	54	61	70	76	82
SSB3	17	26	33	40	46	54	59	66
SSC1	15	26	34	43	49	58	64	71
SSC2	17	31	41	51	58	68	74	80
SSE1	20	33	42	51	58	67	72	78
SSE2	23	40	51	62	69	78	83	88
SSE3	18	28	35	43	48	56	62	68

PHOENIX, ARIZONA SSF (%)						1556 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	33	54	66	77	83	90	93	96
WWB4	39	64	76	86	91	96	98	99
WWC2	39	63	75	85	90	95	97	99
TWA1	26	40	49	58	65	73	79	84
TWA2	29	46	56	67	74	82	87	91
TWA3	29	48	59	70	77	85	89	93
TWA4	29	48	60	71	78	86	90	94
TWB3	26	44	55	66	73	82	86	91
TWD4	35	58	70	81	87	93	96	98
TWE2	36	59	71	82	88	93	96	98
TWF3	26	44	55	67	74	82	87	92
TWJ2	33	56	68	79	86	92	95	97
DGA1	26	43	54	64	70	77	81	85
DGA2	26	45	56	67	74	82	86	90
DGA3	29	51	64	75	81	87	91	93
DGB1	27	47	60	71	77	84	87	91
DGB2	27	48	61	73	80	88	91	94
DGB3	29	53	67	79	85	91	94	96
DGC1	31	54	58	79	85	90	93	95
DGC2	30	54	68	80	86	92	95	97
DGC3	33	59	74	85	90	95	96	98
SSA1	34	52	62	73	79	86	90	94
SSB1	29	46	56	67	73	81	86	90
SSB2	36	56	67	78	84	90	93	96
SSB3	28	44	54	64	71	79	84	89
SSC1	30	49	61	72	78	86	90	94
SSC2	34	56	68	79	85	91	94	97
SSE1	36	56	67	77	83	90	93	96
SSE2	42	64	76	85	90	95	97	99
SSE3	30	47	57	67	74	82	86	91

TUCSON, ARIZONA SSF (%)						1758 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	31	52	64	75	82	89	93	96
WWB4	37	62	75	85	91	96	98	99
WWC2	37	61	74	84	90	95	97	99
TWA1	25	38	47	56	63	72	78	84
TWA2	27	44	55	65	73	81	86	91
TWA3	28	46	58	69	76	84	89	93
TWA4	27	46	58	69	77	85	89	94
TWB3	25	42	53	64	72	81	86	91
TWD4	33	56	69	80	86	93	96	98
TWE2	35	57	70	81	87	93	96	98
TWF3	24	42	53	65	73	81	86	91
TWJ2	31	54	67	78	85	92	95	97
DGA1	24	41	52	62	68	76	80	84
DGA2	24	43	54	65	72	81	85	89
DGA3	27	49	62	74	80	87	90	93
DGB1	24	44	58	69	76	83	87	91
DGB2	25	45	59	72	79	87	91	94
DGB3	27	50	65	78	85	91	94	96
DGC1	28	51	66	78	84	90	93	95
DGC2	28	51	66	79	85	92	95	97
DGC3	31	56	72	84	90	95	96	98
SSA1	33	51	62	72	79	86	90	94
SSB1	29	45	55	66	73	81	86	91
SSB2	35	55	67	77	84	90	94	97
SSB3	27	43	53	64	71	79	84	89
SSC1	28	47	59	70	77	86	90	94
SSC2	32	54	66	78	84	91	94	97
SSE1	35	55	67	77	83	90	93	96
SSE2	41	64	76	85	91	95	97	99
SSE3	30	46	56	67	73	82	86	91

FORT SMITH, ARKANSAS SSF (%)						3338 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	11	21	29	37	43	51	57	64
WWB4	12	27	37	49	57	67	73	80
WWC2	12	27	37	48	55	65	72	79
TWA1	14	19	23	27	31	36	40	45
TWA2	12	20	25	31	36	43	48	54
TWA3	11	19	26	33	38	46	51	58
TWA4	10	19	25	33	38	46	52	59
TWB3	10	18	23	30	35	43	48	54
TWD4	12	25	34	44	51	61	67	75
TWE2	13	26	35	44	52	61	67	75
TWF3	8	16	22	29	34	42	47	54
TWJ2	10	23	32	41	48	58	65	72
DGA1	8	14	19	24	28	33	36	39
DGA2	9	17	23	29	35	42	46	52
DGA3	11	21	28	37	44	53	59	66
DGB1	8	15	19	25	30	36	40	46
DGB2	9	17	23	31	36	45	51	58
DGB3	11	21	29	38	45	56	63	71
DGC1	10	18	24	30	36	44	50	56
DGC2	11	20	27	35	42	52	59	66
DGC3	13	24	32	43	51	63	70	78
SSA1	16	25	31	38	43	50	55	62
SSB1	13	21	26	33	37	44	49	55
SSB2	15	27	35	43	50	59	64	71
SSB3	12	19	25	30	35	41	46	52
SSC1	10	19	25	32	37	45	51	57
SSC2	11	23	31	40	47	56	62	69
SSE1	14	24	31	39	45	53	58	65
SSE2	16	30	39	50	57	66	72	79
SSE3	14	21	27	33	37	44	49	55

TABLE C.3 Annual Passive Heating Performance: SSF (Continued)

LOS ANGELES, CALIFORNIA SSF (%)						1793 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	37	58	70	81	87	93	95	98
WWB4	43	68	80	89	93	97	99	99
WWC2	42	67	79	88	93	97	98	99
TWA1	29	43	52	62	69	77	82	68
TWA2	32	49	60	71	78	86	90	94
TWA3	33	52	63	74	81	88	92	96
TWA4	32	52	64	75	82	89	93	96
TWB3	29	48	59	70	77	85	90	94
TWD4	39	62	74	85	90	95	97	99
TWE2	40	63	75	85	91	95	97	99
TWF3	29	48	59	71	78	86	90	94
TWJ2	37	60	72	83	89	94	97	98
DGA1	29	47	58	68	74	81	85	89
DGA2	29	49	60	71	78	85	89	93
DGA3	32	55	68	79	84	90	93	95
DGB1	30	52	65	76	82	88	91	94
DGB2	30	52	66	78	84	91	94	96
DGB3	33	57	72	83	89	94	96	97
DGC1	34	59	73	84	89	93	95	96
DGC2	34	58	73	84	90	95	97	98
DGC3	37	63	78	89	93	96	97	98
SSA1	41	60	71	80	86	92	95	97
SSB1	35	53	64	74	81	88	91	95
SSB2	42	64	75	84	89	94	97	98
SSB3	34	52	63	73	79	87	90	94
SSC1	33	53	65	76	83	90	93	96
SSC2	38	60	72	83	88	94	96	98
SSE1	43	64	75	84	90	94	97	98
SSE2	50	73	83	91	95	98	99	100
SSE3	36	54	65	75	81	88	92	95

SAN DIEGO, CALIFORNIA SSF (%)						1512 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	39	61	73	83	89	94	97	98
WWB4	46	71	83	91	95	98	99	100
WWC2	45	70	82	91	95	98	99	100
TWA1	30	45	55	65	72	80	85	90
TWA2	34	52	64	74	81	88	92	95
TWA3	35	55	67	78	84	91	94	97
TWA4	34	55	67	78	85	91	94	97
TWB3	31	51	62	73	80	88	92	95
TWD4	41	65	77	87	92	96	98	99
TWE2	43	66	78	88	92	97	98	99
TWF3	31	51	63	74	81	89	92	96
TWJ2	39	63	76	86	91	96	98	99
DGA1	31	51	62	72	78	84	88	91
DGA2	31	52	64	74	81	88	91	95
DGA3	34	58	71	81	87	92	94	95
DGB1	32	56	69	79	85	90	93	95
DGB2	32	56	70	81	87	93	95	97
DGB3	35	61	75	86	91	95	96	97
DGC1	37	63	77	87	91	95	96	97
DGC2	36	63	77	87	92	96	98	99
DGC3	39	68	82	91	94	97	98	98
SSA1	43	62	73	82	88	93	95	98
SSB1	37	56	67	77	83	89	93	96
SSB2	45	66	77	86	91	95	97	99
SSB3	36	54	65	75	81	88	92	95
SSC1	36	56	68	79	85	92	95	97
SSC2	40	63	75	85	91	95	97	99
SSE1	45	67	78	86	91	95	97	99
SSE2	52	75	85	92	96	98	99	100
SSE3	38	57	67	77	83	90	93	96

SACRAMENTO, CALIFORNIA SSF (%)						2845 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	18	31	39	48	55	63	68	74
WWB4	19	37	49	60	67	76	81	87
WWC2	20	37	48	59	66	75	80	85
TWA1	18	25	30	36	41	47	51	57
TWA2	17	27	34	42	47	55	60	66
TWA3	16	28	35	44	50	58	63	69
TWA4	15	27	35	44	50	58	64	70
TWB3	15	25	32	40	46	54	60	66
TWD4	18	34	44	55	62	71	76	82
TWE2	20	35	45	56	63	71	77	82
TWF3	13	24	32	40	46	54	59	66
TWJ2	17	32	42	53	60	69	74	80
DGA1	13	23	29	36	40	46	49	53
DGA2	14	25	32	40	46	54	58	64
DGA3	16	29	38	48	55	64	69	75
DGB1	13	23	31	39	44	51	55	60
DGB2	14	25	34	43	50	58	64	70
DGB3	16	30	39	50	58	67	73	79
DGC1	16	27	36	45	51	59	63	69
DGC2	16	29	39	49	56	65	70	76
DGC3	19	33	44	56	63	73	79	85
SSA1	22	33	41	48	54	61	65	71
SSB1	19	29	36	43	48	55	60	66
SSB2	22	36	45	54	60	68	73	79
SSB3	18	28	34	41	46	53	57	63
SSC1	16	27	35	44	50	58	63	69
SSC2	18	32	42	51	58	67	72	78
SSE1	21	34	42	50	56	64	68	74
SSE2	24	41	50	60	67	75	79	84
SSE3	20	30	36	43	48	55	60	65

FRESNO, CALIFORNIA SSF (%)						2657 DD65		
Type	*LCR =* 200	100	70	50	40	30	25	20
WWA3	18	31	40	49	56	64	69	75
WWB4	20	38	49	61	68	77	82	87
WWC2	20	38	49	60	67	76	81	86
TWA1	18	26	31	37	41	48	52	58
TWA2	18	28	35	42	48	55	60	67
TWA3	17	28	36	44	50	58	64	70
TWA4	16	28	36	44	51	59	64	71
TWB3	15	26	33	41	47	55	60	67
TWD4	19	35	45	56	63	72	77	83
TWE2	20	36	46	56	63	72	77	83
TWF3	14	25	32	40	47	55	60	66
TWJ2	17	33	43	53	60	69	75	81
DGA1	14	23	30	36	41	47	50	54
DGA2	14	25	33	41	47	54	59	65
DGA3	17	30	39	49	56	65	70	76
DGB1	14	24	31	39	45	52	56	61
DGB2	15	26	35	44	50	59	64	70
DGB3	17	30	40	51	58	68	74	80
DGC1	16	28	37	46	52	60	64	70
DGC2	17	30	39	49	56	65	71	77
DGC3	19	34	45	56	64	74	79	85
SSA1	22	34	41	49	54	61	66	72
SSB1	19	29	36	43	49	56	61	66
SSB2	22	36	45	54	60	69	74	79
SSB3	18	28	34	41	46	53	58	64
SSC1	16	28	36	44	50	59	64	70
SSC2	18	33	42	52	59	68	73	79
SSE1	22	34	42	51	57	64	69	75
SSE2	25	41	51	61	67	75	80	85
SSE3	20	30	36	44	49	56	60	66

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

SAN FRANCISCO, CALIFORNIA SSF (%)							3050 DD65	
Type	LCR = 200	100	70	50	40	30	25	20
WWA3	24	41	51	62	69	77	82	88
WWB4	27	49	61	73	80	87	91	95
WWC2	27	48	61	72	79	87	91	94
TWA1	21	31	38	46	51	59	64	71
TWA2	22	35	44	53	59	68	73	80
TWA3	21	36	46	56	63	71	77	83
TWA4	20	36	46	56	63	72	78	84
TWB3	19	33	42	52	59	68	73	79
TWD4	25	44	56	67	75	83	87	92
TWE2	26	46	57	68	75	83	88	92
TWF3	18	32	42	52	59	68	73	80
TWJ2	23	42	54	65	73	81	86	91
DGA1	18	31	40	48	54	61	65	69
DGA2	18	33	42	52	59	67	72	78
DGA3	21	38	49	60	68	76	81	86
DGB1	18	33	43	53	60	68	72	77
DGB2	19	34	45	56	64	73	79	84
DGB3	21	39	51	63	72	81	85	90
DGC1	21	38	49	61	68	76	81	85
DGC2	22	39	51	63	71	80	85	89
DGC3	24	43	57	70	78	86	90	94
SSA1	30	45	54	63	68	76	80	85
SSB1	25	39	48	57	63	70	75	81
SSB2	30	47	58	67	74	81	86	90
SSB3	24	38	46	55	61	68	73	79
SSC1	21	37	47	57	64	72	78	84
SSC2	24	42	54	64	72	80	85	90
SSE1	30	47	57	66	72	79	84	88
SSE2	35	54	65	75	81	87	91	94
SSE3	26	40	48	57	63	71	75	81

SANTA MARIA, CALIFORNIA SSF (%)							3061 DD65	
Type	LCR = 200	100	70	50	40	30	25	20
WWA3	25	44	55	67	74	82	87	92
WWB4	29	53	66	78	84	91	95	97
WWC2	29	52	65	77	84	91	94	97
TWA1	21	32	40	49	55	64	69	76
TWA2	22	37	47	57	64	73	79	85
TWA3	22	39	49	60	67	77	82	88
TWA4	22	38	49	61	68	77	83	88
TWB3	20	35	45	56	63	73	78	84
TWD4	27	48	60	72	79	87	91	95
TWE2	28	49	61	73	80	88	92	95
TWF3	19	35	45	56	64	73	79	85
TWJ2	25	46	58	70	77	86	90	94
DGA1	19	34	43	52	59	66	71	75
DGA2	19	35	46	56	64	72	77	83
DGA3	22	40	53	65	73	81	85	89
DGB1	19	35	47	59	66	74	79	83
DGB2	20	37	49	62	70	79	84	89
DGB3	22	41	55	69	77	86	90	93
DGC1	22	41	54	67	75	83	87	90
DGC2	23	42	55	69	77	85	90	93
DGC3	25	47	62	76	83	91	94	96
SSA1	32	49	60	70	76	83	87	92
SSB1	27	43	53	63	70	78	83	88
SSB2	33	52	64	74	80	88	91	95
SSB3	26	41	51	61	68	76	81	86
SSC1	23	40	50	61	69	78	83	89
SSC2	26	46	58	69	77	85	89	94
SSE1	33	52	63	73	80	87	91	94
SSE2	38	61	72	82	88	93	96	98
SSE3	28	43	53	63	70	76	83	88

DENVER, COLORADO SSF (%)							5022 DD65	
Type	LCR = 100	70	50	40	30	25	20	15
WWA3	21	29	37	43	52	58	68	76
WWB4	27	38	50	58	68	75	82	89
WWC2	27	37	48	56	67	73	80	88
TWA1	19	23	27	31	37	41	46	53
TWA2	19	25	31	36	44	49	55	64
TWA3	19	26	33	39	47	52	59	69
TWA4	18	25	33	39	47	53	61	70
TWB3	17	23	30	36	43	49	56	66
TWD4	25	34	44	52	62	68	76	85
TWE2	26	35	45	52	62	69	76	85
TWF3	16	22	29	35	43	48	55	65
TWJ2	23	32	42	49	59	66	74	83
DGA1	14	19	25	28	33	37	40	45
DGA2	16	22	30	35	43	47	53	61
DGA3	20	28	37	44	54	61	68	76
DGB1	14	19	25	30	37	42	48	54
DGB2	17	23	31	37	46	52	60	68
DGB3	21	29	38	46	57	65	73	82
DGC1	17	24	31	37	46	52	59	66
DGC2	20	27	36	43	53	60	68	77
DGC3	24	33	43	52	64	72	80	88
SSA1	25	31	38	44	51	56	63	71
SSB1	21	26	33	38	45	50	56	65
SSB2	27	35	44	50	59	65	72	81
SSB3	19	25	31	35	42	46	52	61
SSC1	19	25	33	38	46	52	59	68
SSC2	23	31	41	48	57	63	71	80
SSE1	24	31	39	45	54	59	66	74
SSE2	30	40	50	57	67	73	80	87
SSE3	21	27	33	38	45	49	56	64

GRAND JUNCTION, COLORADO SSF (%)							5607 DD65	
Type	LCR = 100	70	50	40	30	25	20	15
WWA3	20	27	35	41	49	55	62	71
WWB4	26	36	47	55	65	71	79	87
WWC2	26	35	46	54	64	70	77	85
TWA1	19	22	26	30	35	38	43	50
TWA2	19	24	30	35	41	46	52	61
TWA3	19	25	31	37	44	49	56	65
TWA4	18	24	31	37	45	50	57	66
TWB3	17	22	29	34	41	46	52	61
TWD4	24	32	42	49	59	65	73	81
TWE2	25	33	43	50	59	66	73	82
TWF3	15	21	28	33	40	45	52	61
TWJ2	22	30	40	47	57	63	70	79
DGA1	14	18	23	26	31	34	37	41
DGA2	16	22	28	33	40	45	50	57
DGA3	20	27	36	42	52	58	65	73
DGB1	14	18	24	28	34	38	43	49
DGB2	16	22	29	35	43	49	56	64
DGB3	20	28	37	44	54	61	69	78
DGC1	17	22	29	34	42	47	53	61
DGC2	19	26	34	41	50	56	64	73
DGC3	23	31	41	49	61	68	76	85
SSA1	24	29	36	41	48	52	58	66
SSB1	20	25	31	35	42	46	52	60
SSB2	25	33	41	47	56	62	68	77
SSB3	18	23	29	33	39	43	48	56
SSC1	18	24	31	36	43	49	55	64
SSC2	22	30	38	45	54	60	67	76
SSE1	23	29	37	42	49	54	61	69
SSE2	28	37	47	54	63	69	75	85
SSE3	20	25	31	35	41	46	51	58

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

HARTFORD, CONNECTICUT SSF (%)							6354 DD65	
Type	LCR = 100	70	50	40	30	25	20	15
WWA3	7	10	13	16	19	22	25	30
WWB4	9	16	23	28	36	42	49	58
WWC2	10	15	22	27	35	40	46	55
TWA1	12	13	14	15	16	17	18	20
TWA2	9	11	13	15	18	20	22	25
TWA3	8	10	13	15	18	21	24	28
TWA4	6	9	12	15	18	21	24	29
TWB3	7	10	12	15	18	20	23	28
TWD4	10	15	21	25	32	37	43	52
TWE2	10	15	21	26	32	37	43	51
TWF3	5	7	10	12	15	17	20	24
TWJ2	8	13	19	23	30	34	40	49
DGA1	4	5	6	6	7	7	6	5
DGA2	7	9	12	14	17	19	22	26
DGA3	10	14	18	22	28	32	37	45
DGB1	4	5	6	6	7	7	7	7
DGB2	7	9	12	15	18	20	23	28
DGB3	10	14	19	23	29	33	39	48
DGC1	5	7	9	10	12	13	14	15
DGC2	9	12	15	18	23	26	30	36
DGC3	12	17	22	27	33	38	45	54
SSA1	13	16	19	21	25	27	30	34
SSB1	11	13	15	17	20	22	25	28
SSB2	14	18	24	27	33	37	43	50
SSB3	10	11	14	15	17	19	21	23
SSC1	6	8	11	13	15	17	20	23
SSC2	8	12	17	21	26	30	35	42
SSE1	10	13	16	18	21	23	26	29
SSE2	13	18	24	29	35	40	45	53
SSE3	11	13	15	17	19	21	23	26

WASHINGTON, DC SSF (%)							5010 DD65	
Type	LCR = 100	70	50	40	30	25	20	15
WWA3	12	16	22	25	31	35	40	48
WWB4	15	23	32	39	48	54	62	72
WWC2	15	23	31	38	46	52	60	69
TWA1	14	16	18	20	23	25	28	32
TWA2	13	16	20	22	27	30	34	40
TWA3	12	15	20	23	28	32	37	43
TWA4	10	14	19	23	29	33	38	45
TWB3	11	14	18	22	27	30	35	42
TWD4	15	21	29	35	43	49	56	65
TWE2	15	22	29	35	43	49	56	65
TWF3	9	12	16	20	25	28	33	40
TWJ2	13	19	27	32	40	46	53	62
DGA1	7	9	12	14	16	17	18	19
DGA2	10	13	18	21	26	29	33	39
DGA3	13	18	25	29	37	42	48	57
DGB1	7	9	12	14	17	19	21	23
DGB2	10	14	18	22	27	31	36	42
DGB3	14	19	25	31	38	44	51	61
DGC1	9	12	16	19	23	25	29	33
DGC2	12	17	22	26	33	37	43	51
DGC3	16	22	29	35	43	50	58	68
SSA1	17	21	26	29	34	38	42	49
SSB1	14	17	21	25	29	32	36	42
SSB2	18	24	31	36	43	48	54	63
SSB3	13	16	20	22	26	29	33	38
SSC1	10	14	18	21	26	30	34	40
SSC2	13	19	25	30	37	42	48	57
SSE1	15	19	24	28	33	37	41	48
SSE2	19	26	34	39	47	53	59	68
SSE3	15	18	22	24	29	31	35	41

MIAMI, FLORIDA SSF (%)							206 DD65	
Type	LCR = 200	100	70	50	40	30	25	20
WWA3	82	96	99	100	100	100	100	100
WWB4	89	98	100	100	100	100	100	100
WWC2	88	98	100	100	100	100	100	100
TWA1	64	84	92	97	98	100	100	100
TWA2	73	91	96	99	100	100	100	100
TWA3	76	93	97	99	100	100	100	100
TWA4	76	93	98	99	100	100	100	100
TWB3	71	90	96	99	100	100	100	100
TWD4	84	97	99	100	100	100	100	100
TWE2	85	97	99	100	100	100	100	100
TWF3	72	91	96	99	100	100	100	100
TWJ2	83	96	99	100	100	100	100	100
DGA1	75	92	97	99	100	100	100	100
DGA2	74	92	97	99	100	100	100	100
DGA3	79	93	96	97	97	97	97	97
DGB1	81	95	98	99	99	99	99	99
DGB2	80	96	99	100	100	100	100	100
DGB3	83	96	98	98	98	98	98	98
DGC1	88	97	98	99	99	99	98	98
DGC2	86	98	99	100	100	100	100	100
DGC3	88	98	98	99	99	98	98	98
SSA1	81	95	99	100	100	100	100	100
SSB1	75	92	97	99	100	100	100	100
SSB2	84	97	99	100	100	100	100	100
SSB3	74	92	97	99	100	100	100	100
SSC1	78	94	98	99	100	100	100	100
SSC2	83	96	99	100	100	100	100	100
SSE1	85	97	99	100	100	100	100	100
SSE2	91	99	100	100	100	100	100	100
SSE3	76	93	97	99	100	100	100	100

ORLANDO, FLORIDA SSF (%)							733 DD65	
Type	LCR = 200	100	70	50	40	30	25	20
WWA3	45	68	80	89	93	97	98	99
WWB4	52	78	88	95	97	99	100	100
WWC2	52	77	87	94	97	99	100	100
TWA1	34	51	61	72	78	86	90	94
TWA2	38	59	70	80	86	92	95	98
TWA3	40	62	73	83	89	94	97	98
TWA4	39	62	74	84	90	95	97	99
TWB3	36	57	69	80	86	92	95	97
TWD4	47	72	83	91	95	98	99	100
TWE2	49	73	84	92	96	98	99	100
TWF3	36	58	70	80	87	93	95	98
TWJ2	45	70	82	90	94	98	99	100
DGA1	37	58	69	78	84	90	93	95
DGA2	36	59	71	81	86	92	95	97
DGA3	40	66	77	86	90	94	95	96
DGB1	38	64	76	85	90	94	96	97
DGB2	38	64	77	87	92	96	98	99
DGB3	41	69	82	90	94	97	97	98
DGC1	44	72	84	91	94	97	97	98
DGC2	42	71	83	92	95	98	99	100
DGC3	46	76	88	94	96	98	98	98
SSA1	46	67	78	87	92	96	98	99
SSB1	40	61	72	82	88	93	96	98
SSB2	48	71	82	90	94	98	99	100
SSB3	39	59	71	81	86	92	95	98
SSC1	41	63	75	85	90	95	97	99
SSC2	46	70	81	90	94	98	99	100
SSE1	50	72	83	91	95	98	99	100
SSE2	57	80	90	95	98	99	100	100
SSE3	41	62	73	82	88	93	96	98

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

TALLAHASSEE, FLORIDA SSF (%) Type	LCR = 200	100	70	50	40	30	25	20	1563 DD65
WWA3	24	41	52	63	70	79	84	90	
WWB4	27	49	62	74	82	89	93	96	
WWC2	27	49	61	73	81	88	92	96	
TWA1	21	31	38	46	52	60	65	72	
TWA2	22	35	44	53	60	70	75	82	
TWA3	22	36	46	56	64	73	79	85	
TWA4	21	36	46	57	64	74	79	86	
TWB3	19	33	42	52	59	69	75	81	
TWD4	25	45	57	69	76	85	89	93	
TWE2	26	46	58	69	77	85	90	94	
TWF3	18	32	42	52	60	69	75	82	
TWJ2	23	42	54	66	74	83	88	92	
DGA1	18	31	40	48	54	62	66	71	
DGA2	18	33	42	53	60	68	74	79	
DGA3	21	37	49	62	69	78	83	87	
DGB1	18	32	43	54	61	70	75	80	
DGB2	19	34	45	58	66	75	81	86	
DGB3	21	38	51	65	73	83	87	92	
DGC1	21	38	49	62	71	79	83	88	
DGC2	21	38	51	65	73	82	87	91	
DGC3	24	43	57	72	80	88	92	95	
SSA1	27	42	52	62	69	77	82	88	
SSB1	23	36	46	55	62	71	77	83	
SSB2	28	45	56	67	74	83	87	92	
SSB3	22	35	44	53	60	69	74	81	
SSC1	21	37	47	57	65	74	80	86	
SSC2	24	42	54	66	73	82	87	92	
SSE1	28	45	55	66	73	81	86	91	
SSE2	32	53	65	76	83	90	93	96	
SSE3	24	37	46	56	63	71	77	83	

ATLANTA, GEORGIA SSF (%) Type	LCR = 200	100	70	50	40	30	25	20	3105 DD65
WWA3	12	22	29	37	43	52	57	65	
WWB4	12	28	38	49	57	67	74	81	
WWC2	13	28	38	48	56	66	72	79	
TWA1	15	20	24	28	32	37	41	46	
TWA2	13	20	26	32	37	44	49	55	
TWA3	12	20	26	33	39	47	52	59	
TWA4	10	19	26	33	39	47	53	60	
TWB3	10	18	24	31	36	43	49	55	
TWD4	12	25	35	45	52	61	68	75	
TWE2	13	26	35	45	52	62	68	75	
TWF3	9	17	23	30	35	43	48	55	
TWJ2	11	23	32	42	49	59	65	73	
DGA1	9	15	20	25	29	34	37	40	
DGA2	10	17	23	30	35	43	47	53	
DGA3	12	21	29	38	44	54	60	67	
DGB1	9	15	20	26	31	37	42	47	
DGB2	10	18	24	32	37	46	52	59	
DGB3	12	22	30	39	46	57	64	72	
DGC1	10	19	25	32	37	45	50	57	
DGC2	11	21	28	36	43	53	59	67	
DGC3	13	25	33	44	52	63	71	79	
SSA1	17	26	32	40	45	52	57	64	
SSB1	14	22	28	34	39	46	51	57	
SSB2	16	28	36	45	52	60	66	73	
SSB3	13	21	26	32	37	43	48	54	
SSC1	11	20	26	33	38	46	51	58	
SSC2	12	24	32	41	47	57	63	70	
SSE1	15	26	33	41	47	55	60	67	
SSE2	17	32	41	51	58	68	74	80	
SSE3	15	23	28	34	39	46	51	57	

BOISE, IDAHO SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	5837 DD65
WWA3	18	23	29	34	40	45	50	57	
WWB4	22	31	40	47	56	62	69	77	
WWC2	22	30	39	46	54	60	67	75	
TWA1	17	20	24	26	30	33	36	41	
TWA2	17	21	26	30	35	38	43	49	
TWA3	16	21	27	31	37	41	46	53	
TWA4	15	21	26	31	37	41	47	54	
TWB3	15	20	25	29	35	39	44	50	
TWD4	20	28	36	43	51	56	63	71	
TWE2	21	29	37	43	51	56	63	71	
TWF3	13	18	23	27	33	37	42	49	
TWJ2	19	26	34	40	48	54	61	69	
DGA1	12	15	19	21	25	26	28	30	
DGA2	14	19	24	28	34	38	42	48	
DGA3	18	24	32	37	45	50	56	64	
DGB1	12	16	20	23	27	29	32	35	
DGB2	15	20	26	30	36	40	46	53	
DGB3	19	25	33	39	47	52	59	68	
DGC1	15	19	25	28	33	37	41	45	
DGC2	17	23	30	35	42	47	53	60	
DGC3	21	28	37	43	52	58	65	74	
SSA1	22	26	32	35	41	44	48	54	
SSB1	18	22	27	31	36	39	43	49	
SSB2	23	30	37	42	49	54	59	67	
SSB3	17	21	25	28	33	36	39	44	
SSC1	15	20	26	30	35	39	44	50	
SSC2	18	25	33	38	46	51	57	65	
SSE1	20	25	31	35	40	44	48	54	
SSE2	25	32	40	46	53	58	64	71	
SSE3	19	23	27	31	35	38	42	47	

CHICAGO, ILLINOIS SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	6125 DD65
WWA3	9	13	16	19	23	26	30	35	
WWB4	12	19	26	32	40	46	53	62	
WWC2	12	18	25	31	38	44	51	60	
TWA1	13	14	16	17	19	20	22	24	
TWA2	11	13	16	18	21	23	26	30	
TWA3	9	12	16	18	22	25	28	33	
TWA4	8	11	15	18	22	25	29	34	
TWB3	9	11	15	17	21	24	27	32	
TWD4	12	17	24	29	36	41	47	56	
TWE2	12	18	24	29	36	40	47	55	
TWF3	7	9	13	15	19	21	25	29	
TWJ2	10	15	22	26	33	38	44	53	
DGA1	5	7	8	9	10	10	11	10	
DGA2	8	11	14	17	20	23	26	30	
DGA3	12	16	21	25	31	35	41	48	
DGB1	5	7	8	9	11	11	12	12	
DGB2	8	11	15	17	21	24	28	33	
DGB3	12	16	22	26	32	37	43	52	
DGC1	7	9	12	13	16	17	19	21	
DGC2	10	14	18	21	26	29	34	41	
DGC3	14	19	25	30	37	42	49	59	
SSA1	15	18	21	24	27	30	33	38	
SSB1	12	14	17	20	23	25	28	32	
SSB2	15	20	26	30	36	40	46	53	
SSB3	11	13	15	17	20	22	24	27	
SSC1	8	11	14	16	19	21	24	29	
SSC2	10	15	20	24	30	34	39	47	
SSE1	12	15	18	21	24	27	30	34	
SSE2	15	21	27	32	38	43	49	57	
SSE3	12	15	17	19	22	24	27	30	

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

MOLINE, ILLINOIS SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	6399 DD65
WWA3	9	13	16	19	24	26	30	36	
WWB4	12	19	26	32	40	46	53	63	
WWC2	12	18	25	31	39	44	51	60	
TWA1	13	14	16	17	19	20	22	24	
TWA2	11	13	16	18	21	23	26	30	
TWA3	9	12	16	18	22	25	28	33	
TWA4	8	11	15	18	22	25	29	34	
TWB3	9	11	15	17	21	24	27	32	
TWD4	12	17	24	29	36	41	47	56	
TWE2	12	18	24	29	36	41	47	55	
TWF3	7	9	13	15	19	21	25	29	
TWJ2	10	15	22	26	33	38	44	53	
DGA1	5	7	8	9	10	11	11	10	
DGA2	8	11	14	17	20	23	26	30	
DGA3	12	16	21	25	31	35	41	49	
DGB1	5	7	8	9	11	11	12	12	
DGB2	8	11	15	17	21	24	28	33	
DGB3	12	16	22	26	32	37	43	52	
DGC1	7	9	12	13	16	17	19	21	
DGC2	10	14	18	21	26	29	34	41	
DGC3	14	19	25	30	37	42	49	59	
SSA1	15	18	21	24	27	30	33	38	
SSB1	12	14	17	20	23	25	28	32	
SSB2	15	20	26	30	36	40	46	53	
SSB3	11	13	15	17	20	22	24	27	
SSC1	8	11	14	16	19	21	24	29	
SSC2	10	15	20	24	30	34	39	47	
SSE1	12	15	18	21	24	27	30	34	
SSE2	15	21	27	32	38	43	49	57	
SSE3	12	15	17	19	22	24	27	30	

SPRINGFIELD, ILLINOIS SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	5563 DD65
WWA3	12	16	21	24	30	33	38	45	
WWB4	15	23	31	38	46	53	60	70	
WWC2	15	22	30	36	45	50	58	67	
TWA1	14	16	18	20	22	24	27	30	
TWA2	13	16	19	22	26	29	32	38	
TWA3	12	15	19	22	27	30	35	41	
TWA4	10	14	19	22	27	31	36	43	
TWB3	11	14	18	21	26	29	33	39	
TWD4	14	21	28	34	42	47	54	63	
TWE2	15	21	28	34	42	47	54	63	
TWF3	9	12	16	19	24	27	31	37	
TWJ2	13	19	26	31	39	44	51	60	
DGA1	7	9	11	13	15	16	17	17	
DGA2	10	13	17	20	25	28	32	37	
DGA3	14	18	24	28	35	40	47	55	
DGB1	7	9	12	13	16	17	19	21	
DGB2	10	14	18	21	26	29	34	40	
DGB3	14	19	25	30	37	42	49	59	
DGC1	9	12	15	18	21	23	26	30	
DGC2	12	16	21	25	31	35	41	49	
DGC3	16	22	28	34	42	48	56	66	
SSA1	17	20	25	28	32	36	40	46	
SSB1	14	17	21	23	28	30	34	40	
SSB2	18	23	29	34	41	46	52	60	
SSB3	13	15	19	21	25	27	30	35	
SSC1	10	14	17	20	25	28	32	38	
SSC2	13	18	24	29	36	40	46	55	
SSE1	14	18	23	26	31	34	38	44	
SSE2	18	25	32	37	45	50	57	65	
SSE3	14	17	21	23	27	29	33	38	

INDIANAPOLIS, INDIANA SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	5585 DD65
WWA3	9	12	16	19	22	25	29	34	
WWB4	11	18	25	31	39	45	52	61	
WWC2	11	18	25	30	37	43	49	58	
TWA1	12	14	15	17	18	19	21	23	
TWA2	10	13	15	17	20	22	25	29	
TWA3	9	12	15	18	21	24	27	31	
TWA4	8	11	14	17	21	24	28	33	
TWB3	8	11	14	17	20	23	26	31	
TWD4	11	17	23	28	35	40	46	55	
TWE2	12	17	23	28	35	39	46	54	
TWF3	6	9	12	14	18	20	23	28	
TWJ2	10	15	21	26	32	37	43	52	
DGA1	5	6	8	8	9	10	10	9	
DGA2	8	11	14	16	20	22	25	29	
DGA3	11	15	20	24	30	34	40	47	
DGB1	5	6	8	9	10	10	11	11	
DGB2	8	11	14	17	20	23	26	31	
DGB3	12	16	21	25	31	36	42	51	
DGC1	7	9	11	13	15	16	17	19	
DGC2	10	13	17	21	25	28	33	39	
DGC3	13	18	24	29	36	41	48	57	
SSA1	15	18	21	24	27	30	33	38	
SSB1	12	15	17	20	23	25	28	32	
SSB2	15	20	26	30	36	40	46	53	
SSB3	11	13	16	17	20	22	24	27	
SSC1	8	10	13	15	18	20	23	27	
SSC2	10	14	19	23	29	33	38	45	
SSE1	12	15	18	21	24	27	30	34	
SSE2	15	21	27	32	38	43	49	56	
SSE3	12	15	17	19	22	24	26	30	

SOUTH BEND, INDIANA SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	6465 DD65
WWA3	7	9	12	14	16	18	20	23	
WWB4	9	14	21	26	33	38	44	52	
WWC2	9	14	20	25	31	36	41	49	
TWA1	12	12	13	14	15	16	16	17	
TWA2	9	11	13	14	16	17	19	21	
TWA3	8	10	12	14	16	18	20	23	
TWA4	6	9	11	13	16	18	21	24	
TWB3	7	9	12	13	16	18	20	23	
TWD4	9	14	19	23	29	34	39	47	
TWE2	10	14	19	23	29	33	38	45	
TWF3	5	7	9	11	13	15	17	20	
TWJ2	8	12	17	21	27	31	36	43	
DGA1	4	4	5	5	5	5	4	1	
DGA2	7	9	11	13	16	17	20	22	
DGA3	10	14	18	21	26	29	34	41	
DGB1	4	4	5	5	5	5	5	3	
DGB2	7	9	12	14	16	18	21	24	
DGB3	10	14	19	22	27	31	36	44	
DGC1	5	7	8	9	10	10	10	10	
DGC2	9	11	15	17	21	23	26	31	
DGC3	12	16	21	25	31	35	41	49	
SSA1	13	15	18	20	23	25	27	29	
SSB1	11	13	15	17	19	20	22	25	
SSB2	14	18	23	26	31	35	39	46	
SSB3	10	11	13	14	16	17	18	19	
SSC1	6	8	10	11	13	14	15	17	
SSC2	8	11	15	18	23	26	30	36	
SSE1	10	12	15	16	18	20	21	23	
SSE2	13	17	23	26	32	36	40	47	
SSE3	11	13	15	16	18	19	20	22	

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

DES MOINES, IOWA SSF (%) Type	LCR = 100	70	50	40	30	6718 DD65 25	20	15
WWA3	11	14	19	22	27	30	34	41
WWB4	13	21	29	35	43	49	57	66
WWC2	14	20	28	34	42	47	54	64
TWA1	13	15	17	18	21	22	24	27
TWA2	12	14	17	20	23	26	29	34
TWA3	11	14	17	20	24	27	31	37
TWA4	9	13	17	20	25	28	32	39
TWB3	10	13	16	19	23	26	30	36
TWD4	13	19	26	31	39	44	51	60
TWE2	14	20	26	31	39	44	50	59
TWF3	8	11	14	17	21	24	28	33
TWJ2	11	17	24	29	36	41	48	57
DGA1	6	8	10	11	12	13	14	14
DGA2	9	12	16	18	23	25	29	34
DGA3	13	17	22	27	33	38	44	52
DGB1	6	8	10	11	13	14	15	17
DGB2	9	13	16	19	23	27	31	36
DGB3	13	18	23	28	34	39	46	56
DGC1	8	11	14	15	18	20	22	26
DGC2	11	15	20	23	29	32	38	45
DGC3	15	20	26	31	39	45	52	62
SSA1	16	19	23	25	29	32	36	41
SSB1	13	16	19	21	25	27	31	35
SSB2	16	22	27	32	38	43	48	56
SSB3	12	14	17	19	22	24	27	30
SSC1	9	12	16	18	22	25	28	33
SSC2	12	16	22	26	33	37	43	51
SSE1	13	16	20	23	27	30	34	39
SSE2	16	22	29	34	41	46	52	61
SSE3	13	16	19	21	24	26	29	33

DODGE CITY, KANSAS SSF (%) Type	LCR = 100	70	50	40	30	5053 DD65 25	20	15
WWA3	21	27	35	41	50	55	63	72
WWB4	26	36	47	55	66	72	80	88
WWC2	26	36	46	54	64	71	78	86
TWA1	19	22	27	30	35	39	44	51
TWA2	19	24	30	35	42	47	53	61
TWA3	19	25	32	37	44	50	57	66
TWA4	18	24	31	37	45	51	58	67
TWB3	17	23	29	34	41	46	53	62
TWD4	24	33	43	50	60	66	74	82
TWE2	25	33	43	50	60	66	74	83
TWF3	16	21	28	33	40	46	52	62
TWJ2	22	30	40	47	57	63	71	80
DGA1	14	18	23	27	31	34	38	42
DGA2	16	22	28	33	41	45	51	58
DGA3	20	27	36	42	52	58	65	74
DGB1	14	18	24	28	35	39	44	50
DGB2	17	22	29	35	44	49	57	65
DGB3	20	28	37	44	55	62	70	79
DGC1	17	22	29	34	42	48	55	62
DGC2	19	26	34	41	51	57	65	74
DGC3	23	31	41	50	61	69	77	86
SSA1	24	30	37	42	49	54	60	68
SSB1	20	25	31	36	43	47	53	62
SSB2	26	33	42	48	57	63	70	78
SSB3	19	24	29	33	40	44	50	57
SSC1	18	24	31	36	44	49	56	65
SSC2	22	30	39	45	55	61	68	77
SSE1	23	30	37	43	51	56	63	71
SSE2	29	38	48	55	64	70	77	85
SSE3	21	26	32	36	42	47	53	61

TOPEKA, KANSAS SSF (%) Type	LCR = 100	70	50	40	30	5243 DD65 25	20	15
WWA3	16	21	27	32	38	43	49	57
WWB4	20	28	38	45	55	61	69	78
WWC2	20	28	37	44	53	60	67	76
TWA1	16	19	22	24	28	31	34	39
TWA2	15	19	24	27	33	36	41	46
TWA3	15	19	24	29	35	39	44	52
TWA4	14	18	24	29	35	40	45	54
TWB3	13	18	23	27	32	36	42	50
TWD4	18	26	34	41	49	55	63	72
TWE2	19	27	35	41	50	55	63	72
TWF3	12	16	21	25	31	35	40	48
TWJ2	17	24	32	38	47	53	60	70
DGA1	10	13	16	19	22	24	26	28
DGA2	13	17	22	26	32	35	40	46
DGA3	16	22	29	34	42	48	55	64
DGB1	10	13	17	19	23	26	29	34
DGB2	13	17	23	27	33	38	43	51
DGB3	17	23	30	36	44	50	58	68
DGC1	13	17	21	25	30	34	38	44
DGC2	15	21	27	32	39	44	51	60
DGC3	19	26	34	40	50	57	65	76
SSA1	20	24	30	33	39	43	48	55
SSB1	16	20	25	29	34	38	42	49
SSB2	21	28	35	40	48	53	60	68
SSB3	15	19	23	26	31	34	38	44
SSC1	14	18	23	27	33	37	43	50
SSC2	17	23	30	36	44	49	56	65
SSE1	18	23	29	33	39	43	49	56
SSE2	23	30	39	45	53	59	66	74
SSE3	17	21	25	29	33	37	41	48

LEXINGTON, KENTUCKY SSF (%) Type	LCR = 100	70	50	40	30	4732 DD65 25	20	15
WWA3	12	16	21	25	30	34	39	45
WWB4	15	23	31	38	47	53	60	70
WWC2	15	22	30	37	45	51	58	67
TWA1	14	16	18	20	23	25	27	31
TWA2	13	16	19	22	26	29	33	38
TWA3	12	15	19	23	27	31	35	41
TWA4	11	14	19	23	28	31	36	43
TWB3	11	14	18	21	26	29	34	40
TWD4	15	21	28	34	42	47	54	64
TWE2	15	22	29	34	42	47	54	63
TWF3	9	12	16	19	24	27	32	38
TWJ2	13	19	26	32	39	45	51	61
DGA1	7	9	12	13	15	16	17	18
DGA2	10	14	17	21	25	28	32	37
DGA3	14	19	24	29	36	41	47	55
DGB1	7	10	12	14	16	17	19	21
DGB2	10	14	18	21	26	30	34	40
DGB3	14	19	25	30	37	43	50	59
DGC1	10	13	16	18	21	24	27	31
DGC2	12	17	22	26	31	36	41	49
DGC3	16	22	29	34	42	48	56	66
SSA1	17	21	25	29	34	37	41	47
SSB1	14	18	21	24	29	32	35	41
SSB2	18	24	30	35	42	47	53	61
SSB3	13	16	20	22	26	28	32	36
SSC1	10	14	18	21	25	28	32	38
SSC2	13	18	25	29	36	41	47	55
SSE1	15	19	24	27	32	35	40	46
SSE2	19	26	33	38	46	51	58	66
SSE3	15	18	21	24	28	31	34	39

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

BATON ROUGE, LOUISIANA SSF (%) Type	LCR = 200	100	70	50	40	1670 DD65 30	25	20
WWA3	21	35	45	56	63	72	78	84
WWB4	23	43	56	68	75	84	89	93
WWC2	23	43	55	67	74	83	88	92
TWA1	19	28	34	41	46	54	59	65
TWA2	19	31	39	47	54	63	68	75
TWA3	19	32	40	50	57	66	72	79
TWA4	18	31	40	50	57	67	73	79
TWB3	17	29	37	46	53	62	68	75
TWD4	22	39	51	62	70	79	84	90
TWE2	23	40	52	63	70	80	85	90
TWF3	16	28	37	46	53	62	68	75
TWJ2	20	37	48	60	68	77	82	88
DGA1	15	27	34	42	47	54	58	63
DGA2	16	28	37	46	53	61	67	73
DGA3	18	33	43	55	63	72	77	83
DGB1	15	27	36	46	53	62	67	72
DGB2	16	29	39	50	58	68	74	80
DGB3	19	33	45	57	66	76	82	87
DGC1	18	32	42	53	61	71	76	81
DGC2	19	33	44	56	65	75	80	86
DGC3	21	38	50	64	73	83	88	92
SSA1	24	38	47	56	63	71	76	82
SSB1	21	33	41	50	56	65	70	77
SSB2	25	41	51	62	69	77	83	88
SSB3	20	31	39	48	54	63	68	75
SSC1	19	32	41	51	58	67	73	79
SSC2	21	37	48	59	66	76	81	87
SSE1	24	40	49	60	67	75	80	86
SSE2	28	47	59	70	77	85	89	93
SSE3	22	33	41	50	56	65	70	77

NEW ORLEANS, LOUISIANA SSF (%) Type	LCR = 200	100	70	50	40	1465 DD65 30	25	20
WWA3	24	41	52	63	70	79	84	89
WWB4	28	50	63	74	81	89	93	96
WWC2	28	49	62	73	80	88	92	95
TWA1	21	31	38	46	52	60	65	72
TWA2	22	35	44	54	60	70	75	81
TWA3	22	36	46	57	64	73	79	85
TWA4	21	36	46	57	64	74	79	85
TWB3	20	33	42	52	60	69	75	81
TWD4	25	45	57	69	76	85	89	93
TWE2	27	46	58	69	77	85	89	94
TWF3	19	33	42	53	60	69	75	82
TWJ2	24	43	55	66	74	83	88	92
DGA1	18	32	40	49	55	62	66	71
DGA2	19	33	43	53	60	68	73	79
DGA3	21	38	50	62	69	78	83	87
DGB1	18	33	43	54	61	70	75	80
DGB2	19	34	45	58	66	75	80	86
DGB3	22	39	51	65	73	83	87	91
DGC1	21	38	50	62	70	79	83	87
DGC2	22	39	51	65	73	82	87	91
DGC3	24	44	57	72	80	88	92	95
SSA1	28	43	52	62	69	78	82	88
SSB1	24	37	46	56	63	72	77	83
SSB2	28	46	57	68	75	83	87	92
SSB3	23	36	44	54	61	69	75	81
SSC1	22	37	47	58	65	74	79	85
SSC2	25	43	54	66	73	82	87	91
SSE1	28	45	55	67	74	82	86	91
SSE2	33	53	66	76	83	90	93	96
SSE3	25	38	47	56	63	72	77	83

SHREVEPORT, LOUISIANA SSF (%) Type	LCR = 200	100	70	50	40	2175 DD65 30	25	20
WWA3	17	30	39	49	56	65	71	78
WWB4	19	38	49	61	69	79	84	90
WWC2	19	37	49	60	68	78	83	89
TWA1	17	25	30	36	41	48	52	58
TWA2	17	27	34	42	48	56	61	68
TWA3	16	27	35	44	50	59	65	72
TWA4	15	27	35	44	51	60	66	73
TWB3	14	25	32	40	47	55	61	68
TWD4	18	34	45	56	63	73	79	85
TWE2	19	35	46	57	64	74	79	86
TWF3	13	24	31	40	46	55	61	68
TWJ2	16	32	42	53	61	71	77	84
DGA1	13	22	29	36	41	47	51	55
DGA2	13	24	32	40	47	55	60	66
DGA3	16	28	38	48	56	66	72	78
DGB1	13	22	30	38	45	53	58	64
DGB2	14	25	33	43	50	60	66	73
DGB3	16	29	39	50	59	70	76	83
DGC1	15	26	35	45	52	62	68	74
DGC2	16	28	38	49	57	68	74	80
DGC3	18	32	44	56	66	77	83	88
SSA1	21	33	41	49	56	64	70	76
SSB1	18	28	35	43	49	58	63	70
SSB2	21	36	45	55	62	71	77	83
SSB3	17	27	34	41	47	55	60	67
SSC1	15	27	35	44	51	60	66	73
SSC2	17	32	42	52	60	69	75	82
SSE1	21	34	43	52	59	68	73	80
SSE2	24	41	52	63	70	79	84	89
SSE3	19	29	36	44	50	58	63	70

PORTLAND, MAINE SSF (%) Type	LCR = 100	70	50	40	30	7499 DD65 25	20	15
WWA3	7	10	13	15	18	21	24	28
WWB4	9	15	22	28	35	41	47	57
WWC2	9	15	21	26	33	38	45	53
TWA1	12	13	14	15	16	17	18	19
TWA2	9	11	13	15	17	19	21	24
TWA3	8	10	13	15	18	20	22	26
TWA4	6	9	12	14	18	20	23	28
TWB3	7	10	12	14	17	19	22	26
TWD4	10	15	20	25	31	36	42	50
TWE2	10	15	21	25	31	35	41	49
TWF3	5	7	10	12	15	17	19	23
TWJ2	8	13	18	22	29	33	39	47
DGA1	4	5	5	6	6	6	6	4
DGA2	7	9	12	14	17	19	21	25
DGA3	10	14	18	22	27	31	36	43
DGB1	4	5	5	6	6	7	6	5
DGB2	7	9	12	14	17	20	22	26
DGB3	11	14	19	23	28	33	38	46
DGC1	5	7	8	10	11	12	13	13
DGC2	9	12	15	18	22	25	29	34
DGC3	12	16	22	26	32	37	43	53
SSA1	13	16	19	21	24	26	29	32
SSB1	11	13	15	17	20	22	24	27
SSB2	14	18	23	27	33	37	42	49
SSB3	10	11	13	15	17	18	20	22
SSC1	6	8	10	12	14	16	18	21
SSC2	8	12	16	20	25	28	33	40
SSE1	10	13	15	17	20	22	24	27
SSE2	13	18	24	28	34	38	44	51
SSE3	11	13	15	17	19	20	22	25

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

BALTIMORE, MARYLAND SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	4731 DD65
WWA3	13	18	24	28	35	39	45	53	
WWB4	17	26	35	42	52	58	66	75	
WWC2	17	25	34	41	50	56	64	73	
TWA1	15	17	20	22	25	28	31	36	
TWA2	14	17	21	25	30	33	38	44	
TWA3	13	17	22	26	31	35	41	48	
TWA4	12	16	22	26	32	36	42	50	
TWB3	12	16	20	24	29	33	38	46	
TWD4	16	23	31	38	46	52	59	69	
TWE2	17	24	32	38	46	52	59	69	
TWF3	10	14	19	22	28	32	37	44	
TWJ2	14	21	29	35	44	49	57	66	
DGA1	8	11	14	16	19	20	22	24	
DGA2	11	15	19	23	28	32	37	42	
DGA3	15	20	26	32	39	45	52	60	
DGB1	8	11	14	17	20	22	25	29	
DGB2	11	15	20	24	30	34	40	47	
DGB3	15	21	27	33	41	47	55	65	
DGC1	11	14	18	22	26	29	34	39	
DGC2	13	18	24	29	36	41	47	56	
DGC3	17	24	31	37	47	53	62	72	
SSA1	18	22	27	31	37	41	46	52	
SSB1	15	19	23	27	31	35	40	46	
SSB2	19	26	33	38	45	51	57	66	
SSB3	14	17	21	24	29	32	36	41	
SSC1	12	16	20	24	30	33	38	46	
SSC2	15	21	28	33	41	46	52	61	
SSE1	16	21	26	31	36	40	46	53	
SSE2	21	28	36	42	51	56	63	72	
SSE3	16	19	23	26	31	34	38	44	

BOSTON, MASSACHUSETTS SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	5622 DD65
WWA3	10	14	18	21	26	29	33	40	
WWB4	13	20	28	34	43	49	56	66	
WWC2	13	20	27	33	41	47	54	63	
TWA1	13	15	16	18	20	21	23	26	
TWA2	11	14	17	19	23	25	28	33	
TWA3	10	13	17	20	24	27	31	36	
TWA4	9	12	16	19	24	27	32	38	
TWB3	9	12	16	18	23	26	29	35	
TWD4	13	18	25	31	38	43	50	59	
TWE2	13	19	26	31	38	43	50	58	
TWF3	7	10	14	16	20	23	27	33	
TWJ2	11	17	23	28	35	41	47	56	
DGA1	6	7	9	10	12	12	13	13	
DGA2	9	12	15	18	22	25	28	33	
DGA3	12	17	22	26	32	37	43	51	
DGB1	6	7	9	11	12	13	14	16	
DGB2	9	12	16	18	23	26	30	36	
DGB3	13	17	23	27	34	39	46	55	
DGC1	8	10	13	15	17	19	22	25	
DGC2	11	15	19	23	28	32	37	44	
DGC3	14	20	26	31	38	44	51	62	
SSA1	15	19	22	25	29	32	36	41	
SSB1	13	15	19	21	25	27	31	36	
SSB2	16	21	27	32	38	43	48	56	
SSB3	11	14	17	19	22	24	27	31	
SSC1	9	12	15	17	21	24	27	32	
SSC2	11	16	21	26	32	36	42	50	
SSE1	13	16	20	23	27	30	34	39	
SSE2	16	22	29	34	41	46	52	61	
SSE3	13	16	19	21	24	26	29	33	

DETROIT, MICHIGAN SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	6234 DD65
WWA3	7	10	13	16	18	20	23	26	
WWB4	9	15	22	27	35	40	46	55	
WWC2	9	15	21	26	33	38	44	52	
TWA1	12	13	14	15	16	16	17	18	
TWA2	9	11	13	15	17	19	21	23	
TWA3	8	10	13	15	17	19	22	25	
TWA4	7	9	12	14	17	19	22	25	
TWB3	7	10	12	14	17	20	23	27	
TWD4	10	15	20	25	31	35	41	49	
TWE2	10	15	20	25	31	35	40	48	
TWF3	5	7	10	12	14	16	19	22	
TWJ2	8	13	18	22	28	33	38	46	
DGA1	4	5	6	6	6	6	5	4	
DGA2	7	9	12	14	17	19	21	24	
DGA3	10	14	18	22	27	31	36	43	
DGB1	4	5	6	6	7	7	6	5	
DGB2	7	9	12	14	17	20	22	26	
DGB3	11	14	19	23	28	32	38	46	
DGC1	5	7	9	10	11	12	12	13	
DGC2	9	12	15	18	22	25	28	33	
DGC3	12	17	22	26	32	37	43	52	
SSA1	13	16	19	21	24	26	28	32	
SSB1	11	13	15	17	20	21	24	28	
SSB2	14	18	23	27	32	36	41	48	
SSB3	10	11	13	15	17	18	20	21	
SSC1	6	8	10	12	14	16	18	20	
SSC2	8	12	16	20	25	28	32	39	
SSE1	10	13	15	17	20	21	23	25	
SSE2	13	18	24	28	33	37	43	49	
SSE3	11	13	15	17	19	20	22	24	

SAULT STE. MARIE, MICHIGAN SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	9201 DD65
WWA3	5	7	8	10	11	12	13	13	
WWB4	6	11	17	21	27	31	37	44	
WWC2	7	11	16	20	25	29	34	40	
TWA1	10	11	11	12	12	12	12	11	
TWA2	8	9	10	11	12	13	13	14	
TWA3	6	7	9	10	12	13	14	15	
TWA4	4	6	8	10	12	13	14	16	
TWB3	6	7	9	10	12	13	15	16	
TWD4	7	11	16	19	25	28	33	39	
TWE2	8	12	16	19	24	27	31	37	
TWF3	3	5	6	8	9	10	11	12	
TWJ2	6	9	14	17	22	25	30	36	
DGA1	2	3	3	2	2	1	0	−4	
DGA2	5	7	9	11	13	14	15	17	
DGA3	9	12	15	18	23	26	30	35	
DGB1	2	2	3	2	2	1	0	−2	
DGB2	5	7	9	11	13	14	16	18	
DGB3	9	12	16	19	24	27	32	38	
DGC1	4	5	5	6	6	6	5	3	
DGC2	7	9	12	14	17	19	22	25	
DGC3	10	14	19	22	28	31	36	43	
SSA1	12	13	15	17	19	20	21	22	
SSB1	9	11	12	14	15	16	17	18	
SSB2	12	16	20	23	27	30	34	39	
SSB3	8	9	11	11	12	13	13	12	
SSC1	4	5	7	7	8	8	8	7	
SSC2	6	9	12	14	18	20	23	27	
SSE1	8	9	11	12	13	13	13	11	
SSE2	10	14	18	22	26	29	32	36	
SSE3	10	11	12	13	14	15	15	14	

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

MINNEAPOLIS, MINNESOTA SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	8165 DD65
WWA3	7	9	12	14	17	19	21	24	
WWB4	9	14	21	26	33	38	45	54	
WWC2	9	14	20	25	32	36	42	50	
TWA1	11	12	13	14	15	16	16	17	
TWA2	9	11	13	14	16	18	19	21	
TWA3	7	10	12	14	16	18	20	23	
TWA4	6	8	11	13	15	19	21	25	
TWB3	7	9	12	13	16	18	21	24	
TWD4	9	14	19	24	30	34	40	48	
TWE2	10	14	20	24	29	34	39	46	
TWF3	5	7	9	11	13	15	17	20	
TWJ2	7	12	17	21	27	31	37	44	
DGA1	4	4	5	5	5	5	4	2	
DGA2	7	9	11	13	16	18	20	23	
DGA3	10	13	18	21	26	30	35	41	
DGB1	3	4	5	5	6	5	5	3	
DGB2	7	9	12	14	17	19	21	25	
DGB3	10	14	19	22	28	31	37	44	
DGC1	5	6	8	9	10	11	11	11	
DGC2	8	11	15	17	21	24	27	32	
DGC3	12	16	21	25	31	36	42	50	
SSA1	12	15	17	19	21	23	25	28	
SSB1	10	12	14	16	18	19	21	23	
SSB2	13	17	22	25	30	34	38	45	
SSB3	9	10	12	13	15	16	17	18	
SSC1	6	8	10	11	13	14	16	18	
SSC2	8	11	15	19	23	27	31	37	
SSE1	9	11	13	15	17	18	20	21	
SSE2	12	16	21	25	31	34	39	46	
SSE3	10	12	14	15	17	18	19	20	

MERIDIAN, MISSISSIPPI SSF (%) Type	LCR = 200	100	70	50	40	30	25	20	2393 DD65
WWA3	15	28	36	45	52	61	67	74	
WWB4	16	34	46	58	66	75	81	87	
WWC2	17	34	45	56	64	74	80	86	
TWA1	16	23	28	33	38	44	49	54	
TWA2	15	24	31	38	44	52	57	64	
TWA3	14	25	32	41	47	55	61	68	
TWA4	13	24	32	41	47	56	62	69	
TWB3	13	22	29	37	43	52	57	64	
TWD4	16	31	41	52	60	70	76	82	
TWE2	17	32	42	53	60	70	76	83	
TWF3	11	21	29	37	43	51	57	64	
TWJ2	14	29	39	50	57	67	73	80	
DGA1	11	20	26	32	37	43	46	50	
DGA2	12	22	29	37	43	51	56	62	
DGA3	14	26	35	45	52	62	68	75	
DGB1	11	20	27	34	40	48	53	59	
DGB2	12	22	30	39	46	56	62	69	
DGB3	14	26	36	46	55	66	72	80	
DGC1	13	24	31	41	47	57	63	69	
DGC2	14	26	34	45	52	63	69	76	
DGC3	16	30	40	52	61	73	79	86	
SSA1	20	31	38	46	52	61	66	72	
SSB1	16	26	33	41	46	54	59	66	
SSB2	20	33	42	52	59	68	74	80	
SSB3	16	25	31	39	44	52	57	63	
SSC1	14	24	32	41	47	55	61	68	
SSC2	15	29	38	49	56	65	71	78	
SSE1	19	31	40	49	55	64	70	76	
SSE2	22	38	49	60	67	76	81	87	
SSE3	17	27	33	41	46	54	59	66	

SAINT LOUIS, MISSOURI SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	4754 DD65
WWA3	15	20	26	30	36	41	47	55	
WWB4	19	27	37	44	53	59	67	76	
WWC2	19	27	36	42	51	57	65	74	
TWA1	16	18	21	23	27	29	32	37	
TWA2	15	19	23	26	31	35	39	46	
TWA3	14	18	23	27	33	37	42	50	
TWA4	13	18	23	27	33	38	43	51	
TWB3	13	17	22	25	31	35	40	47	
TWD4	18	25	33	39	48	53	61	70	
TWE2	18	26	33	39	48	53	61	70	
TWF3	11	15	20	24	29	33	38	46	
TWJ2	16	23	31	37	45	51	58	67	
DGA1	9	12	15	18	20	22	24	26	
DGA2	12	16	21	25	30	34	38	44	
DGA3	16	21	28	33	41	46	53	62	
DGB1	10	13	16	18	22	24	27	31	
DGB2	12	17	22	26	32	36	41	49	
DGB3	16	22	29	34	43	48	56	66	
DGC1	12	16	20	23	28	31	35	41	
DGC2	15	20	26	30	37	42	49	57	
DGC3	19	25	33	39	48	54	63	73	
SSA1	19	24	29	32	38	42	47	53	
SSB1	16	20	24	28	33	36	41	47	
SSB2	21	27	34	39	46	52	58	67	
SSB3	15	18	22	25	30	33	37	43	
SSC1	13	17	22	26	31	35	40	47	
SSC2	16	22	29	34	42	47	54	63	
SSE1	18	22	28	32	38	42	47	54	
SSE2	22	29	37	43	52	57	64	73	
SSE3	17	20	24	28	32	35	40	46	

SPRINGFIELD, MISSOURI SSF (%) Type	LCR = 100	70	50	40	30	25	20	15	4571 DD65
WWA3	16	22	28	33	40	45	52	60	
WWB4	21	30	40	47	57	63	71	80	
WWC2	21	29	39	46	55	62	69	78	
TWA1	17	19	23	25	29	32	36	41	
TWA2	16	20	25	29	34	38	43	51	
TWA3	15	20	26	30	36	41	48	55	
TWA4	14	19	25	30	37	41	48	56	
TWB3	14	18	24	28	34	38	44	52	
TWD4	19	27	36	42	51	57	65	74	
TWE2	20	28	36	43	51	57	65	74	
TWF3	12	17	22	26	33	37	43	51	
TWJ2	18	25	33	40	49	55	62	72	
DGA1	11	14	18	20	24	26	28	30	
DGA2	13	18	23	27	33	37	42	48	
DGA3	17	23	30	36	44	50	57	66	
DGB1	11	14	18	21	25	28	32	37	
DGB2	14	18	24	28	35	39	46	54	
DGB3	17	24	31	37	46	52	60	71	
DGC1	13	18	22	26	32	36	41	47	
DGC2	10	21	28	33	41	46	54	63	
DGC3	20	27	35	42	52	59	67	78	
SSA1	21	26	31	36	42	46	51	59	
SSB1	17	22	27	30	36	40	45	52	
SSB2	22	29	37	42	50	55	62	71	
SSB3	16	20	25	28	33	37	41	48	
SSC1	14	19	25	29	35	39	45	53	
SSC2	18	24	32	38	46	51	58	68	
SSE1	19	25	31	36	42	47	52	60	
SSE2	24	32	41	47	56	62	69	77	
SSE3	18	22	27	30	36	39	44	51	

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

HELENA, MONTANA SSF (%) Type	LCR = 100	70	50	40	30	8197 DD65 25	20	15
WWA3	11	14	19	22	27	30	34	39
WWB4	14	21	29	35	43	49	55	64
WWC2	14	20	28	34	41	47	53	62
TWA1	13	15	17	19	21	22	24	27
TWA2	12	14	18	20	24	26	29	33
TWA3	11	14	18	20	25	28	31	36
TWA4	9	13	17	20	25	28	32	38
TWB3	10	13	16	19	23	26	30	35
TWD4	13	19	26	31	39	44	50	58
TWE2	14	20	26	31	39	43	49	57
TWF3	8	11	14	17	21	24	28	33
TWJ2	12	17	24	29	36	41	47	55
DGA1	6	8	10	11	13	13	14	14
DGA2	9	12	16	19	23	26	29	33
DGA3	13	17	23	27	34	38	44	51
DGB1	6	8	10	12	14	15	16	17
DGB2	9	13	17	20	24	27	31	37
DGB3	13	18	24	28	35	40	46	55
DGC1	8	11	14	16	19	21	23	26
DGC2	11	15	20	24	30	33	38	44
DGC3	15	20	27	32	40	45	52	61
SSA1	16	19	23	25	29	32	35	39
SSB1	13	16	19	21	25	27	30	34
SSB2	17	22	27	32	38	42	47	54
SSB3	12	14	17	19	22	24	26	29
SSC1	9	12	16	18	22	25	28	32
SSC2	12	17	22	27	33	37	42	49
SSE1	13	17	20	23	27	29	32	35
SSE2	17	23	29	34	40	45	50	57
SSE3	13	16	19	21	24	26	29	32

ELY, NEVADA SSF (%) Type	LCR = 100	70	50	40	30	7818 DD65 25	20	15
WWA3	18	24	32	37	46	51	58	67
WWB4	23	33	44	52	62	69	76	85
WWC2	23	32	43	50	60	67	75	83
TWA1	17	20	24	27	32	35	40	47
TWA2	17	21	27	31	38	43	49	57
TWA3	16	22	28	33	41	46	52	61
TWA4	15	21	28	33	41	46	53	63
TWB3	15	20	26	31	38	43	49	58
TWD4	21	29	39	46	56	62	70	79
TWE2	22	30	40	47	56	63	70	79
TWF3	13	18	25	29	37	42	48	57
TWJ2	19	27	37	44	53	60	68	77
DGA1	11	15	20	23	27	30	33	37
DGA2	14	19	25	30	37	41	47	54
DGA3	18	24	32	39	48	55	62	71
DGB1	11	15	20	24	30	34	39	45
DGB2	14	19	26	31	39	45	52	61
DGB3	18	25	33	40	51	58	66	76
DGC1	14	19	25	30	38	43	49	57
DGC2	17	23	31	37	46	53	60	70
DGC3	21	29	38	46	57	65	74	83
SSA1	23	29	36	40	48	52	58	66
SSB1	19	24	30	34	41	46	51	59
SSB2	25	32	41	47	55	61	68	76
SSB3	18	22	28	32	38	42	48	55
SSC1	16	21	27	32	40	45	51	60
SSC2	19	27	35	42	51	57	64	74
SSE1	22	28	36	41	49	54	60	68
SSE2	27	37	46	53	62	68	75	83
SSE3	20	24	30	34	41	45	51	58

OMAHA, NEBRASKA SSF (%) Type	LCR = 100	70	50	40	30	6606 DD65 25	20	15
WWA3	12	16	21	24	30	33	38	45
WWB4	15	22	31	37	47	53	60	70
WWC2	15	22	30	36	45	51	58	68
TWA1	14	16	18	20	22	24	27	30
TWA2	13	15	19	22	26	29	32	38
TWA3	11	15	19	22	27	30	35	41
TWA4	10	14	19	22	27	31	36	43
TWB3	11	14	18	21	25	29	33	40
TWD4	14	21	28	34	42	47	54	64
TWE2	15	21	28	34	42	47	54	63
TWF3	9	12	16	19	24	27	31	37
TWJ2	13	19	26	31	39	49	51	61
DGA1	7	9	11	13	15	16	17	17
DGA2	10	13	17	20	25	28	32	37
DGA3	13	18	24	28	35	40	47	55
DGB1	7	9	11	13	15	17	19	21
DGB2	10	14	18	21	26	29	34	40
DGB3	14	19	25	29	37	42	49	59
DGC1	9	12	15	18	21	23	26	30
DGC2	12	16	21	25	31	35	41	49
DGC3	16	21	28	33	42	48	56	66
SSA1	16	20	24	27	32	35	39	45
SSB1	14	17	20	23	27	30	34	39
SSB2	18	23	29	34	40	45	51	59
SSB3	12	15	18	21	24	26	29	34
SSC1	10	13	17	20	25	28	32	38
SSC2	13	18	29	29	36	40	47	55
SSE1	14	18	22	25	30	33	37	40
SSE2	18	24	31	37	44	49	56	65
SSE3	14	17	20	23	26	29	32	37

LAS VEGAS, NEVADA SSF (%) Type	LCR = 200	100	70	50	40	2602 DD65 30	25	20
WWA3	24	41	52	63	71	80	85	90
WWB4	28	50	63	75	82	89	93	96
WWC2	28	49	62	74	81	88	92	96
TWA1	21	31	38	46	52	61	66	73
TWA2	22	35	44	54	61	70	76	82
TWA3	22	37	47	57	64	74	79	85
TWA4	21	36	47	58	64	74	80	86
TWB3	19	33	43	53	60	69	75	82
TWD4	25	45	57	69	77	85	89	93
TWE2	27	46	58	70	77	85	90	94
TWF3	18	33	43	53	60	70	76	82
TWJ2	24	43	55	67	75	83	88	92
DGA1	18	32	40	49	55	63	67	72
DGA2	18	33	43	53	60	69	74	80
DGA3	21	38	50	62	70	78	83	88
DGB1	18	33	44	55	62	71	75	80
DGB2	19	35	46	58	67	76	81	86
DGB3	21	39	52	65	74	83	87	92
DGC1	21	38	51	63	71	79	84	88
DGC2	21	39	52	65	74	83	87	91
DGC3	24	44	58	72	80	88	92	95
SSA1	26	40	50	59	66	74	79	85
SSB1	22	35	44	53	60	69	74	80
SSB2	27	44	54	65	72	81	85	90
SSB3	21	34	42	51	57	66	71	78
SSC1	22	37	47	58	65	75	80	86
SSC2	24	43	55	66	73	82	87	92
SSE1	27	43	53	64	71	79	84	89
SSE2	31	51	63	74	80	88	91	95
SSE3	23	36	45	54	60	69	74	80

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

RENO, NEVADA SSF (%) Type	LCR = 100	70	50	40	30	6027 DD65 25	20	15
WWA3	25	33	41	48	57	63	70	78
WWB4	31	42	54	62	72	78	84	91
WWC2	31	41	53	60	70	76	83	90
TWA1	21	25	30	35	41	45	50	58
TWA2	22	28	35	40	48	53	60	69
TWA3	22	29	37	43	51	57	64	73
TWA4	21	29	37	43	52	58	65	74
TWB3	20	26	34	40	48	53	60	69
TWD4	28	38	48	56	66	72	79	87
TWE2	29	39	49	57	66	72	79	87
TWF3	19	25	33	39	47	53	60	69
TWJ2	26	36	46	54	64	70	77	85
DGA1	17	23	29	33	38	42	46	50
DGA2	19	26	34	39	47	52	58	65
DGA3	23	32	41	49	58	64	71	79
DGB1	17	23	30	36	43	48	53	60
DGB2	20	27	35	42	51	57	64	72
DGB3	24	32	43	51	62	69	76	84
DGC1	21	28	36	43	52	57	64	71
DGC2	23	31	41	48	59	65	72	80
DGC3	27	37	48	57	69	75	83	89
SSA1	29	36	43	49	56	61	67	75
SSB1	24	30	37	43	50	55	61	69
SSB2	31	39	48	55	64	69	76	83
SSB3	23	29	35	40	47	52	58	65
SSC1	22	29	37	43	51	57	64	73
SSC2	26	35	45	52	61	67	75	83
SSE1	29	36	45	51	59	64	70	78
SSE2	35	45	55	62	71	76	82	89
SSE3	25	31	38	43	50	55	61	68

LOS ALAMOS, NEW MEXICO Type	LCR = 100	70	50	40	30	6437 DD65 25	20	15
WWA3	20	27	35	41	49	55	62	72
WWB4	25	36	47	55	66	72	80	88
WWC2	25	35	46	54	64	71	78	86
TWA1	18	22	26	29	34	38	43	50
TWA2	18	23	29	34	41	46	52	61
TWA3	18	24	31	36	44	49	56	66
TWA4	17	23	31	36	45	50	57	67
TWB3	16	22	28	33	41	46	53	62
TWD4	23	32	42	49	59	66	74	83
TWE2	24	33	43	50	60	66	74	83
TWF3	15	20	27	32	40	45	52	62
TWJ2	21	30	40	47	57	63	71	80
DGA1	13	17	22	26	31	34	37	41
DGA2	15	21	28	33	40	45	50	58
DGA3	19	26	35	42	52	58	65	74
DGB1	13	18	23	27	34	38	44	50
DGB2	16	21	28	34	43	49	56	65
DGB3	20	27	36	43	54	62	70	80
DGC1	16	22	28	34	42	48	55	63
DGC2	18	25	33	40	50	57	65	74
DGC3	22	31	41	49	61	69	77	86
SSA1	25	31	38	44	51	56	63	71
SSB1	21	26	32	37	44	49	56	64
SSB2	27	34	43	50	59	65	72	80
SSB3	19	24	30	35	42	46	52	60
SSC1	17	23	30	36	43	49	56	65
SSC2	21	29	38	45	54	61	68	78
SSE1	24	31	39	45	53	59	65	74
SSE2	30	39	50	57	67	73	79	87
SSE3	21	27	33	37	44	49	55	63

ALBUQUERQUE, NEW MEXICO SSF (%) Type	LCR = 100	70	50	40	30	4293 DD65 25	20	15
WWA3	28	37	46	54	63	69	76	85
WWB4	35	47	59	67	77	83	89	94
WWC2	34	46	58	66	76	82	88	94
TWA1	22	27	33	38	45	50	56	64
TWA2	24	31	39	45	53	59	66	75
TWA3	25	32	41	48	57	63	70	79
TWA4	24	32	41	48	58	64	71	80
TWB3	22	29	38	44	53	59	66	75
TWD4	31	42	53	61	71	77	84	91
TWE2	32	43	54	62	72	78	84	91
TWF3	21	29	37	44	53	59	66	76
TWJ2	29	40	51	59	69	75	82	90
DGA1	19	26	33	37	44	48	52	58
DGA2	21	29	38	44	52	57	64	71
DGA3	25	35	46	54	64	70	76	84
DGB1	20	27	35	41	50	55	61	68
DGB2	22	30	40	47	58	64	71	79
DGB3	26	36	47	56	68	75	82	89
DGC1	23	32	42	49	60	66	72	79
DGC2	25	34	46	54	65	72	79	86
DGC3	30	40	53	63	75	82	88	93
SSA1	30	38	46	52	61	66	73	81
SSB1	25	32	40	46	54	60	67	75
SSB2	32	42	52	59	68	74	81	88
SSB3	24	30	38	43	51	57	63	72
SSC1	24	32	41	48	57	63	71	79
SSC2	29	39	50	57	67	73	80	88
SSE1	31	39	49	55	64	70	77	85
SSE2	38	49	60	67	76	82	88	93
SSE3	26	33	40	46	54	60	66	75

ALBANY, NEW YORK SSF (%) Type	LCR = 100	70	50	40	30	6891 DD65 25	20	15
WWA3	7	9	12	14	17	18	21	24
WWB4	8	14	21	26	33	38	45	54
WWC2	9	14	20	25	31	36	42	51
TWA1	11	12	13	14	15	15	16	17
TWA2	9	10	12	14	16	17	19	21
TWA3	7	9	12	13	16	18	20	23
TWA4	6	8	11	13	16	18	21	25
TWB3	7	9	11	13	16	18	20	24
TWD4	9	13	19	23	30	34	40	48
TWE2	9	14	19	23	29	33	39	46
TWF3	5	7	9	11	13	15	17	20
TWJ2	7	12	17	21	27	31	37	45
DGA1	3	4	5	5	5	4	4	2
DGA2	6	8	11	13	15	17	20	23
DGA3	10	13	17	21	26	29	34	41
DGB1	3	4	4	5	5	5	4	3
DGB2	6	9	11	13	16	18	21	24
DGB3	10	14	18	22	27	31	36	44
DGC1	5	6	7	8	10	10	10	10
DGC2	8	11	14	17	20	23	27	32
DGC3	12	16	21	25	31	35	41	50
SSA1	12	15	17	19	22	24	27	30
SSB1	10	12	14	16	18	20	22	25
SSB2	13	17	22	26	31	35	39	46
SSB3	9	11	12	14	15	16	18	19
SSC1	6	7	9	11	13	14	16	18
SSC2	7	11	15	18	23	26	31	37
SSE1	9	11	14	16	18	20	21	23
SSE2	12	17	22	26	32	36	41	48
SSE3	11	12	14	16	17	19	20	22

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

BUFFALO, NEW YORK Type	LCR = 100	70	50	40	30	6931 DD65 25	20	15
WWA3	5	6	8	9	11	11	12	13
WWB4	6	11	16	21	27	31	37	44
WWC2	6	11	16	19	25	29	34	41
TWA1	10	11	11	12	12	12	11	11
TWA2	8	9	10	11	12	12	13	13
TWA3	6	7	9	10	11	12	13	14
TWA4	4	6	8	9	11	12	14	16
TWB3	6	7	9	10	12	13	14	16
TWD4	7	11	15	19	24	28	32	39
TWE2	8	11	15	19	23	27	31	37
TWF3	3	5	6	7	9	10	11	12
TWJ2	5	9	13	17	22	25	29	36
DGA1	2	2	2	2	1	0	−1	−4
DGA2	5	7	9	10	12	13	14	16
DGA3	9	12	15	18	22	25	29	34
DGB1	2	2	2	2	1	0	0	−4
DGB2	5	7	9	10	12	14	15	17
DGB3	9	12	16	19	23	27	31	37
DGC1	4	4	5	5	5	5	4	2
DGC2	7	9	12	14	16	18	21	24
DGC3	10	14	18	22	27	31	35	42
SSA1	11	13	15	17	19	20	21	22
SSB1	9	11	12	13	15	16	17	18
SSB2	12	15	19	23	27	30	34	40
SSB3	8	9	11	11	12	13	13	13
SSC1	4	5	6	7	8	8	8	7
SSC2	6	8	12	14	17	20	23	27
SSE1	8	9	11	12	13	13	14	13
SSE2	10	14	18	22	26	29	33	38
SSE3	10	11	12	13	14	15	15	15

NEW YORK, NEW YORK Type	LCR = 100	70	50	40	30	4851 DD65 25	20	15
WWA3	10	14	19	22	27	30	35	41
WWB4	13	21	29	35	44	50	57	67
WWC2	13	20	28	34	42	48	55	64
TWA1	13	15	17	18	21	22	24	27
TWA2	11	14	17	20	23	26	30	35
TWA3	10	14	17	20	25	28	32	38
TWA4	9	13	17	20	25	28	33	39
TWB3	9	13	16	19	23	26	30	36
TWD4	13	19	26	31	39	44	51	60
TWE2	14	20	26	32	39	44	51	60
TWF3	7	11	14	17	21	24	28	34
TWJ2	11	17	24	29	36	42	48	57
DGA1	6	8	10	11	12	13	14	14
DGA2	9	12	16	18	23	25	29	34
DGA3	12	17	22	27	33	38	44	52
DGB1	6	8	10	11	13	14	16	17
DGB2	9	12	16	19	23	27	31	37
DGB3	13	17	23	28	35	40	47	56
DGC1	8	11	13	15	18	20	23	26
DGC2	11	15	20	23	29	33	38	45
DGC3	15	20	26	31	39	45	53	63
SSA1	16	19	23	26	30	33	37	43
SSB1	13	16	19	22	26	28	32	37
SSB2	17	22	28	33	39	44	50	58
SSB3	12	14	17	20	23	25	28	32
SSC1	9	12	15	18	22	25	29	34
SSC2	11	16	22	27	33	37	43	52
SSE1	13	17	21	24	28	31	35	41
SSE2	17	23	30	35	43	48	54	62
SSE3	13	16	19	22	25	27	31	35

SYRACUSE, NEW YORK Type	LCR = 100	70	50	SSF (%) 40	30	6681 DD65 25	20	15
WWA3	5	7	9	10	12	13	14	15
WWB4	6	12	17	22	28	33	38	46
WWC2	7	11	17	21	26	30	36	43
TWA1	11	11	12	12	12	13	12	12
TWA2	8	9	10	11	13	13	14	15
TWA3	6	8	9	11	12	14	15	16
TWA4	5	7	9	10	12	14	15	16
TWB3	6	7	9	11	13	14	16	16
TWD4	7	11	16	20	25	29	34	39
TWE2	8	12	16	20	25	28	33	39
TWF3	4	5	7	8	10	11	12	13
TWJ2	6	10	14	18	23	26	31	38
DGA1	2	3	3	3	2	1	0	−3
DGA2	6	7	9	11	13	14	16	17
DGA3	9	12	16	18	23	26	30	36
DGB1	2	3	3	3	2	1	0	−2
DGB2	6	7	9	11	13	15	16	19
DGB3	9	12	16	19	24	28	32	38
DGC1	4	5	5	6	6	6	5	4
DGC2	7	9	12	14	17	19	22	25
DGC3	11	14	19	22	28	31	36	44
SSA1	12	14	16	17	19	20	22	24
SSB1	9	11	13	14	16	17	18	19
SSB2	12	16	20	23	28	31	35	41
SSB3	8	10	11	12	13	13	14	14
SSC1	4	6	7	8	9	9	9	9
SSC2	6	9	12	15	19	21	24	29
SSE1	8	10	11	13	14	14	15	15
SSE2	10	14	19	22	27	30	34	40
SSE3	10	11	12	13	15	15	16	16

CHARLOTTE, NORTH CAROLINA Type	LCR = 200	100	70	50	SSF (%) 40	30	3226 DD65 25	20
WWA3	13	23	31	39	45	54	59	66
WWB4	13	29	40	51	59	69	75	82
WWC2	13	29	39	50	58	67	74	81
TWA1	15	20	24	29	33	38	42	47
TWA2	13	21	27	33	38	45	50	57
TWA3	12	21	27	35	40	48	54	60
TWA4	11	20	27	35	41	49	54	61
TWB3	11	19	25	32	37	45	50	57
TWD4	13	26	36	46	53	63	69	76
TWE2	14	27	37	47	54	63	69	77
TWF3	9	18	24	31	36	44	50	56
TWJ2	11	24	34	44	51	61	67	74
DGA1	9	16	21	26	30	35	39	42
DGA2	10	18	24	31	37	44	49	55
DGA3	12	22	30	39	46	55	61	68
DGB1	9	16	21	28	32	39	44	49
DGB2	10	19	25	33	39	48	54	61
DGB3	12	23	31	40	48	58	65	73
DGC1	11	20	26	33	39	47	53	59
DGC2	12	22	29	38	45	55	61	69
DGC3	14	26	35	45	53	65	72	80
SSA1	17	26	33	40	45	53	58	64
SSB1	14	22	28	35	40	47	52	58
SSB2	17	29	37	46	52	61	67	74
SSB3	14	21	26	33	37	44	49	55
SSC1	11	20	27	34	40	48	53	60
SSC2	12	25	33	42	49	58	64	72
SSE1	16	26	34	42	47	55	61	68
SSE2	18	32	42	52	59	69	74	81
SSE3	15	23	29	35	40	47	51	57

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

RALEIGH-DURHAM, NORTH CAROLINA Type	LCR = 200	100	70	50	SSF (%) 40	30	3520 DD65 25	20
WWA3	11	21	28	36	41	50	55	62
WWB4	11	26	37	48	55	66	72	79
WWC2	12	26	36	46	54	64	70	77
TWA1	14	19	22	27	30	35	39	44
TWA2	12	19	24	30	35	42	47	53
TWA3	11	19	25	32	37	45	50	56
TWA4	9	18	24	32	37	45	51	57
TWB3	10	17	23	29	34	41	46	53
TWD4	11	24	33	43	50	60	66	73
TWE2	12	25	34	43	50	60	66	73
TWF3	8	16	21	28	33	41	46	52
TWJ2	10	22	31	40	47	57	63	71
DGA1	8	14	19	23	27	32	35	38
DGA2	9	16	22	29	34	41	45	51
DGA3	11	20	27	36	43	52	58	65
DGB1	8	14	19	24	29	35	39	44
DGB2	9	17	23	30	35	44	49	56
DGB3	11	21	28	37	44	55	61	70
DGC1	9	17	23	30	35	42	48	54
DGC2	10	20	27	35	41	50	57	64
DGC3	13	24	32	42	50	61	68	77
SSA1	16	24	30	37	42	50	54	61
SSB1	13	21	26	32	37	44	48	54
SSB2	15	26	34	43	49	58	63	70
SSB3	12	19	24	30	34	41	45	51
SSC1	10	18	24	31	36	44	49	56
SSC2	11	22	30	39	46	55	61	68
SSE1	14	24	31	38	44	52	57	63
SSE2	16	30	39	49	56	65	71	77
SSE3	14	21	26	32	37	43	48	54

BISMARCK, NORTH DAKOTA Type	LCR = 100	70	50	SSF (%) 40	30	9057 DD65 25	20	15
WWA3	8	11	15	17	21	23	26	30
WWB4	11	17	24	30	37	43	49	58
WWC2	11	17	23	28	36	40	47	55
TWA1	12	13	15	16	17	18	19	21
TWA2	10	12	15	16	19	21	23	26
TWA3	9	11	14	16	20	22	25	29
TWA4	7	10	14	16	20	22	26	30
TWB3	8	10	13	16	19	21	24	29
TWD4	11	16	22	27	33	38	44	52
TWE2	11	16	22	27	33	37	43	51
TWF3	6	8	11	13	17	19	21	25
TWJ2	9	14	20	24	31	35	41	49
DGA1	5	6	7	8	8	8	8	7
DGA2	8	10	13	15	19	21	24	27
DGA3	11	15	20	23	29	33	38	45
DGB1	4	6	7	8	9	9	9	9
DGB2	8	10	14	16	20	22	25	29
DGB3	11	15	21	25	30	35	40	48
DGC1	6	8	10	12	14	15	16	17
DGC2	10	13	17	20	24	27	31	37
DGC3	13	18	24	28	35	39	46	55
SSA1	13	16	19	21	24	26	28	31
SSB1	11	13	15	17	20	22	24	27
SSB2	14	18	23	27	33	36	41	48
SSB3	10	11	13	15	17	18	20	21
SSC1	7	9	12	14	17	18	21	24
SSC2	9	13	18	22	27	31	35	42
SSE1	10	13	16	18	20	22	24	26
SSE2	13	18	24	28	34	38	43	50
SSE3	11	13	15	17	19	20	22	24

FARGO, NORTH DAKOTA Type	LCR = 100	70	50	SSF (%) 40	30	9278 DD65 25	20	15
WWA3	6	8	11	12	15	16	18	20
WWB4	8	13	20	24	31	36	42	50
WWC2	8	13	19	23	29	33	39	46
TWA1	11	12	13	13	14	14	15	15
TWA2	9	10	12	13	15	16	17	18
TWA3	7	9	11	13	15	16	18	20
TWA4	6	8	10	12	15	16	19	21
TWB3	7	8	11	12	15	16	18	21
TWD4	8	13	18	22	28	32	37	44
TWE2	9	13	18	22	27	31	36	43
TWF3	4	6	8	10	12	13	15	17
TWJ2	7	11	16	20	25	29	34	41
DGA1	3	4	4	4	4	3	2	0
DGA2	6	8	11	12	15	16	18	20
DGA3	10	13	17	20	25	28	33	39
DGB1	3	4	4	4	4	4	3	1
DGB2	6	8	11	13	15	17	19	22
DGB3	10	13	18	21	26	30	35	41
DGC1	5	6	7	8	9	9	9	8
DGC2	8	11	14	16	20	22	25	29
DGC3	11	15	20	24	30	34	39	47
SSA1	12	14	16	17	19	21	22	24
SSB1	9	11	13	14	16	17	18	20
SSB2	12	16	20	23	28	31	36	41
SSB3	8	10	11	12	13	14	14	14
SSC1	5	7	8	10	11	12	13	14
SSC2	7	10	14	17	21	24	28	33
SSE1	8	10	12	13	14	15	16	15
SSE2	11	15	20	23	28	31	35	41
SSE3	10	11	13	14	15	16	16	17

CINCINNATI, OHIO Type	LCR = 100	70	50	SSF (%) 40	30	5079 DD65 25	20	15
WWA3	10	13	17	21	25	28	32	38
WWB4	13	20	27	33	42	47	55	64
WWC2	13	19	27	32	40	45	52	62
TWA1	13	14	16	18	20	21	23	25
TWA2	11	14	17	19	22	25	28	32
TWA3	10	13	16	19	23	26	30	35
TWA4	9	12	16	19	23	26	31	36
TWB3	9	12	15	18	22	25	29	34
TWD4	12	18	25	30	37	42	49	58
TWE2	13	19	25	30	37	42	48	57
TWF3	7	10	13	16	20	23	26	31
TWJ2	11	16	23	28	35	40	46	55
DGA1	6	7	9	10	11	12	12	12
DGA2	9	12	15	18	21	24	27	32
DGA3	12	16	22	26	32	36	42	50
DGB1	6	7	9	10	12	13	14	14
DGB2	9	12	15	18	22	25	29	34
DGB3	12	17	23	27	33	38	44	53
DGC1	8	10	13	15	17	18	20	23
DGC2	11	15	19	22	27	31	36	42
DGC3	14	20	26	31	38	43	50	60
SSA1	15	19	23	25	29	32	36	41
SSB1	13	16	19	21	25	27	31	35
SSB2	16	22	27	32	38	42	48	56
SSB3	12	14	17	19	22	24	27	30
SSC1	8	11	15	17	21	23	26	31
SSC2	11	16	21	25	31	35	41	49
SSE1	13	16	20	23	27	30	33	38
SSE2	16	22	29	34	41	46	52	60
SSE3	13	16	19	21	24	26	29	33

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

CLEVELAND, OHIO **SSF (%)** — 6160 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	6	9	11	13	15	16	18	20
WWB4	8	13	20	24	31	36	42	50
WWC2	8	13	19	23	29	34	39	47
TWA1	11	12	13	14	14	15	15	15
TWA2	9	10	12	13	15	16	17	19
TWA3	7	9	11	13	15	16	18	20
TWA4	6	8	10	12	15	17	19	22
TWB3	7	9	11	13	15	16	19	21
TWD4	9	13	18	22	28	32	37	45
TWE2	9	14	18	22	28	31	36	43
TWF3	5	6	8	10	12	13	15	17
TWJ2	7	11	16	20	25	29	34	41
DGA1	3	4	4	4	4	4	2	0
DGA2	7	8	11	12	15	16	18	21
DGA3	10	13	17	20	25	28	33	39
DGB1	3	4	4	5	4	4	3	1
DGB2	7	9	11	13	15	17	19	22
DGB3	10	14	18	21	26	30	35	42
DGC1	5	6	7	8	9	9	9	8
DGC2	8	11	14	16	20	22	25	29
DGC3	12	16	21	24	30	34	39	47
SSA1	13	15	18	19	22	24	26	28
SSB1	10	12	14	16	18	19	21	23
SSB2	13	17	22	25	30	34	38	44
SSB3	9	11	13	14	15	16	17	18
SSC1	5	7	9	10	11	12	13	14
SSC2	7	11	14	17	21	24	28	33
SSE1	9	12	14	15	17	18	19	20
SSE2	12	17	22	25	31	34	39	45
SSE3	11	13	14	16	17	18	19	20

COLUMBUS, OHIO **SSF (%)** — 5705 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	8	11	14	16	20	22	25	29
WWB4	10	16	23	29	36	41	48	57
WWC2	10	16	22	27	34	39	46	54
TWA1	12	13	14	15	17	17	18	20
TWA2	10	12	14	16	18	20	22	25
TWA3	8	11	13	16	19	21	24	27
TWA4	7	10	13	15	19	21	24	29
TWB3	8	10	13	15	18	20	23	27
TWD4	10	15	21	26	32	37	43	51
TWE2	11	16	21	26	32	36	42	50
TWF3	6	8	11	13	16	18	20	24
TWJ2	9	13	19	23	30	34	40	48
DGA1	4	5	6	7	7	7	7	5
DGA2	7	10	12	15	18	20	22	26
DGA3	11	14	19	23	28	32	37	44
DGB1	4	5	6	7	8	8	8	7
DGB2	7	10	13	15	18	21	24	28
DGB3	11	15	20	24	29	33	39	47
DGC1	6	8	10	11	12	13	14	15
DGC2	9	12	16	19	23	26	30	35
DGC3	13	17	23	27	33	38	44	53
SSA1	14	17	20	22	25	27	30	34
SSB1	11	13	16	18	21	23	25	29
SSB2	15	19	24	28	34	38	43	50
SSB3	10	12	14	16	18	20	22	24
SSC1	7	9	11	13	16	17	19	22
SSC2	9	13	17	21	26	30	34	41
SSE1	11	14	17	19	22	24	26	29
SSE2	14	19	25	29	36	40	45	53
SSE3	12	14	16	18	20	22	24	26

OKLAHOMA CITY, OKLAHOMA **SSF (%)** — 3899 DD65

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	12	22	29	37	44	52	58	65
WWB4	12	26	38	50	58	68	74	81
WWC2	13	27	38	49	56	66	73	80
TWA1	14	20	23	28	32	37	41	46
TWA2	13	20	26	32	37	44	49	55
TWA3	12	20	26	33	39	47	52	59
TWA4	10	19	26	33	39	47	53	60
TWB3	10	18	24	31	36	44	49	56
TWD4	12	25	34	45	52	62	68	76
TWE2	13	26	35	45	53	62	68	76
TWF3	9	17	23	30	35	43	48	55
TWJ2	11	23	32	42	49	59	66	73
DGA1	8	15	20	25	29	34	37	41
DGA2	9	17	23	30	35	43	47	53
DGA3	11	21	29	38	45	54	60	67
DGB1	8	15	20	26	31	37	42	47
DGB2	10	18	24	31	37	46	52	59
DGB3	12	22	29	39	46	57	64	72
DGC1	10	18	24	32	37	46	51	58
DGC2	11	21	28	36	43	53	60	68
DGC3	13	25	33	44	52	64	71	79
SSA1	16	25	32	39	44	51	57	63
SSB1	14	21	27	33	38	45	50	56
SSB2	16	27	35	44	51	60	65	72
SSB3	13	20	25	31	36	42	47	53
SSC1	11	19	26	33	38	46	52	58
SSC2	12	23	32	41	48	57	63	71
SSE1	15	25	32	40	46	54	59	66
SSE2	17	31	40	51	58	67	73	80
SSE3	15	22	27	34	38	45	50	56

MEDFORD, OREGON **SSF (%)** — 4935 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	16	21	26	31	36	40	45	51
WWB4	20	28	37	43	52	58	64	72
WWC2	20	28	36	42	50	56	62	70
TWA1	17	19	22	24	28	30	33	37
TWA2	16	20	24	27	32	35	39	44
TWA3	15	19	24	28	33	37	41	47
TWA4	14	19	24	28	34	37	42	49
TWB3	14	18	23	26	31	35	40	46
TWD4	19	26	34	39	47	52	59	67
TWE2	20	26	34	40	47	52	59	66
TWF3	12	16	21	25	30	33	38	44
TWJ2	17	24	31	37	45	50	56	64
DGA1	11	14	17	19	21	23	24	25
DGA2	13	17	22	26	31	34	38	43
DGA3	17	23	29	34	41	46	52	59
DGB1	11	14	18	20	23	25	28	30
DGB2	14	18	23	27	33	37	41	47
DGB3	17	23	30	36	44	49	55	63
DGC1	13	17	22	25	30	32	36	39
DGC2	16	21	27	32	39	43	48	55
DGC3	20	26	34	40	49	54	61	69
SSA1	21	26	30	34	39	42	46	51
SSB1	18	22	26	29	34	37	41	46
SSB2	22	28	35	40	47	51	57	64
SSB3	17	20	24	27	31	34	37	42
SSC1	14	18	23	27	32	35	39	44
SSC2	17	23	30	35	42	46	52	59
SSE1	19	24	29	33	38	41	45	50
SSE2	24	31	38	44	51	55	61	68
SSE3	18	22	26	29	33	36	40	44

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

SALEM, OREGON **SSF (%)** — 4654 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	15	20	25	29	35	38	43	48
WWB4	19	27	36	42	50	56	63	71
WWC2	19	27	35	41	49	54	60	68
TWA1	16	19	22	24	27	29	31	35
TWA2	16	19	23	26	30	33	37	42
TWA3	15	19	23	27	32	35	40	45
TWA4	14	18	23	27	32	36	40	47
TWB3	14	18	22	25	30	34	38	44
TWD4	18	25	32	38	46	51	57	65
TWE2	19	26	33	38	46	51	57	65
TWF3	12	16	20	24	28	32	36	42
TWJ2	16	23	30	36	43	48	55	63
DGA1	10	13	16	18	20	21	23	23
DGA2	13	17	22	25	30	33	37	41
DGA3	17	22	28	33	40	45	51	58
DGB1	11	13	17	19	22	24	26	28
DGB2	13	18	22	26	32	35	40	45
DGB3	17	23	29	35	42	47	54	62
DGC1	13	16	21	24	28	30	33	37
DGC2	16	21	26	31	37	41	46	53
DGC3	19	26	33	39	47	53	59	68
SSA1	21	25	29	33	37	40	44	49
SSB1	17	21	25	28	33	36	39	44
SSB2	22	28	34	39	46	50	55	62
SSB3	16	20	23	26	30	33	36	40
SSC1	14	18	22	25	30	33	37	42
SSC2	17	22	29	33	40	45	50	57
SSE1	19	23	28	32	36	39	43	47
SSE2	23	30	37	42	49	54	59	66
SSE3	18	22	25	28	32	35	38	42

HARRISBURG, PENNSYLVANIA **SSF (%)** — 5226 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	11	14	19	22	28	31	36	42
WWB4	14	21	29	36	45	51	58	68
WWC2	14	20	28	34	43	48	56	65
TWA1	13	15	17	19	21	23	25	28
TWA2	12	14	18	20	24	27	30	35
TWA3	10	14	18	21	25	28	33	39
TWA4	9	13	17	20	25	29	34	40
TWB3	10	13	16	19	24	27	31	37
TWD4	13	19	26	32	40	45	52	61
TWE2	14	20	27	32	40	45	52	61
TWF3	8	11	14	17	22	25	29	35
TWJ2	11	17	24	29	37	42	49	58
DGA1	6	8	10	11	13	14	15	15
DGA2	9	12	16	19	23	26	30	35
DGA3	12	17	23	27	34	38	45	53
DGB1	6	8	10	12	14	15	16	18
DGB2	9	12	16	19	24	27	32	38
DGB3	13	18	23	28	35	40	47	57
DGC1	8	11	14	16	19	21	24	27
DGC2	11	15	20	24	29	33	39	46
DGC3	15	20	27	32	40	46	53	64
SSA1	16	19	23	26	31	34	38	44
SSB1	13	16	19	22	26	29	32	38
SSB2	17	22	28	33	40	44	50	58
SSB3	12	14	17	20	23	25	28	33
SSC1	9	12	16	19	23	26	30	35
SSC2	12	17	22	27	34	38	44	52
SSE1	13	17	21	24	29	32	36	42
SSE2	17	23	30	36	43	48	55	63
SSE3	13	16	19	22	25	28	31	36

PHILADELPHIA, PENNSYLVANIA **SSF (%)** — 4875 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	12	17	22	26	32	36	41	49
WWB4	16	24	33	40	49	55	63	72
WWC2	16	23	32	38	47	53	61	70
TWA1	14	16	19	21	24	26	29	33
TWA2	13	16	20	23	27	31	35	41
TWA3	12	16	20	24	29	33	38	44
TWA4	11	15	20	24	29	33	39	46
TWB3	11	15	19	22	27	31	36	42
TWD4	15	22	30	35	44	49	57	66
TWE2	16	22	30	36	44	49	56	66
TWF3	9	13	17	20	25	29	34	40
TWJ2	13	20	27	33	41	47	54	63
DGA1	8	10	12	14	17	18	19	20
DGA2	10	14	18	22	26	30	34	39
DGA3	14	19	25	30	37	42	49	58
DGB1	7	10	13	15	17	19	22	24
DGB2	11	14	19	22	28	31	37	43
DGB3	14	20	26	31	39	44	52	62
DGC1	10	13	17	19	23	26	30	34
DGC2	13	17	23	27	33	38	44	52
DGC3	16	22	29	35	44	50	58	69
SSA1	17	21	26	29	34	38	43	49
SSB1	14	18	22	25	29	33	37	43
SSB2	19	24	31	36	43	48	54	63
SSB3	13	16	20	22	26	29	33	38
SSC1	11	14	19	22	27	30	35	42
SSC2	14	19	26	31	38	43	49	58
SSE1	15	20	25	28	34	37	42	48
SSE2	19	26	34	40	48	53	60	68
SSE3	15	18	22	25	29	32	36	41

PITTSBURGH, PENNSYLVANIA **SSF (%)** — 5937 DD65

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	7	9	12	14	17	19	21	24
WWB4	9	15	21	26	33	38	45	53
WWC2	9	14	20	25	32	36	42	50
TWA1	12	12	13	14	15	16	16	17
TWA2	9	11	13	14	16	18	19	22
TWA3	8	10	12	14	17	18	21	23
TWA4	6	9	11	14	17	19	21	25
TWB3	7	9	12	14	16	18	21	24
TWD4	9	14	20	24	30	34	40	48
TWE2	10	14	20	24	30	34	39	46
TWF3	5	7	9	11	14	15	17	20
TWJ2	8	12	17	21	27	31	37	44
DGA1	4	5	5	5	5	5	4	2
DGA2	7	9	11	13	16	18	20	23
DGA3	10	14	18	21	26	30	35	41
DGB1	4	4	5	6	6	6	5	3
DGB2	7	9	12	14	17	19	21	25
DGB3	10	14	19	22	28	32	37	44
DGC1	5	7	8	9	10	11	11	11
DGC2	9	11	15	17	21	24	27	32
DGC3	12	16	21	26	32	36	42	50
SSA1	13	16	19	21	23	25	28	31
SSB1	11	13	15	17	19	21	23	26
SSB2	14	18	23	27	32	36	40	47
SSB3	10	11	13	15	17	18	19	21
SSC1	6	8	10	11	13	15	16	18
SSC2	8	12	16	19	23	27	31	37
SSE1	10	12	15	17	19	21	23	24
SSE2	13	18	23	27	33	37	42	48
SSE3	11	13	15	17	19	20	21	23

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

PROVIDENCE, RHODE ISLAND **SSF (%)** *5974 DD65*

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	10	13	18	21	26	29	33	40
WWB4	13	20	28	34	43	49	56	66
WWC2	13	19	27	33	41	47	54	63
TWA1	13	14	16	18	20	21	23	26
TWA2	11	14	17	19	22	25	28	33
TWA3	10	13	16	19	24	27	31	36
TWA4	9	12	16	19	24	27	31	38
TWB3	9	12	15	18	22	25	29	35
TWD4	12	18	25	30	38	43	50	59
TWE2	13	19	25	30	38	43	50	59
TWF3	7	10	13	16	20	23	27	32
TWJ2	11	16	23	28	35	40	47	56
DGA1	6	7	9	10	11	12	13	13
DGA2	8	11	15	18	22	24	28	33
DGA3	12	16	21	26	32	37	43	51
DGB1	5	7	9	10	12	13	14	15
DGB2	9	12	15	18	22	26	30	36
DGB3	12	17	22	27	34	39	45	55
DGC1	7	10	12	14	17	19	21	25
DGC2	10	14	19	22	28	31	37	44
DGC3	14	19	26	31	38	44	52	62
SSA1	15	19	22	25	30	33	36	42
SSB1	12	15	19	21	25	28	31	36
SSB2	16	21	27	32	38	43	49	57
SSB3	11	14	17	19	22	24	27	31
SSC1	8	11	15	17	21	24	27	32
SSC2	11	16	21	25	32	36	42	50
SSE1	13	16	20	23	27	30	34	39
SSE2	16	22	29	34	42	47	53	61
SSE3	13	16	19	21	24	27	30	34

CHARLESTON, SOUTH CAROLINA **SSF (%)** *2150 DD65*

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	18	31	40	50	57	66	72	79
WWB4	19	38	50	62	70	79	85	90
WWC2	20	38	49	61	69	78	84	89
TWA1	17	25	30	37	41	48	53	59
TWA2	17	27	34	42	48	57	62	69
TWA3	16	28	36	45	51	60	66	73
TWA4	15	27	36	45	52	61	67	74
TWB3	14	25	33	41	47	56	62	69
TWD4	18	35	45	56	64	74	79	86
TWE2	19	36	46	57	65	74	80	86
TWF3	13	24	32	41	47	56	62	69
TWJ2	17	32	43	54	62	72	77	84
DGA1	13	23	29	36	41	48	51	56
DGA2	13	24	32	41	47	55	60	67
DGA3	16	29	38	49	57	66	72	78
DGB1	13	23	31	39	45	54	59	65
DGB2	14	25	34	43	51	61	67	74
DGB3	16	29	39	51	60	71	77	83
DGC1	15	27	36	46	53	63	69	75
DGC2	16	29	38	49	58	68	75	81
DGC3	18	33	44	57	66	77	83	89
SSA1	22	33	41	50	56	65	70	76
SSB1	18	29	36	44	50	58	64	70
SSB2	22	36	46	56	63	72	77	83
SSB3	17	27	34	42	48	56	61	68
SSC1	16	28	36	45	51	60	66	73
SSC2	18	32	42	53	60	70	76	82
SSE1	21	34	43	53	60	69	74	80
SSE2	24	42	53	64	71	80	85	90
SSE3	19	29	36	44	50	58	64	70

RAPID CITY, SOUTH DAKOTA **SSF (%)** *7332 DD65*

Type	LCR = 100	70	50	40	30	25	20	15
WWA3	13	18	23	27	33	37	42	50
WWB4	17	25	34	40	50	56	63	73
WWC2	17	24	33	39	48	54	61	70
TWA1	15	17	19	21	24	27	30	34
TWA2	13	17	21	24	28	32	36	42
TWA3	13	17	21	25	30	34	38	45
TWA4	11	16	21	25	30	34	39	47
TWB3	11	15	20	23	28	32	37	43
TWD4	16	23	30	36	45	50	57	66
TWE2	17	23	31	37	45	50	57	66
TWF3	10	13	18	21	26	30	35	41
TWJ2	14	21	28	34	42	47	54	64
DGA1	8	11	13	15	18	19	20	21
DGA2	11	15	19	22	27	31	35	40
DGA3	14	20	26	31	38	43	50	58
DGB1	8	11	14	16	19	21	23	26
DGB2	11	15	20	23	29	33	38	44
DGB3	15	20	27	32	40	45	53	62
DGC1	10	14	18	21	25	27	31	35
DGC2	13	18	24	28	34	39	45	53
DGC3	17	23	31	36	45	51	59	69
SSA1	18	22	26	30	34	38	42	48
SSB1	15	19	22	25	30	33	37	42
SSB2	19	25	31	36	43	48	54	62
SSB3	13	16	20	23	26	29	33	37
SSC1	11	15	20	23	28	31	36	42
SSC2	14	20	27	32	39	44	50	59
SSE1	16	20	25	28	33	37	41	47
SSE2	20	27	34	40	47	52	59	67
SSE3	15	18	22	25	29	32	35	40

KNOXVILLE, TENNESSEE **SSF (%)** *3486 DD65*

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	10	18	24	31	36	44	49	55
WWB4	9	23	32	43	50	60	66	74
WWC2	10	23	32	42	49	58	65	72
TWA1	13	17	21	24	27	32	35	39
TWA2	11	17	22	27	31	37	41	47
TWA3	10	17	22	28	33	39	44	50
TWA4	8	16	21	28	33	40	45	51
TWB3	9	15	20	26	30	37	41	47
TWD4	10	21	29	38	45	54	60	68
TWE2	11	22	30	39	46	55	60	68
TWF3	7	14	19	25	29	36	40	46
TWJ2	8	19	27	36	43	52	58	65
DGA1	7	12	16	20	23	27	29	32
DGA2	8	15	19	25	30	36	40	45
DGA3	10	18	25	32	38	47	53	60
DGB1	7	12	16	21	24	29	32	36
DGB2	8	15	20	26	31	38	43	49
DGB3	10	19	26	33	40	49	55	64
DGC1	8	15	20	25	29	36	40	45
DGC2	9	18	24	31	36	44	50	57
DGC3	12	22	29	38	45	55	62	71
SSA1	15	22	28	34	38	45	49	55
SSB1	12	19	24	29	33	39	43	49
SSB2	14	24	31	39	45	53	59	65
SSB3	12	18	22	27	31	36	40	45
SSC1	9	16	21	27	32	38	43	49
SSC2	9	19	27	35	41	49	55	63
SSE1	13	21	27	34	39	48	51	57
SSE2	14	27	35	44	51	60	65	73
SSE3	13	19	24	29	33	39	43	48

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

MEMPHIS, TENNESSEE **SSF (%)** *3237 DD65*

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	11	21	27	35	41	49	54	61
WWB4	11	26	36	47	54	65	71	78
WWC2	12	26	35	46	53	63	69	77
TWA1	14	19	22	27	30	35	38	43
TWA2	12	19	24	30	35	41	46	52
TWA3	11	19	25	31	36	44	49	55
TWA4	9	18	24	31	37	44	50	56
TWB3	10	17	23	29	34	41	46	52
TWD4	11	24	32	42	49	59	65	72
TWE2	12	25	33	43	50	59	65	72
TWF3	8	16	21	28	33	40	45	51
TWJ2	10	22	30	40	47	56	62	70
DGA1	8	14	18	23	26	31	34	37
DGA2	9	16	22	28	33	40	44	50
DGA3	11	20	27	36	42	51	57	64
DGB1	8	14	19	24	28	34	38	43
DGB2	9	17	22	29	35	43	48	55
DGB3	11	21	28	37	43	54	60	69
DGC1	10	17	23	29	34	41	46	52
DGC2	11	20	26	34	40	49	56	63
DGC3	13	24	31	41	49	60	67	76
SSA1	16	24	30	37	42	49	54	60
SSB1	13	21	26	32	36	43	47	53
SSB2	15	26	34	42	49	57	63	70
SSB3	12	19	24	30	34	40	44	50
SSC1	10	18	24	31	36	43	48	54
SSC2	11	22	30	38	45	54	59	67
SSE1	14	24	30	38	43	51	56	62
SSE2	16	29	38	48	55	64	70	77
SSE3	14	21	26	32	36	43	47	53

NASHVILLE, TENNESSEE **SSF (%)** *3704 DD65*

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	8	15	20	26	31	37	42	47
WWB4	7	19	28	37	44	54	60	68
WWC2	8	19	27	36	43	52	58	66
TWA1	12	16	18	21	24	27	30	33
TWA2	10	15	19	23	27	32	35	40
TWA3	8	14	19	24	28	34	38	43
TWA4	7	13	18	24	28	34	38	44
TWB3	7	13	17	22	26	32	35	41
TWD4	8	18	25	34	40	48	54	61
TWE2	9	19	26	34	40	48	54	61
TWF3	6	11	16	21	24	30	34	39
TWJ2	6	16	23	31	37	46	51	59
DGA1	6	10	13	16	18	21	23	25
DGA2	7	12	17	21	25	31	34	39
DGA3	9	16	22	28	34	41	47	54
DGB1	6	10	13	16	19	22	25	28
DGB2	7	13	17	22	26	32	36	42
DGB3	9	17	22	29	35	43	49	57
DGC1	7	12	16	20	24	29	32	36
DGC2	8	15	20	26	31	38	43	49
DGC3	10	19	25	33	39	49	55	64
SSA1	13	20	25	30	34	39	43	49
SSB1	11	17	21	25	29	34	38	42
SSB2	12	21	28	35	40	48	53	60
SSB3	10	15	19	23	27	31	35	39
SSC1	7	13	18	23	26	32	36	41
SSC2	8	16	23	30	35	43	48	55
SSE1	11	18	23	29	33	39	44	49
SSE2	12	23	31	39	45	53	59	66
SSE3	12	17	21	25	29	34	37	41

AUSTIN, TEXAS **SSF (%)** *1737 DD65*

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	21	37	47	58	65	75	80	86
WWB4	24	45	58	70	77	86	90	94
WWC2	24	44	57	69	76	85	89	94
TWA1	20	29	35	42	48	56	61	67
TWA2	20	32	40	49	56	65	70	77
TWA3	19	33	42	52	59	68	74	81
TWA4	18	32	42	52	60	69	75	82
TWB3	17	30	38	48	55	64	70	77
TWD4	22	41	52	64	72	81	86	91
TWE2	24	42	53	65	73	81	86	91
TWF3	16	29	38	48	55	64	70	77
TWJ2	21	39	50	62	70	79	84	90
DGA1	16	28	36	44	49	57	61	66
DGA2	16	29	38	48	55	64	69	75
DGA3	19	34	45	57	65	74	79	84
DGB1	16	29	38	48	56	64	69	75
DGB2	17	30	41	52	60	70	76	82
DGB3	19	35	46	60	68	79	84	89
DGC1	19	33	44	56	64	74	79	84
DGC2	19	34	46	59	68	77	83	88
DGC3	22	39	52	66	75	85	89	93
SSA1	25	39	48	58	65	73	78	84
SSB1	21	34	42	51	58	67	72	79
SSB2	26	42	53	63	71	79	84	89
SSB3	20	32	40	49	56	65	70	77
SSC1	19	33	42	53	60	69	75	81
SSC2	22	39	50	61	68	78	83	89
SSE1	25	41	51	62	69	77	82	88
SSE2	29	49	61	72	79	87	91	94
SSE3	22	34	43	52	58	67	72	79

BROWNSVILLE, TEXAS **SSF (%)** *650 DD65*

Type	LCR = 200	100	70	50	40	30	25	20
WWA3	39	60	72	82	88	94	96	98
WWB4	45	70	82	90	94	98	99	100
WWC2	45	69	81	90	94	97	99	99
TWA1	30	45	54	64	71	79	84	89
TWA2	33	51	63	73	80	87	91	95
TWA3	34	54	66	76	83	90	93	96
TWA4	34	54	66	77	84	90	94	97
TWB3	31	50	61	72	79	87	91	95
TWD4	41	64	76	86	91	96	98	99
TWE2	42	65	77	87	92	96	98	99
TWF3	30	50	62	73	80	88	91	95
TWJ2	39	62	75	85	90	95	97	99
DGA1	31	50	61	70	76	83	87	90
DGA2	31	51	63	73	80	87	90	94
DGA3	34	57	70	80	86	91	93	95
DGB1	32	54	67	78	84	89	92	94
DGB2	32	55	69	80	86	92	95	97
DGB3	34	60	74	85	90	94	96	97
DGC1	36	62	76	85	90	94	95	97
DGC2	35	61	75	86	91	95	97	99
DGC3	39	66	80	90	94	97	98	98
SSA1	42	62	73	82	87	93	96	98
SSB1	36	55	66	76	83	89	93	96
SSB2	44	65	77	86	91	95	97	99
SSB3	35	54	65	75	81	88	92	95
SSC1	35	55	67	76	84	91	94	97
SSC2	39	62	74	84	90	95	97	99
SSE1	45	66	77	86	91	95	97	99
SSE2	51	74	85	92	96	98	99	100
SSE3	37	56	67	77	83	90	93	96

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

DALLAS, TEXAS SSF (%) Type	LCR = 200	100	70	50	40	30	25	20
						2297 DD	65	
WWA3	17	30	39	49	56	66	72	79
WWB4	19	37	49	62	70	79	85	90
WWC2	19	37	49	61	69	78	84	89
TWA1	17	24	30	36	41	48	52	59
TWA2	16	26	33	42	48	56	62	69
TWA3	15	27	35	44	50	60	65	73
TWA4	14	26	35	44	51	60	66	74
TWB3	14	24	32	40	47	56	62	69
TWD4	19	34	45	56	64	74	79	86
TWE2	19	35	46	57	65	74	80	86
TWF3	13	23	31	40	46	56	62	69
TWJ2	16	32	42	54	61	71	77	84
DGA1	12	22	29	36	41	47	51	56
DGA2	13	24	31	40	47	55	60	66
DGA3	15	28	38	49	56	66	72	78
DGB1	12	22	30	38	45	54	59	64
DGB2	13	24	33	43	51	61	67	74
DGB3	16	28	38	50	59	71	77	83
DGC1	15	26	35	45	53	63	69	75
DGC2	15	28	38	49	57	68	74	81
DGC3	18	32	43	57	66	77	83	89
SSA1	21	32	40	49	56	64	70	78
SSB1	17	28	35	43	49	58	63	70
SSB2	21	35	45	55	62	71	77	83
SSB3	17	26	33	41	47	55	60	67
SSC1	15	27	35	44	51	60	66	73
SSC2	17	32	42	52	60	70	76	82
SSE1	20	33	42	52	59	68	74	80
SSE2	23	41	52	63	70	79	84	90
SSE3	18	28	35	43	49	58	63	70

EL PASO, TEXAS SSF (%) Type	LCR = 200	100	70	50	40	30	25	20
						2685 DD	65	
WWA3	22	38	49	60	68	77	83	88
WWB4	25	47	60	72	80	88	92	95
WWC2	25	46	59	71	79	87	91	95
TWA1	20	29	36	44	49	58	63	70
TWA2	20	33	41	51	58	67	73	80
TWA3	20	34	44	54	61	71	77	83
TWA4	19	34	44	54	62	72	77	84
TWB3	18	31	40	50	57	67	73	79
TWD4	23	42	54	66	74	83	88	93
TWE2	24	43	55	67	75	84	88	93
TWF3	16	30	40	50	57	67	73	80
TWJ2	21	40	52	64	72	81	86	91
DGA1	16	29	37	46	52	59	64	69
DGA2	17	30	40	50	57	66	71	77
DGA3	19	35	47	59	67	76	81	86
DGB1	16	30	40	51	58	67	72	78
DGB2	17	31	42	55	63	73	79	84
DGB3	19	36	48	62	71	81	86	91
DGC1	19	35	47	59	68	77	82	86
DGC2	20	36	48	62	70	80	85	90
DGC3	22	40	55	69	78	87	91	94
SSA1	25	39	49	58	65	74	79	85
SSB1	21	34	43	52	59	68	73	80
SSB2	26	42	53	64	71	80	85	90
SSB3	20	32	41	50	56	65	71	77
SSC1	20	34	44	55	62	72	77	84
SSC2	22	40	51	63	71	80	85	90
SSE1	25	41	52	62	69	78	83	89
SSE2	29	49	61	73	80	87	91	95
SSE3	22	35	43	52	59	68	73	80

HOUSTON, TEXAS SSF (%) Type	LCR = 200	100	70	50	40	30	25	20
						1434 DD	65	
WWA3	21	37	47	58	66	74	80	86
WWB4	24	45	58	70	77	86	90	94
WWC2	24	44	57	69	76	85	90	94
TWA1	20	29	36	42	48	55	61	66
TWA2	20	32	40	49	56	65	70	77
TWA3	20	33	42	52	59	68	74	81
TWA4	18	32	42	52	59	68	74	80
TWB3	18	30	38	48	55	64	70	77
TWD4	22	41	52	64	72	81	86	91
TWE2	24	42	53	65	72	81	86	91
TWF3	16	29	38	48	56	64	70	76
TWJ2	21	38	50	62	69	78	84	89
DGA1	16	28	36	44	49	56	61	66
DGA2	18	29	38	48	55	63	68	74
DGA3	19	34	45	57	64	74	79	84
DGB1	16	28	38	48	55	64	69	74
DGB2	17	30	40	52	60	70	76	81
DGB3	19	35	46	59	68	78	83	88
DGC1	18	33	44	56	64	73	78	83
DGC2	19	34	45	58	67	77	82	88
DGC3	21	39	52	66	75	84	89	93
SSA1	25	39	49	58	65	73	78	84
SSB1	21	34	42	52	58	67	72	78
SSB2	26	42	53	64	71	80	85	90
SSB3	20	32	41	50	56	65	70	77
SSC1	19	33	42	52	60	69	75	81
SSC2	22	38	49	61	68	77	83	88
SSE1	25	41	51	62	69	77	82	88
SSE2	29	49	61	72	79	87	90	94
SSE3	22	34	43	52	59	67	73	78

LUBBOCK, TEXAS SSF (%) Type	LCR = 200	100	70	50	40	30	25	20
						3561 DD	65	
WWA3	17	30	40	50	57	67	73	80
WWB4	18	38	50	63	71	80	86	91
WWC2	19	37	49	61	69	79	85	91
TWA1	17	24	30	36	41	48	53	60
TWA2	16	26	34	42	48	57	63	70
TWA3	15	27	35	44	51	60	67	74
TWA4	14	26	35	45	52	61	67	75
TWB3	14	24	32	41	47	56	62	70
TWD4	17	34	45	57	65	75	80	87
TWE2	19	35	46	58	65	75	81	87
TWF3	12	23	31	40	47	56	63	70
TWJ2	18	32	43	54	62	72	78	85
DGA1	12	22	29	36	41	48	52	57
DGA2	13	23	32	41	47	56	61	67
DGA3	15	28	38	49	57	67	73	79
DGB1	12	22	30	39	46	55	60	66
DGB2	13	24	33	43	51	62	68	75
DGB3	15	28	39	51	60	72	78	84
DGC1	14	26	35	46	54	65	70	76
DGC2	15	28	38	50	59	70	76	82
DGC3	17	32	44	57	67	79	84	90
SSA1	21	33	41	50	56	65	70	77
SSB1	17	28	35	43	50	58	64	71
SSB2	21	35	45	55	63	72	77	84
SSB3	16	26	33	41	47	55	61	67
SSC1	15	27	35	45	52	61	67	74
SSC2	17	32	42	53	61	71	77	83
SSE1	20	34	43	53	60	69	74	81
SSE2	23	41	52	63	71	80	85	90
SSE3	18	28	36	44	50	58	64	70

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

SAN ANTONIO, TEXAS SSF (%) Type	LCR = 200	100	70	50	40	30	25	20
						1570 DD	65	
WWA3	23	40	50	61	69	78	83	88
WWB4	26	48	61	73	80	88	92	95
WWC2	26	47	60	72	79	87	91	95
TWA1	21	30	37	45	50	59	64	71
TWA2	21	34	42	52	59	68	74	80
TWA3	21	35	45	55	62	71	77	83
TWA4	20	35	45	55	63	72	78	84
TWB3	19	32	41	51	58	67	73	80
TWD4	24	43	55	67	75	83	88	93
TWE2	26	44	56	68	75	84	88	93
TWF3	18	31	41	51	58	68	74	80
TWJ2	22	41	53	65	73	82	87	91
DGA1	17	30	38	47	53	60	64	69
DGA2	18	32	41	51	58	67	72	78
DGA3	20	36	48	60	68	77	81	86
DGB1	17	31	41	52	59	68	73	78
DGB2	18	33	44	56	64	74	79	85
DGB3	20	37	50	63	72	81	86	91
DGC1	20	36	48	60	68	77	82	88
DGC2	21	37	49	63	71	80	85	90
DGC3	23	42	56	70	78	87	91	94
SSA1	27	41	51	61	68	76	81	87
SSB1	23	36	45	54	61	70	75	82
SSB2	27	45	55	66	73	82	86	91
SSB3	22	34	43	52	59	68	73	80
SSC1	21	35	45	56	63	72	78	84
SSC2	23	41	53	64	71	80	85	91
SSE1	27	44	54	65	72	80	85	90
SSE2	31	52	64	75	82	89	92	96
SSE3	24	37	45	55	62	70	76	82

BRYCE CANYON, UTAH SSF (%) Type	LCR = 100	70	50	40	30	25	20	15
						9136 DD	65	
WWA3	16	22	30	35	43	49	56	65
WWB4	21	31	42	49	60	67	75	84
WWC2	21	30	40	48	58	65	73	82
TWA1	16	19	22	25	30	33	38	44
TWA2	15	20	25	29	36	40	46	55
TWA3	15	20	26	31	38	43	50	59
TWA4	14	19	26	31	39	44	51	60
TWB3	13	18	24	29	35	40	47	55
TWD4	19	28	37	44	54	60	68	78
TWE2	20	28	38	45	54	60	68	78
TWF3	12	17	23	27	34	39	46	55
TWJ2	17	25	35	42	51	58	65	75
DGA1	10	14	18	21	25	28	30	34
DGA2	12	17	23	28	35	39	44	51
DGA3	16	23	31	37	46	52	60	69
DGB1	10	14	18	22	27	31	36	41
DGB2	13	18	24	29	37	42	49	58
DGB3	17	23	32	38	48	55	64	74
DGC1	13	17	23	28	35	39	46	54
DGC2	15	21	29	35	43	50	58	67
DGC3	19	27	36	43	55	62	72	81
SSA1	23	29	35	40	47	52	58	66
SSB1	18	23	29	34	40	45	51	59
SSB2	24	32	40	46	55	61	68	76
SSB3	17	22	27	32	38	42	47	55
SSC1	14	19	25	30	37	42	49	58
SSC2	18	25	33	40	49	55	62	72
SSE1	21	28	35	41	48	53	60	68
SSE2	27	36	46	53	62	68	75	83
SSE3	19	24	30	34	40	45	50	58

SALT LAKE CITY, UTAH SSF (%) Type	LCR = 100	70	50	40	30	25	20	15
						5969 DD	65	
WWA3	13	25	32	37	44	49	55	64
WWB4	23	33	43	50	60	66	73	82
WWC2	23	32	42	49	59	65	72	80
TWA1	18	21	25	28	32	35	39	45
TWA2	18	22	28	32	38	42	47	54
TWA3	17	22	29	33	40	44	50	58
TWA4	16	22	28	33	40	45	51	60
TWB3	16	21	26	31	37	42	48	55
TWD4	22	30	39	45	55	60	66	75
TWE2	23	31	39	46	55	61	66	75
TWF3	14	19	25	30	36	41	46	54
TWJ2	20	28	37	43	52	58	65	74
DGA1	12	16	20	23	27	30	33	38
DGA2	15	20	26	30	36	41	46	52
DGA3	19	26	33	39	47	53	60	68
DGB1	13	17	21	25	30	33	37	41
DGB2	15	21	27	32	39	44	50	58
DGB3	19	26	34	40	50	56	64	73
DGC1	15	20	26	31	37	41	46	52
DGC2	18	24	31	37	45	51	58	66
DGC3	22	29	38	46	56	62	70	79
SSA1	23	28	34	38	44	48	54	60
SSB1	19	24	29	33	39	43	48	55
SSB2	24	31	39	45	52	58	64	72
SSB3	18	22	27	31	36	39	44	50
SSC1	16	22	28	32	39	43	48	57
SSC2	20	27	35	41	49	55	62	70
SSE1	22	27	34	38	45	49	55	62
SSE2	27	35	44	50	58	63	70	79
SSE3	20	24	29	33	38	42	47	53

BURLINGTON, VERMONT SSF (%) Type	LCR = 100	70	50	40	30	25	20	15
						7878 DD	65	
WWA3	4	6	8	9	10	11	12	13
WWB4	6	10	16	20	26	31	36	44
WWC2	6	10	15	19	25	29	34	41
TWA1	10	11	11	11	11	11	11	10
TWA2	7	8	9	10	11	12	12	13
TWA3	6	7	8	10	11	12	13	14
TWA4	4	6	8	9	11	12	14	15
TWB3	5	7	8	10	11	12	14	16
TWD4	7	10	15	19	24	27	32	39
TWE2	7	11	15	18	23	26	31	37
TWF3	3	4	6	7	8	9	10	11
TWJ2	5	9	13	16	21	25	29	35
DGA1	2	2	2	1	1	0	−1	−5
DGA2	5	7	8	10	11	13	14	16
DGA3	8	11	15	17	22	25	29	34
DGB1	2	2	2	1	1	0	−1	−4
DGB2	5	7	9	10	12	13	15	17
DGB3	9	12	15	18	23	26	31	37
DGC1	3	4	4	4	5	4	3	2
DGC2	7	9	11	13	16	18	20	23
DGC3	10	13	18	21	26	30	35	42
SSA1	11	13	14	16	17	18	20	21
SSB1	9	10	11	13	14	15	16	17
SSB2	11	15	19	22	26	29	33	38
SSB3	8	9	10	10	11	11	12	11
SSC1	4	5	6	6	7	7	7	7
SSC2	5	8	11	14	17	19	22	27
SSE1	7	8	10	11	12	12	12	11
SSE2	9	13	17	21	25	28	32	37
SSE3	9	10	11	12	13	13	14	14

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

NORFOLK, VIRGINIA SSF (%) Type	LCR = 200	100	70	50	40	30	25	20	3493 DD65
WWA3	12	22	29	37	42	51	56	63	
WWB4	12	27	37	49	56	67	73	80	
WWC2	12	27	37	47	55	65	71	78	
TWA1	14	19	23	27	31	36	40	45	
TWA2	12	20	25	31	36	43	48	54	
TWA3	11	20	26	33	38	46	51	57	
TWA4	10	19	25	33	38	46	52	59	
TWB3	10	18	23	30	35	42	48	54	
TWD4	12	25	34	44	51	61	67	74	
TWE2	13	26	35	44	51	61	67	74	
TWF3	8	16	22	29	34	42	47	53	
TWJ2	10	23	32	41	48	58	64	72	
DGA1	8	15	19	24	28	33	36	39	
DGA2	9	17	23	29	35	42	46	52	
DGA3	11	21	28	37	44	53	59	66	
DGB1	8	15	20	25	30	36	40	45	
DGB2	9	17	23	31	36	45	50	58	
DGB3	11	21	29	38	45	56	63	71	
DGC1	10	18	24	31	36	44	49	56	
DGC2	11	20	27	36	42	52	58	66	
DGC3	13	24	33	43	51	62	70	78	
SSA1	16	25	31	38	43	50	55	62	
SSB1	13	21	26	33	38	44	49	55	
SSB2	16	27	35	44	50	59	64	71	
SSB3	13	20	25	31	35	42	46	52	
SSC1	10	19	25	32	37	45	50	57	
SSC2	11	23	31	40	46	56	62	69	
SSE1	15	25	31	39	45	53	58	64	
SSE2	16	30	40	50	57	66	72	78	
SSE3	14	22	27	33	38	44	49	55	

RICHMOND, VIRGINIA SSF (%) Type	LCR = 200	100	70	50	40	30	25	20	3941 DD65
WWA3	9	17	23	30	35	43	48	54	
WWB4	8	22	31	42	49	59	65	73	
WWC2	9	22	31	41	48	57	64	71	
TWA1	13	17	20	24	26	31	34	38	
TWA2	11	17	21	26	30	36	40	46	
TWA3	9	16	21	27	32	38	43	49	
TWA4	8	15	21	27	32	39	44	50	
TWB3	8	15	19	25	29	36	40	46	
TWD4	9	20	28	37	44	53	59	67	
TWE2	10	21	29	38	45	54	60	67	
TWF3	6	13	18	24	28	35	39	45	
TWJ2	8	19	26	35	42	51	57	64	
DGA1	6	11	15	19	22	26	28	30	
DGA2	7	14	19	24	29	35	39	44	
DGA3	9	18	24	31	37	46	52	59	
DGB1	6	11	15	20	23	28	31	35	
DGB2	8	14	19	25	30	37	42	48	
DGB3	10	18	25	33	39	48	55	63	
DGC1	8	14	19	24	29	35	39	44	
DGC2	9	17	23	30	35	43	49	56	
DGC3	11	21	28	37	44	54	61	70	
SSA1	14	21	27	33	37	43	48	53	
SSB1	12	18	23	28	32	38	42	47	
SSB2	13	23	30	38	44	52	57	64	
SSB3	11	17	21	26	29	35	39	44	
SSC1	8	15	20	26	31	37	42	48	
SSC2	9	19	26	34	40	48	54	61	
SSE1	12	20	26	33	37	44	49	55	
SSE2	13	25	34	43	49	58	64	71	
SSE3	13	19	23	28	32	37	41	46	

ROANOKE, VIRGINIA SSF (%) Type	LCR = 100	70	50	40	30	25	20	4314 DD65
WWA3	17	23	30	35	42	47	54	
WWB4	22	31	41	49	59	65	73	
WWC2	21	30	40	47	57	64	71	
TWA1	17	20	23	26	30	33	37	
TWA2	16	21	26	30	36	40	45	
TWA3	16	21	27	31	38	43	49	
TWA4	15	20	26	31	38	43	50	
TWB3	14	19	25	29	35	40	46	
TWD4	20	28	37	44	53	59	67	
TWE2	21	29	38	44	53	59	67	
TWF3	13	17	23	28	34	39	45	
TWJ2	18	26	35	41	50	57	64	
DGA1	11	14	18	21	25	27	30	
DGA2	13	18	24	28	35	39	44	
DGA3	17	23	31	37	46	52	59	
DGB1	11	15	19	22	27	30	35	
DGB2	14	19	25	30	37	42	48	
DGB3	18	24	32	38	48	54	63	
DGC1	14	18	24	28	34	38	44	
DGC2	16	22	29	35	43	49	56	
DGC3	20	28	36	43	54	61	70	
SSA1	21	27	32	37	43	48	54	
SSB1	18	22	28	32	38	42	47	
SSB2	23	30	38	44	52	57	64	
SSB3	17	21	26	29	35	39	44	
SSC1	15	20	26	30	37	41	47	
SSC2	18	25	33	39	48	53	61	
SSE1	20	26	33	37	44	49	55	
SSE2	25	34	43	49	58	64	71	
SSE3	18	23	28	32	37	41	46	

SEATTLE-TACOMA, WASHINGTON SSF (%) Type	LCR = 100	70	50	40	30	25	20	5188 DD65
WWA3	14	18	23	26	30	33	36	
WWB4	17	25	32	38	46	51	57	
WWC2	17	24	32	37	44	49	55	
TWA1	16	18	20	22	25	26	28	
TWA2	14	18	21	24	27	30	33	
TWA3	14	17	21	24	29	31	35	
TWA4	12	17	21	24	29	32	35	
TWB3	13	16	20	23	27	30	34	
TWD4	17	23	30	35	42	46	52	
TWE2	17	24	30	35	42	46	51	
TWF3	11	14	18	21	25	28	31	
TWJ2	15	21	28	33	39	44	49	
DGA1	9	12	14	16	17	18	18	
DGA2	12	16	20	23	27	30	33	
DGA3	16	21	27	31	37	41	46	
DGB1	10	12	15	17	19	20	21	
DGB2	13	16	21	24	29	32	35	
DGB3	16	22	28	33	39	44	49	
DGC1	12	15	19	21	24	26	28	
DGC2	15	19	25	28	34	37	42	
DGC3	19	24	31	36	44	49	54	
SSA1	19	23	27	30	34	36	39	
SSB1	16	20	23	26	30	32	35	
SSB2	21	26	32	36	42	46	51	
SSB3	15	18	22	24	27	29	31	
SSC1	12	16	20	22	26	28	31	
SSC2	15	20	26	30	36	40	45	
SSE1	17	21	25	28	32	34	38	
SSE2	21	27	34	38	44	48	53	
SSE3	17	20	23	26	29	31	33	

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

SPOKANE, WASHINGTON SSF (%) Type	LCR = 100	70	50	40	30	25	20	6839 DD65
WWA3	11	14	18	21	24	27	29	
WWB4	14	20	28	33	40	45	51	
WWC2	14	20	27	32	38	43	48	
TWA1	14	15	17	19	21	22	23	
TWA2	12	15	18	20	23	24	27	
TWA3	11	14	17	20	23	25	28	
TWA4	10	13	17	20	23	26	29	
TWB3	10	13	17	19	22	25	28	
TWD4	13	19	25	30	36	41	46	
TWE2	14	20	26	30	36	40	45	
TWF3	8	11	14	17	20	22	25	
TWJ2	12	17	23	28	34	38	43	
DGA1	7	9	10	11	12	12	12	
DGA2	10	13	16	19	22	25	27	
DGA3	13	18	23	27	33	36	41	
DGB1	7	9	11	12	14	14	14	
DGB2	10	13	17	20	24	26	29	
DGB3	14	18	24	28	34	39	44	
DGC1	9	12	14	16	19	20	21	
DGC2	12	16	20	24	29	32	35	
DGC3	16	21	27	32	39	43	49	
SSA1	16	19	22	25	28	30	32	
SSB1	13	16	19	21	24	26	28	
SSB2	17	22	27	31	36	40	44	
SSB3	12	15	17	19	21	22	24	
SSC1	10	12	15	18	20	22	24	
SSC2	12	17	22	25	30	34	38	
SSE1	13	17	20	22	24	26	27	
SSE2	17	22	28	32	37	41	45	
SSE3	14	16	19	21	23	25	26	

MADISON, WISCONSIN SSF (%) Type	LCR = 100	70	50	40	30	25	20	7731 DD65
WWA3	8	11	14	17	20	23	26	
WWB4	10	16	24	29	37	42	49	
WWC2	10	16	23	28	35	40	47	
TWA1	12	13	14	15	17	18	19	
TWA2	10	12	14	16	19	20	23	
TWA3	8	11	14	16	19	21	24	
TWA4	7	10	13	16	19	22	25	
TWB3	8	10	13	15	18	21	24	
TWD4	10	16	22	26	33	38	44	
TWE2	11	16	22	26	33	37	43	
TWF3	6	8	11	13	16	18	21	
TWJ2	9	14	19	24	30	35	41	
DGA1	4	5	6	7	8	8	7	
DGA2	7	10	13	15	18	20	23	
DGA3	11	15	19	23	28	32	38	
DGB1	4	5	6	7	8	8	8	
DGB2	8	10	13	15	19	21	24	
DGB3	11	15	20	24	30	34	40	
DGC1	6	8	10	11	13	14	15	
DGC2	9	12	16	19	23	26	30	
DGC3	13	17	23	27	34	39	45	
SSA1	14	16	19	22	25	27	30	
SSB1	11	13	16	18	21	22	25	
SSB2	14	19	24	28	33	37	42	
SSB3	10	12	14	16	18	19	21	
SSC1	7	9	12	13	16	18	20	
SSC2	9	13	18	21	27	30	35	
SSE1	11	13	16	18	21	23	25	
SSE2	14	19	25	29	35	39	45	
SSE3	12	14	16	17	20	21	23	

CHARLESTON, WEST VIRGINIA SSF (%) Type	LCR = 100	70	50	40	30	25	20	4594 DD65
WWA3	11	15	20	23	28	31	36	
WWB4	14	21	30	36	45	50	58	
WWC2	14	21	29	35	43	48	55	
TWA1	14	15	18	19	21	23	25	
TWA2	12	15	18	21	24	27	30	
TWA3	11	14	18	21	26	29	33	
TWA4	10	13	18	21	26	29	34	
TWB3	10	13	17	20	24	27	31	
TWD4	14	20	27	32	40	45	52	
TWE2	15	20	27	32	40	45	51	
TWF3	8	11	15	18	22	25	29	
TWJ2	12	18	25	30	37	42	49	
DGA1	7	9	11	12	14	14	15	
DGA2	10	13	16	19	24	26	30	
DGA3	13	18	23	28	34	39	45	
DGB1	7	9	11	12	14	15	17	
DGB2	10	13	17	20	25	28	32	
DGB3	13	18	24	29	36	41	47	
DGC1	9	12	15	17	20	22	24	
DGC2	12	16	21	24	30	34	39	
DGC3	15	21	28	33	40	46	53	
SSA1	17	20	24	27	32	35	39	
SSB1	14	17	20	23	27	30	33	
SSB2	18	23	29	34	40	45	51	
SSB3	13	15	19	21	24	27	30	
SSC1	10	13	16	19	23	26	30	
SSC2	12	17	23	27	34	38	44	
SSE1	14	18	22	26	30	33	37	
SSE2	18	24	31	37	44	49	55	
SSE3	14	17	20	23	26	29	32	

MILWAUKEE, WISCONSIN SSF (%) Type	LCR = 100	70	50	40	30	25	20	7445 DD65
WWA3	8	11	14	16	20	22	25	
WWB4	10	16	23	29	37	42	49	
WWC2	10	16	23	28	35	40	46	
TWA1	12	13	15	15	17	18	19	
TWA2	10	12	14	16	18	20	22	
TWA3	9	11	14	16	19	21	24	
TWA4	7	10	13	15	19	22	25	
TWB3	8	10	13	15	18	21	24	
TWD4	10	16	21	26	33	37	43	
TWE2	11	16	22	26	32	37	43	
TWF3	6	8	11	13	16	18	21	
TWJ2	9	14	19	24	30	35	40	
DGA1	4	6	6	7	8	8	7	
DGA2	7	10	13	15	18	20	23	
DGA3	11	15	19	23	28	32	37	
DGB1	4	5	6	7	8	8	8	
DGB2	8	10	13	15	19	21	24	
DGB3	11	15	20	24	30	34	40	
DGC1	6	8	10	11	13	14	15	
DGC2	9	12	16	19	23	26	30	
DGC3	13	17	23	27	34	39	45	
SSA1	14	17	20	22	25	27	30	
SSB1	11	14	16	18	21	23	25	
SSB2	15	19	24	28	34	38	43	
SSB3	10	12	14	16	18	19	21	
SSC1	7	9	12	13	16	18	20	
SSC2	9	13	18	21	26	30	35	
SSE1	11	14	16	19	21	23	26	
SSE2	14	19	25	29	35	39	45	
SSE3	12	14	16	18	20	22	24	

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

SHERIDAN, WYOMING SSF (%) Type	LCR = 100	70	50	40	30	7717 DD65 25	20	15
WWA3	12	17	22	26	31	35	40	47
WWB4	16	24	32	39	48	54	61	71
WWC2	16	23	31	38	46	52	59	68
TWA1	14	16	19	21	23	25	28	32
TWA2	13	16	20	23	27	30	34	40
TWA3	12	16	20	23	28	32	36	43
TWA4	11	15	20	23	29	33	37	44
TWB3	11	14	19	22	27	30	35	41
TWD4	15	22	29	35	43	48	55	65
TWE2	16	22	30	35	43	48	55	64
TWF3	9	13	17	20	25	28	33	39
TWJ2	13	20	27	32	40	46	53	62
DGA1	7	10	12	14	16	17	19	19
DGA2	10	14	18	21	26	29	33	38
DGA3	14	19	25	30	37	42	48	56
DGB1	7	10	13	15	17	19	21	23
DGB2	10	14	19	22	27	31	36	42
DGB3	14	19	26	31	38	44	51	60
DGC1	10	13	17	19	23	26	29	33
DGC2	13	17	23	27	33	37	43	51
DGC3	16	22	30	35	43	49	57	67
SSA1	17	21	25	28	33	36	40	46
SSB1	14	17	21	24	28	31	35	40
SSB2	18	24	30	35	42	46	52	60
SSB3	13	16	19	22	25	28	31	35
SSC1	11	14	18	22	26	30	34	40
SSC2	13	19	25	30	37	42	48	56
SSE1	15	19	24	27	32	35	39	44
SSE2	19	25	33	38	46	50	57	65
SSE3	15	18	21	24	28	30	34	38

SUFFIELD, ALBERTA Type	LCR = 100	70	50	40	30	9423 DD65 25	20	15
WWA3	11	15	19	23	27	30	34	39
WWB4	14	21	29	35	44	49	56	65
WWC2	14	21	28	34	42	47	53	62
TWA1	14	15	17	19	21	23	25	28
TWA2	12	15	18	21	24	27	30	34
TWA3	11	14	18	21	25	28	32	37
TWA4	10	13	18	21	25	29	33	38
TWB3	10	13	17	20	24	27	31	36
TWD4	14	20	27	32	39	44	50	59
TWE2	14	20	27	32	39	44	50	58
TWF3	8	11	15	18	22	25	28	33
TWJ2	12	18	24	29	37	41	46	56
DGA1	7	9	11	12	13	14	15	14
DGA2	10	13	17	19	24	26	30	34
DGA3	13	18	23	28	34	38	44	51
DGB1	7	9	11	13	15	16	17	18
DGB2	10	13	17	20	25	28	32	37
DGB3	13	18	24	29	36	41	47	55
DGC1	9	12	15	17	20	22	24	26
DGC2	12	16	21	25	30	34	39	45
DGC3	15	21	28	33	40	46	52	61
SSA1	15	18	22	24	28	30	33	37
SSB1	12	15	18	21	24	26	29	32
SSB2	16	21	27	31	37	41	46	53
SSB3	11	14	16	18	21	22	24	27
SSC1	10	13	16	19	23	25	28	33
SSC2	12	17	23	27	33	37	43	50
SSE1	13	16	19	22	25	27	30	33
SSE2	16	22	28	32	39	43	48	55
SSE3	13	16	18	20	23	25	27	30

Canada

EDMONTON, ALBERTA SSF (%) Type	LCR = 100	70	50	40	30	10671 DD65 25	20	15
WWA3	9	12	16	18	21	23	26	28
WWB4	11	18	25	30	37	42	48	56
WWC2	12	17	24	29	36	40	46	53
TWA1	12	14	15	17	18	19	20	22
TWA2	10	13	15	17	20	22	24	26
TWA3	9	12	15	17	20	23	25	28
TWA4	8	11	14	17	21	23	26	29
TWB3	8	11	14	17	20	22	25	28
TWD4	11	17	23	27	34	38	43	50
TWE2	12	17	23	27	33	37	42	49
TWF3	6	9	12	14	17	19	22	25
TWJ2	10	15	21	25	31	35	41	47
DGA1	5	7	8	9	9	9	9	7
DGA2	8	11	14	17	20	22	25	28
DGA3	12	16	21	25	30	34	39	45
DGB1	5	7	8	9	10	11	11	10
DGB2	8	11	15	17	21	24	27	30
DGB3	12	16	22	26	32	36	41	48
DGC1	7	9	12	13	15	17	18	18
DGC2	10	14	18	21	26	29	33	37
DGC3	14	19	25	29	36	41	46	53
SSA1	13	16	19	21	23	25	27	28
SSB1	11	13	16	17	20	21	23	25
SSB2	14	19	23	27	32	35	40	45
SSB3	10	12	14	15	17	18	18	19
SSC1	8	10	13	15	17	19	21	22
SSC2	10	14	19	23	28	31	35	40
SSE1	10	13	15	17	19	20	21	21
SSE2	13	18	23	27	32	36	40	45
SSE3	11	13	16	17	19	20	21	22

VANCOUVER, BRITISH COLUMBIA SSF (%) Type	LCR = 100	70	50	40	30	5607 DD65 25	20	15
WWA3	15	19	24	27	31	34	37	41
WWB4	18	25	33	39	46	51	57	65
WWC2	18	25	32	38	45	49	55	62
TWA1	16	18	21	23	25	27	29	32
TWA2	15	18	22	25	28	31	34	37
TWA3	14	18	22	25	29	32	35	40
TWA4	13	17	22	25	30	33	36	41
TWB3	13	17	21	24	28	31	35	39
TWD4	17	24	31	36	43	47	53	60
TWE2	18	24	31	36	42	47	52	59
TWF3	11	15	19	22	26	29	32	37
TWJ2	16	22	29	33	40	45	50	57
DGA1	10	12	15	17	18	19	20	19
DGA2	12	16	21	24	28	31	34	37
DGA3	16	22	28	32	38	42	47	53
DGB1	10	13	16	18	20	21	22	23
DGB2	13	17	22	25	30	33	36	41
DGB3	17	22	29	33	40	45	50	57
DGC1	13	16	20	22	26	27	29	31
DGC2	15	20	25	29	35	38	42	48
DGC3	19	25	32	37	45	49	55	62
SSA1	20	23	27	30	34	36	39	42
SSB1	16	20	24	26	30	32	35	38
SSB2	21	26	32	36	42	46	51	57
SSB3	15	19	22	24	27	29	31	34
SSC1	13	17	21	23	27	29	32	35
SSC2	16	21	27	31	37	41	45	51
SSE1	18	22	26	28	32	34	36	38
SSE2	21	28	34	38	44	48	52	58
SSE3	17	20	24	26	29	31	33	36

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

WINNIPEG, MANITOBA SSF (%) Type	LCR = 100	70	50	40	30	10776 DD65 25	20	15
WWA3	8	10	13	16	19	21	24	28
WWB4	10	16	23	28	36	41	46	57
WWC2	10	16	22	27	34	39	45	54
TWA1	12	13	14	15	16	17	18	19
TWA2	10	11	14	15	18	20	22	25
TWA3	8	10	13	15	18	20	23	27
TWA4	7	9	13	15	18	21	24	28
TWB3	8	10	13	15	18	20	23	27
TWD4	10	15	21	25	32	37	43	51
TWE2	11	16	21	25	32	36	42	49
TWF3	5	8	10	12	15	17	20	24
TWJ2	8	13	19	23	29	34	40	47
DGA1	4	5	6	7	7	7	6	5
DGA2	7	9	12	14	18	20	22	26
DGA3	10	14	19	22	28	32	37	44
DGB1	4	5	6	7	7	8	8	7
DGB2	7	10	13	15	18	21	24	28
DGB3	11	15	19	23	29	34	39	47
DGC1	6	7	9	10	12	13	14	15
DGC2	9	12	16	19	23	26	30	35
DGC3	12	17	22	27	34	38	45	53
SSA1	12	15	17	19	22	23	26	28
SSB1	10	12	14	16	18	20	22	24
SSB2	13	17	22	25	31	34	39	46
SSB3	9	10	12	13	15	16	17	18
SSC1	6	9	11	13	15	17	19	21
SSC2	9	12	17	20	26	29	34	40
SSE1	9	11	14	15	18	19	21	22
SSE2	12	17	22	26	31	35	40	46
SSE3	11	12	14	15	17	18	20	21

OTTAWA, ONTARIO SSF (%) Type	LCR = 100	70	50	40	30	8461 DD65 25	20	15
WWA3	8	11	14	17	20	23	26	31
WWB4	10	16	24	29	37	43	50	59
WWC2	10	16	23	28	36	41	47	56
TWA1	12	13	14	15	17	18	19	21
TWA2	10	12	14	16	19	20	23	26
TWA3	8	11	14	16	19	22	25	29
TWA4	7	10	13	16	19	22	26	31
TWB3	8	10	13	15	19	21	24	29
TWD4	10	15	22	28	33	38	44	53
TWE2	11	18	22	26	33	38	44	52
TWF3	6	8	11	13	16	18	21	26
TWJ2	9	14	19	24	31	35	41	50
DGA1	4	5	6	7	8	8	7	6
DGA2	7	10	13	15	18	20	23	27
DGA3	11	14	19	23	28	33	38	46
DGB1	4	5	6	7	8	8	9	8
DGB2	7	10	13	15	19	21	25	29
DGB3	11	15	20	24	30	34	40	49
DGC1	6	7	9	11	13	14	15	17
DGC2	9	12	16	19	24	27	31	37
DGC3	13	17	23	27	34	39	46	55
SSA1	13	16	19	21	24	26	29	33
SSB1	11	13	15	17	20	22	24	28
SSB2	14	18	23	27	33	37	42	49
SSB3	10	11	13	15	17	18	20	22
SSC1	7	9	11	13	16	18	21	24
SSC2	9	13	18	21	27	31	36	43
SSE1	10	13	16	18	21	23	25	28
SSE2	13	18	24	28	35	39	44	52
SSE3	11	13	15	17	19	21	23	25

HALIFAX, NOVA SCOTIA SSF (%) Type	LCR = 100	70	50	40	30	7167 DD65 25	20	15
WWA3	10	13	17	20	25	28	32	38
WWB4	12	19	27	33	42	47	55	64
WWC2	12	19	26	32	40	45	52	61
TWA1	13	14	16	17	19	21	23	25
TWA2	11	13	16	19	22	24	27	32
TWA3	10	13	16	19	23	26	29	35
TWA4	8	12	16	19	23	26	30	36
TWB3	9	12	15	18	22	24	28	34
TWD4	12	18	24	30	37	42	49	58
TWE2	13	18	25	30	37	42	48	57
TWF3	7	10	13	16	19	22	26	31
TWJ2	10	16	22	27	34	39	46	55
DGA1	6	7	9	10	11	11	12	11
DGA2	8	11	15	17	21	24	27	31
DGA3	12	16	21	25	32	36	42	50
DGB1	5	7	9	10	11	12	13	14
DGB2	9	12	15	18	22	25	29	34
DGB3	12	17	22	26	33	38	45	54
DGC1	7	10	12	14	16	18	20	23
DGC2	10	14	18	22	27	31	36	43
DGC3	14	19	25	30	38	43	51	60
SSA1	15	19	22	25	29	32	36	41
SSB1	13	15	19	21	25	27	30	35
SSB2	16	21	27	31	38	42	48	56
SSB3	11	14	17	19	22	24	26	30
SSC1	8	11	14	17	20	23	26	30
SSC2	11	15	21	25	31	35	41	48
SSE1	13	16	20	23	27	29	33	37
SSE2	16	22	29	34	41	46	52	59
SSE3	13	16	19	21	24	26	29	33

TORONTO, ONTARIO SSF (%) Type	LCR = 100	70	50	40	30	7280 DD65 25	20	15
WWA3	8	11	14	17	21	23	27	31
WWB4	10	17	24	30	38	43	50	59
WWC2	11	16	23	28	36	41	47	56
TWA1	12	13	15	16	17	18	19	21
TWA2	10	12	14	16	19	21	23	27
TWA3	9	11	14	16	20	22	25	29
TWA4	7	10	13	16	20	22	26	31
TWB3	8	10	13	16	19	21	24	29
TWD4	11	16	22	27	33	38	44	53
TWE2	11	16	22	27	33	38	44	52
TWF3	6	8	11	13	16	19	22	26
TWJ2	9	14	20	24	31	35	41	50
DGA1	5	6	7	7	8	8	8	7
DGA2	8	10	13	15	18	21	23	27
DGA3	11	15	19	23	29	33	38	46
DGB1	4	5	7	7	8	9	9	9
DGB2	8	10	13	16	19	22	25	29
DGB3	11	15	20	24	30	35	41	49
DGC1	6	8	10	11	13	14	16	17
DGC2	9	12	16	19	24	27	31	37
DGC3	13	17	23	28	34	39	46	55
SSA1	14	17	20	22	25	28	31	35
SSB1	11	14	16	18	21	23	26	29
SSB2	15	19	24	28	34	38	43	51
SSB3	10	12	14	16	18	20	22	24
SSC1	7	9	12	14	17	18	21	24
SSC2	9	13	18	22	27	31	36	43
SSE1	11	14	17	19	22	24	27	30
SSE2	14	19	25	30	36	40	46	53
SSE3	12	14	16	18	20	22	24	27

APPENDICES

TABLE C.3 **Annual Passive Heating Performance: SSF (Continued)**

NORMANDIN, QUEBEC Type	LCR = 100	SSF (%) 70	50	40	30	11364 DD65 25	20	15
WWA3	6	9	11	14	17	19	21	25
WWB4	8	14	21	26	33	39	45	54
WWC2	8	14	20	25	32	36	43	51
TWA1	11	12	13	13	14	15	16	17
TWA2	8	10	12	13	16	17	19	22
TWA3	7	9	11	13	16	18	20	24
TWA4	5	8	11	13	16	18	21	25
TWB3	6	8	11	13	16	18	20	24
TWD4	8	13	19	23	30	34	40	48
TWE2	9	14	19	23	29	34	39	47
TWF3	4	6	8	10	13	15	17	20
TWJ2	7	11	17	21	27	31	37	45
DGA1	3	3	4	5	5	4	4	2
DGA2	6	8	10	13	15	17	20	23
DGA3	9	13	17	20	26	30	35	42
DGB1	3	3	4	4	5	5	5	4
DGB2	6	8	11	13	16	18	21	25
DGB3	10	13	18	21	27	31	37	45
DGC1	4	6	7	8	9	10	11	12
DGC2	8	10	14	16	20	23	27	33
DGC3	11	15	20	25	31	36	42	51
SSA1	12	14	16	18	21	23	25	27
SSB1	9	11	13	15	17	19	20	23
SSB2	12	16	21	24	30	33	38	44
SSB3	8	10	11	12	14	15	16	17
SSC1	5	7	9	11	13	14	16	18
SSC2	7	11	15	18	23	27	31	37
SSE1	8	10	13	14	16	18	19	20
SSE2	11	16	21	25	30	34	39	45
SSE3	10	11	13	14	16	17	19	20

D
SUNSHADING

D.1 Introduction

This appendix presents a graphic-analytic method for the design of fixed sunshading devices. Although it is assumed that the reader is to an extent familiar with the principles of sunshading and shading mask construction, a brief review of these topics is presented, to develop the necessary background for the design methods that will be demonstrated. It is further assumed that the reader recognizes the importance of sunshading and the importance of the effect of insolation on thermal gain (and loss), daylighting, glare, and so on. A full discussion of these topics is found in Chapters 1 and 6 of this volume.

The shadow cast by a projection from a wall depends on:

1. The shape and dimensions of the projection.
2. The direction in which the wall faces.
3. The position of the sun.

The first two factors are fixed; the third varies with the hour of the day and the date, that is, with the apparent motion of the sun.

D.2 Solar Position: Altitude and Azimuth

Refer to Fig. 19.4*a* and Tables B.11 to B.14. The position of the sun at any instant with respect to an observer on the ground is defined by its *altitude angle A* and its *azimuth angle Az*. Note that in our discussion *azimuth is measured from south*. (In other texts it is measured from north; there is no consensus on this point.) The altitude of the sun varies during the day, starting and ending at 0° at sunrise and sunset, and reaching a daily maximum at *solar* noon. (See Section D.3 for explanation of solar and clock time.) The altitude angle at noon varies from day to day, reaching a yearly maximum at the summer solstice on June 21, a minimum at the winter solstice on December 21 and a point halfway between on the vernal and autumnal equinoxes of March 21 and September 21. These seasonal changes are shown graphically on Fig. 19.4*b* and Fig. D.1. Note that the altitude change is ap-

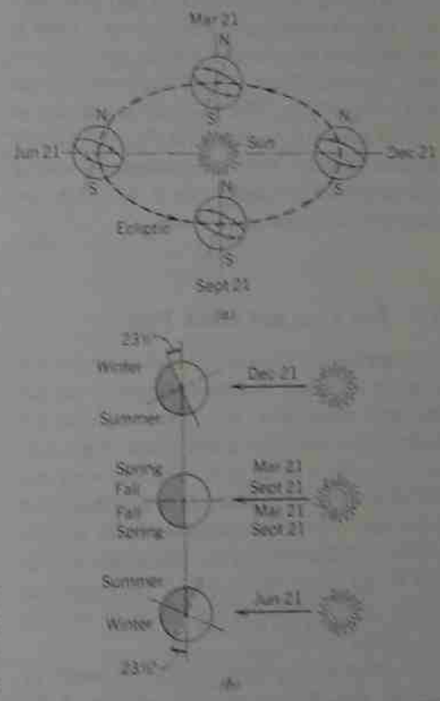


Fig. D.1 *The ecliptic is the annual path of the earth around the sun. The tilt of the earth's axis to the plane of the ecliptic results in the seasonal variations. Note in* (a) *and* (b) *that the northern hemisphere tilts away from the sun in December, resulting in winter's low sun altitude and cold weather. In June the effect is reversed.*

proximately 23½° every three months, making the daily change approximately a quarter-degree and the maximum difference in altitude angle about 47°, between the summer and winter solstices. See Tables 19.2 and B.11 to B.14 for accurate altitude/azimuth figures.

Referring to the ecliptic (Fig. D.1*a*), we can see that the height of the sun (its altitude angle), depends on the observer's position on the earth, specifically, his latitude. This can be expressed as follows:

maximum solar altitude = 113.5° − latitude

equinox solar altitude = 90° − latitude

minimum solar altitude = 66.5° − latitude

These relations are shown graphically in Fig. 19.4*c*.

On the equinoxes (March 21 and September 21), the sun rises due east and sets due west. In the northern hemisphere, the sun rises north of east between March 22 and September 20 and sets north of west. This is shown graphically on Fig. 19.4*b* and is projected, in Fig. D.2, for one specific latitude. Note the positions of sunrise and sunset with respect to the E–W line, to understand the explanation above.

D.3 Sun Time and Clock Time

Although for the purpose of sunshading it is not normally important to differentiate between sun time and clock time, it is important that the reader know that such a difference exists, and can be as much as an hour. The following is a brief discussion of timekeeping. The interested reader can refer to the References for a more detailed explanation. (In our discussion we will refer to the sun's motion rather than apparent motion, since relative to the observer, the sun does indeed move.)

The basis of all timekeeping is the length of the solar day, that is, one full rotation of the earth on its axis. More rigidly defined, it is the interval between two sun passages across the observer's meridian. However, because the sun moves about 1° per day on the ecliptic (360° in 365 days), it must move approximately 361° in a solar day. Furthermore, the sun's motion on the ecliptic is not uniform—it moves more rapidly when further from the earth. As a result, the actual length of the solar day varies. Since it is impractical for us to use timepieces that need daily adjustment, we use an average, or *mean solar day*, as the basis for timekeeping. The difference between mean (clock) and apparent (actual) solar time is called the equation of time and can be determined from a curve called the *analemma* or from tabulations in various sources. Furthermore, the 360° earth circumference is divided into 24 one-hour time zones, each therefore separated from the adjacent zone by 15° of longitude, which corresponds to approximately 1000 miles. Therefore an observer at any point other than directly on a time meridian (which is normally in the center of the time zone) must make a time correction of up to 30 min to correspond to actual solar time. (In some countries a reference meridian is more than 30 min from the time zone extremes. In such places, the longitude correction plus the equation of time correction can total well over an hour, and one is no

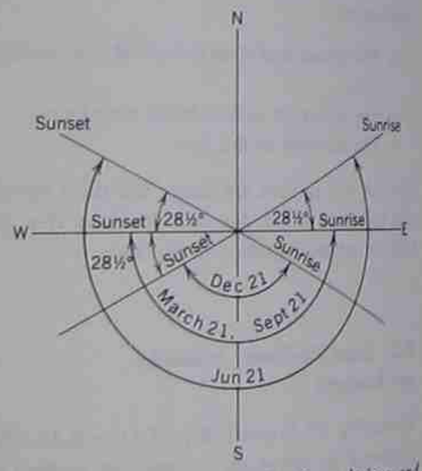
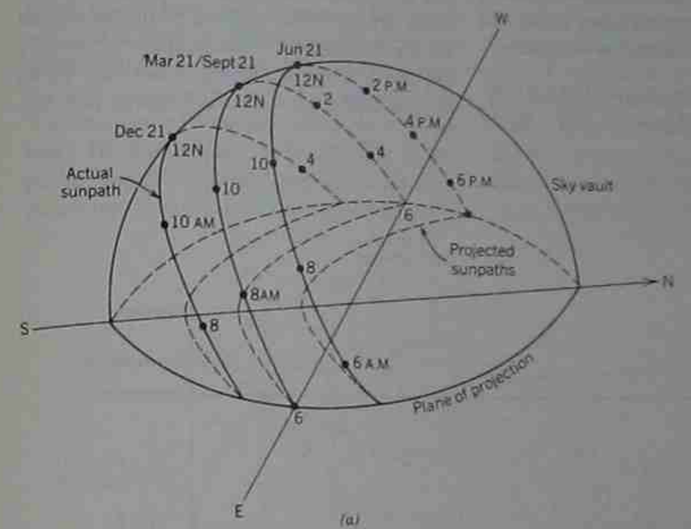


Fig. D.2 *Projected sunpaths for solstices and equinoxes at latitude 32° N (Jerusalem, Savannah, Tucson). The sun's azimuth angle, like its altitude, varies with time of day and date. The sun's azimuth path from sunrise to sunset, for this latitude is shown in horizontal projection. Sunrise on June 21 is 28½° North of East, and sunset is correspondingly North of West. On December 21 sunrise and sunset are 28½° South of East and West.*

longer able to neglect it. This situation does *not* exist in the continental United States.) Although not vital, because the length of shaded time is the same, it is good practice to make a table of mean time versus apparent solar time for any project where shading and insolation are important. In any case, the designer must remember that unless otherwise specifically noted (and this is rare), all sun charts show sun time, that is, actual solar time. This includes the well-known Libbey-Owens-Ford (LOF) *Sun Angle Calculator* (1975).

D.4 Sunpath Projection

The design of sunshading devices necessitates projecting the three-dimensional solar path onto a two-dimensional surface. There are basically two types of projection: vertical and horizontal. A version of the former is familiar to users of Waldram diagrams in daylight design. Horizontal projections are more common. The basic idea behind the horizontal projection is shown in Fig. D.3. The sky vault is represented as a hemisphere that projects as a circle, the center of



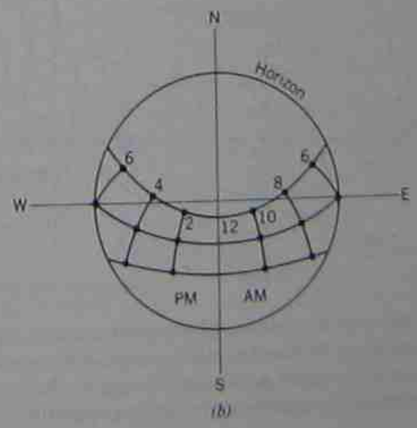


Fig. D.3 *Basis of horizontal projection of the sunpaths. The sky vault* (a) *is represented as a hemisphere, which projects as a circle* (b) *on the projection plane. The sunpaths in* (a) *project as curved lines on the projection plane* (b), *the exact shape of which depends on the projection method (Fig. D.4). The numbers on the sunpaths in* (a) *are hours: 6 A.M., 8 A.M., 10 A.M., 12 noon, 2 P.M., 4 P.M., 6 P.M. When hour points are connected between sunpaths* (b), *they form hour lines, which are useful for interpolation in completed diagrams.*

APPENDICES

which is the zenith. The observer looks down onto the hemispherical sky vault and projects the sunpaths onto the two-dimensional, projected circle. The four methods of projection are:

Gnomonic.

Orthographic.

Stereographic.

Equidistant.

The position of the observer's eye for each of these projections is shown in Fig. D.4. Spacing between circles of equal altitude is the basic difference between the four methods. In all of them, lines of equal azimuth project as straight lines emanating from the center of the circle.

1. The *gnomonic projection* is derived from the sundial. The observer is at the center of the projection; therefore low sun angles (sunrise, sunset) extend to infinity. For this reason, the method is rarely used for solar charts but is used frequently for buildings shadow studies. The method is illustrated in the sun peg shadow charts of Fig. 3.12.

2. The *orthographic projection* views the sky vault from infinity and projects as in a standard architectural plan, that is, with all projection lines parallel.

3. The *stereographic projection* is used widely throughout the world, except in the United States. The observer is fixed at the top of the hemisphere, resulting in wide-spaced, low-angle altitudes. This makes it particularly useful for northern latitudes, that is, above 40°N, since the sun at these latitudes is usually low in the sky. A special protractor is required (see Section D.5).

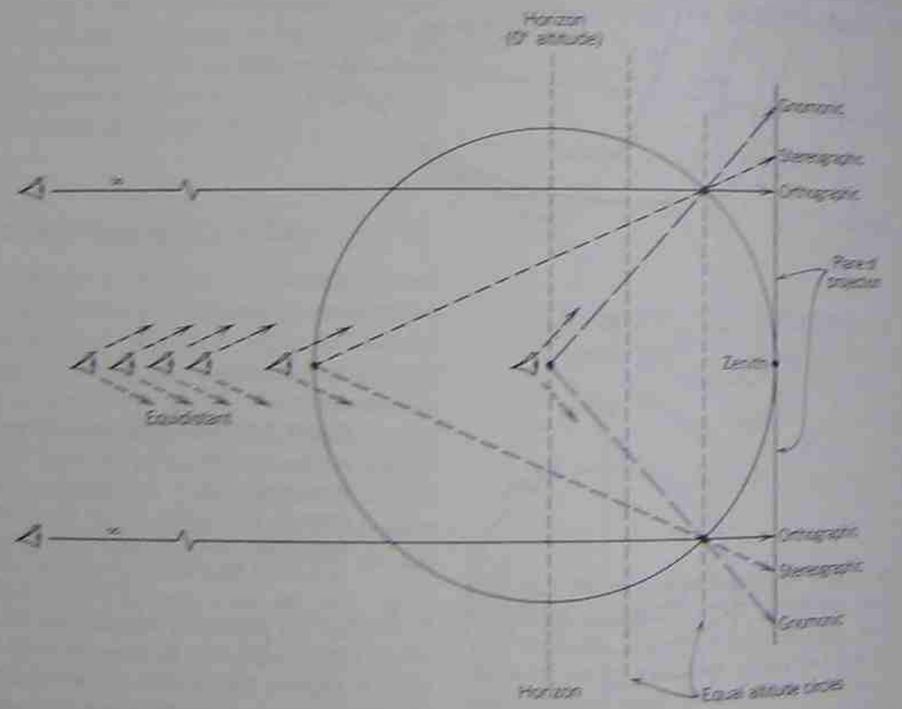


Fig. D.4 *The four standard horizontal projection methods, with observer position and projected point. Note that in the equidistant projection the observer position varies and therefore the projected point also varies. The projected point is therefore not shown. Note also that as the altitude drops and approaches the horizon, the gnomonic projection extends out to infinity.*

tion D.5). The principal advantage of this projection is that it is very simple to draw sunpaths at any scale and for any latitude without having to rely on published sunpaths. Thus for any serious sunshading design, the designer can prepare a large-scale sunpath chart at the exact latitude of the project and do accurate graphical analysis. For a detailed description of the method of preparing the charts and protractor, see Szokolay (1980, pp. 314–317).

4. The *equidistant projection* is used almost exclusively in the United States because of the ready availability and wide acceptance of the LOF sunpath charts (*Sun Angle Calculator*, 1975). These charts, one of which is illustrated in Fig. D.5, show the altitude circles as spaced equidistantly, a projection that requires moving the observer during projection, as shown in Fig. D.4. This method is equally applicable to all latitudes. Its disadvantage is the difficulty of preparing sunpaths and the required shadow angle protractor. Thus the user is essentially limited to published material, with its limitations of size and latitude. The LOF diagrams are available only in steps of 4° of latitude.

D.5 Shadow Angles and Shading Masks

The sun's altitude and azimuth angles are very useful in developing the sunpath diagrams but are much less so in defining the shadow angles cast by a projection, on a wall exposed to the sun. Since there is no universal agreement on angle nomenclature, we will very carefully define the angles involved. Refer to Fig. D.6, which shows the shadow cast by a horizontal overhang on a wall exposed to sunlight. Note that the shadow is defined by two angles: the *vertical shadow angle (VSA)*, which indicates the position of the leading edge of the shadow as defined from the leading edge of the overhang, and the *horizontal shadow angle (HSA)*, which defines the leading edge of a shadow cast by a vertical element (above here, and indicated by a

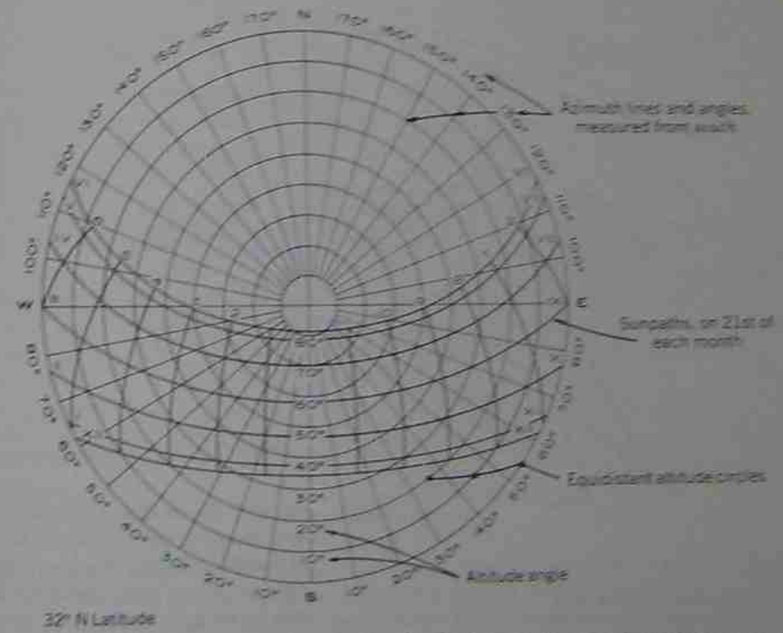


Fig. D.5 *Typical equidistant sunpath projection for 32°N latitude. This latitude is approximately that of Savannah, Georgia, Tucson, Arizona, San Diego, California, and Jerusalem, Israel. In all of these locations sun shading is desirable at least from the vernal to the autumnal equinox. [Diagram after Libbey-Owens-Ford, Sun Angle Calculator, (1975).]*

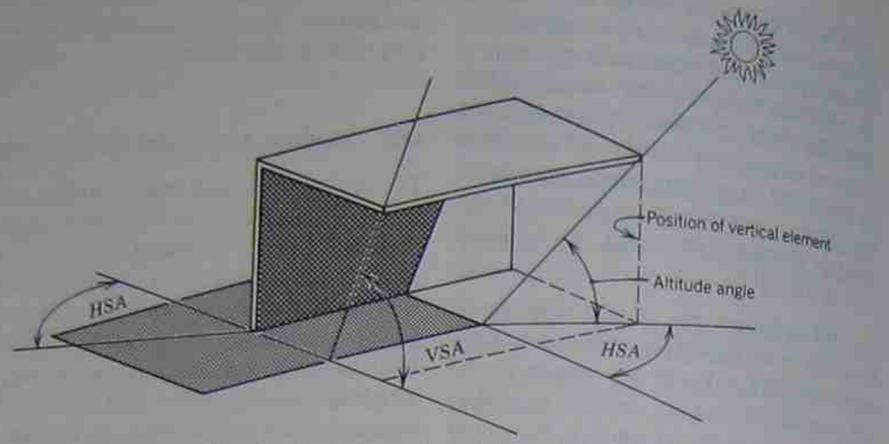
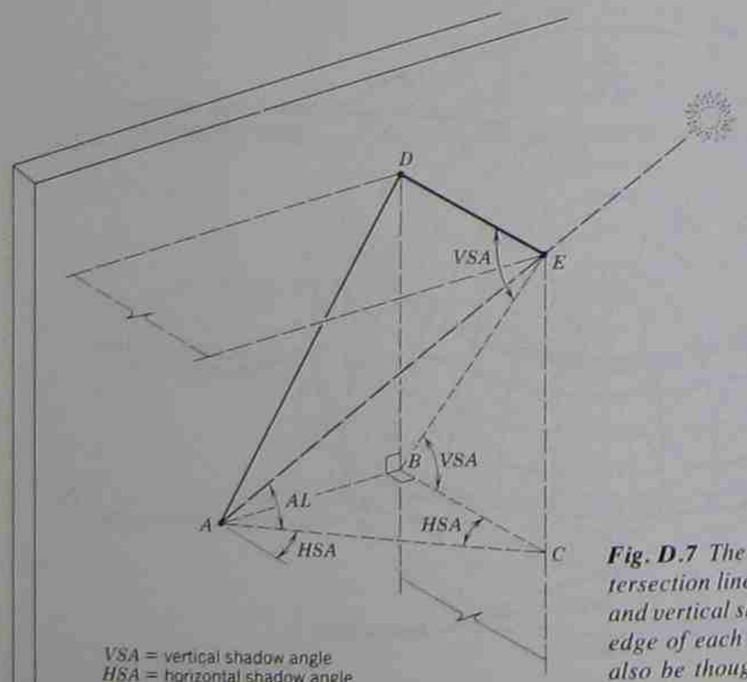


Fig. D.6 *The shadow cast by a horizontal overhang is best defined by angles* VSA *and* HSA, *the vertical shading angle and horizontal shading angles, respectively. VSA is also known in the United States as the profile angle.*

dotted line), as defined with respect to that element's leading edge. The terms VSA and HSA are in use throughout the world, although in the United States, the vertical shadow angle is also known widely as the *profile angle* because it is so designated on the LOF sun angle calculator. Figure D.7 shows the same information in slightly different form; line *DA* is the shadow

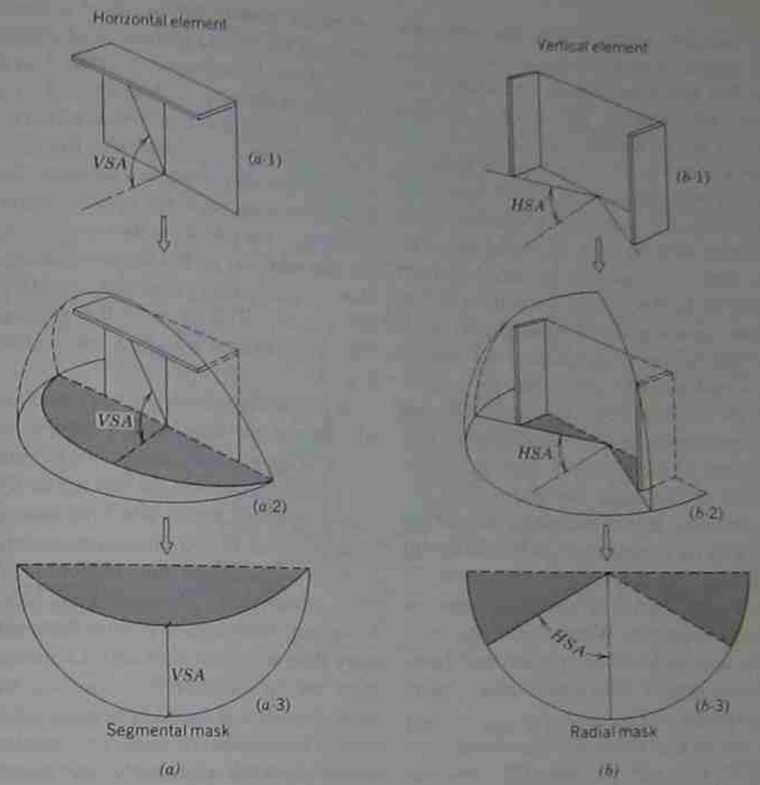


VSA = vertical shadow angle
HSA = horizontal shadow angle
AL = altitude angle
DA = shadow of line *DE*

$$\tan HSA = \frac{AB}{BC} = \frac{AB}{DE}$$

$$\tan VSA = \frac{DB}{DE} = \frac{\tan AL}{\cos HSA}$$

Fig. D.7 *The shadow* DA *cast by the intersection line* DE, *between a horizontal and vertical shading element, defines the edge of each of these shadows. DE can also be thought of as a pin, normal to, and extending from the wall, casting a shadow* DA *on the wall. The location and size of line* DA *are best defined in terms of angles* VSA *and* HSA.



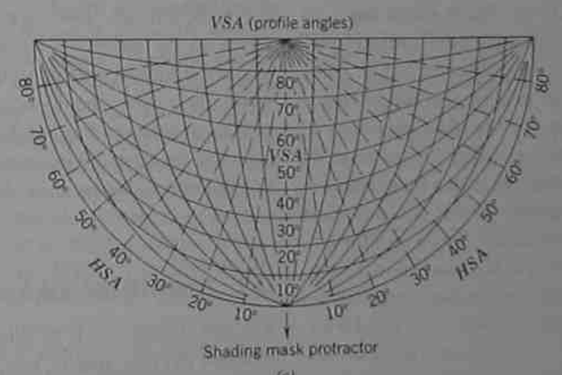


Fig. D.8 *A shading mask is the horizontal projection of the shadow cast by elements with the same* VSA *or* HSA. *Thus any* infinitely long *horizontal element with the* VSA *shown in* (a-1) *will have a shading mask as shown in* (a-3). *Similarly, any* infinitely high *vertical elements with the* HSA *shown in* (b-1) *still have the shadow mask shown in* (b-3). *A protractor of the type shown in* (c) *is required to draw the segmental horizontal element mask properly. This device must be drawn to the same scale and with the same projection method (equidistant, stereographic) as the sunpath diagram on which it will be used. The protractor of* (c) *matches the sunpath diagram of Fig. D.5 and is drawn with equidistant projection.*

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cast by line *DE*, which is the intersection between a horizontal projection and a vertical projection. This line is particularly important in determining the required extent of a shading element, as will be shown below.

Refer now to Fig. D.8. The locus of the leading edge of the shadow cast by all horizontal elements with the same VSA (profile angle) (Fig. D.8*a*-1) projects as a segmental line (Fig. D.8*a*-2), and when plotted on the projection plane (similar to the sunpath projection in Fig. D.3), shows as a segmental mask (Fig. D.8*a*-3). To draw this segment, a protractor is required, as shown in Fig. D.8*c*. Note that the angular notation on the segmental section of the protractor corresponds to VSA as shown on Fig. D.8*a*-3. Users of the LOF sun angle calculator can use the profile angle overlay to draw the required segment. It is important not to confuse the VSA with its complement. A simple way to remember this is to consider the limits of VSA. With no shading, VSA is 90° and the segment on Fig. D.8*a*-3 disappears. With a very deep overhang, VSA approaches 0° and the *unshaded* area in Fig. D.8*a*-3 shrinks. This action shows clearly on the protractor of Fig. D.8*c*.

Refer now to Fig. D.8*b*. Vertical shading elements Fig. D.8*b*-1 with the same HSA show as radii (*b*-2) and project as radial lines from the center, on the radial mask, at angle HSA from normal to the wall (*b*-3). These radial lines can be drawn with the assistance of an ordinary protractor, or by use of the protractor in Fig. D.8*c*. The reader must bear in mind that full segments and full radial lines are the shading masks of *infinitely long elements*, which, of course, do not actually exist. Shading masks that appear in the literature (Olgyay, 1975; Ramsey and Sleeper, 1981) are frequently drawn as if for infinite elements, and the reader must know how to truncate them if accurate shading design is desired.

D.6 Use of Shading Masks

Once a shading mask has been drawn, it is applicable to any latitude and exposure direction. The use of the mask is straightforward. It is drawn on some transparent medium (e.g., paper or plastic sheet), laid on top of a sunpath diagram of the proper latitude, *and drawn to the same scale*. Its centerpoint is placed on the centerpoint of the sunpath diagram, and it is rotated until its facing direction (the direction of a normal to the wall) is aligned with the appropriate azimuth line on the sunpath diagram. Assuming that the shading mask has been correctly drawn to provide 100% shading for the *entire window*, the shaded hours for the window in question can then be read directly from the sunpath diagram underneath. (This is why the shading mask must be drawn on a transparent medium.) See Fig. D.9.

It is extremely important to keep in mind that a horizontal overhang shading element the same width as the window can provide full shade for the window only when the sun is exactly opposite the window, that is, when the bearing angle is 0°. (See Fig. 19.9*a*.) This situation obtains for only an instant. See Fig. D.10. At all other times, some part of the window will be exposed to the sun. Therefore, to provide full shading for more than an instant with only a horizontal element and no vertical (side) elements, *the overhand must extend beyond the sides of the window*. The amount of such extension can be determined both graphically and analytically. Since graphic solutions are amply treated in the literature (Harkness and Mehta, 1978; Lim et al., 1979; Cowan, 1980) we will restrict ourselves to the analytic solution, leaving to the reader the parallel graphic solution. In doing this work, the reader should keep in mind the requirement that shading masks for 100% coverage must be prepared in order that the extremities of the opening be shaded.

D.7 Finite Horizontal Elements

The first design step is to establish the required *depth* of the unit, that is, the amount it projects from the wall. Although any percent coverage desired is possible, most elements are designed to give either 50 or 100% coverage. The reason for this is explained in the illustrative design example below. Figure D.11 shows how the required depth and the corresponding segmental mask are determined. The next step is to determine the required side extensions beyond the window's sides. This can best be illustrated by a practical example, using the analytic technique.

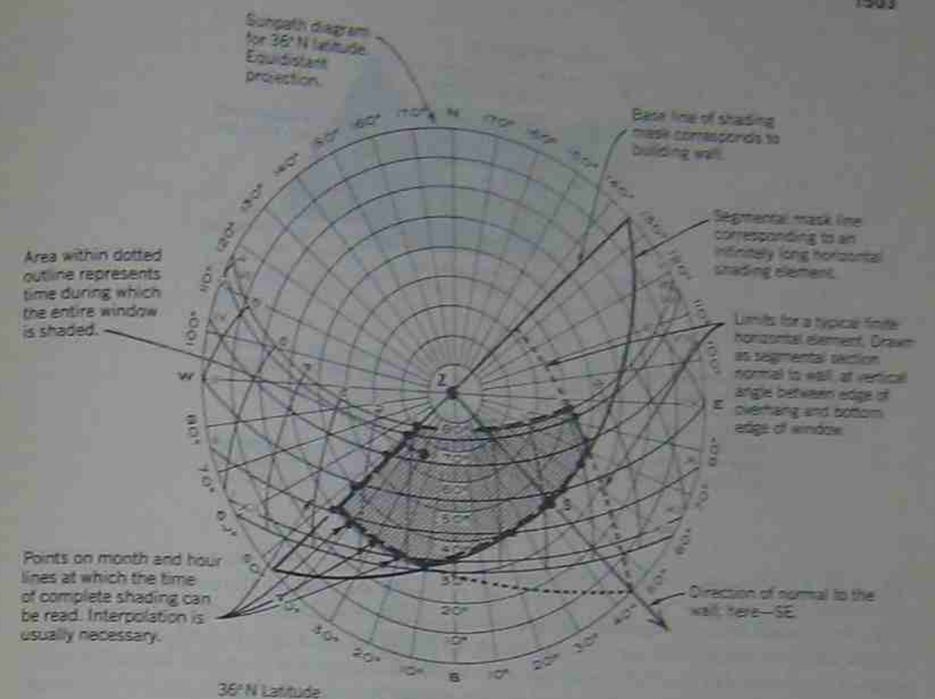

Fig. D.9 *A typical shading mask for a horizontal overhang on a window is laid over a sunpath diagram, to permit determination of the shaded hours. The mask is drawn to provide full shading for the entire window. The hours during which the entire window is shaded are determined by the intersection of the mask perimeter with the date/hour lines of the sunpath diagram, and are tabulated on the figure. However, only at the hours falling along the normal-to-the-wall line ZS (where the bearing angle is 0°) and within the dotted area is a window fully shaded by an overhang element only as wide of as the window. Indeed, line ZS is the shading mask of such an element with respect to 100% shading of the entire window (see Fig. D.10). Note that the element shown here is not symmetrical about the center, indicating an extension to the left to provide a larger shade period after noon. This is typical with east-facing windows, and is reversed for western exposures.*

Time of Day When Window is Fully Shaded

With Required Overhang Extensions			With Element Same Width as Window
Date	From	To	Time
21 June	0900	1240	1115
21 July/May	0850	1250	1100
21 Aug./Apr.	0845	1330	1035
21 Sept./Mar.	0940	1400	0955
21 Oct./Feb.	1040	1410	—
21 Nov./Jan.	12N	1300	—
21 Dec.	1230		—

First however, a few remarks about the example presented are in order.

Due to the symmetry of solar motion about the ecliptic, the position of the sun is symmetrical on both sides of its maximum/minimum positions, that is, the solstices. Thus the sun's position on May 21 is the same as on July 21, since both dates are one month from the summer solstice. As a result, any *fixed* shading device will

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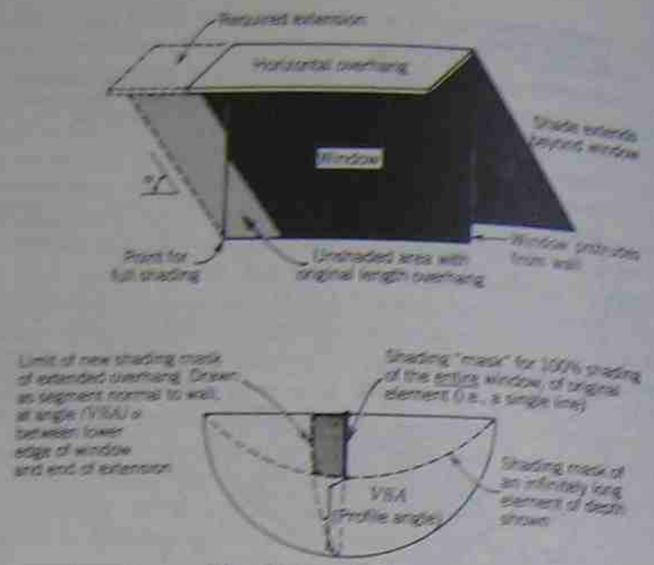
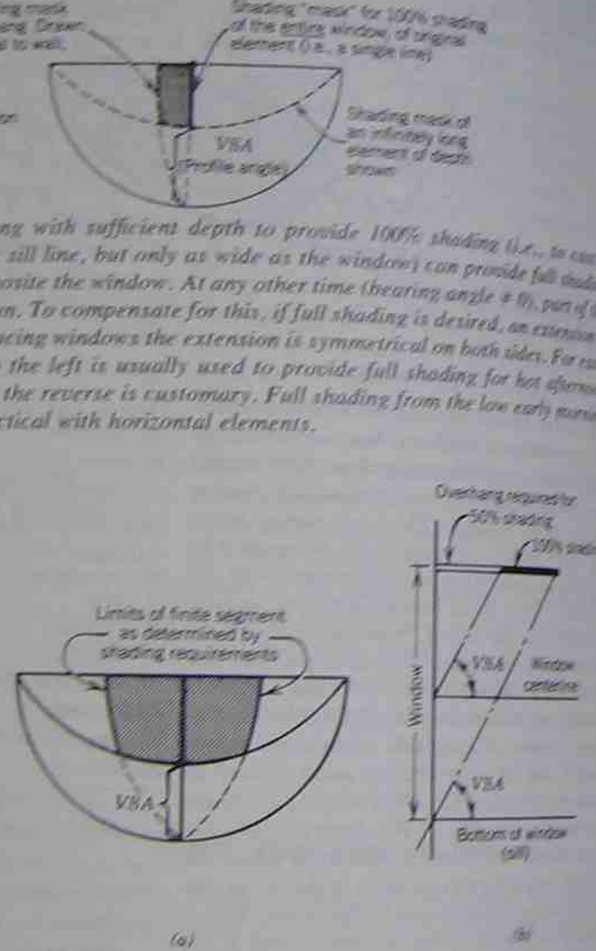


Fig. D.10 *A horizontal overhang with sufficient depth to provide 100% shading (i.e., to cast a shadow reaching to the window sill line, but only as wide as the window) can provide full shading only when the sun is exactly opposite the window. At any other time (bearing angle ≠ 0), part of the window will be exposed to the sun. To compensate for this, if full shading is desired, an extension is required, as shown. For south-facing windows the extension is symmetrical on both sides. For east-facing windows an extension to the left is usually used to provide full shading for hot afternoon hours; for west-facing windows, the reverse is customary. Full shading from the low early morning or late afternoon sun is not practical with horizontal elements.*

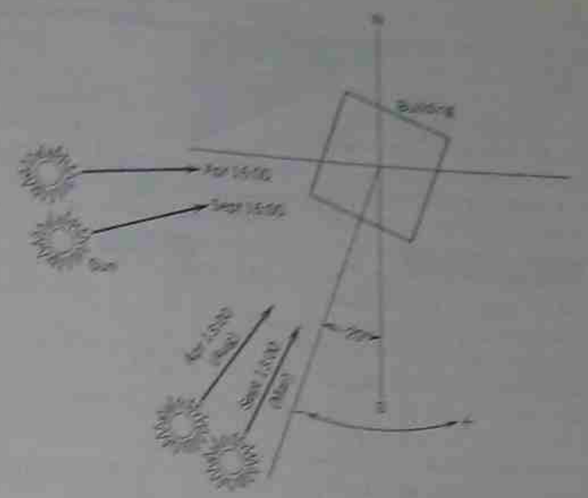
Fig. D.11 *To find the required depth of a horizontal overhang, having established the required segmental shading mask (a) it is only necessary to read VSA (profile angle) off the protractor in Fig. D.8c that corresponds to the segment in (a) and plot this angle as shown in (b) (wall section). Angle VSA can be plotted for 50% coverage, 100% coverage, or any other figure. The depth of the overhang can then be measured directly from the section, which is drawn to scale. Alternatively, if the overhang depth is known, the corresponding segment can be drawn.*



give the same shade in the spring (before 21 Jun) as in the summer (after 21 Jun). Since in many locations spring is cool, the desired summer shading will produce spring shading that *may not* be desirable. The solutions to this apparent dilemma are either to use a movable or variable size fixed shading device, or to compromise with the amount of shading, that is, to design for 50% shading for late summer, giving 50% insolation in early spring and 100% shading in early summer (and late spring).

The example that follows requires 100% shading for most of the summer (spring) for two reasons:

1. At the selected latitude of 32°N, sunshading is frequently desirable in the spring.
2. We wish to show that 100% shading using only a horizontal overhand can result in a very large element and that the shading characteristic of such an element can be duplicated with a much smaller combined horizontal–vertical element.



(a)

Date	Time	Sun Azm	Shade direction	VSA	HSA[a]	DE[b] (depth, cm)	AB[c] (extension, cm)
Apr 21	13:00	−37°		67°	−17°	42	−40
	15:00	−84°		54.5°	−68°	71	−256
Sept 21	13:00	−27°		55°	−7°	70	−16
	15:00	−73°		37.5°	−53°	130*	−172

[a] *HSA* = (Sun azm − Bldg. bearing), i.e. (Azm −20°)
[b] *DE* = Window height/tan *VSA* = 100/*VSA*
[c] *AB* = *DE* tan *HSA* = overhang depth × tan *HSA* = 130 tan *HSA*;
the negative sign indicates an extension to the left.

(b)

Fig. D.12 *Sketches for solution of Example D.1 (see text).* *[See continuation on next page]*

EXAMPLE D.1. Design a simple horizontal over-the-widow shading element that will provide 100% window shading from 1 P.M. to 4 P.M., from April 21 to September 21 for a window 100 cm (39 in.) high and 150 cm (59 in.) wide, in a wall facing 20° west of south. The building is at latitude 32°N.

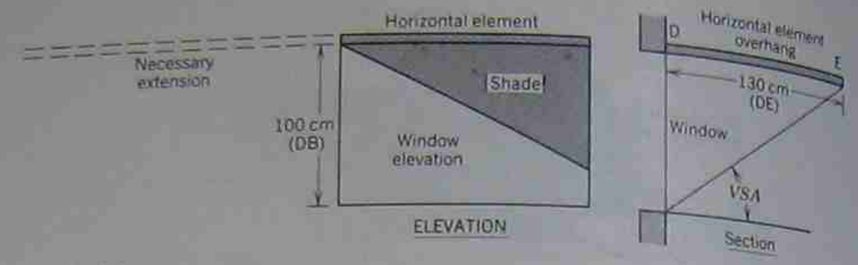


Fig. D.12 (continued)

ANALYTIC SOLUTION

STEP 1. The first step is to draw a sketch (Fig. D.12*a*) showing the orientation of the building. All the sketches connected with this example are shown in Fig. D.12.

STEP 2. Using either the LOF sun angle calculator, or Fig. D.5, tabulate the sun positions for the four times that bracket the shading period. Tabulate them as shown in Fig. D.12*b* and show sun directions as in Fig. D.12*a*. The purpose of establishing sun direction is to be able to immediately determine the required shading element end treatment, by sketching the direction in which the shade falls. This is shown in the fourth column of the tabulation of Fig. D.12*b*.

STEP 3. By inspection of the solar azimuth and the bearing angle (the angle between perpendicular to the wall and the vertical plane through the sun), it is apparent that all shadows fall to the right, and therefore the horizontal element must be lengthened to the left. Maximum extension is required for shading at 1600 on April 21. The next step is to establish the shadow angles *VSA* and *HSA* for each condition. These can be read directly from the LOF sun chart (profile angle = *VSA*; bearing from normal line = *HSA*) or by overlaying the protractor of Fig. D.8*c* on Fig. D.5. *HSA* need not be read off: It is simply the difference between sun azimuth and building bearing (20°) and so

can be calculated directly. Fill in the required angles in the *VSA* and *HSA* columns of the table in Fig. D.12*b*.

STEP 4. At this point it is advisable to draw sketches of the window in elevation, section, and plan to understand the calculations. See Fig. D.12*c*. It is necessary for us first to establish the depth of the overhang, and with that known, to then calculate the required extension of the left. Refer now to Fig. D.7. Note carefully that the first item that we wish to calculate is the depth of the overhand, *DE*. Since

$$\tan VSA = \frac{DB}{DE}$$

and we know the window height, *DB*, to be 100 cm [39 in.], we have

$$DE = \frac{100 \text{ cm}}{\tan VSA}$$

We perform this simple calculation for every VSA, and we will select the deepest overhang as the one required. The figures are listed under column *DE* (depth) of Fig. D.12*b*.

STEP 5. Having found the overhand depth required, we can calculate the end treatment needed, that is, the amount that the overhang must be extended to cover the window. Study Fig. D.7. The extension needed is obviously *AB*, since the area *ABD* is unshaded. Therefore, if we move *D* a distance of *AB* (on the figure—to the right; in our example—to the left), point *A* will move to *B*, and shading will be complete. Since

$$\tan HSA = \frac{AB}{DE}$$

and we have already established that *DE* is 130 cm [51 in.], we have

$$AB = 130 \tan HSA$$

These four values are calculated and tabulated in Fig. D.12*b*. We find that the required extension to the left, beyond the window, is 266 cm (105 in.). At this point we can complete the sketch in Fig. D.12*c* with dimensions.

STEP 6. This step is the evaluation stage that follows every design. Our evaluation would be that if, indeed, the stated shading hours must be maintained, an overhang 130 cm (51 in.) deep and 416 cm (164 in.) wide (266 + 150) is excessively large, and we would recommend a vertical element on the left side. The type of vertical element recommended is shown in Fig. D.12*d*; it is a sloping element that reaches from the front edge of the overhang to the window. To understand how such a unit shades, refer again to Fig. D.7. Note very carefully that because *DA* is the shadow of *DE*, triangle *DAB* is the shadow area corresponding to a vertical side element *DEB*. That is, if *DEB* were solid, *DAB* would be its shade. We thus see the extremely important and useful fact that *a sloping side element like DEB is equivalent to an infinitely long extension on that side*. Thus the full segmental areas shown in shading masks can be established not by an impossible infinitely long horizontal element, but by a horizontal element the width of the window and two sloping elements. In our case, such an element would eliminate the necessity for a massive 266-cm (105 in.) side extension.

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E

ECONOMIC ANALYSIS

E.1 Economic Decisions

As has been pointed out repeatedly in this text, economic factors are a major consideration in almost every decision in the building design process. The discussion below is necessarily brief but covers the essential principles. For in-depth study of economic analyses in the design and construction process, the reader is referred to the references at the end of the appendix. Publications of the National Bureau of Standards (Marshall and Ruegg, 1980a, 1980b; Ruegg et al., 1978) are the sources of some of the principles explicated below, and are so referenced.

The most common economic questions are:

1. How can the cost of different systems *that produce the same end result* be compared? This may apply to the purchase of a single item such as a motor, to the lighting of a room, or to the choice of the type of HVAC installation for an entire system. The principle involved is the same.

2. Assuming that improving a system, existing or proposed, will reduce operating costs and that many different types of improvement are possible, what preliminary economic guidelines can be established to determine whether any proposed investment appears cost effective? Stated otherwise, how can the initial, simple rate of return of a proposed investment be determined so that it can be compared to the *minimum expected rate of return* on investment?

3. Having determined in answer to question 2 that a number of different proposals, each with its own investment and payback (savings) figures, are apparently cost effective, how can these be compared to determine which is *most* cost effective? Put another way, which proposal has the maximum *net benefit or savings*? This is the type of decision that must be made when comparing energy conservation projects, such as the lighting control systems described in Section 21.4.

4. Having established which of the proposals is most cost effective, how can the *actual* rate of return of the investment be determined? This figure, often referred to as *internal rate of return* (*IRR*), can then be compared to the required rate of return, to determine whether the investment is economically desirable.

5. What is the *payback period* of the investment?

These questions are considered individually in the discussion below.

E.2 Life-Cycle Cost (LCC)

Cost comparisons made on the basis of first cost are legitimate only when operating costs do not bear consideration, either because there are none or because the builder is not the owner. Proposals for pouring a concrete slab might represent the former situation, and speculative construction for immediate sale the latter. In such cases the technique of cost comparison is simple. However, when operating costs are involved that vary from system to system, the only reasonable way to determine and compare system costs is by *life-cycle costing*. The basic theory and calculation techniques are well known (see AIA, 1977; Marshall and Ruegg, 1980a, 1980b; Ruegg et al., 1978), so they will be reviewed only briefly here.

Stated simply, a life-cycle cost represents the total cost of an item or system over its entire life cycle, that is, the sum of first cost and all future costs, less salvage. When the life cycle of the system being studied does not correspond to that of the building in which it is installed (as is usually the case), the designer must decide

which life cycle to use. For instance, a lighting system has an estimated life of 15 to 20 years, whereas the building life is usually at least double that. It is usually wiser to make the study over the shorter period, since almost certainly, changes in technology will present an entirely different picture when the time comes to replace the system. This is true of most mechanical/electrical systems being designed today.

Life-cycle cost, in equation form is

$$LCC = IC + MC + AC + OC \qquad \text{(E.1)}$$

where

LCC = life-cycle cost
IC = investment cost, (i.e., first cost minus salvage)
MC = maintenance and repair cost
AC = amortization (replacement) cost (not always included in life-cycle cost calculation)
OC = operating costs, including labor and energy

All costs are expressed in terms of present value, which is explained below. Costs can also be annualized. We use the present value format because we feel it gives a clearer answer to the economic decision questions posed above. When calculating costs, the designer must include related ancillary costs. For instance, in comparing lighting systems, the cost figures must reflect the impact on the HVAC system and the wiring system. [For lighting system cost comparisons, see IESNA (1981).]

When the life cycle is short—say two years maximum, the last three components of Equation E.1 can be assumed to be constant without introducing an intolerable error. However, for longer periods this is obviously not a valid assumption because of escalating labor and energy costs. Since these two factors weigh heavily in all economic comparisons, and since they generally exist in different proportions in the systems being considered, escalation in their costs will obviously change the economic balance when costs are projected over the equipment life. It is therefore necessary to change the usual present value formula to reflect this escalation.

The present value of future payments of 1.00, made at the *end* of a series of n periods, is

$$PV = \frac{(1+i)^n - 1}{i(1+i)^n} \qquad \text{(E.2)}$$

where

PV = present value
i = interest (discount) rate expressed as a decimal (e.g., 8% = 0.08)
n = number of periods

The factor i is more accurately the discount rate rather than the simple interest rate, the difference being that the latter reflects inflation, either actual or anticipated. If, however, the future payments escalate, the expression becomes:

$$PV = \frac{1 - \left(\frac{K}{1+i}\right)^n}{\frac{1+i}{K} - 1} \qquad \text{(E.3)}$$

where K is the escalation rate per period, and the remaining items are as in equation E.2. Thus for a 5% annual escalation, $K = 1.05$, and so on. The values of PV are tabulated in Table E.1 for interest (discount) rates of 8, 10, and 12%, and escalation rates of 3, 5, 8, and 10%. Other values can be calculated from the equations. Tables 15.5 and 16.4 were calculated assuming a 3% annual energy cost escalation.

It is apparent that the result of a life-cycle-cost analysis depends heavily on accurate forecasting when using escalation and that comparative results can readily shift not only with escalation estimates of the various components but also with the length of the life cycle.

E.3 Initial (Simple) Rate of Return

Addressing the second question in Section E.1, we wish to determine whether to examine a proposed cost-saving investment in detail. That is, is the initial (simple) rate of return sufficient? The difference between initial and *actual* rates of return is that the former is simply

$$\text{initial rate of return} = \frac{\text{annual savings}}{\text{investment}}$$

whereas the actual (internal) rate of return depends on the life of the project and the *total* savings accrued during this life cycle. The calcu-

TABLE E.1*a* **Present Value of n Future Payments Beginning at the End of the First Period**

	Interest (Discount) Rate per Period						
n	6%	8%	10%	12%	15%	20%	25%
1	0.94	0.93	0.91	0.89	0.87	0.83	0.80
2	1.83	1.78	1.74	1.69	1.63	1.53	1.44
3	2.67	2.58	2.49	2.40	2.28	2.11	1.95
4	3.47	3.31	3.17	3.04	2.86	2.59	2.36
5	4.21	3.99	3.79	3.61	3.35	2.99	2.69
6	4.92	4.62	4.36	4.11	3.78	3.33	2.95
7	5.58	5.21	4.87	4.56	4.16	3.61	3.16
8	6.21	5.75	5.34	4.97	4.49	3.84	3.33
9	6.80	6.25	5.76	5.33	4.77	4.03	3.46
10	7.36	6.71	6.15	5.65	5.02	4.19	3.57
11	7.89	7.14	6.50	5.94	5.23	4.33	3.66
12	8.83	7.54	6.81	6.19	5.42	4.44	3.73
13	8.85	7.90	7.10	6.42	5.58	4.53	3.78
14	9.30	8.24	7.37	6.63	5.72	4.61	3.82
15	9.71	8.56	7.61	6.81	5.85	4.68	3.86
16	10.11	8.85	7.82	6.97	5.95	4.73	3.89
17	10.48	9.12	8.02	7.12	6.05	4.78	3.91
18	10.83	9.37	8.20	7.25	6.13	4.81	3.93
19	11.16	9.60	8.37	7.37	6.20	4.84	3.94
20	11.47	9.82	8.51	7.47	6.26	4.87	3.95
21	11.76	10.02	8.65	7.56	6.31	4.89	3.96
22	12.04	10.20	8.77	7.65	6.36	4.91	3.97
23	12.30	10.37	8.88	7.72	6.40	4.93	3.98
24	12.55	10.53	8.99	7.78	6.43	4.94	3.98
25	12.78	10.68	9.08	7.84	6.46	4.95	3.99

lation method for the latter is given in Section E.5.

Initial rate of return is a useful criterion in that it can be very easily calculated and then compared to the *minimum* desired rate of return on investment. We emphasize *minimum*, since actual rate of return is always lower than the simple, initial rate of return, except where savings escalate during the project life cycle. If this preliminary comparison indicates that the simple rate of return exceeds the minimum by a margin of a few percent, it is likely that the project is economically feasible, and a detailed analysis can be undertaken.

E.4 Cost-Effectiveness Comparisons

This analysis is undertaken in answer to question 3, that is, several projects are being considered, all of which meet the stated criterion. Which is most desirable from a cost-effectiveness viewpoint? (If only one project is under consideration, the analysis proceeds directly to the IRR calculation described in the next section.)

The difference between life-cycle project cost and life-cycle project savings, that is, net lifetime savings, is a measure of cost effectiveness. Therefore, to compare the cost effective-

TABLE E.1*b* **Present Value of *n* Future Payments Beginning at the End of the First Period and Escalating at *K* per Period**

	Interest (Discount) Rate per Period 8%			
	Annual (Periodic) Escalation Rate K			
n	1.03	1.05	1.08	1.10
1	0.95	0.97	1.00	1.02
2	1.86	1.92	2.00	2.06
3	2.73	2.84	3.00	3.11
4	3.56	3.73	4.00	4.19
5	4.35	4.60	5.00	5.28
6	5.10	5.44	6.00	6.40
7	5.82	6.26	7.00	7.54
8	6.50	7.06	8.00	8.70
9	7.15	7.84	9.00	9.88
10	7.78	8.59	10.00	11.08
11	8.37	9.33	11.00	12.30
12	8.94	10.04	12.00	13.55
13	9.48	10.73	13.00	14.82
14	9.99	11.41	14.00	16.11
15	10.48	12.06	15.00	17.43
16	10.95	12.70	16.00	18.77
17	11.40	13.32	17.00	20.13
18	11.82	13.92	18.00	21.53
19	12.23	14.51	19.00	22.94
20	12.62	15.08	20.00	24.39
21	12.99	15.63	21.00	25.86
22	13.34	16.17	22.00	27.35
23	13.68	16.69	23.00	28.88
24	14.00	17.20	24.00	30.43
25	14.30	17.69	25.00	32.01

TABLE E.1*c* **Present Value of *n* Future Payments Beginning at the End of First Period and Escalating at *K* per Period**

	Interest (Discount) Rate per Period 10%			
	Annual (Periodic) Escalation Rate K			
n	1.03	1.05	1.08	1.10
1	0.94	0.96	.96	.98
2	1.81	1.87	1.89	1.95
3	2.63	2.74	2.79	2.89
4	3.40	3.57	3.66	3.82
5	4.12	4.36	4.49	4.74
6	4.80	5.12	5.29	5.64
7	5.43	5.84	6.07	6.52
8	6.02	6.53	6.82	7.38
9	6.57	7.18	7.54	8.23
10	7.09	7.81	8.23	9.07
11	7.58	8.41	8.90	9.89
12	8.03	8.98	9.55	10.69
13	8.46	9.53	10.17	11.49
14	8.85	10.05	10.77	12.26
15	9.23	10.55	11.35	13.03
16	9.58	11.27	11.91	13.78
17	9.90	11.48	12.45	14.51
18	10.21	11.91	12.97	15.23
19	10.50	12.32	13.47	15.95
20	10.76	12.72	13.95	16.64
21	11.02	13.09	14.42	17.34
22	11.25	13.45	14.87	18.00
23	11.47	13.80	15.30	18.66
24	11.68	14.12	15.72	19.31
25	11.87	14.44	16.12	19.95

TABLE E.1*d* **Present Value of *n* Future Payments Beginning at the End of First Period and Escalating at *K* per Period**

	Interest (Discount) Rate per Period 12%			
	Annual (Periodic) Escalation Rate K			
n	1.03	1.05	1.08	1.10
1	.92	.94	.96	.98
2	1.77	1.82	1.89	1.95
3	2.54	2.64	2.79	2.89
4	3.26	3.41	3.66	3.82
5	3.92	4.14	4.49	4.74
6	4.52	4.82	5.29	5.64
7	5.08	5.45	6.07	6.52
8	5.59	6.05	6.82	7.38
9	6.06	6.61	7.54	8.23
10	6.49	7.13	8.23	9.07
11	6.89	7.63	8.90	9.89
12	7.26	8.09	9.55	10.69
13	7.59	8.52	10.17	11.49
14	7.90	8.92	10.77	12.26
15	8.19	9.30	11.35	13.03
16	8.45	9.66	11.91	13.78
17	8.69	9.99	12.45	14.51
18	8.91	10.31	12.97	15.23
19	9.11	10.60	13.47	15.95
20	9.30	10.87	13.95	16.64
21	9.47	11.13	14.42	17.34
22	9.63	11.37	14.87	18.00
23	9.78	11.60	15.30	18.66
24	9.91	11.81	15.72	19.31
25	10.04	12.01	16.12	19.95

ness of two projects, it is necessary simply to calculate this differential. To express this as an equation, we write:

net savings = life-cycle savings
− life-cycle cost

Since this is true for all projects, a comparative differential can be calculated by using the differential in each term of the life-cycle-cost equation, that is,

$$\Delta_{nc} = \Delta_{savings} - \Delta_{costs}$$

Taking a very simple example, assume the following conditions:

	Project A	Project B
Investment	$10,000	$15,000
Life cycle	10 years	8 years
Annual savings	$2,000	$3,200
Initial rate of return	20%	21.3%
Discount rate	12%	12%

Since project B has an apparently higher rate of return, we would formulate the differential as B minus A. Using Table E.1*a*, the present worth of lifetime savings for project B (without escalation) is $3200 × (4.97) or $15,904, and that of project A is $2000 × (5.65) or $11,120. Therefore, the differential cost benefit (CB) of B minus A is $\Delta_{savings}$ minus $\Delta_{investment}$, or

$$\Delta_{CB} = (\$15{,}904 - \$11{,}120) - (\$15{,}000 - \$10{,}000) = \$4784 - \$5000 = -\$216$$

indicating that project A is more cost effective despite the apparently higher rate of return of project B. If we include escalation in costs, obviously the life savings of the longer life project (A) will shrink more than the savings of shorter life project B. Using Table E.1*d*, we find that the projects are about equal, with 3% annual escalation. Above that, project B is more cost effective.

E.5 Internal Rate of Return (IRR)

This figure represents the rate of return at which lifetime savings are exactly equal to lifetime costs. It cannot be calculated directly, but only by trial and error. We must assume a rate of return, calculate present value of savings, and compare PV to lifetime costs. Because of its difficulty, IRR is frequently neglected, and its real rate of return used instead, although as we saw above, this can readily give misleading results. To illustrate calculation of IRR, we will return to our very simple example and calculate IRR for projects A and B.

For project A, we need a present worth factor of $10,000/$2000 = 5, in 10 years. Referring to Table E.1*a*, we see that at a discount rate of 15%, the present worth factor is 5.019, indicating that IRR is slightly above this. (It is actually 15.1%.) For project B we need a 8-year present worth factor of $15,000/$3200 = 4.69. Referring again to Table E.1*a*, we see that this factor falls between 12 and 15%. By a series of trials with equation E.2, we arrive at 13%, which is 1.4% less than the same factor for project A, confirming the conclusion reached in the preceding step.

E.6 Payback Period

The payback period referred to in most proposals is the reciprocal of the *initial* rate of return and is usually referred to as the *simple* payback period. However, just as we have seen that the actual rate of return differs from the simple rate (and is usually less than it), so the actual or *discounted payback period* is different, and usually longer than the simple one. This period is, logically, the period of time required for the accumulated net savings to equal the initial investment, with all figures expressed in present value dollars. To illustrate, let us return to the example given above.

1. *Proposal A.* As in the IRR calculation, we need a present worth factor of $10,000/$2000, or 5, at a 12% discount rate. From Table E.1*a* we find this to be about 8½ years. This compares to a simple payback period of 5 years. Note that this is *not* the reciprocal of internal rate of return.
2. *Proposal B.* Here we need a present worth factor of $15,000/$3200 or 4.7. At 12% discount rate, from Table E.1*a*, the

is about 7.3 years. This compares to a simple payback period of 4.7 years.

Note from these results the very important fact that a shorter payback period does not necessarily indicate a more cost-effective investment. Here, proposal A has a better return precisely because it yields good savings for a longer period. Summing up the results of our simple study, we have:

	Project A	Project B
Initial rate of return	20%	21.3%
Internal rate of return	15.1%	13.7%
Simple payback period	5 years	4.7 years
Discounted payback period	8.1 years	7.3 years

This shows very clearly that although initial rate of return and simple payback period are indicators of a proposal's value, they are useless in comparative studies.

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F

SOUND TRANSMISSION DATA FOR WALLS

To use Appendix F:

1. Find desired construction Type Code in Index F.1.
2. Find desired STC corresponding to the selected construction Type Code.
3. Refer to Table F.1 for details of wall construction.
4. Refer to Index F.2 for wall thickness weight, STC, fire rating, and the transmission losses at standard octave midpoints.

EXAMPLE. An interior masonry partition with an STC between 50 and 55 is desired. Of particular interest is the TL at 1000 Hz.

1. From Index F.1, we find Type Code "c."
2. From Index F.1, we note that constructions W6, W12b, W15b, and W22b have appropriate STC ratings.
3. From Table F.1 we decide that construction W15b is most suitable for the proposed use.
4. From Index F.2 we find that construction W15b has a transmission loss of 55 db at 1000 Hz.

INDEX F.1 Sound Transmission Class: Walls

Type Code:

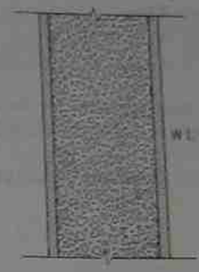
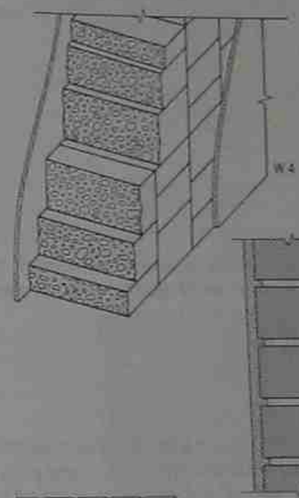
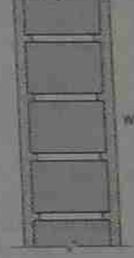
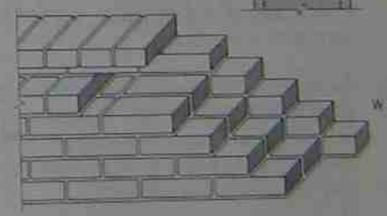
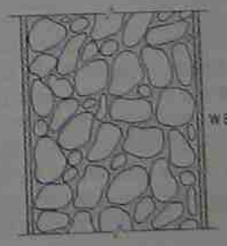
a. Wooden stud
b. Metal stud
c. Masonry
d. Concrete
e. Staggered stud
f. Plaster
g. Gypsum wallboard
h. Wet resilient element
i. Absorbent blanket or fill
j. Fiber board
k. Lead
l. Gypsum core board
m. Double wall

STC	Type	Item No.	STC	Type	Item No.
63	d,f	W4	46	a,f	W30a
62*	c,f,j,m	W23	46	a,f	W31a
56	c	W7	46	a,f,k	W31c
56*	c,f	W8	46	a,e,g,j	W37
55*	b,g,j	W83	45	c,d	W10b
54*	c,f,m	W22b	45	a,f,i	W38
54	b,f,h	W52	45	b,f,h	W50a
53*	d,f	W2	45	g,l,m	W65a
53	c,f,h	W15b	44	c	W12a
52*	c,f	W6	44	a,e,g	W34a
51	b,f	W44a	44	a,e,g	W35a
51	b,g,h,j	W67	44	a,f,h	W40a
50	c,k	W12b	43	c,d	W10a
50	b,g,j	W60	43*	d,j,m	W21
50	g,i,l,m	W85b	43	a,e,f	W35a
49*	c,f,m	W22a	43	a,e,f	W36a
48	c,d	W9	43	b,f,k	W43b
48	a,e,f,i	W35b	42*	c,f	W5
48	b,f,k	W43c	42	a,f	W14a
47	d	W1	41	b,f	W43a
47	a,g,k	W26b	41	b,g	W55a
47	a,f,k	W31b	40	c,f	W13
47	a,g,h	W39a	40	a,g	W32a
46	c,f	W11a	39	a,g	W28a
46	c,f,h	W15a	36	g,l	W60

*Field measurement.

Designation	Thickness (in.)	Weight (lb/ft²)	Transmission Loss (db) 125	250	500	1K	2K	4K	STC	Fire Rating hr
W1	3	39	35	40	44	52	58	64	47	½
W2	7	80	39	42	50	58	64	—	53	3
W4	Approx. 16	184	50	54	59	65	71	68	63	4+
W5	5½	55	34	34	41	50	66	—	42	2.5
W6	10	100	41	43	49	55	57	—	52	4+
W7	12	121	45	45	53	58	60	61	56	4+
W8	25	280	50	53	52	58	61	—	56	4+
W9	12	79	46.5	44	46	52	54	56	48	4
W10a	6	34	32	33	40	47	51	48	43	1
W10b	6	34	37	36	42	49	55	58	45	1
W11a	5¼	35.8	36	37	44	51	55	62	46	2
W12a	3¾	26.1	40	40	40	48	55	56	44	1.5
W12b	5	31	41	46	46	56	63	67	50	1.5
W13	4	21.5	39	34	38	43	48	46	40	3
W14a	5	23.4	37	42	39	44	49	49	42	4
W15a	5	27	38	37	44	51	56	59	46	3
W15b	6	31	45	44	50	55	56	59	53	4
W20	7	22.9	32	46	49	53	58	66	52	3
W21	10¼	37	41	42	46	51	52	—	43	Not available
W22a	12	100	37	41	48	60	60.5	—	49	4+
W22b	12	100	40	44	55	67.5	70	—	54	4+
W23	18	120	48	54	58	64	69	—	62	4+
W28a	5	6	21	28	35	42	45	41	39	0.5
W28b	Approx. 5⅛	12	27	37	43	52	56	—	47	0.5
W30a	5¾	13.4 to 15.7	32	37	42	47	47	63	46	0.75
W31a	5¾	13.4 to 15.7	32	37	42	48	48	63	46	0.75
W31b	Approx. 5⅞		33	41	45	52	55	65	47	0.75
W31c	Approx. 5⅞	17–19	32.5	40	43	47	50	62	46	0.75
W32a	5½	8.2	27	31	39	45	52.5	48	40	1
W34a	5	6.2	36	36	40	47	52	45	44	0.5
W35a	6½	13.4	41	41	46	49	41	54	44	1.5
W35b	5¾	15.6	48	46	48	48	48	59	43	1
W36a	6¼	11.1	36	33	42	42	41	51	43	0.75
W36b	6¼	12.8	37	37	49	50	52	66	48	1
W37	5¾	13.8	39	40	42	47.5	55	51.5	46	0.5
W38	5⅜	14.2	39	45	48	50	44	54	45	1
W39a	6¼	6.7	30	40	46	50	49	49	47	1
W40a	Approx. 6½	14.4	43	41	48	50	42	56	44	1
W43a	3⅜	12.3	27	37	43	46	39	47	41	0.75
W43b	3½	15.2	35	43	45	47	48	58	43	0.75
W43c	Approx. 3½	18.2	36	45	47	50	53	61	48	0.75
W44a	5	15.7	34	38	47	50	52	58	51	1
W50a	5¼	13	35	46	48	51	48	43	45	0.75
W52	5	19	50	52	55	56	52	60	54	1
W55a	4⅞	6	29	36	40	46	40	46	41	1
W60	3½	5.4	34	40	47	50	53	54	50	1
W63	6⅛	11.5	36	47	51	57	57	62	55	2
W67	6½	11.3	41	46	49	51	50	60	51	2
W80	2¼	10.2	34	34	37	38	39	45	36	1
W85a	5⅛	14.6	36	35	45	51	53	57	45	3
W85b	6	12.8	37	37	54	56	56	62	50	3

TABLE F.1 **Acoustic Characteristics of Walls: For Other Data See Index F.2**

Designation	Description	Section Sketch
Solid Concrete		
W1	3-in.-thick solid concrete wall poured in situ in test opening. All surface cavities were sealed with thin mortar mix.	
W2	6-in.-thick concrete wall with ½-in.-thick layer of plaster on both sides.	
W4	Wall of 4, 6, and 8 × 8 × 16 in. sand and gravel aggregate solid concrete blocks; on each side, ¼- to ½-in.-thick layer of cement gypsum plaster and sand.	
W5	4½-in.-thick brick wall with ½-in.-thick layer of plaster on each side.	
W6	9-in.-thick brick wall with ½-in.-thick layer of plaster on each side	
W7	12-in.-thick brick wall.	
W8	24-in.-thick stone wall with ½-in.-thick layer of plaster on both sides.	

APPENDICES

TABLE F.1 Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)

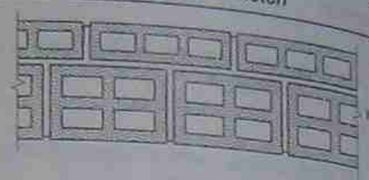
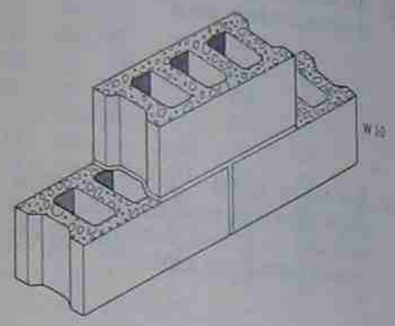
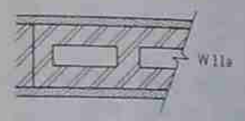
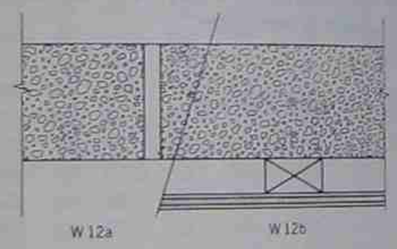
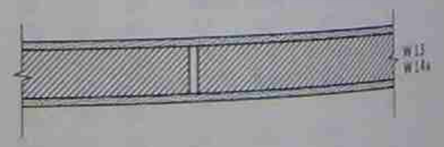
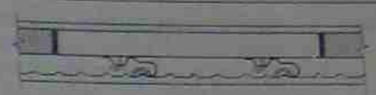
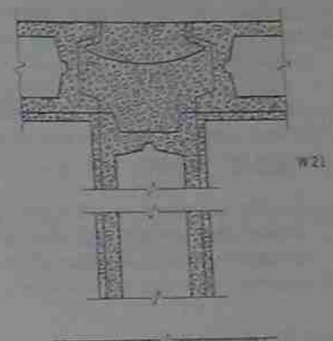
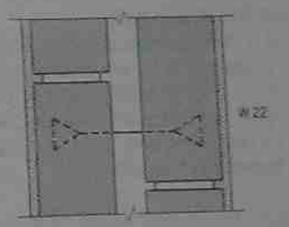
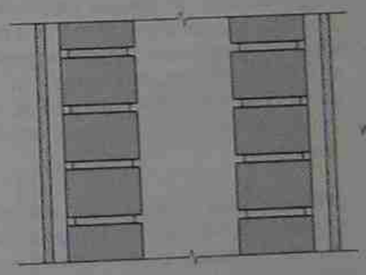
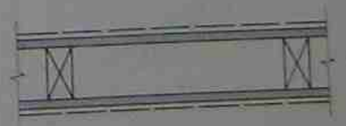
Designation	Description	Section Sketch
Hollow Concrete Block		
W9	12-in. wall made of hollow 8 × 8 × 12 in. and 8 × 4 × 16 in. concrete blocks.	 W9
W10a	6-in. hollow concrete blocks constructed with vertical mortar joints staggered.	
W10b	Similar to W10a except wall painted.	 W10
Cinder Block		
W11a	4 × 8 × 16 in. hollow cinder blocks; on each side, ⅝ in. of sanded gypsum plaster.	 W11a
Cement Block		
W12a	3⅝ × 7¾ × 13½ in. lightweight-aggregate cement blocks with ½-in. mortar joints; three coats of masonry paint applied to each side of partition.	 W12a W12b
W12b	Same as W12a except 1 × 2-in. furring strips were nailed vertically to partition on one side; 1/16-in. layer of lead, 3.94 lb/ft², nailed to furring strips, ¼-in. plywood-covered lead with joints caulked.	
Hollow Gypsum Block		
W13	3-in. hollow gypsum blocks cemented together with ⅜-in. mortar joints; on each side, ½-in. sanded gypsum plaster.	 W13 W14a
W14a	4-in. hollow gypsum blocks cemented together with ⅜-in. mortar joints; on each side, ½-in. sanded gypsum plaster.	

TABLE F.1 Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)

Designation	Description	Section Sketch
Hollow Gypsum Block, Resilient One Side, Plaster Both Sides		
W15a	3 × 12 × 30 in. hollow gypsum blocks with ½-in. mortar joints. On one side 7/16-in. sanded gypsum plaster; on the other side resilient clips, spaced 18 in. on centers vertically and 16 in. on centers horizontally, held to ¾-in. metal channels 16 in. on centers, to which expanded metal lath was wire-tied; 11/16-in. sanded gypsum plaster. 1/16-in. white-coat finish applied to both sides.	 W15
W15b	Similar to W15a except 4 × 12 × 30 in. gypsum blocks were used.	
Hollow Concrete		
W21	Precast concrete hollow wall panels with in situ concrete posts and beams. Panels have 1½-in.-thick concrete shells with 6¼-in. air space between them. Layer of fiberboard ½-in. thick is adhered to the exposed surfaces of the panel.	 W21
Double Walls		
W22a	Double wall with 4½-in.-thick brick leaves separated by a 2-in. cavity (wire ties between leaves); ½-in. plaster on exposed sides.	 W22
W22b	Similar to W22a but no wire ties between the leaves.	
W23	Double wall with 4½-in.-thick brick leaves, 6-in. cavity (no ties); on exposed sides, ½-in. plaster on 1-in.-thick wood-wool slabs mortared to the brick walls.	 W23
Wood Stud Walls		
W28a	2 × 4 in. wooden studs, 16 in. on centers, ½-in. gypsum wallboard nailed to each side. All joints taped and finished.	 W28
W28b	Similar to W28a except a layer of lead, 2.95 lb/ft², was laminated to each side of panel.	

APPENDICES

TABLE F.1 Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)

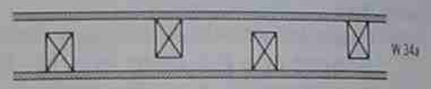
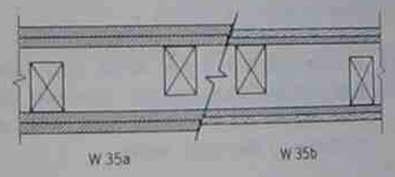
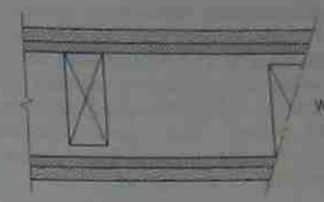
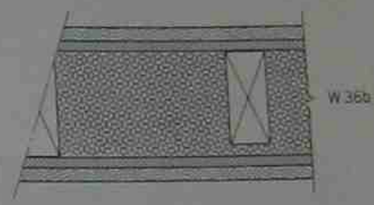
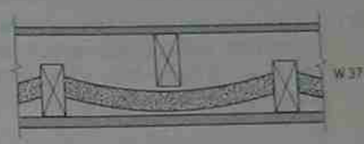
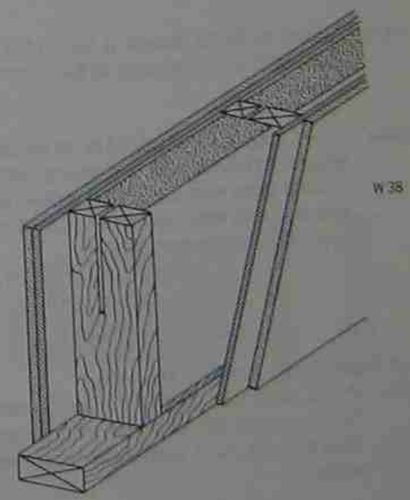
Designation	Description	Section Sketch
W30a	2 × 4 in. wooden studs, 16 in. on centers, attached to 2 × 4 in. wooden floor and ceiling plates, ⅜-in. gypsum lath nailed to studs on both sides, ½-in. sanded plaster with white-coat finish.	
W31a	2 × 4 in. wooden studs, 16 in. on centers, ⅜-in. gypsum lath nailed to studs on both sides, ½-in. sanded plaster with white-coat finish.	
W31b	Similar to W31a except a 0.065-in.-thick layer of lead weighing 3.85 lb/ft² was laminated to each side of panel.	
W31c	Similar to W31a except a 0.13-in.-thick layer of lead weighing 7.9 lb/ft² was laminated to one side of panel.	
W32a	2 × 4 in. wooden studs, 16 in. on centers; on each side two layers of ⅜-in. gypsum wallboard cemented together; joints in exposed surfaces taped and finished.	
Staggered Wood Stud Walls		
W34a	2 × 3 in. wooden studs, 16 in. on centers, staggered 8 in. on centers, attached to 2 × 4 in. wooden plates at ceiling and floor; ½-in. gypsum wallboard nailed 7 in. on centers on both sides to studs. All joints taped and finished.	
W35a	2 × 3 in. wooden studs, 16 in. on centers, staggered 8 in. on centers (attached to 2 × 4 in. wooden plates at floor and ceiling) two layers of ⅝-in. tapered-edge gypsum wallboard, first layer nailed 7 in. on centers, second layer nailed 16 in. on centers. All exposed joints taped and finished.	
W35b	Similar to W35a except the wall was constructed with ⅜-in. perforated gypsum lath and ½-in. sanded gypsum plaster with white-coat finish.	

TABLE F.1 Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)

Designation	Description	Section Sketch
W36a	2 × 4 in. wooden studs, 16 in. on centers, staggered 8 in. on centers, and offset ½ in. On each side ⅜-in. gypsum lath nailed to studs, ½-in. gypsum vermiculite plaster, machine applied, and a hand-applied white-coat finish.	
W36b	Same as W36a except the space between the studs contained vermiculite fill with a density of 6.3 lb/ft³.	
W37	2 × 4 in. wooden studs, 16 in. on centers, staggered 8 in. on centers, attached to 2 × 4¾ in. wooden floor and ceiling plates; ½-in. gypsum wallboard nailed on both sides to studs, 0.9-in. wood-fiber wool blanket stapled on the inside of one side of the wall. All joints taped and finished.	
Slotted Wood Studs		
W38	2 × 4 in. slotted wooden studs, 16 in. on centers, attached to 2 × 4 in. wooden floor and ceiling plates; ⅜-in. gypsum lath nailed 7 in. on centers to studs, ½-in. gypsum plaster with white-coat finish applied to both sides. 3-in. mineral fiber batts stapled between studs.	

APPENDICES

TABLE F.1 **Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)**

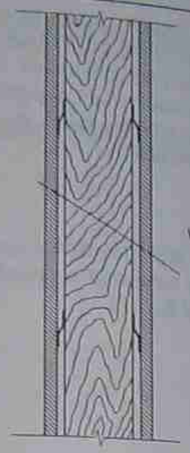
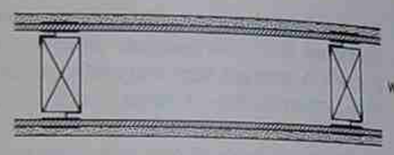
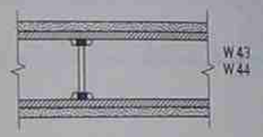
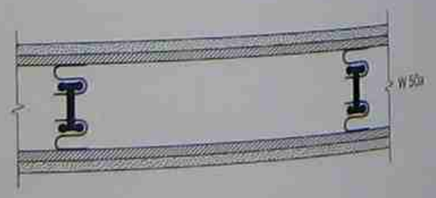
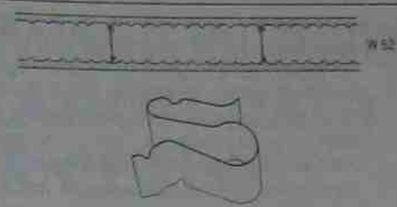
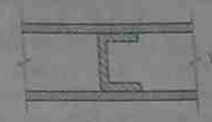
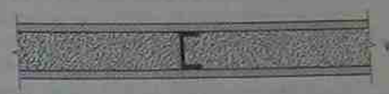
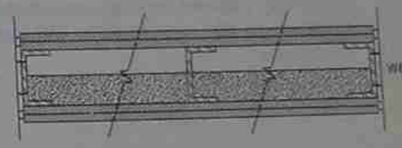
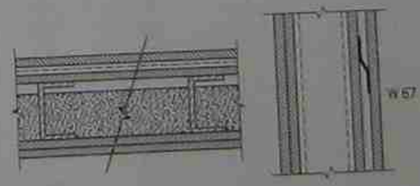
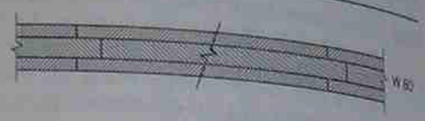
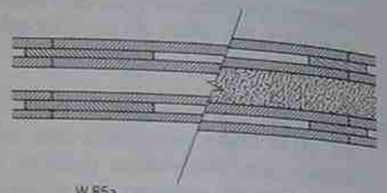
Designation	Description	Section Sketch
Wood Studs; Resilient Mounting		
W39a	2 × 4 in. wooden studs, 16 in. on centers, attached to 2 × 4 in. wooden floor and ceiling plates; resilient channels nailed horizontally to both sides of studs 24 in. on centers, ⅝-in. gypsum wallboard screwed 12 in. on centers to channels. All joints taped and finished.	 W 39a
W40a	2 × 4 in. wooden studs, 16 in. on centers; resilient clips, nailed to studs on both sides, held ⅜-in. gypsum lath, ½-in. sanded gypsum plaster with white-coat finish.	 W 40a
Steel Truss Stud Wall		
W43a	1⅝-in. steel truss studs; ⅜-in. gypsum lath, ½-in. plaster on both sides.	 W 43 W 44
W43b	Similar to W43a except a layer of lead, 2.95 lb/ft², was laminated to one side of partition.	
W43c	Similar to W43a except a layer of lead, 2.95 lb/ft², was laminated to each side of partition.	
W44a	3¼-in. steel truss studs, 24 in. on centers, attached to metal floor and ceiling tracks; on both sides ⅜-in. perforated gypsum lath attached with wire clips wire-tied to studs, ½-in. sanded gypsum plaster.	
Steel Truss Studs; Resilient Mountings		
W50a	2½-in. steel truss studs 16 in. on centers, ⅜-in. gypsum lath attached with resilient clips to studs, ½-in. plaster applied to both sides.	 W 50a

TABLE F.1 **Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)**

Designation	Description	Section Sketch
W52	3¼-in. steel truss studs, 16 in. on center; on each side resilient clips fastened 16 in. on centers to studs, ¼-in. metal rod wire-tied to clips, diamond mesh metal lath wire-tied to metal rods, ¾-in. sanded gypsum plaster.	 W 52
Metal Channel Stud Wall		
W55a	3⅝-in. metal channel studs, 24 in. on centers, set into 3⅝-in. metal floor and ceiling runners; ⅝-in. gypsum wallboard screwed to studs on both sides. All joints taped and finished.	 W 55a
W60	2½-in. metal channel studs, 24 in. on centers, set in 2½-in. metal floor and ceiling runners; ½-in. vinyl-coated gypsum wallboard adhesively attached and screwed to studs on both sides. All joints sealed with caulking compound. Aluminum batten strips screwed 12 in. on centers to gypsum board at joints; top and bottom finished with aluminum ceiling and base trim. 2-in. mineral fiber blankets hung between studs.	 W 60
W63	3⅝-in. metal channel studs, 24 in. on centers, set into 3⅝-in. metal runners, which were attached through continuous beads of nonsetting resilient caulking compound to floor and ceiling, respectively. Two layers of ⅝-in. gypsum wallboard attached to both sides of studs. First layer screwed 8 in. on centers at joints and 12 in. on centers in field; second layer laminated and screwed 24 in. on centers to first layer, with joints staggered 24 in. 1½-in.-thick mineral fiber felt, 3 lb/ft³, stapled between studs. All exposed joints taped and finished. The ¼-in. clearance around the perimeter closed with a nonsetting resilient caulking compound.	 W 63
W67	3⅝-in. metal channel studs, 24 in. on centers, set in 3⅝-in. metal floor and ceiling runners; ⅝-in. gypsum wallboard screwed to studs on both sides. On one side, resilient channels screwed horizontally, 24 in. on centers to inner layer; ⅝-in. gypsum wallboard screwed to channels. On the other side, ⅝-in. gypsum wallboard laminated directly to inner layer. 3-in. mineral fiber blankets hung between studs. All exposed joints taped and finished.	 W 67

APPENDICES

TABLE F.1 **Acoustic Characteristics of Walls: For Other Data See Index F.2 (Continued)**

Designation	Description	Section Sketch
Gypsum Partitions		
W80	24-in.-wide panels constructed of 1 × 24 in. gypsum core board offset 1½ in. at edges to form tongue-and-groove edge; ⅝-in. vinyl-faced gypsum wallboard laminated to both sides of core board. Panels inserted into two-piece metal floor and ceiling tracks. Gypsum to gypsum screws at ¼ and ½ points along vertical edges of face boards.	 W 80
W85a	Double wall with 1⅜-in. air space. Each leaf consisted of 24-in.-wide panels of ⅝-in. gypsum core board strips, 7½ and 4⅜ in. wide, offset 1½ in. at edges to form tongue and groove; ⅝-in., vinyl-faced, gypsum wallboard laminated to both sides of core board strips. Panels screwed 12 in. on centers to 1¼ × 1 in. angle floor and ceiling runners.	 W 85a W 85b
W85b	Similar to W85a except space between leaves was 2⅛ in. and contained 2-in. mineral fiber blankets stapled to one leaf. ¼-in. perimeter clearance closed with a nonsetting resilient caulking compound. Vertical face layer joints sealed with joint compound.	

G

SOUND TRANSMISSION AND IMPACT INSULATION DATA FOR FLOOR/CEILING CONSTRUCTION

To use Appendix G:

1. Find desired construction Type Code in Index G.1 or G.2. Index G.1 lists the constructions by STC. Index G.2 lists the constructions by IIC.
2. Find desired STC/IIC ratings corresponding to selected Type Code.
3. Refer to Table G.1 for details of construction.
4. Refer to Index G.3 for thickness weight, STC, IIC, fire rating, and transmission loss at standard octave midpoints.

INDEX G.1 **Sound Transmission Class: Floor/Ceiling Constructions**

Type Code:

a. *Wooden joist*
b. *Metal joist*
c. *Concrete or masonry*
d. *Plaster ceiling*
e. *Gypsum board ceiling*
f. *With resilient elements*
h. *With carpeting*
i. *With absorbent blankets*
j. *With separate ceiling joists*

STC	IIC	Type	Item No.	STC	IIC	Type	Item No.
55[a]	57[a]	c,d,f	F14	46[a]	42[a]	c,d	F23
54[a]	64[a]	c,d,f	F17b	45	44	a,e,f	F44
52	80	a,e,i,j	F48	44	42	c,f	F3-2d
51[a]	53[a]	c,d,f	F10	44	41	c	F3-1a
51[a]	48[a]	c,d	F7a	44	80	c,h	F2-1a
50[a]	53[a]	c,e,f	F25	44	29	c	F1-c
50[a]	51[a]	c,e	F27	44	25	c	F1a
50[a]	48[a]	c,d	F16	43[a]	43[a]	a,d	F32b
49[a]	48[a]	c,d	F9	42[a]	32[a]	c	F22
48[a]	47[a]	c,d	F12	40	32	a,e,i	F40a
48	33	b,c,d	F60a	39[a]	37[a]	a,e	F34
47	62	b,c,e	F58	37	33	a,e	F38a
47[a]	42[a]	c,d	F24	37	32	a,e	F39a
47	59	b,c,d,h	F57b	34[a]	32[a]	a,e	F30
47	37	b,c,d	F57a	29[a]	32[a]	a,e	F35a
46	74	b,c,d	F60c	29	56	a,e,h	F35b

[a]Field measurement.

EXAMPLE. A standard (simple) wooden joist floor–ceiling construction is required with a minimum IIC of 55. Any STC above 35 is acceptable.

1. Since IIC is the determining factor, refer to Index G.2. Basic Type Code is "a."
2. From index G.2 we note that none of the listed "a" constructions gives an IIC of 55. However, from Section 27.25 we note that the addition of carpeting will add 10 to 27 points to the IIC, making items F34, F38a, F39a, and F30 all suitable. We have discounted special and resilient constructions, because of the requirement for standard (simple) construction.
3. From Table G.1 we select construction F30 as being most appropriate for application of carpeting.
4. From Index G.3 we have (without carpet) thickness 9½ in., STC 34, IIC 32 (+ carpet), fire rating ¼ h. With high pile carpeting on foam rubber pad, this construction will have IIC > 55, STC > 35.

INDEX G.2 **Impact Insulation Class: Floor/Ceiling Constructions**

Type Code:

a. *Wooden joist*
b. *Metal joist*
c. *Concrete or masonry*
d. *Plaster ceiling*
e. *Gypsum board ceiling*
f. *With resilient ceiling element*
g. *With resilient floor element*
h. *With carpeting*
i. *With absorbent blankets*
j. *With separate ceiling joists.*

IIC	STC	Type	Item No.	IIC	STC	Type	Item No.
80	52	a,e,h,i,j	F48	44	45	a,e,f	F44
80	44[b]	c,h	F2-1a	43[a]	43[a]	a,d,g	F32b
74	46	b,c,d,h	F60c	42[a]	47[a]	c,d	F24
64[a]	54[a]	c,d,g	F17b	42[a]	46[a]	c,d	F23
62	47	b,c,e,h	F58	42	44[b]	c,g	F3-2(d)
59	47[b]	b,c,d,h	F57b	41	44[b]	c	F3-1(a)
57[a]	55[a]	c,d,g	F14	37	47	b,c,d	F57a
56[a]	29[b]	a,e,h	F35b	37[a]	39[a]	a,e	F34
53[a]	51[a]	c,d,g	F10	33	48	b,c,d	F60a
53[a]	50[a]	c,e,g	F25	33	37	a,e	F38a
51[a]	50[a]	c,e	F27	32[a]	42[a]	c	F22
48[a]	51[a]	c,d	F7a	32	40	a,e,i	F40a
48[a]	50[a]	c,d	F16	32	37	a,e	F39a
48[a]	49[a]	c,d,g	F9	32[a]	34[a]	a,e	F30
47[a]	48[a]	c,d	F12	32[a]	29[a]	a,e	F35a
				29	44[b]	c	F1c
				25	44	c	F1a

[a]Field measurement.
[b]Estimated on the basis of similar structures.

INDEX G.3 **Floor/Ceiling Sound Transmission and Construction Data**

Designation[a]	Thickness (in.)	Weight (lb/ft²)	Transmission Loss (db) 125	250	500	1K	2K	4K	STC	IIC	Fire Rating (h)
F1a	4	53	59	67	75	78	77	75	44	25	1
F1c	4⅛	54	59	66	73	76	74	—	44	29	1
F2-1(a)	4⅜	54	38	36	32	23	—	—	44	80	1
F3-1(a)	4½	55	59	64	58	42	26	—	44	41	1
F3-11(d)	4⅛	53	65	67	72	67	48	40	44	42	1
F7a	5½	61	66	70	68	66	59	37	51	48	2
F9	6⅝	65	63	69	71	68	55	38	49	48	2
F10	8¼	90	60	61	59	54	45	—	51	53	2½
F12	10	62	68	65	67	66	61	50	48	47	3
F14	9½	83	59	58	55	48	42	—	55	57	3
F16	8⅛	65	56	60	60	62	54	—	50	48	2
F17b	9¼	57	56	50	44	40	30	—	54	64	2
F22	6¼	28	76	69	80	79	75	—	42	32	¾
F23	9½	45	71	73.5	72	71	66	54	46	42	¾
F24	10¼	65	67	66	67	66	62	—	47	42	¾
F25	10	45	65	61	57	51	39	—	50	53	¾
F27	7⅝	50	62	66	61	58	46	—	50	51	¾
F30	9½	7	79	79	80	76	69	—	34	32	¼
F32b	11	12	69	72	68	64	55	—	43	43	¾
F34	10¼	9.9	83	80	71	57	52	45	39	37	1
F35a	10	9.2	83	83	72	54	52	43	29	32	—
F35b	10	9.2	58	44	38	24	23	—	29	56	—
F38a	11¾	9	86.5	85.5	85	80	68.5	—	37	33	½
F39a	11⅞	9.5	80	80	81	71	66	58	37	32	1
F40a	11⅞	10	78	84	80	70	65	58	40	32	1
F44	10½	10.1	71	74	70	63.5	61	—	45	44	¾
F48	12⅜	10.7	34	28	20	17	18	—	52	80	¾
F57a	18⁹⁄₁₆	23.2	79	72	72	70	63.5	—	47	37	3
F57b	18⁹⁄₁₆	23.2	59	43	32	18	—	—	47	59	3
F58	21½	20.4	56	41	33	23	17	—	47	62	1
F60a	11	38.2	66	68.5	74	76	75	—	48	33	1½
F60c	11⅝	39	46	38	33.5	25	20	9	46	74	1½

[a]Material extracted from *A Guide to Airborne, Impact and Structure-Borne Noise Control in Multi-Family Dwellings*, HUD/FHA/NBS, 1971.

APPENDICES

TABLE G.1 **Acoustic Characteristics of Floors: For Acoustic Data see Index G.3**

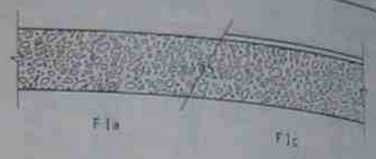
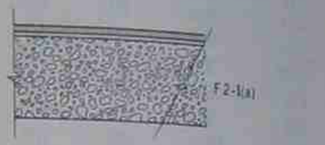
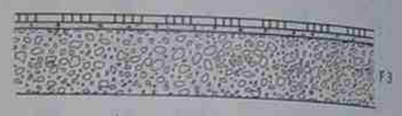
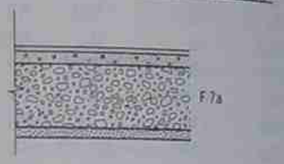
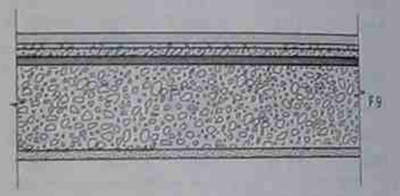
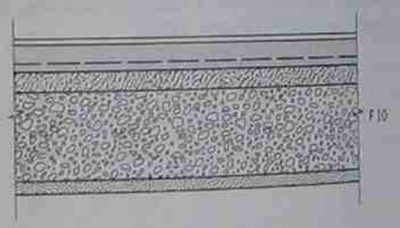
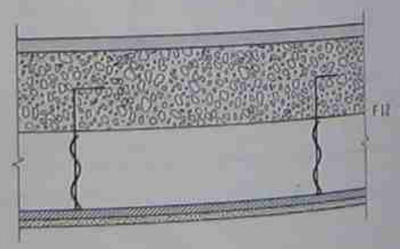
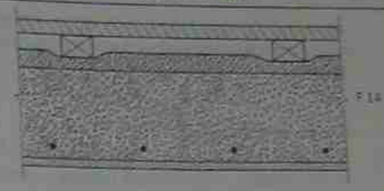
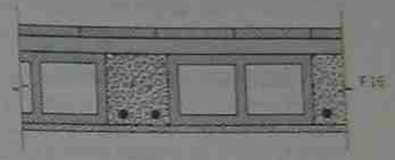
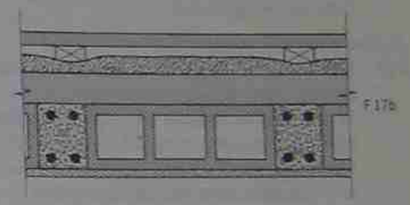
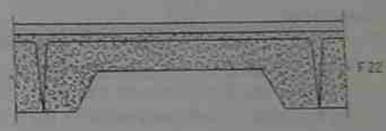
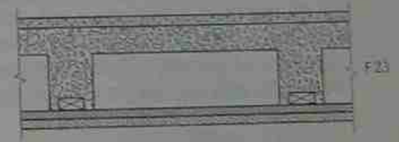
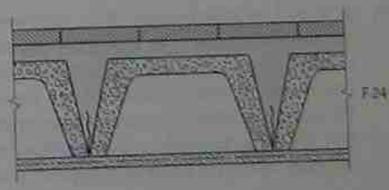
Code[a]	Description	Section Sketch
	Reinforced Concrete Slab	
F1a	4-in.-thick reinforced concrete slab, isolated from support structure. Concrete was reinforced with 6 × 6 in. No. 6 AWG reinforcing mesh placed at the centerline horizontal plane of the slab. All surface cavities were sealed with a thin mortar mix.	 F1a F1c
F1c	Same as F1a except ⅛-in.-thick vinyl tile was adhered to concrete.	
	Reinforced Concrete with Floor Coverings	
	See also F1c above.	
F2-1(a)	4-in.-thick reinforced concrete slab with carpeting and pad. The carpeting was of ¼-in. wool loop pile with ⅛-in. woven jute backing, 0.49 lb/ft²; the foam rubber pad was ¼ in. thick and weighed 0.53 lb/ft².	 F2-1(a)
F3-1(a)	4-in. reinforced concrete slab with ½ × 9 × 9 in. oak blocks, 1.8 lb/ft², set in mastic.	 F3
F3-2(d)	4 in. concrete slab with ⅛-in. cork.	
F7a	4⅜-in.-thick reinforced concrete slab. On the floor side, ¾-in.-thick, sand-cement screed with ⅛-in. linoleum floor covering. On the ceiling side, ⅜-in. layer of plaster.	 F7a
F9	4⅜-in.-thick reinforced concrete slab. On the floor side, ½-in.-thick layer of bitumen with ½-in.-thick soft wood fiberboard, which was covered with a thin layer of bitumen with sand and a ¾-in.-thick sand-cement screed. On the ceiling side ⅜-in. layer of plaster.	 F9
	Reinforced Concrete Slab, Floating Floor	
F10	5-in.-thick reinforced concrete. On the floor side, 1½-in.-thick wire mesh reinforced sand-cement screed floating on ½-in.-thick bitumen-bonded, glass-wool quilt covered with building paper. On the screed, ½-in.-thick pitch-mastic with a linoleum floor covering. On the ceiling side, ½-in. layer of plaster.	 F10
F12	4⅜-in.-thick reinforced concrete slab. On the floor side, ¾-in.-thick sand-cement screed. On the ceiling side, brick wire mesh, suspended 4 in. with wire hangers, held ⅞-in. gypsum plaster.	 F12

TABLE G.1 **Acoustic Characteristics of Floors: For Acoustic Data see Index G.3 (Continued)**

Code[a]	Description	Section Sketch
F14	6-in.-thick reinforced concrete slab. On the floor side, ¾-in.-thick tongue-and-groove wood flooring nailed to 1½ × 2 in. wooden battens, 16 in. on centers, floating on 1-in.-thick, glass-wool quilt. On the ceiling side, ½-in. layer of plaster.	 F14
	Concrete with Hollow Blocks	
F16	5 × 10 in. hollow masonry blocks, 14 in. on centers, with spaces between blocks filled with 5-in.-thick reinforced concrete. On the floor side, ⅞-in.-thick wood blocks adhered to 1½-in.-thick, sand-cement screed. On the ceiling side, ¾-in. layer of plaster.	 F16
F17b	4 × 12½ in. hollow masonry blocks, 15½ in. on centers, with spaces between blocks filled with 4-in.-thick reinforced concrete. On the floor side, 2-in.-thick, sand-cement screed; linoleum on 1-in.-thick wood flooring nailed to 1 × 2 in. wooden battens, spaced 15½ in. on centers, floating on glass-wool quilt, approximately 1 in. thick. On the ceiling side, ¾-in. layer of plaster.	 F17b
	Concrete Channel Slab	
F22	Prefabricated concrete channel slabs mortared together 20 in. on centers. Each slab had a 3-in.-deep trapezoidal channel with bases of 11 and 14¾ in. On the floor side, ¾-in.-thick, sand-cement finish.	 F22
	Ribbed Concrete	
F23	7¼-in. ribbed concrete floor. Ribs were 5¼ × 3¾ in., spaced 21 in. on centers, with 1 × 2 in. wooden nailing strips cast into ends. On the floor side, the slab was 2 in. thick with a ¾-in.-thick, sand-cement screed. On the ceiling side, ⅝-in.-thick wooden laths nailed to nailing strips, held ⅝-in.-thick plaster.	 F23
	Concrete Channel Beam	
F24	7-in. precast trapezoidal concrete channel beams, 14 in. on centers, with spaces between beams filled with sand-cement mix. On the floor side, 1½-in.-thick, sand-cement screed with 1-in.-thick, wood-block floor	 F24

APPENDICES

TABLE G.1 Acoustic Characteristics of Floors: For Acoustic Data see Index G.3 (Continued)

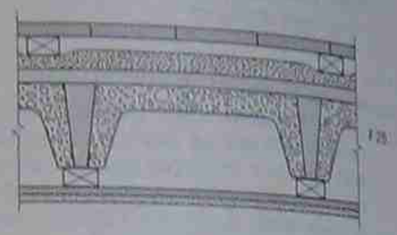
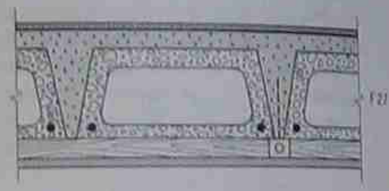
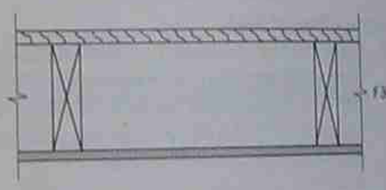
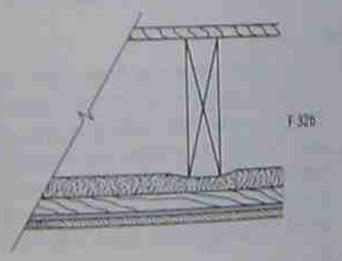
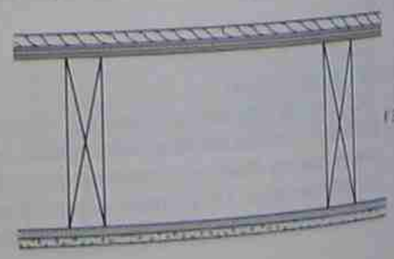
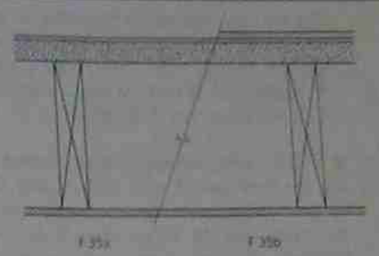
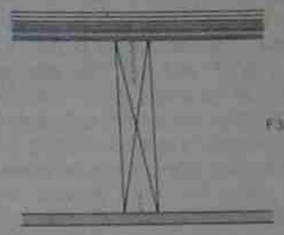
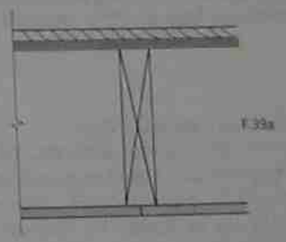
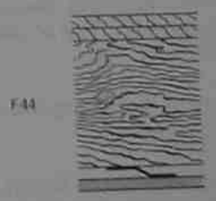
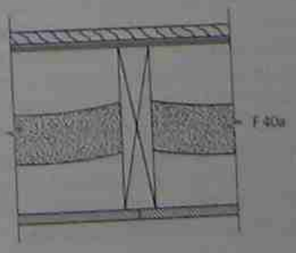
Code*	Description	Section Sketch
	covering. On the ceiling side, approximately ¾-in.-thick layer of plaster on expanded metal lath.	
	Precast Concrete Beam, Floating Floor	
F25	5-in. precast concrete channel beams, 14½ in. on centers, with spaces between beams filled with a sand-cement mix. On the floor side, ⅞-in.-thick, tongue-and-groove wood flooring nailed to 1 × 2 in. wooden battens, 20 in. on centers, on approximately 1-in.-thick, glass-wool quilt on ¾-in.-thick, sand-cement screed. On the ceiling side, ⅞-in. layer of plaster on ⅜-in. gypsum wallboard nailed to 1 × 2 in. wooden battens spaced 14½ in. on centers.	 F25
	Hollow Concrete Beam	
F27	5-in. precast trapezoidal hollow concrete beams, 14½ in. on centers, with bases of 14 and 12½ in. Spaces between beams filled with sand-cement mix. On the floor side, 1-in.-thick, sand-cement screed with 3/16-in. cork tile floor covering. On the ceiling side, ⅜-in.-thick gypsum wallboard attached to 1 × 2 in. wooden battens held by metal clips.	 F27
	Wooden Joist	
F30	2 × 8 in. wooden joists 16 in. on centers. On the floor side, ⅞-in., tongue-and-groove flooring nailed to joists; on the ceiling side, ⅜-in. gypsum wallboard nailed to joists with joints sealed.	 F30
F32b	2 × 8 in. wooden joists 18 in. on centers. On the floor side, ⅞-in., tongue-and-groove wood flooring nailed to joists. On the ceiling side, 1-in. battens nailed through glass-wool quilt, approximately 1 in. thick; ½-in. layer plaster on ¼-in.-thick wood lath.	 F32b
F34	2 × 8 in. wooden joists, 16 in. on centers. On the floor side, ½-in.-thick C-D plywood nailed 8 in. on centers to joists, 25/32-in.-thick hard wood flooring on plywood. On the ceiling side, ½-in.-thick gypsum wallboard nailed 6 in. on centers to joists. All joints taped and finished; ceiling tile adhered to gypsum board.	 F34

TABLE G.1 Acoustic Characteristics of Floors: For Acoustic Data see Index G.3 (Continued)

Code*	Description	Section Sketch
F35a	2 × 8 in. wooden joists, 16 in. on centers. On the floor side, 1⅛-in.-thick, tongue-and-groove wood fiberboard nailed to joists, vinyl tile floor covering. On the ceiling side, ½-in.-thick gypsum wallboard nailed 6 in. on centers to joists. All joints taped and finished.	 F35a F35b
F35b	Similar to F35a except fiberboard covered with carpet and pad.	
F38a	2 × 10 in. wooden floor joists spaced 16 in. on centers. ⅝-in. fir plywood subfloor nailed to joists 8 in. on centers; ½-in. plywood underlayment nailed to subfloor with joints staggered to miss joints of the subfloor; ⅛ × 9 × 9 in. vinyl asbestos tile glued to underlayment. On the ceiling side, ½-in. gypsum wallboard nailed 12 in. on centers with all joints and nailheads taped and finished.	 F38a
F39a	2 × 10 in. wooden joists 16 in. on centers. On the floor side, ½-in.-thick plywood subfloor nailed 6 in. on centers along edges and 10 in. on centers in field, building paper underlayment, 25/32 × 2¼ in. oak wood flooring nailed at each joist intersection and midway between joists. On the ceiling side, ⅝-in.-thick gypsum wallboard, nailed 6 in. on centers to joists. All joints taped and finished.	 F39a
	Wooden Joist, Resilient Ceiling	
F44	2 × 8 in. wooden joists 16 in. on centers. On the floor side, ¾-in.-thick wood subfloor, layer of building paper, and ¾-in.-thick tongue-and-groove fir finish flooring. On the ceiling side, resilient runners bridged across joists and nailed 12 in. on centers to joists; ⅝-in.-thick gypsum wallboard screwed to resilient runners. All joints taped and finished.	 F44
	Wooden Joist with Insulation	
F40a	2 × 10 in. wooden joists 16 in. on centers with 3-in.-thick mineral fiber batts stapled between joists. On the floor side, ½-in.-thick plywood subfloor nailed 6 in. on centers along edges and 10 in. on centers in field, building paper underlayment, 25/32 ×	 F40a

APPENDICES

TABLE G.1 Acoustic Characteristics of Floors: For Acoustic Data see Index G.3 (Continued)

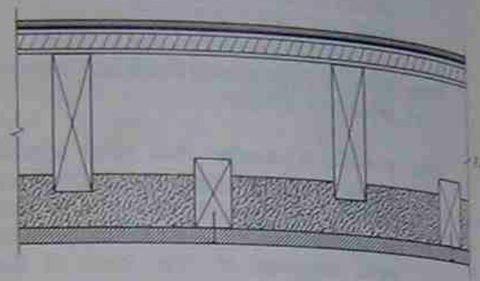
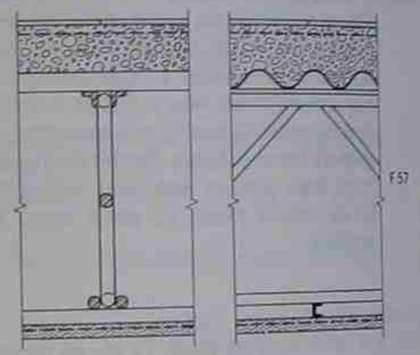
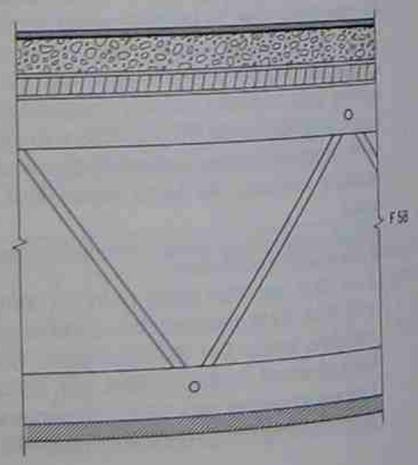
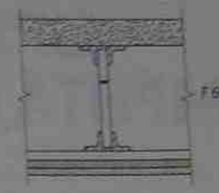
Code[a]	Description	Section Sketch
	2¼ in. oak wood flooring nailed at each joist intersection and midway between joists. On the ceiling side, ⅝-in.-thick gypsum wallboard nailed 6 in. on centers to joists. All joints taped and finished.	
F48	2 × 8 in. wooden joists, 16 in. on centers. On the floor side, 1⅛-in.-thick regular C-D rough plywood nailed 6 in. on centers along periphery and 16 in. on centers at other bearings, plywood covered with an all-hair pad (40 oz/yd²) and all-wool pile (44 oz/yd²) carpet. The total weight of the carpet was 4.14 lb/yd² and the total thickness was ⅜ in. On the ceiling side, 2 × 4 in. wooden joists, 16 in. on centers, staggered 8 in. on centers relative to the floor joists, 3-in.-thick fibered glass blankets stapled between ceiling joists, ⅝-in.-thick gypsum wallboard nailed to ceiling joists. All joints taped and finished; entire periphery of panel caulked and sealed. The ceiling was supported independently from the floor structure.	
	Steel Joist with Concrete Floor	
F57a	2½-in.-thick perlite concrete, 72 lb/ft³ on 28-gauge corrugated steel units supported by 14-in. steel bar joists; ⅛-in.-thick asphalt tile cemented to concrete. On the ceiling side, ¾-in. furring channels, 13½ in. on centers, wire-tied to joists, 3.4 lb/yd² diamond mesh metal lath wire-tied to furring channels, 9/16-in. coat of plaster with 1/16-in., white-coat finish.	
F57b	Same as F57a except carpet and pad in lieu of asphalt tile.	
F58	18-in. steel joists 16 in. on centers. On the floor side, ⅝-in.-thick C-D rough plywood nailed to joists, 1⅝-in.-thick foamed concrete, 100 lb/ft³, slab constructed on the plywood; concrete covered with an all-hair pad (40 oz/yd²) and an all-wool pile (44 oz/yd²) carpet. Total weight of the carpet, 4.14 lb/yd², total thickness, ⅜ in. On the ceiling side, ⅝-in.-thick gypsum wallboard nailed to joists. All joints taped and finished; entire periphery of panel caulked and sealed.	

TABLE G.1 Acoustic Characteristics of Floors: For Acoustic Data see Index G.3 (Continued)

Code[a]	Description	Section Sketch
F60a	7-in. steel bar joists spaced 27 in. on centers. On the floor side, ⅜-in. metal rib lath attached to top of joists, and 2-in.-thick poured concrete floor. On the ceiling side, ¾-in. metal furring channels wire-tied to joists 16 in. on centers; ⅜ × 16 × 48 in. plain gypsum lath held with wire clips and sheet metal end joint clips; 7/16-in. sanded gypsum plaster and 1/16-in., white-coat finish.	
F60c	Structure F60a with nylon carpeting and foam rubber pad placed on the floor. The carpet pad had an uncompressed thickness of ¼ in., backed with a woven jute fiber cloth. The carpet had ⅛-in. woven backing and ¼-in. looped pile spaced 7 loops per inch with a total thickness of ⅜ in.	

[a]Material extracted from *A Guide to Airborne, Impact and Structure-Borne Noise Control in Multi-Family Dwellings*, HUD/FHA/NBS, 1971.

H

OPTIONS FOR COMPUTATION ASSISTANCE

This book presents "manual" calculation procedures—simple enough to require only a hand-held calculator and an informed and patient user. It is by now obvious, however, that some very time-consuming procedures are required for the detailed environmental analysis of buildings. If a machine can be made to perform repetitious calculations automatically, its human user can be freed to do higher-grade tasks. Three degrees of such automatic computation assistance are available. In order of increasing complexity, they are the handheld *programmable calculator*, the *micro-* (or "personal") *computer*, and the *mainframe computer*. It is important to realize that with each step toward greater complexity, the user gets faster and more thorough analysis. But each step also requires a greater purchase cost for the hardware (machine) and greater training time for the user—whether to learn how to run the software (prepared programs, which are themselves more expensive with each step) or to learn how to program the machine. There is also decreasing mobility with each step. Hand-held calculators may be small enough to carry in a wallet, and programmable calculators (which should be accompanied by a printer unit) can be stuffed into a briefcase. Some personal computers are portable, but again, the question of a printer unit arises. Mainframe computers may be accessible by telephone line, but printed analysis requires access to fixed-in-place equipment. Finally, with each step, a typical user of prepared software becomes more remote from the calculation process—for better or for worse.

The point of this introduction, then, is to help you select the appropriate tool for the task. Quick approximations require no more than a hand-held calculator; thorough analysis of many alternative designs for a given problem will be more efficiently done with automatic computation.

There is a rapidly growing array of software for the automatic calculations associated with building energy performance. Table H.1 presents a guide to the selection of software for building thermal analysis. If your architectural idea cannot be reduced to numbers, it cannot be assisted by computer analysis.

H.1 Hand-Held Calculators

This book presents manual procedures that require a common device, the hand-held calculator. It should have trigonometric functions and one or two memories. For acoustics, logarithms are essential as well. Powered by batteries or by photovoltaic cells, hand-held calculators are truly portable, and inexpensive enough for every professional to own at least one.

H.2 Microcomputers

These machines are commonplace in architectural offices, since their services include word processing, graphics, billing, and other project management functions in addition to their role in a building's technical analysis. There are three broad categories of microcomputer software available for building design assistance:

1. *Specific issue design tools*
   This software is aimed at particular issues such as thermal analysis, daylighting, acoustics, fire protection, etc., that arise during the design process. Some programs overlap between issues; relating daylighting to thermal performance is particularly common.
2. *Compliance tools*
   Some state governments certify software that demonstrates how a building design complies with the state energy code; this can include thermal, lighting and electrical criteria.
3. *Whole-building design tools*
   These are performance simulations, usually concerned with energy consumption. Preliminary design tools can work with rules-of-thumb that yield approximate results, quickly guiding the designer to more efficient solutions. The tools for evaluating a finished building design include both monthly and yearly energy consumption and life-cycle costs.

Table H.1 **Considerations in Choosing Computer Software for Heating or Cooling Analysis**

Part A. Facts and Figures
- Package name and version
- Price
- Systems available for (applications)
- Required supporting software
- Memory requirements
- Diskette capacity required
- Utility programs included
- Internal format, records, types
- Portability
- User skill level required
- System upgrade policy and cost

Part B. Qualitative Factors
- Documentation
  - Organization for learning—tutorials, examples
  - Organization for reference
  - Readability
  - Includes all needed information
  - Table of contents and index
- Menus (optional)
  - Ease of use
  - Includes all needed information
- Ease of use
  - Initial startup and installation
  - Conversion of external data
  - Operator use
  - Application implementation (speed, accuracy, etc.)
- Error recovery
  - From input error
  - Restart from interruption
  - From data media damage (bad disk)
- Support
  - For initial startup
  - For system improvement

Part C. Technical Factors
- General technical user concerns
  - Speed and convenience
  - Validity and accuracy
  - Ability to modify analysis
  - Source code availability
- Building types
  - Residential buildings
  - Commercial and nonresidential buildings
  - Underground or below-grade considerations
  - Special conditions
- Weather and climate
  - Weather data source
  - Availability of weather data files
  - Ease of generating weather data
- Building or system loads analysis
  - Method of analysis
  - Orientation and shading
  - Number of building zones
  - Building schedules and internal gains
  - Temperature setpoints and deadbands
- Solar features or systems analysis
  - Method of analysis
  - Orientation and shading
  - System types modeled
  - Component properties and ranges
  - Multiple solar features
  - System limitations
- Report generation
  - Summary and detail report formats
  - Flexibility of report formats
  - Ability to generate custom reports
  - Ability to print reports to disk files
- Special features
  - Supports graphics output
  - Terminals supported
  - Printers or plotters supported
  - Other special features

Source: M. Steven Baker, *Computer-Aided Solar Design* presentation at Oregon Solar Conference, September 1984.

APPENDICES

The following list of software sources and programs in each of the above categories is presented in the approximate order in which these issues are encountered within this text—that is, design strategies first, acoustics last. We recognize the danger of immediate obsolescence of such lists.

(a) Design Strategies

CLIMATE CONSULTANT. Prof. Murray Milne, Graduate School of Architecture, UCLA. 405 Hilgard Avenue, Los Angeles, California, 90024-1467. A detailed data base which can be queried by users, this is a sophisticated elaboration on the climate design strategy method given in Figs. 2.9 and 2.10.

(b) Solar Position and Performance

CALPAS. Berkeley Solar Group, 454 Santa Clara Ave., Oakland, California, 94610. A series of programs for daylighting, passive and other thermal analysis. Available for the IBM PC. The buyer receives the program, user's manual, one year of user support services, a full-day seminar, five weather files, and a newsletter. (A mainframe computer subscription service is also available.)

F-CHART. F-Chart Software (4406 Fox Bluff Rd., Middleton, WI 53562). The programs allow analysis of four collector types and eight system types (including passive direct gain and storage wall systems). They run on either Apple or IBM machines.

UISUN. Prof. Bruce Haglund, Department of Architecture, University of Idaho. Moscow, Idaho, 83843. Rapid feedback to designers of passive solar heated buildings, using rule-of-thumb assumptions early on, more detailed data later in the design process. Performs the detailed Solar Load Ratio analysis (for which Appendix C is an approximation) to obtain Solar Savings Fraction. Runs on IBM compatible machines.

MICROPAS. Enercomp, Inc., 123 C Street, Davis, California, 95616. This is an hourly simulation of energy performance for residential and small commercial buildings. It runs on IBM PCs.

SOLAR 5. Prof. Murray Milne, Graduate School of Architecture, UCLA. 405 Hilgard Avenue, Los Angeles, California, 90024-1467. Using information about the climate, orientation, geometry and shading configuration, users get a three-dimensional plot of building energy performance.

SUNDAY. Ecotope, Inc., 2812 E. Madison, Seattle WA 98112. This daily building load simulation gives surprisingly accurate yearly results for a relatively quick and simple program. It is particularly applicable to superinsulated, direct gain solar or conventional buildings designs.

SUNPATCH. P.O. Box 14523, San Luis Obispo, California. Cal Poly Prof. David Lord developed this program that both calculates sun position and illustrates sun penetration, for as many as 32 windows simultaneously.

AESOP. Designers Software Exchange, Graduate School of Design, Harvard University, Cambridge MA 02138. Used for designing an exterior shading device, the program also calculates sunrise, sunset, and solar position.

(c) HVAC.

HVAC&R Software Directory

ASHRAE, 1791 Tullie Circle, Atlanta, Georgia 30329. An annual bibliography of computer programs in heating, ventilating, air-conditioning and refrigerating.

(d) Fire Protection

HAZARD 1.0. One-Stop Data Shop, National Fire Protection Association. Batterymarch Park, Quincy, Mass., 02269. The user specifies the fire and its growth, the building and its characteristics, occupants' locations and characteristics. The program then calculates the development of fire effects over time, occupant behaviors, activation of detectors, and predicted fatal injury or survival of every occupant.

(e) Daylighting.

MICROLITE 1.0.

Designers Software Exchange (DSE), Graduate School of Design, Harvard University, Cambridge, MA 02138. Calculates illuminance or daylight factor at any point within a room, utilizing sky component (SC) and reflected components (IRC and ERC).

SUPERLITE 1.01.

Distributed by J. J. Kim, School of Architecture, Arizona State University, Tempe, AZ 85287. Versions for PC and mainframe. Accepts nonrectangular spaces, side lighting and skylights, clear and overcast sky, light shelves and overhangs, and exterior obstructions. PC version yields only numerical results; mainframe version also produces contour plots.

(f) Lighting. There are many good lighting programs available today that will perform all of the required calculations rapidly and accurately. Some will also plot output in a variety of forms and a few will produce three-dimensional graphics. Indeed, because of the very wide choice available the lighting designer seeking to acquire a program should have guidelines by which to make a selection. One interesting fact is that some lighting manufacturers make excellent programs available free of charge. These programs usually come with a complete data base containing the manufacturer's fixtures. However, a few of these programs permit users to enter their own data, and by so doing the program becomes nonproprietary. A few important characteristics to look for when selecting a program are:

1. Clearly written adequate documentation.
2. Menu driven.
3. Data entry echo and printout.
4. Capability to stop at any point and continue at a later date, without data loss.
5. Clear error messages in plain English.
6. Large-capacity data base, with capability of machine reading of IES format files.
7. Rapid calculation of both zonal cavity and point illuminance, surface exitances, ESI, VCP.
8. Capability of considering several fixture types per area and of subdividing large areas.
9. Capability of calculating coefficients from candela data, and printing CU table.
10. Perform annual-owning and life-cycle cost analysis.
11. Produce graphic output in the form of isolux maps, shaded graphics, fixture layout.
12. Automatic periodic saves.

A few readily available programs:

1. LUMEN-MICRO, LUMENS, LUMEN DATA, LUMEN POINT. Lighting Technologies, 2540 Frontier, Suite 107 Boulder, CO 80301-2458. A very comprehensive group of sophisticated lighting analysis programs for interior and exterior lighting. Zonal cavity and point-by-point interior lighting calculations, and point exterior calculations. Built-in plus user-created data base, economic analyses, VCP, RVP, ESI, exitance calculations, contouring, and shaded perspective graphics of interior illuminances.

2. ICON/ECON. Cooper Lighting, POB 1207, Americus, GA 31709. Zonal cavity, indoor point-by-point illuminance, ESI, LEF, VCP. Printout of proportionally spaced fixture rows. Exterior area, street, and floodlighting calculations.

3. LIGHT. Elite Software, POB 1194, Bryan, TX 77806. Zonal cavity calculations, economic analyses with modified life-cycle calculations. Accepts user photometrics.

4. CALA (Computer Aided Lighting Analysis). Holophane Division, Manville Sales Corporation, 214 Oakwood Avenue, Newark, OH 43055. Comprehensive interior calculations including zonal cavity and point-by-point, plus drawing plan and perspective views. Exterior point calculations; area and floodlighting. Built-in plus user photometric data base.

5. Data*Light 1. General Electric, Lamp Technical Services, Nela Park, OH 44112. Specialized program for calculation of lighting levels using MR-16 halogen sources.

6. POINT; ISOPOINT. Lighting Analysts Inc., 10572 Mountain Road, Littleton, CO 80127. Interior and exterior point calculations;

interior without interflectance. Isolux (isofootcandle) charts for any fixture in data base. User photometrics.

7. MICRO-SITE-LITE, MICRO-EYE-LITE, MICRO-COST-LITE. Lighting Sciences, Inc., 7830 East Evans Road, Scottsdale, AZ 85260. A family of computer programs for indoor and outdoor lighting analyses. Point calculations, user photometrics, cost comparisons, and tabular/graphic output of illuminance, exitance, ESI, VCP, RVP.

8. CALFS. Rosser Fabrap International, 524 Peachtree Street, Atlanta, GA 30308. Specialty lighting program whose purpose is to produce lighting fixture schedules. Extensive data base provides alternative luminaires for the specified unit.

9. LUM-H. Globe Lighting, Gardena, CA. Calculates zonal cavity illuminances, utilization, and exitance coefficients when zonal flux is input. Accepts user photometrics. Also does basic cost analyses.

10. PHOTO TOOLS. Chas. H. Loch, 2726 Winding Trail Place, Boulder, CO 80302. A series of photometric utilities that produce a complete photometric luminaire report, including polar candela plots, cd table, CU table, and roadway luminaire data.

(g) Acoustic.

From TPM Software, POB 77, Cabin John, MD 20818.

1. TL/STC: for computing and modeling sound transmission loss and STC.
2. OPTRT 60: for computing the absorption and reverberation times of an enclosed space.
3. DNLAIR, DNLROAD: community noise calculation and assessment.
4. AISI: evaluation of Articulation Index (AI) and Speech Intelligibility (SI) for open and confined spaces.

(h) Graphic Plots

MATLAB. The Math Works, Inc., 21 Eliot Street, South Natick MA 01760. Contains graphics utility for performing contour and three-dimensional mesh plots with user-defined parameters.

(i) Compliance Tools

WATTSUN. Washington State Energy Office, 809 Legion Way S.E., Olympia, Washington 98504-1211. This calculates heat loss and provides annual space heating energy budget, to demonstrate compliance with several Pacific northwest jurisdictions.

CALRES. California Energy Commission, Publications Unit 1516 9th Street, Sacramento, California 95814. Calculates the annual heating and cooling energy use for residence designs, including the effects of solar gain and thermal mass, to demonstrate compliance with California's energy code.

(j) Whole-building Tools

ADM-DOE. ADM Associates, Inc., 3299 Ramos Circle, Sacramento, California 95827. A microcomputer translation of the mainframe DOE-2 series, which is described in Section H.3.

MICRO-DOE2. Acrosoft International Inc., 9745 East Hampden Avenue, Suite 230, Denver, Colorado 80231. Another microcomputer translation of the mainframe DOE-2 series.

H.3 Mainframe Computers

Most universities, many municipal governments, and some larger architectural firms own these machines. Many other professionals buy access to big computers through time sharing. The more complicated thermal analysis programs require extensive training for operators, and as much as several days to generate the input data. When a detailed performance comparison is required for several alternative designs on larger buildings, these programs are appropriate.

Most mainframe computer programs for thermal analysis require hourly data for input; this usually requires the purchase of a tape of data for a typical meteorological year (TMY), available from the U.S. Department of Commerce, National Climatic Center (Asheville, NC 28801)

for a variety of locations. The resulting energy analysis is thus based on a very detailed, sequential analysis of the building's use of energy for all purposes. As can be imagined, considerable detail about the building's configuration and equipment must be included as input for this analysis.

The most widely used of the mainframe computer programs include:

DOE series, often considered the standard evaluation technique; contact National Energy Software Center, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.

BLAST series (Building Loads Analysis and System Thermodynamics); contact BLAST Support Office, 1206 West Green Street, Urbana, IL 61801. (These programs have been compared in an analysis done at the Solar Energy Research Institute, Golden, Colorado.)

CALPAS series, developed by the Berkeley Solar Group, at the address listed in Section H.2.

TRNSYS, a detailed simulation program for active solar systems, developed at the Solar Energy Laboratory, University of Wisconsin, Madison.

SUPERLITE, which includes daylighting in overall energy analysis; developed at the Lawrence Berkeley Laboratory, Berkeley, California. The microcomputer version is described in Section H.2.

Again, these large, detailed, complex programs are not for the casual user. It is more likely that a consulting engineer rather than an architect will utilize them. They represent a sophisticated opportunity for analyzing energy performance and choosing between alternative designs.

REFERENCES

ASHRAE (1990). *ASHRAE Journal's HVAC & R Software Directory*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga.

F-Chart Software (1980). *Solar Energy Programs*. F-Chart Software, 4406 Fox Bluff Road, Middleton, WI 53562.

Novitski, B. J. (1991). "Energy Conservation Software," in *Architecture*, May 1991, Affiliated Publications, New York.

The DOE-2 User News, The Simulation Research Group, Applied Science Division, Lawrence Laboratory, Berkeley California.

I

METRICATION; SI UNITS; CONVERSIONS

I.1 General Comments on Metrication

The building profession has been slower than most in adopting the metric (more accurately the Système International, i.e., SI) system of units for many reasons, a discussion of which is not relevant here. The change will come. Many of the major professional societies use a mixture of both systems because certain units are so entrenched that changing them is an almost insurmountable task. However, the advantages of the SI system are well known to all and need no justification here. In this book we have followed current industry practice—a mixture of the two systems. For this reason tables of conversions and approximations are presented below to enable the reader to live with both systems. Also given below are some useful facts that should make use of the SI (metric) system a bit easier.

I.2 SI Nomenclature, Symbols

For a full discussion of the SI system the reader is referred to *AIA Metric Building and Construction Guide*, edited by S. Braybrooke (Wiley, New York, 1980). The units in common use include the basic SI units; meter, kilogram, and second (MKS), plus a host of derived, supplementary, and non-SI units such as pascal (pressure), radian (solid angle), and kilowatt-hour (energy), respectively. Also, multiple and submultiple units such as liter, metric ton, and millibar are so common that they stand as separate units instead of being expressed as 10^{-3}m, 10^{3}kg and 10^{-2}Pa. For this reason we omit a detailed analysis of the subject and simply supply data that by experience we have found useful.

Table I.1 lists prefixes with their accepted symbols. Symbols do not change in plural. That

TABLE I.1 **These Prefixes May Be Applied to All SI Units**

Multiples and Submultiples	*Prefixes*	*Symbols*
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M[a]
1 000 = 10^{3}	kilo	k[a]
100 = 10^{2}	hecto[b]	h
10 = 10	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c[a]
0.001 = 10^{-3}	milli	m[a]
0.000 001 = 10^{-6}	micro	μ[a]
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p

[a]Most commonly used.
[b]A hectare is a square hectometer (i.e., 10^{4} m^{2}).

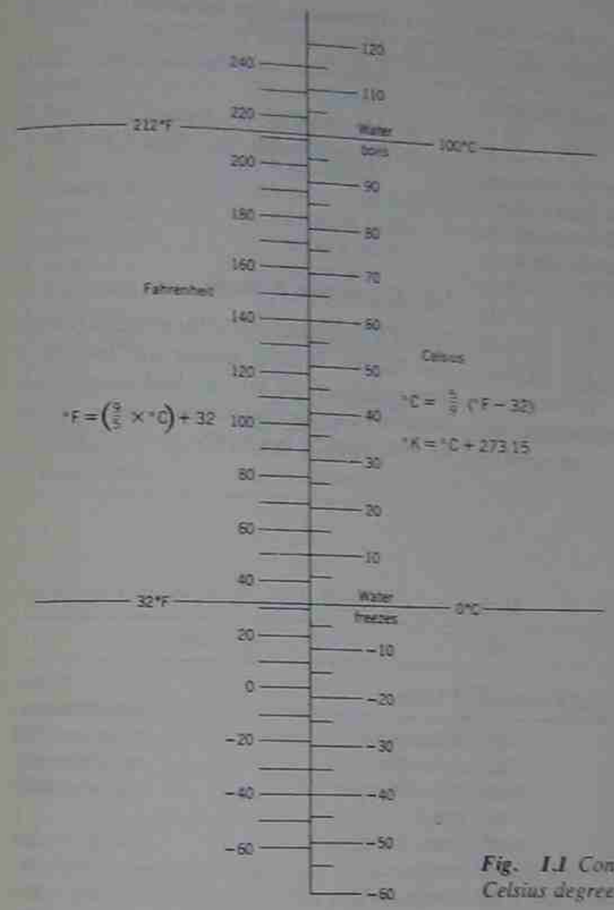


Fig. I.1 Conversion: Fahrenheit degrees–Celsius degrees.

is, 6 millimeters is written 6 mm and 20 kilograms is written 20 kg. All units and prefixes except Fahrenheit and Celsius are uncapitalized when written out, as in megaton or meter.

I.3 Common Usage

1. *Length:* meter (m), kilometer (km), millimeter (mm), micrometer (μm), nanometer (nm).
2. *Area:* square meter (m^{2}), hectare (ha).
3. *Volume:* cubic meter (m^{3}), liter (L).
4. *Flow:* cubic meters per second (m^{3}/s).
5. *Velocity, Airflow:* meters per second (m/s).
6. *Weight:* kilogram (kg), gram (g).

The SI system clearly differentiates between mass (kg) and force (kg·m/s^{2}), the latter being given a separate name and symbol, newton (N). Weight is not used, because it is a force that depends on acceleration and is therefore variable. However, the construction industry in large measure continues to use the terms mass, weight, and force interchangeably.

7. *Force:* newton (N), kilonewton (kN). A newton is the force required to accelerate 1 kg at 1.0 m/s^{2}.
8. *Pressure:* pascal (Pa), kilopascal (kPa). A pascal is a newton per square meter (N/m^{2}).

9. *Energy, Work, Quantity of Heat:* joule (J), kilojoule (kJ), megajoule (MJ). A joule is a watt-second (W·s).
10. *Temperature:* degree Celsius (°C), degree kelvin (K).

The SI unit (kelvins) is not used as commonly as °C. (Celsius is the accepted term; "centigrade" is obsolete). The Celsius and Kelvin scales are subdivided equally but start at different points, that is, 0 K is −273.15°C. Therefore, to determine Kelvin from Celsius, simply add 273.15. Increments are equal because of equal subdivision; that is, a change of 10 K is the same as a 10°C change. Because of its special importance, a separate Fahrenheit/Celsius conversion chart is given in Fig. 1.1.

11. *Illumination:* see Table 18.1.
12. *Acoustics:* see Table 27.15.
13. *CGS/MKS Conversions:* see Table 27.15.
14. *Abbreviations:* see Table I.2.
15. *Approximations:* see Table I.3.

I.4 Conversion Factors

Table I.4 is an alphabetized list of useful conversion factors. Because normal use involves a hand calculator, we have avoided scientific notation and used decimal notation instead; that is, we write 0.00378, not 3.78×10^{-3} or 3.78E-3.

TABLE I.2 **Typical Abbreviations: All Systems of Units**

atmospheres	atm	kilopascals	kPa
British thermal units	Btu	kilowatts	kW
British thermal units per hour	Btu/h	kilowatt-hours	kWh
calorie	cal	liters	L
cubic feet	cf, ft^3	liters per second	L/s
cubic feet per minute	cfm, ft^3/min	megajoules	MJ
cubic feet per second	cfs, ft^3/s	meganewtons	MN
cubic meters	m^3	megapascals	MPa
feet	ft	meters	m
feet per second	fps, ft/s	meters per second	m/s
gallons	gal	miles per hour	mph
gallons per hour	gph, gal/h	millimeters	mm
gallons per minute	gpm, gal/min	millimeters of mercury	mm Hg
grams	g	newtons	N
hectares	ha	ounces	oz
horsepower	hp	pounds	lb
inches	in.	pounds of force	lbf
inches of mercury	in. Hg	pounds per cubic foot	lb/ft^3
joules	J	second	sec, s
kilocalories	kcal	square feet	ft^2
kilograms	kg	square inches	$in.^2$
kilograms per second	kg/s	square meters	m^2
kilojoules	kJ	watts	W
kilometers	km	watts per square meter	W/m^2
kilometers per hour	kph, km/h	yards	yd
kilonewtons	kN		

TABLE I.3 **Common Approximations**

Approximate Common Equivalents			
1 inch	= 25 millimeters	1 millimeter	= 0.04 inch
1 foot	= 0.3 meter	1 liter	= 61 cubic inches
1 yard	= 0.9 meter	1 meter	= 3.3 feet
1 mile	= 1.6 kilometers	1 meter	= 1.1 yards
1 square inch	= 6.5 square centimeters	1 kilometer	= 0.6 mile
1 square foot	= 0.09 square meter	1 square centimeter	= 0.16 square inch
1 square yard	= 0.8 square meter	1 square meter	= 11 square feet
1 acre	= 0.4 hectare	1 square meter	= 1.2 square yards
1 cubic inch	= 16 cubic centimeters	1 hectare	= 2.5 acres
1 cubic foot	= 0.03 cubic meter	1 cubic centimeter	= 0.06 cubic inch
1 cubic yard	= 0.8 cubic meter	1 cubic meter	= 35 cubic feet
1 quart	= 1 liter	1 cubic meter	= 1.3 cubic yards
1 gallon	= 0.004 cubic meter	1 liter	= 1 quart
1 ounce	= 28 grams	1 cubic meter	= 250 gallons
1 pound	= 0.45 kilogram	1 kilogram	= 2.2 pounds
1 horsepower	= 0.75 kilowatt	1 kilowatt	= 1.3 horsepower

TABLE I.4 **Useful Conversion Factors: Alphabetized**

Multiply	*By*	*To Get*
acres	4047	square meters
atmospheres	33.93	feet of water
atmospheres	29.92	inches of mercury
atmospheres	760.0	millimeters of mercury
Btu (energy)	0.252	kilocalories
	1.055	kilojoules
Btu/h (power)	0.2928	watts
Btu/h/ft^2 (energy transfer)	3.152	watts per square meter
BtuF (heat capacity)	1.897	kilojoules per kelvin[a]
Btu/lb°F (specific heat)	4.182	kilojoules per kilogram per kelvin[a]
Btu/h/Fft (thermal conductivity[b])	1.729	watts per kelvin[a] per meter
Btu/hFft^2 (conductance[c])	5.673	watts per kelvin[a] per square meter
Btu/Fday (building load coefficient, BLC)	0.022	watts per kelvin[a]
Btu/Fdayft^2 (load–collector ratio, LCR)	0.236	watts per kelvin[a] per square meter
cubic feet	0.028	cubic meters
cubic feet	7.481	gallons
cubic feet	28.32	liters
cubic feet per minute	0.472	liters per second
cubic feet per second	2.832	liters per second
cubic inches	16.39	cubic centimeters
cubic meters	35.32	cubic feet
cubic meters	1.308	cubic yards
cubic meters	264.2	gallons
cubic meters	0.765	cubic meters
cubic yards	0.305	meters
feet	304.8	millimeters
feet	0.3048	meters per second
feet per second	1.356	watts
foot-pounds of force per second		

APPENDICES

TABLE I.4 Useful Conversion Factors: Alphabetized (Continued)

Multiply	By	To Get
gallons	3.785	liters
gallons per hour	0.00152	liters per second
gallons per minute	0.0022	cubic feet per second
gallons per minute	0.06308	liters per second
grams	0.035	ounces (avoirdupois)
hectares	2.471	acres
horsepower	0.746	kilowatts
horsepower	746	watts
inches	25.4	millimeters
inches of mercury	0.033	atmospheres
inches of mercury	1.133	feet of water
inches of mercury (60°F)	3377	newtons per square meter
inches of mercury	0.491	pounds per square inch
inches of water	0.002458	atmospheres
inches of water	0.036	pounds per square inch
inches of water (60°F)	248.8	newtons per square meter
kilocalories	3.968	British thermal units
kilocalories	4190	joules
kilograms	2.205	pounds
kilograms per cubic meter	1.686	pounds per cubic yard
kilograms per square meter	0.0033	feet of water
kilograms per square meter	0.0029	inches of mercury
kilograms per square meter	0.205	pounds per square foot
kilograms per square meter	0.001422	pounds per square inch
kilojoules	0.948	British thermal units
kilojoules per kilogram	0.430	British thermal units per pound
kilometers	0.621	miles
kilometers per hour	0.621	miles per hour
kilonewtons	0.1004	tons of force
kilonewtons	224.8	pounds of force
kilopascals	20.89	pounds of force per square foot
kilowatts	1.341	horsepower
kilowatt-hours	3.6	megajoules
liters	0.03532	cubic feet
liters	61.02	cubic inches
liters	0.2642	gallons
liters	1.057	quarts
liters per second	2.119	cubic feet per minute
liters per second	951.0	gallons per hour
liters per second	15.85	gallons per minute
megajoules	0.278	kilowatt-hours
meganewtons	100.36	tons of force
megapascals	145.04	pounds of force per square inch
megapascals	9.324	tons of force per square foot
meters	3.281	feet
meters	1094	yards
meters per second	196.86	feet per minute
meters per second	2.237	miles per hour
miles	1.609	kilometers
miles per hour	1.609	kilometers per hour
miles per hour	0.447	meters per second

TABLE I.4 Useful Conversion Factors: Alphabetized (Continued)

Multiply	By	To Get
milliliters	0.061	cubic inches
milliliters	0.035	fluid ounces
millimeters	0.039	inches
millimeters of mercury	133.3	newtons per square meter
million gallons per day	18.94	cubic meters per hour
newtons	0.225	pounds of force
ounces (avoirdupois)	28.35	grams
ounces (fluid)	28.41	milliliters
pounds	0.454	kilograms
pounds of force	4.448	newtons
pounds of force per square foot	47.88	pascals
pounds of force per square inch	6.895	kilopascals
pounds per cubic foot	16.02	kilograms per cubic meter
pounds per cubic yard	0.593	kilograms per cubic meter
pounds per square foot	4.882	kilograms per square meter
square feet	0.0929	square meters
square inches	645.2	square millimeters
square kilometers	0.386	square miles
square meters	10.76	square feet
square meters	1.196	square yards
square miles	2.590	square kilometers
square yards	0.836	square meters
tons of force	9.964	kilonewtons
tons of force per square foot	107.25	kilopascals
tons of force per square inch	15.44	megapascals
torr (millimeters of mercury at 0°C)	133.3	newtons per square meter
watts	3.412	British thermal units per hour
watts	0.738	foot-pounds of force per second
watts per square meter	0.317	British thermal units per square foot
yards	0.914	meters

Add your own conversion factors here.

Multiply	By	To Get
Multiply	By	To Get
Multiply	By	To Get

[a]°K or °C.
[b]Thermal conductivity (K).
[c]Thermal conductance (C) or transmittance (U).

APPENDICES

J

BUILDING AUTOMATION; INTELLIGENT BUILDINGS

J.1 Building Automation System (BAS)

(a) General. The trend in modern construction, except for small or simple structures, is clearly to use integrated system design plus centralized monitoring and control of building systems. The subsystems almost always included in a building automation system (BAS) are HVAC, energy management, and lighting control. Inclusion of security, life safety (fire alarm, fire control and suppression, plus emergency aspects of vertical transportation), material handling, and some aspects of communications depends on the specific needs of the building. This trend toward building automation, which previously had been economically justifiable only in large owner-user facilities, is today not only economically feasible but very nearly an economic necessity because of high labor costs and the relatively low cost of computer and microprocessor controls. What the rapid advances in microelectronics and computer technology have done is to make possible and practical detailed, multipoint monitoring and control in real time, the result of which (assuming proper programming and BAS operation) is a highly cost-efficient and environmentally appropriate facility. Indeed, the advantages of such an arrangement are so great that retrofitting of existing buildings, which is obviously more cost intensive than new construction, has become a major industry.

Because the technique of building automation has grown so rapidly in the past few years, the terminology surrounding it and its equipment suffers from a lack of standardization and uniformity. Thus terms such as *building automation, intelligent buildings, computerized building control, integrated computer control, supervisory data systems, integrated building control, facilities management system,* and so on, are used almost interchangeably. The expression *building automation system* (BAS) will be used in the discussion that follows. Since every BAS is by definition programmed, any discussion necessarily involves basic computer terminology in addition to that which specifically applies to BAS. A short glossary should prove helpful in this regard.

(b) Glossary

Algorithm. Detailed description, often in flow-diagram form, of the method for solving a problem. The outline used for computer or microprocessor programming.

Alphanumeric. Characters, which are either alphabet letters, symbols, or numbers.

Analog Data. Numerical information about physical variables given in representative, continuously variable form (e.g., dial meter, temperature gauges, etc.).

Artificial Intelligence. Branch of computer science concerned with computer programs that "learn" on the basis of experience and modify their own behavior accordingly.

Baud. Rate at which information is transmitted in terms of discrete events per second.

Building Automation Systems (BAS). Building-wide computer-based system that monitors and controls selected aspects of building operations. The BAS is understood to include all of the equipment involved and their interconnections.

Central Processing Unit (CPU). That portion of a computer, microprocessor, or programmable controller that processes data and executes programs. The "brains" of the computer.

Converter. General term for a device that converts data or energy from one form to another. Data converters are analog to digital (ADC) or digital to analog (DAC). Energy-form converters (e.g., temperature or illuminance to voltage) are properly called *transducers.*

Digital Data. Data in digital form, usually binary.

Direct Digital Control (DDC). Control arrangement that processes input data according to a programmed algorithm and yields a control function (e.g., the action of a local microprocessor controller or a computer control function).

Duplex, Duplex Transmission. Simultaneous bidirectional data transmission.

Energy Management System (EMS). Computer-based system for monitoring and controlling facility energy use. Frequently part of a BAS.

Hardware. All physical equipment associated with a computer system, as opposed to software.

I/O. Input/output.

Load Control, Load Management. Arrangement whereby energy-using devices are monitored and controlled. Part of EMS.

Local Area Network (LAN). Signal network providing intercomputer communications.

Logic. Factors involved in the design of a CPU.

Microprocessor. A CPU, usually in the form of a single integrated circuit (IC), preprogrammed to perform specific functions in response to specific input.

Modem. Device that connects a data-originating device to a communication line; from "*mod*ulator–*dem*odulator."

Multiplexer) (MX, MUX). Use of a single communications line for simultaneous transmission of multiple signals.

Operating System. Software, which controls input to, output from, and operation of, the CPU.

Point. General term to describe either a sensor/monitor location or a specific control signal in a BAS.

Programmable Controller. Electronic device containing a microprocessor, a programming means or device, and I/O interfaces. See Fig. 16.14 and Section 16.16.

Protocol. Conventions governing format and timing of signaling between communication devices (e.g., between computers in area networks).

RAM, ROM, PROM, EPROM. random access memory, read-only memory, programmable *ROM*, erasable *PROM.*

Real time. Arrangement in which a computer receives and processes data without introduction of any deliberate time delay (i.e., effectively, immediate response.)

RS-232. Standard for interconnecting digital communications devices, such as computers, printers, and monitors.

Software. Computer programs as opposed to hardware.

Stand-Alone. Descriptive term for a control device that can perform independently and usually can also interconnect as a subsystem controller in a larger system.

UPS. uninterrupted power supply.

(c) System Arrangement. A block diagram of a general BAS is given in Fig. J.1. Any specific BAS may contain more or fewer monitors, sensors, dependent and stand-alone local controllers, and interconnected systems but the overall arrangement remains the same. Actually, depending on the equipment manufacturer and the system complexity, some of the functions and levels can be telescoped or grouped. We will however discuss the general case. To concretize the discussion we will use fire control and evacuation system terminology as a relatively simple straightforward example of overall system design, function and interconnection.

Level 5 is the lowest system level. It contains automatic operation passive sensors such flame, smoke, ionization, temperature, and water-flow detectors; physical condition indicators such as smoke and fire door position sensors; and man-

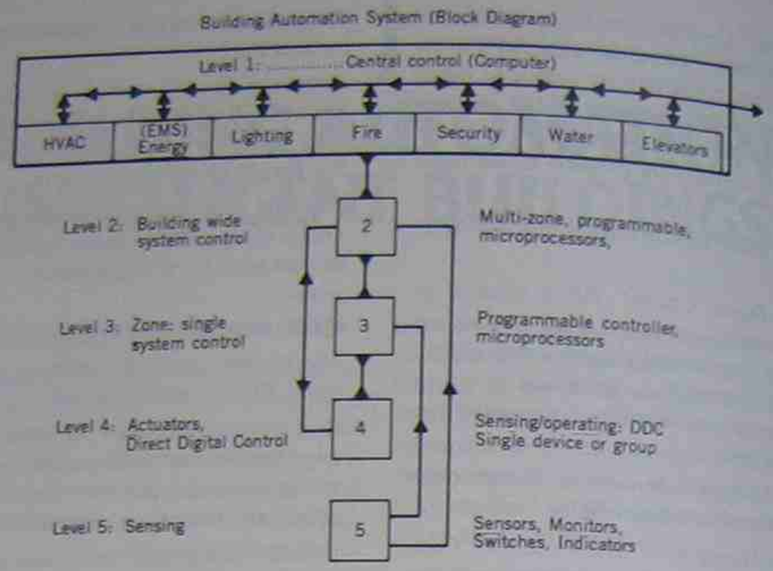


Fig. J.1 *Overall block diagram of a BAS (building automation system). In an actual system the various levels and devices can be combined and telescoped by use of equipment that combines several level functions in a single housing.*

ual fire alarm pull stations. All yield a digital signal (on–off) which is transmitted to level 3. As level 5 is purely a sensor/monitor level, it does not receive any control or operating signals.

Level 4 contains sensor/operators or actuators (i.e., devices that both transmit a condition signal and receive an operation signal). In our example, this level could contain fire and smoke door actuators, smoke vent controls, sprinkler system valves, and fan control (override) switches. This last item can either reside at this level or can be controlled through the HVAC system via level 1, 2, or 3. Control at this level is of a single device or block.

Level 3 could represent a floor, zone, or area controller, with either relay circuitry or microprocessor control (programmable controller), depending on system complexity. This level receives information from levels 4 and 5, processes it, returns control information to level 4, operates specific local audible and visible alarms directly, and sends alarm and condition information to the level 2 building controller and to the master controller (computer) at level 1. It also receives and processes signals from levels 1 and 2, containing such information as alarm reset, alarm device operation for building emergency evacuation, and any reprogram or reset function.

Level 2 contains the building's central fire and evacuation system (life safety system) controls. This level can contain some of the level 1 programming logic relating to firemen's control of elevator operation and HVAC fan functioning, or it can simply act as an input/output (I/O) device to level 1 for these functions, again depending on system design and complexity. In some facilities these life safety system functions may be controlled from a separate console that is interconnected with the BAS. In a multibuilding facility, this level contains the individual building fire system central control, interconnections to other building fire-system controllers, as well as external connections for city alarm, and external supervisory services.

Level 1 is the central computer console. This level receives status reports on individual devices from level 4 or 5; on areas, zones, and subsystems from level 3; and on the entire fire/evacuation system from level 2. Hard-copy printout of all alarms and periodic status reports are generally made at this level, although they can also be accomplished at level 2. Video display terminals (VDT) at level 1 can be used to view the status of any area and all the devices in the fire/evacuation system (Fig. J.2) or any other system (Fig. J.3) graphically or tabularly (Fig. J.4). Pictorial graphics for nontechnical end users are also possible (Fig. J.5). At this level interconnection is made to HVAC, elevator, security, and lighting systems in preprogrammed alarm modes, with manual override possible. A fire emergency scenario (Fig. J.2), depending on level 1 programming, might interconnect with the HVAC, elevator, security, water, electrical, and lighting systems to activate exhaust and pressurizing fans and deactivate supply fans, place elevators in fire-evacuation mode (see Section 24.5), override access barriers to permit unhindered facility evacuation, connect fire pumps to emergency power feeders, disconnect high-voltage feeders, and activate emergency lighting, all via preprogrammed intersystem functions. The system operator could then view any part of any system and reactivate or override preprogrammed functions as desired.

Fig. J.2 *The central computer's monitor screen shows a selected building area and its zoning (Johnson Plaza East, third floor, zones 1 to 6), all of the area's fire/evacuation system devices and their status, and the control system's present functioning. The illustrated screen shows an active alarm condition with messages: elevators being recalled to lobby; floor is now pressurized; audio evacuation messages active;* CALL FIRE DEPARTMENT. *(Courtesy of Johnson Controls.)*

Returning to Fig. J.1, we can consider a much more complex, nonemergency system; energy. Here level 5 senses and continuously monitors inside and outside temperature and humidity, duct air temperature, space pressurization, airflow, and the operating and load status of all fans, compressors, and refrigeration devices. Level 4 contains monitors and DDC controls for valves, boilers, chillers, fans, humidifiers, dampers, cooling towers, and compressors (see Fig. J.6). Levels 2 and 3 contain electric load managers for duty cycling and demand limiting (see Section 14.13), HVAC controls for economizers, run-time optimizers, supply air and supply water reset, chilled and condenser water reset, enthalpy switching, load sequencing, and the like. These functions are performed either by a stand-alone EMS controller (see Fig. 16.14*b*) or by individual demand, HVAC, and chiller load managers controlled by level 1 logic. Finally, level 1 contains the programming for all of the foregoing functions, any of which can be displayed at the VDT terminal at any time. The system operator can then reprogram any function after analyzing system performance (Fig. J.2) at the level 1 computer and obtain immediate visual and hard-copy readout of the changes. A discussion of building automation controls as applied to HVAC systems is given in Section 7.3*h*.

J.2 Intelligent Buildings

Although the term "intelligent building" seems to attribute a human characteristic to an inanimate object, the term's actual meaning, at least as defined by the Intelligent Buildings Institute (*Guideline*, 1987), is "a building which provides

(a)

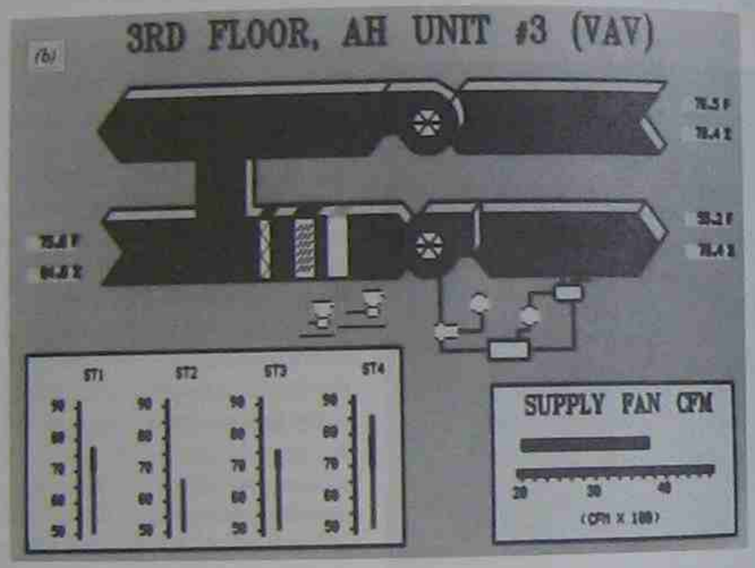
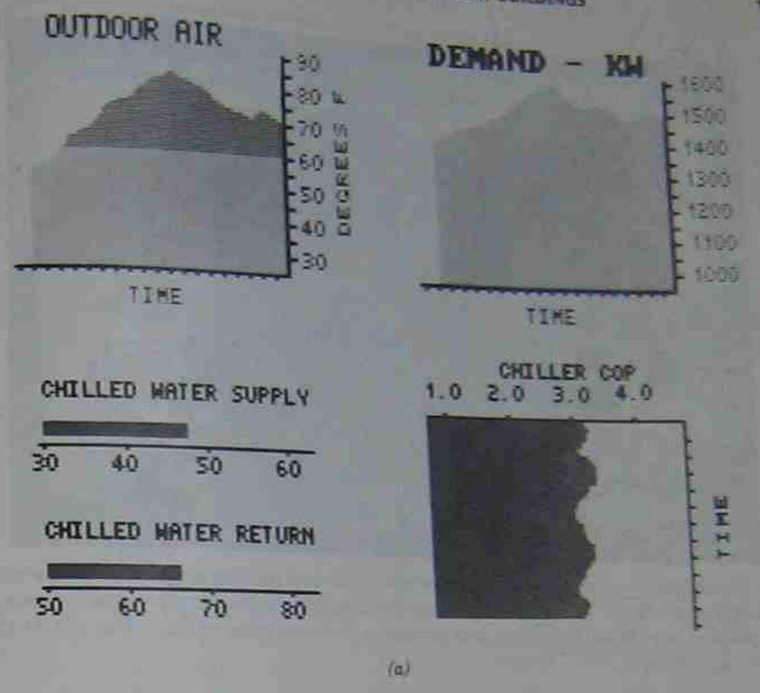
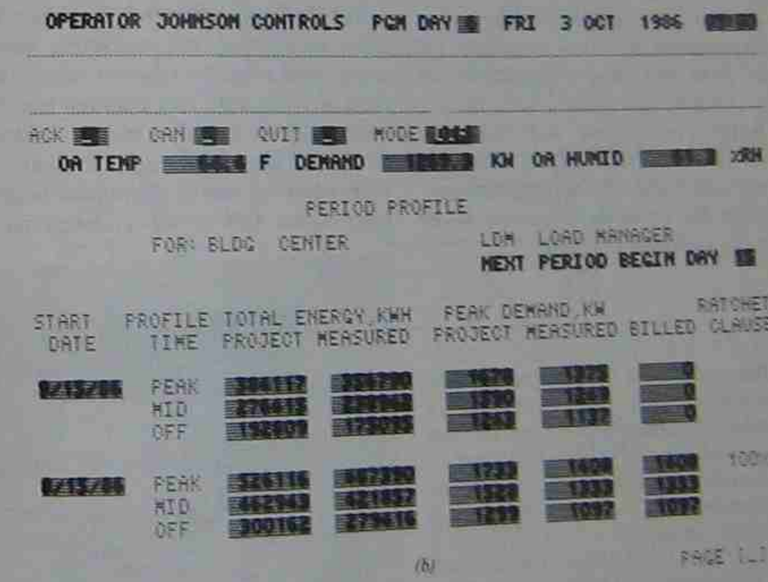


Fig. J.3 (a) *Computer screen shows any section of any building system and the status of all components. Here we see chiller status (on–off, COP, tons, run time), water temperature and flow in supply and return lines, and condenser water temperature.* (b) *Portion of the system showing status of air-handling unit 3. (Courtesy of Johnson Controls.)*

a productive and cost-effective environment through optimization of its four basic elements—structure, systems, services and management—and the interrelationships between them. . . . Optimal building intelligence is the matching of solutions to occupant need." In the framework of such a definition, the intelligence of a building resides essentially in its designers' and operators' abilities. An intelligent building is, therefore, not necessarily packed with electronic systems, nor even one with an extensive BAS, unless it is necessitated by the building program and can demonstrate its cost-effectiveness. Rather, it is a building designed with fore-



(a)



(b)

Fig. J.4 *The status of various aspects of the building's M-E systems can be displayed individually or grouped* (a). *Similarly, detailed data on any aspect of operation can be displayed* (b) *and printed, as desired. (Courtesy of Johnson Controls.)*

APPENDICES

Fig. J.5 *It is frequently desirable for both demonstration and training purposes to utilize pictorial graphics in a nontechnical mode. In this illustration a building system is superimposed on a visual building graphic in order to concretize and simplify a technical concept. (Courtesy of CSI Control Systems International.)*

thought and perhaps some inspiration, both of which are necessary to satisfy immediate and predictable need, and yet also to anticipate the occupants' future requirements, since modern building usage is rarely static. Referring to the IBI-defined characteristics of an intelligent building and addressing each of the four components individually, but in the framework of our study, we can comment as follows.

(a) Building Structure. These are essentially architectural and marketing considerations, since as has been pointed out repeatedly, there is a vast difference between speculative construction for immediate return, construction for rental, and owner–user buildings. Since every additional inch of slab-to-slab height and every square foot of utility closet space in-

Fig. J.6 *Illustrated units are a stand-alone direct digital control actuator (level 4) for use in a VAV (variable air volume) system and its room temperature and setpoint transmitter (level 5). This unit provides adjustable setpoint, local indication, night setback, morning warmings, and adjustable flow setting for a VAV terminal. It communicates back to level 2 (or 1) via standard data links and accepts and executes level 2 or 1 control settings for its functions when not operated in stand-alone configuration. It can also monitor conditioned air use by a terminal for cost apportionment. (Courtesy of Barber-Coleman Co., Environmental Control Division.)*

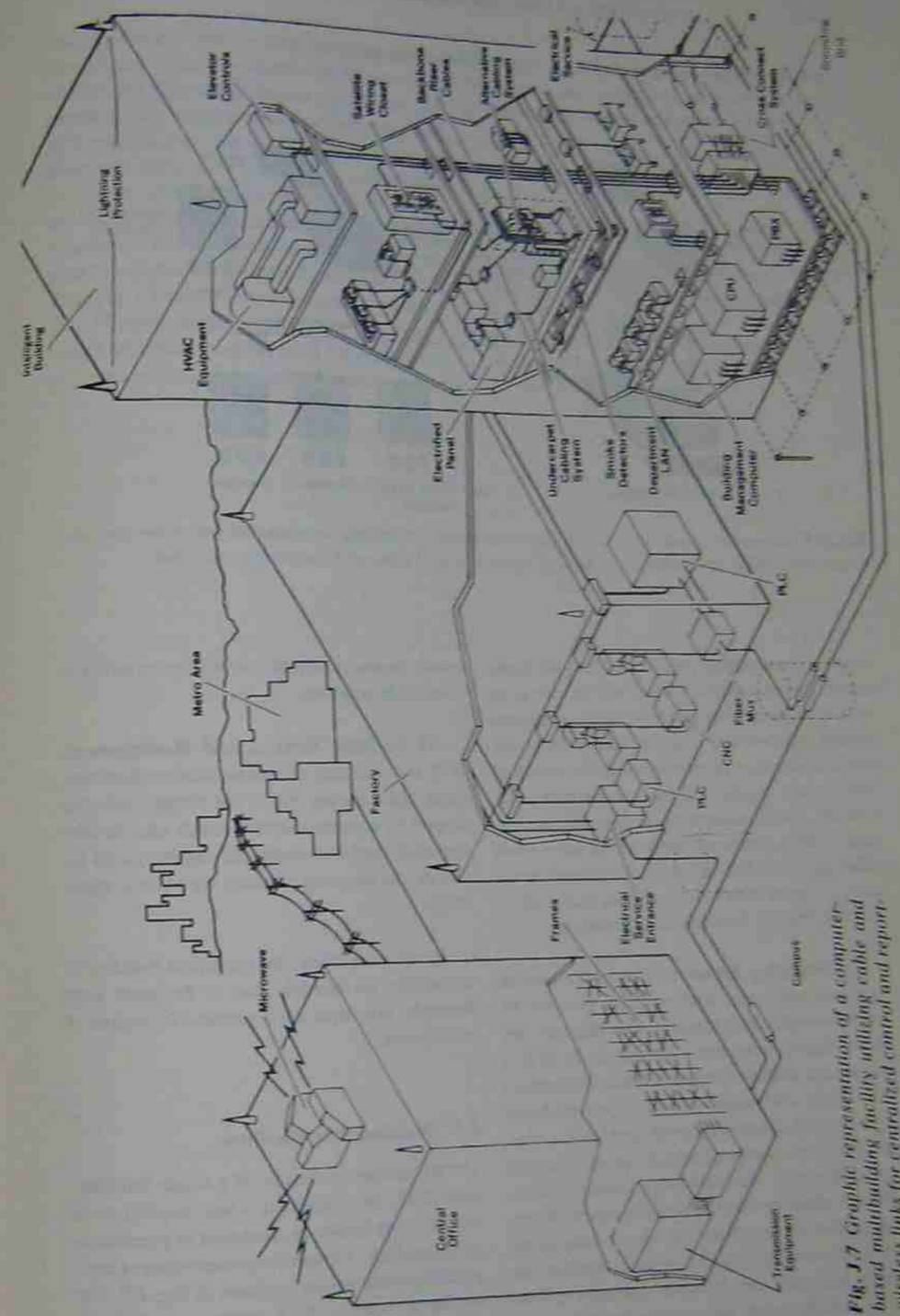


Fig. J.7 *Graphic representation of a computer based multibuilding facility utilizing cable and wireless links for centralized control and reporting. (Courtesy of AMP, Inc.)*

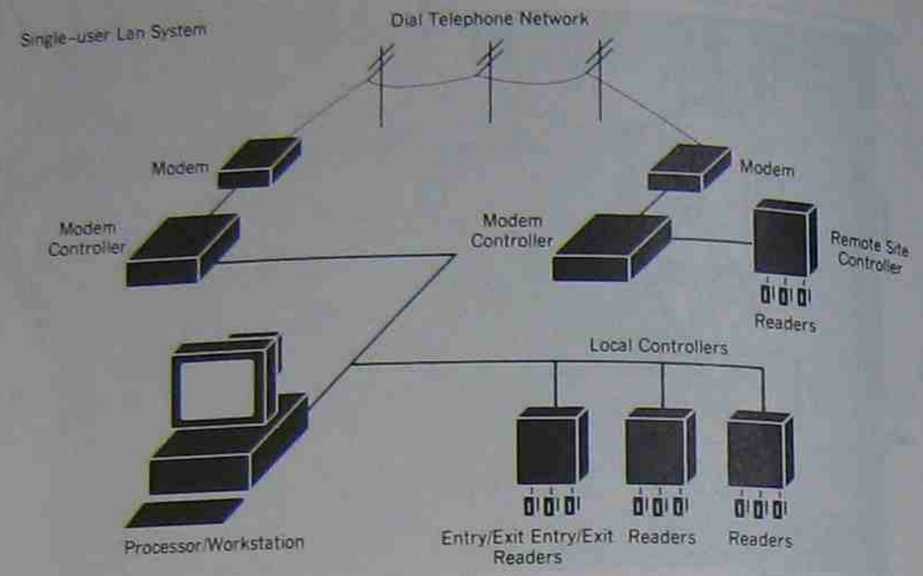


Fig. J.8 *Computer control of a single system (security) at multiple locations via telephone link, in a single-user local area network (LAN). (Courtesy of CSI Control Systems International.)*

creases construction costs or reduces occupant space, the speculative builder will be interested only if an immediate return is likely; the rental builder will consider it in the light of his or her immediate rental prospects; and the informed owner–user builder will analyze the rate of return for initial investment and decide accordingly. These comments apply all the more when referring to additional costs for unseen items such as spare ducts and conduits and "frills" such as fixtures, finishes, and furnishings.

(b) Building Systems. This is the area of high-tech equipment such as BAS, plus all the individual subsidiary systems. One difficulty lies in the highly proprietary nature of all of this equipment, making integration between systems and future alterations difficult if not problematic. Second, the resistance of some major manufacturers to open protocol (i.e., interequipment communication compatibility) places another difficult problem into the design process. Experience has shown clearly, however, that in the very fast-moving building systems market, today's high-tech can become tomorrow's albatross, and therefore planning for future requirements means intelligent preparation as much as immediate provision.

(c) Building Services and Management. With the exception of communication facilities, these items are not within our scope, and with respect to communications, which are the lifeline of all modern commercial and industrial facilities, the foregoing remarks are equally applicable.

In summary, then, the intelligent building is essentially the building that is designed with foresight. Hindsight will determine the degree of intelligence.

J.3 Multibuilding Facilities

The advantages in the use of a single building-wide BAS are redoubled when applied to a multibuilding facility as compared to precomputer technology. A graphic representation of such a multibuilding system is shown in Fig. J.7. The intelligent building BAS controls its building systems and interconnects via telephone cables (and microwave link) to other buildings in the network and to the central office. It matters little whether the various buildings in the network are geographically concentrated in campus fashion as would be the case in an industrial park, a university campus, or a multibuilding industrial facility, or spread out; the control, monitoring, and alarm functions remain the same. The same principle of building interconnection can be applied to a particular system rather than the BAS. Thus Fig. J.8 shows a single processor–workstation (PC-type computer) controlling the security aspect of a number of facilities via controllers, modems, and telephone cable connections in a single-user local area network (LAN) system. This workstation can then be incorporated into a multisystem, multiuser computer network.

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APPENDICES

K

ASHRAE STANDARDS FOR ENERGY EFFICIENT BUILDING DESIGN

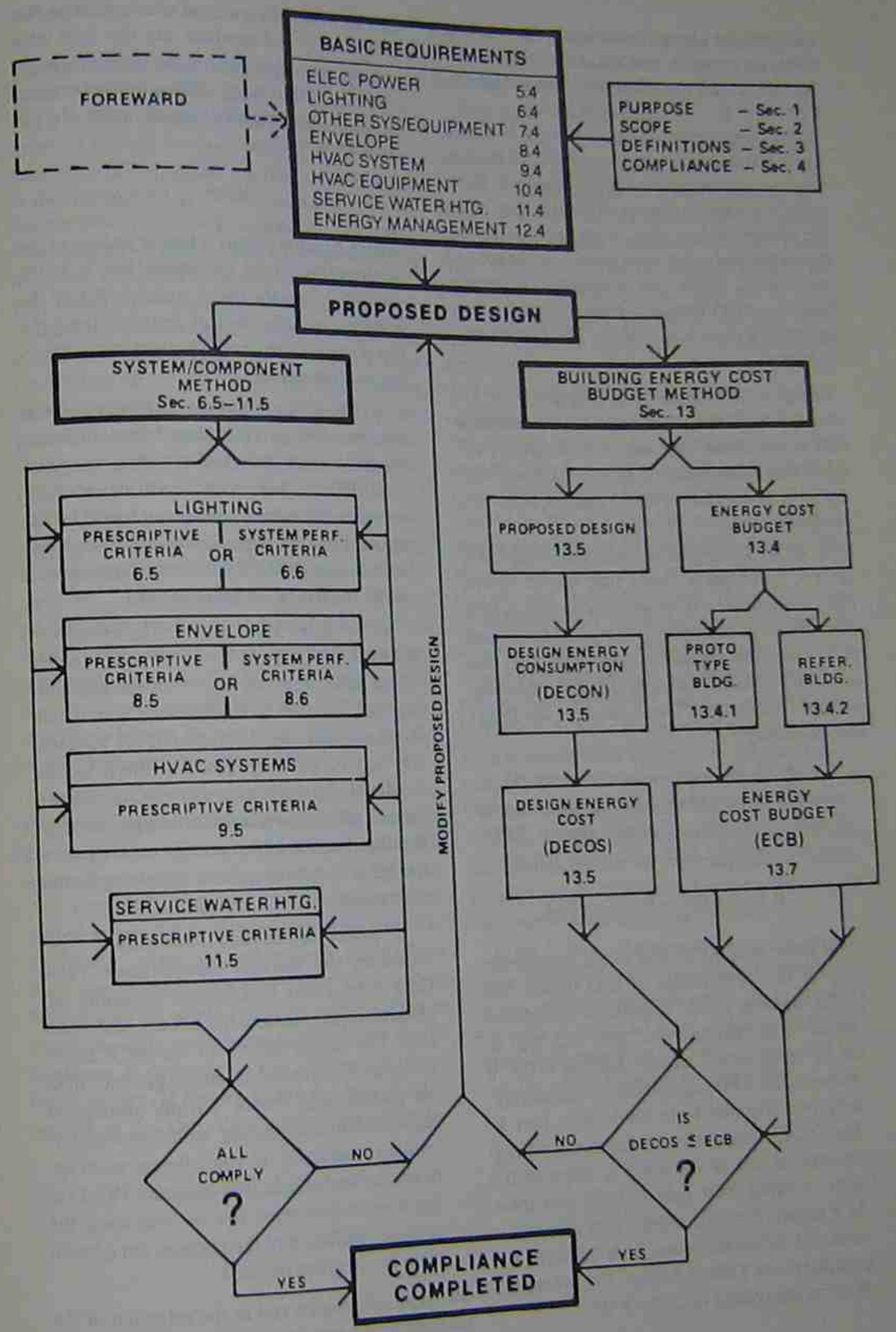
K.1 Criteria for Components of the Envelope: Nonresidential Buildings

The design guidelines in this section are taken from ASHRAE/IES Standard 90.1-1989, *Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*, published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga. This standard presents two types of design procedures: the system/component method and the building energy cost budget method. Both methods rely heavily on the use of microcomputers, although there is a "prescriptive path" within the system/component method which allows the designer to quickly check the window areas and the U values of the major components of a building envelope. This quick prescriptive path is presented here. First, the features of the computer-based methods should be understood. The two procedures are diagrammed in Fig. K.1.

The building energy cost budget method is based on the quasi-free market cost of energy to the consumer. Although we may question the wisdom of basing today's energy design decisions on today's massive subsidies of nonrenewable energy sources, the method is especially recommended by ASHRAE for buildings that have high internal heat gains, unusual operating schedules, or innovative energy designs. With this method, credit is more readily given for daylighting, passive solar heating, heat recovery, better zonal temperature control, thermal storage, and off-peak electrical energy use. Further, this method provides a way to judge the relative effectiveness of several design alternatives in reducing energy costs. First, an *energy cost budget* is determined; for a given building size and type, this budget will vary only with climate, the number of stories, and the choice of energy performance simulation tools. This budget is based on monthly energy usage simulations of either a "prototype" or a "reference" building, with detailed conventional assumptions of its internal loads, orientation, shape, envelope, and HVAC system characteristics. Then, monthly energy simulations of the actual design are made. The yearly total energy use simulations, and resulting costs, of the budget and the actual building are compared; if the actual building energy costs are lower, the design complies with this Standard. Software to assist the energy cost budget analysis is provided when the standard is purchased from ASHRAE.

The system performance method presents requirements for maximum overall thermal transmittance of each major component of the envelope: roofs, opaque walls, windows, and floors. The requirements vary with several climate variables, such as heating and cooling degree days, and with average annual insolation on vertical surfaces at each orientation. Therefore, the calculations are so complex as to require the use of a computer, and software to assist the system performance analysis is provided when the standard is purchased from ASHRAE. By-hand cal-

Fig. K.1. *Alternative methods of achieving compliance.*



culations for electric lighting density are somewhat less complex, and are explained in Section 20.5c. The necessary data are given in Table K.2 Parts C to F.

The prescriptive criteria method is a relatively fast and simple way to check for building envelope compliance with the standard. However, it is somewhat more restrictive than either the energy budget cost or the system performance methods. For each major climate zone of the United States, an Alternate Component Package (ACP) table has been prepared. These appear in Tables K.4 to K.35. The procedure is as follows.

STEP 1. Determine the appropriate ACP Tables K.4 to K.35 for your climate. If your location is not listed, compare your location's climate data with those of nearby locations (see Table K.1) to choose the listed location best matching yours.

STEP 2. Determine the maximum allowable percent fenestration. Note that this compares total window area to total gross *wall* area (not floor area). In the appropriate ACP table, you must enter the applicable horizontal line, and applicable vertical column, to find maximum percent fenestration. These substeps are therefore necessary:

a. Find the internal load density (ILD), which is the sum of the lighting power density (LPD), the equipment power density (EPD), and the occupant load adjustment (OLA):

$$\text{ILD} = \text{LPD} + \text{EPD} + \text{OLA}$$

and enter your ACP table in the appropriate one of the three ranges of ILD shown. The LPD, lighting power density, is determined either by estimating from Table K.2, Part A, or by using actual electric lighting W/ft², if known. The EPD, equipment power density, may be estimated from Table K.2, Part B. The OLA, occupant load adjustment, will ordinarily be 0.0 W/ft², since a value of 0.6 W/ft² sensible heat gain is built into these ACP tables. If your occupant heat gain rate is markedly different, adjust from 0.6 W/ft² accordingly; see Table 5.8, page 214, where 0.6 W/ft² is equivalent to 2 Btu/h-ft².

b. Select the external shading projection factor (PF) and continue into the ACP table on the appropriate one of the three PF ranges listed. (If no external shading projections are used in the proposed design, enter the PF range 0 to 0.259.)

$$\text{PF} = \frac{P_d}{H}$$

where P_d is the depth (in feet or inches) of the external horizontal projection and H is the sum of the height (same units as P_d) of the window and the vertical distance from the top of the window to the bottom of the external shading device.

c. Select the shading coefficient of the window (SC_x), including the internal, integral, and external shading devices EXCEPT the device whose PF has already been determined. SC values are found in Tables 4.18 to 4.20, pages 164 to 168. Then continue on into the ACP table in the appropriate one of the five SC_x ranges listed.

d. To enter the vertical "fenestration" columns of your ACP table, select either "base case" (no thermal credit for daylighting) or "perimeter daylighting," in which case automatic daylighting controls for electric lighting must be used. In many cooler locations, the perimeter daylighting thermal credits are not available, although the daylighting contribution to energy used by electric lights is still recognized in lighting power allowances.

e. Select appropriate fenestration type, based on the thermal transmittance value (U_{sf}) of the entire fenestration assembly (including frames, sash, edge effects, and spacers). The ranges shown in the ACP tables generally correspond to single glazing, double glazing, and "more": triple glazing, or high-performance glazing with low-emissivity films, and so on. In some fenestration options, the visible light transmittance (VLT) of the fenestration must not be less than the shading coefficient of the glazing, not considering any shading devices.

Substeps a through e end in the selection of the maximum percent fenestration area (of gross wall area) allowable in this climate by this standard.

STEP 3. Determine the maximum U_{ow} for the opaque wall assembly. Here, the mass of the wall is influential. For ordinary lightweight construction [where the heat capacity (HC) is less than 5 Btu/ft²-°F], simply use the value indicated as the maximum U_{ow}. For more massive walls, the maximum U_{ow} will depend on the same range of internal load density (ILD) as was used to select the percent fenestration. (Note that HC, Btu/ft²-°F = density, lb/ft³ × thickness, ft × specific heat, Btu/lb-°F; these quantities for individual materials are found in Table 4.2, page 136.) When HC = 5 or more, the U_{ow} depends on whether the wall insulation is inside or integral with the wall mass (INT INS) or outside the wall mass (EXT INS, in which case the mass can better reduce the impact of internal heat gains). Then, using the percent fenestration (of wall area) of your design (or the maximum percent allowable, whichever is less) find the maximum U_{ow}, interpolating as necessary. If your percent fenestration is less than the minimum listed, select the U_{ow} for the smallest percent fenestration listed. Similarly, if your percent fenestration is greater than the maximum percent fenestration listed, select the U_{ow} for the largest percent fenestration listed.

STEP 4. Determine the minimum R value for insulation on walls below grade, or for a slab on grade. There is but one value shown for the minimum R value of insulation for walls down to one story below grade. (No insulation is required either for walls more than one story below grade, or for any below-grade walls where there are fewer than 3000 HDD65.) For an unheated slab on grade (building's heat source is above the slab, not integral with or below it), the minimum R depends on the *minimum distance listed*, either (1) first vertically downward to the bottom of the slab, then horizontally either beneath the slab or outward from the building, or (2) vertically downward from the top of the slab. For a heated slab, an R value of 2 must be added to these minimum R values.

STEP 5. Note the maximum overall thermal transmittance for the roof assembly, U_{or}. This includes the gross area of a roof assembly exposed to outside air (or unconditioned space) and includes skylight surfaces but excludes service openings such as for plumbing vents or fans. The roof assembly includes all roof or ceiling components through which heat may flow between indoor and outdoor (or unconditioned) environments. Skylights used in conjunction with automatic daylight controls on all-electric lighting in the area served by the skylights can be *excluded* from the U_{or} calculation, up to the maximum percent roof areas listed in Table K.3. However, these minimum areas can be increased by 50% if a shading device is used that blocks over 50% of the solar gain through the skylight during the peak cooling design condition (usually, July or August). The information on HDD65 and CDH80 for your location are found in Table K.1. The visible light transmittance (VLT) for skylights should only be interpolated between the 0.5 and 0.75 values shown in Table K.3. Note that *vertical glazed surfaces* such as monitors or clerestories are not considered skylights, but instead are to be included in the wall fenestration calculations.

STEP 6. Note the maximum overall thermal transmittance value for walls adjacent to unconditioned space. This includes both the opaque and glazed elements of such a wall.

STEP 7. Note the maximum overall thermal transmittance value for the floor assembly, over outside or unconditioned space, U_{of}. The floor assembly includes all floor components through which heat may flow between indoor and outdoor (or unconditioned) environments.

TABLE K.1 **Degree Days and Annual Average Insolation on Vertical Surfaces**[a]

City	HDD50	HDD65	(CDH74)[b]	VSN	VSEW	VSS	CDD50	CDD65	CDH80	DR	NO HRS 8AM–4PM T ≤ 55	NO HRS 8AM–4PM 55 ≤ T ≤ 69	ACP Table
ALABAMA													
Birmingham	765	2882	(21533)	464	789	908	5182	1825	6272	17.5	720	760	K.9
Mobile	164	1580	(28912)	486	816	919	6478	2419	7479	16.6	408	774	K.12
Montgomery	491	2261	(24564)	462	823	981	5821	2116	8473	19.5	609	734	K.12
ALASKA													
Adak	3562	8913	(0)	280	434	652	124	0	0	9.9	2754	156	K.35
Anchorage	5301	10540	(35)	272	538	926	236	0	0	13.8	2398	521	K.35
Annette Island	2545	7277	(308)	285	482	739	756	12	0	10.1	2169	719	K.35
Bethel	8285	13449	(238)	252	453	789	312	0	0	14.3	2555	347	—[c]
Big Delta	9355	14069	(582)	249	527	989	777	16	25	19.0	2141	606	—[c]
Fairbanks	9841	14414	(752)	241	492	919	922	19	8	18.2	2083	682	—[c]
Gulkana	8865	13846	(106)	257	522	943	498	4	6	18.5	2225	615	—[c]
Juneau	4223	9350	(34)	254	410	642	348	0	0	12.7	2367	540	K.35
King Salmon	6843	11992	(64)	270	499	860	330	4	6	15.4	2395	502	—[c]
Kodiak	3775	8896	(335)	276	509	852	360	6	0	10.6	2519	384	K.35
McGrath	9967	14868	(405)	246	467	841	578	3	0	15.9	2265	596	—[c]
Nome	9061	14418	(272)	242	478	871	119	0	0	9.0	2710	210	—[c]
Summit	9210	14530	—	247	488	893	155	0	0	13.6	2616	298	—[c]
Yakutat	4486	9714	(1)	247	402	650	248	0	0	9.3	2471	439	K.35
ARIZONA													
Phoenix	90	1382	(54404)	488	1116	1310	7830	3647	34521	21.2	373	746	K.17
Prescott	1477	4462	(3828)	473	1090	1334	3385	895	3973	24.0	1021	725	—[c]
Tucson	178	1601	(35946)	500	1112	1280	6822	2769	19657	21.9	399	716	K.14
Winslow	1695	4603	(10636)	471	1092	1338	3708	1141	7347	27.7	1130	634	—[c]
Yuma	43	782	(62507)	493	1151	1330	8921	4186	37892	23.5	247	697	—[c]
ARKANSAS													
Fort Smith	1149	3394	(23485)	462	842	1005	5307	2077	10413	22.4	925	547	K.22
Little Rock	912	3091	(23839)	465	831	981	5351	2055	8450	17.5	865	626	—[c]
CALIFORNIA													
Arcata	582	5020	(19)	407	724	926	1038	1	0	8.9	1396	1509	—[c]
Bakersfield	305	2194	(29954)	474	1053	1211	5879	2294	15447	28.9	645	848	K.13
China Lake	409	2444	(26531)	468	1091	1312	6222	2782	26739	27.4	582	772	K.14
Daggett	237	1916	(40146)	475	1102	1309	6516	2720	22302	27.0	472	841	K.14
El Toro	32	1577	(6921)	486	977	1163	4764	834	2391	22.3	215	1474	K.8
Fresno	492	2700	(19366)	459	1029	1199	5070	1803	13085	31.8	780	785	K.11
Long Beach	54	1483	(7756)	482	956	1144	4947	900	1616	16.1	263	1502	K.8
Los Angeles	3	1494	(4306)	482	962	1146	4456	472	136	14.1	145	1849	K.8
Mount Shasta	1947	5583	(2097)	419	909	1153	2395	556	2073	16.2	1544	756	K.26
Oakland	157	2922	(435)	453	909	1102	2792	82	23	16.4	770	1905	K.6
Point Mugu	8	2193	(1232)	477	936	1131	3435	145	70	12.3	209	2146	K.6
Red Bluff	589	2884	(22618)	428	951	1177	5110	1930	14404	29.5	860	810	K.11
Sacramento	381	2753	(12556)	444	987	1185	4274	1171	7315	34.6	834	990	K.11
San Diego	2	1275	(4643)	490	950	1121	4865	662	383	11.5	102	1911	K.8
San Francisco	186	3238	(265)	454	941	1146	2496	73	204	20.2	782	1796	K.7
Santa Maria	138	3041	(131)	476	950	1128	2663	92	513	20.9	414	2016	K.7
Sunnyvale	142	2708	(1430)	456	947	1145	3112	204	421	16.9	610	1794	K.6
COLORADO													
Colorado Springs	2587	5996	(3658)	435	976	1321	2557	491	2075	24.0	1357	725	K.26
Denver	2652	6083	(5908)	428	971	1321	2611	567	2934	25.5	1329	739	K.26
Eagle	4232	8317	(248)	432	976	1296	1480	90	1008	35.4	1650	660	K.33
Grand Junction	2616	5701	(12097)	438	1003	1303	3611	1221	6147	27.4	1383	518	K.28
Pueblo	2223	5285	(10983)	442	992	1309	3384	971	5899	27.5	1077	720	K.26
CONNECTICUT													
Hartford	2953	6277	(4840)	384	646	834	2857	706	2197	23.7	1459	598	K.24
DELAWARE													
Wilmington	2133	5084	(8167)	414	726	921	3602	1078	2188	17.2	1289	617	K.23
DISTRICT OF COLUMBIA													
Washington	2004	4828	(10000)	419	724	905	3734	1083	3592	18.6	1205	657	K.23
FLORIDA													
Apalachicola	163	1366	(26051)	508	887	971	6967	2695	8289	14.3	322	778	K.13
Daytona	81	787	(27107)	503	860	953	7404	2635	5252	14.8	177	641	K.13
Jacksonville	206	1357	(24148)	495	849	943	7045	2721	7488	16.4	354	674	K.13
Miami	3	185	(39401)	527	874	936	9338	4045	9166	12.4	55	259	K.15
Orlando	33	532	(33985)	511	881	974	8288	3312	9757	17.1	131	571	K.16
Tallahassee	307	1721	(25185)	495	845	944	6462	2401	7323	16.1	421	747	K.13
Tampa	37	575	(33677)	518	890	974	7985	3047	8905	14.9	147	592	K.13
West Palm Beach	10	177	(35175)	519	846	906	9203	3904	10324	13.1	22	308	K.15
GEORGIA													
Atlanta	866	3070	(16803)	467	807	930	4837	1566	3799	17.6	915	749	K.10
Augusta	664	2584	(19510)	468	803	933	5458	1904	6904	21.3	690	774	K.9
Macon	514	2330	(24443)	476	822	939	5769	2111	8097	18.7	667	787	K.12
Savannah	410	1967	(22773)	474	805	926	6112	2194	6308	16.6	529	725	K.12
HAWAII													
Barbers Point	0	3	—	592	978	965	9314	3842	3617	11.2	1	97	K.4
Hilo	0	0	(14770)	557	817	805	8494	3019	1112	11.0	0	153	K.4
Honolulu	0	0	(36213)	588	953	932	9625	4150	4537	9.8	0	69	K.4
Lihue	0	2	(25602)	567	895	893	9219	3746	1912	9.6	0	140	K.4

TABLE K.1 **Degree Days and Annual Average Insolation on Vertical Surfaces**[a] ***(continued)***

City	HDD50	HDD65	(CDH74)[b]	VSN	VSEW	VSS	CDD50	CDD65	CDH80	DR	NO HRS 8AM–4PM T < 55	NO HRS 8AM–4PM 55 ≤ T ≤ 69	ACP Table
IDAHO													
Boise	2276	5667	(7979)	399	916	1228	2828	744	4512	28.9	1542	647	K.26
Lewiston	2015	5426	(7923)	370	729	988	2709	645	4121	29.7	1467	748	K.23
Pocatello	3404	7075	(3286)	405	935	1262	2330	526	3293	32.8	1681	546	K.32
ILLINOIS													
Chicago	3000	6151	(8196)	402	729	936	3339	1015	3190	16.6	1426	613	K.24
Moline	3085	6250	(8616)	405	736	959	3204	894	2808	19.5	1357	640	K.24
Springfield	2490	5448	(12436)	422	768	962	3675	1158	4038	20.2	1260	600	K.27
INDIANA													
Evansville	1948	4625	(14797)	426	736	890	4063	1265	4288	18.4	1141	611	K.27
Fort Wayne	3023	6145	(6816)	395	664	826	3096	743	1629	17.7	1400	601	K.24
Indianapolis	2624	5620	(9082)	407	692	851	3430	951	2263	18.0	1375	602	K.24
South Bend	3038	6280	(6606)	396	690	857	2917	684	1840	21.1	1415	635	K.24
IOWA													
Burlington	3009	6094	(9712)	419	802	1030	3393	1002	2598	17.1	1354	649	K.24
Des Moines	3275	6447	(10484)	413	788	1027	3116	812	2383	17.5	1423	667	K.29
Mason City	4311	7735	(6687)	400	783	1053	2708	658	1882	20.8	1548	610	K.31
Sioux City	3608	6750	(10117)	406	794	1064	3326	993	3488	18.6	1438	602	K.29
KANSAS													
Dodge City	2280	5131	(18470)	450	942	1196	4008	1384	7186	26.0	1252	637	K.28
Goodland	2757	6090	(10079)	434	935	1228	3047	905	5147	26.3	1358	625	K.26
Topeka	2458	5201	(16640)	434	837	1068	4120	1388	5212	22.3	1192	608	K.27
KENTUCKY													
Covington	2154	5030	(9281)	408	687	843	3656	1057	2638	18.3	1316	661	K.23
Lexington	1921	4649	(11208)	425	729	872	3904	1157	2853	15.6	1211	618	K.27
Louisville	1851	4539	(13268)	424	727	883	4144	1357	4716	17.6	1192	636	K.27
LOUISIANA													
Baton Rouge	237	1573	(26938)	488	806	889	6682	2543	8814	17.2	440	677	K.12
Lake Charles	214	1455	(28573)	489	795	864	6849	2615	7883	14.8	396	668	K.12
New Orleans	179	1392	(32758)	497	838	923	6840	2578	7380	15.1	324	789	K.12
Shreveport	447	2265	(28295)	484	843	954	6022	2365	10039	18.1	687	697	K.12
MAINE													
Bangor	4132	7998	(1232)	378	693	950	1853	243	454	21.5	1721	669	K.31
Caribou	5297	9483	(920)	357	649	922	1410	121	203	18.1	1862	692	K.34
Portland	3531	7305	(1104)	376	643	856	1946	245	399	19.6	1604	665	K.30
MARYLAND													
Baltimore	2020	4946	(15162)	419	739	932	3683	1134	3825	18.6	1268	593	K.23
Patuxent	1418	4002	(11022)	429	758	943	4180	1289	2966	12.9	1118	729	K.20
MASSACHUSETTS													
Boston	2416	5775	(5358)	387	659	849	2810	695	1601	16.5	1495	713	K.23
MICHIGAN													
Alpena	4282	8164	(837)	371	661	862	1928	335	894	17.3	1707	695	K.31
Detroit	2799	5997	(4889)	390	676	858	3199	922	2238	18.8	1404	632	K.24
Flint	3471	6917	(2929)	379	641	811	2502	473	921	18.1	1563	634	K.30
Grand Rapids	3392	6777	(4555)	390	688	872	2680	590	1461	22.2	1562	622	K.29
Sault Sainte Marie	5087	9282	(844)	359	640	858	1399	119	246	21.0	1838	733	K.34
Traverse City	3934	7654	(2968)	369	642	818	2193	438	1124	21.0	1651	679	K.30
MINNESOTA													
Duluth	5797	9918	(849)	355	633	886	1511	157	258	20.0	1882	650	K.34
International Falls	6414	10535	(1614)	351	669	962	1473	119	167	22.0	1870	656	K.34
Minneapolis	4563	8060	(6806)	380	709	972	2751	773	2509	20.7	1620	566	K.31
Rochester	4544	8100	(3901)	383	691	927	2360	442	590	18.8	1584	652	K.31
MISSISSIPPI													
Jackson	546	2424	(25152)	481	833	942	5927	2330	8789	17.2	646	640	K.12
Meridian	546	2446	(23827)	480	811	905	5723	2148	9508	20.2	613	719	K.12
MISSOURI													
Columbia	2225	4994	(14475)	431	790	972	3940	1234	4242	21.5	1189	633	K.27
Saint Louis	2111	4860	(17843)	432	797	983	4193	1467	5379	18.7	1124	614	K.27
Springfield	1839	4509	(16262)	446	812	982	4115	1311	4170	20.4	1215	544	K.27
MONTANA													
Billings	3627	7156	(6167)	380	814	1160	2544	598	2695	25.6	1650	617	K.29
Cut Bank	4718	8941	(1378)	357	768	1150	1368	117	702	27.6	1834	672	K.31
Dillon	4140	8210	(1690)	386	838	1187	1564	159	784	28.6	1814	639	K.31
Glasgow	5082	8828	(4762)	361	752	1115	2272	543	2642	26.0	1688	570	K.34
Great Falls	3728	7454	(3574)	366	776	1133	2199	450	1886	26.7	1684	641	K.30
Helena	3926	7817	(2547)	372	771	1098	1911	328	1771	28.3	1784	651	K.30
Lewistown	4027	8089	(2127)	368	753	1084	1629	216	1270	29.8	1740	673	K.31
Miles City	4435	7989	(10094)	374	800	1156	2694	773	4364	26.9	1568	565	K.31
Missoula	3492	7560	(1068)	363	704	957	1629	221	1513	30.8	1843	658	K.30
NEBRASKA													
Grand Island	3315	6477	(11957)	420	843	1115	3309	996	4580	24.5	1431	611	K.29
North Platte	3447	6905	(8494)	419	880	1183	2731	715	3468	26.2	1514	592	K.32
Omaha	2981	5968	(10509)	414	806	1066	3618	1130	3883	19.6	1355	586	K.24
Scottsbluff	3335	6900	(7339)	413	861	1168	2603	693	3745	28.3	1457	620	K.32

TABLE K.1 **Degree Days and Annual Average Insolation on Vertical Surfaces** (continued)

City	HDD50	HDD65	CDH76	VSN	VSEW	VSS	CDD50	CDD65	CDH80	DR	NO WRS 8AM–4PM T < 55	55 ≤ T < 65	ACP Table
NEVADA													
Elko	3345	7178	(3840)	420	1000	1332	1987	355	4065	37.8	1540	969	K.33
Ely	3683	7696	(659)	432	1014	1350	1650	157	1317	30.1	1329	883	K.32
Las Vegas	449	2399	(43153)	436	1138	1417	6567	3043	26408	25.5	604	718	K.14
Lovelock	2438	5845	(7845)	418	1094	1452	2813	745	6859	34.7	1358	826	K.26
Reno	2181	5941	(2192)	428	1068	1401	2180	365	4059	39.3	1308	752	K.28
Tonopah	2308	5832	(5868)	427	1130	1502	2742	611	3777	28.4	1257	660	K.26
Winnemucca	2774	6471	(4284)	418	1014	1350	2264	486	5366	41.0	1383	808	K.26
Yucca Flats	1684	4802	—	450	1112	1399	3378	1041	11988	35.9	1004	670	—
NEW HAMPSHIRE													
Concord	3742	7425	(1993)	375	630	824	2254	463	1865	20.8	1533	693	K.30
NEW JERSEY													
Lakehurst	2174	5265	(5594)	407	712	917	3299	915	3019	20.5	1312	645	K.23
Newark	2027	4956	(9107)	406	710	912	3596	1009	3487	17.7	1325	644	K.23
NEW MEXICO													
Albuquerque	1633	4423	(11012)	469	1105	1361	3942	1257	5705	25.3	1148	703	K.21
Clayton	2138	5176	(6793)	457	1019	1310	3122	685	2083	20.0	1150	770	K.26
Roswell	1008	3486	(20216)	490	1081	1280	4536	1539	11135	26.1	825	677	K.21
Truth or Consequences	1074	3592	(14599)	488	1113	1326	4457	1500	6882	23.4	889	744	K.21
Tucumcari	1344	3922	(14754)	470	1048	1300	4451	1554	8424	26.9	914	710	K.21
NEW YORK													
Albany	3458	6770	(2998)	395	719	942	2812	619	1308	19.7	1487	635	K.29
Binghampton	3585	7397	(1646)	370	592	733	2373	410	672	18.5	1837	862	K.30
Buffalo	3213	6721	(3044)	371	609	746	2476	509	779	18.2	1571	697	K.29
Massena	4583	8397	(2012)	380	708	942	2026	365	913	20.9	1874	827	K.31
New York (Central Pk)	1986	5022	(9537)	392	650	817	3273	834	911	12.5	1335	790	K.23
New York (LAG)	1986	5022	(9189)	392	650	817	3273	834	911	12.5	1335	790	K.23
Rochester	3482	6995	(3784)	374	622	771	2557	595	1642	20.1	1812	808	K.29
Syracuse	3448	6858	(3516)	371	611	764	2579	513	926	20.2	1521	730	K.29
NORTH CAROLINA													
Asheville	1407	4203	(6292)	449	782	946	3442	763	1298	21.1	1083	815	K.19
Cape Hatteras	635	2745	(12440)	460	819	972	4978	1813	5039	10.0	768	820	K.9
Charlotte	1086	3412	(15139)	458	809	968	4098	1549	4269	19.8	892	777	K.20
Cherry Point	569	2556	(13152)	461	826	986	5277	1798	3814	18.2	690	757	K.9
Greensboro	1261	3760	(11020)	449	810	964	4014	1298	3642	17.4	1018	718	K.20
Raleigh	1131	3509	(11845)	445	774	935	4485	1389	3697	16.8	918	740	K.20
NORTH DAKOTA													
Williston	5196	8992	(4934)	371	748	1114	2178	496	2067	27.8	1704	936	K.34
Fargo	5582	9242	(4284)	371	751	1077	2388	573	2288	22.2	1730	946	K.34
Minot	5336	9178	(4157)	358	724	1059	2064	431	1570	24.5	1800	981	K.34
OHIO													
Akron	2881	6172	(4808)	396	664	812	2845	861	1100	17.3	1460	680	K.24
Columbus	2424	5493	(7490)	401	671	819	3195	789	2268	22.6	1375	709	K.23
Dayton	2573	5549	(8280)	408	696	855	3367	868	1346	17.1	1388	811	K.23
Toledo	3132	6514	(5081)	393	676	853	2791	699	1794	17.8	1500	692	K.24
Youngstown	3129	6557	(2975)	383	624	760	2693	546	1128	21.4	1523	879	K.24
OKLAHOMA													
Oklahoma City	1417	3825	(22978)	465	875	1053	4901	1834	9878	20.8	980	753	K.21
Tulsa	1429	3732	(26468)	453	820	991	5244	2072	10065	19.7	983	891	K.20
OREGON													
Astoria	1080	5226	(30)	350	588	782	1357	29	143	12.3	1571	1036	K.18
Medford	1531	4893	(6151)	405	814	1005	2681	568	4081	32.9	1442	749	K.19
North Bend	629	4678	(58)	392	740	977	1429	2	0	11.8	1351	1353	—
Portland	1151	4577	(1851)	364	647	841	2321	272	1096	22.8	1421	1060	K.18
Redmond	2535	6665	(1972)	395	835	1127	1573	209	2390	34.4	1631	885	K.25
Salem	1128	4926	(1081)	373	680	874	1849	172	1024	29.3	1489	916	K.18
PENNSYLVANIA													
Allentown	2692	5760	(5804)	401	642	864	3105	698	1146	17.0	1335	710	K.24
Avoca (Scranton)	2931	6236	(3774)	389	646	811	2823	652	1847	19.7	1503	705	K.24
Erie	3006	6426	(2222)	384	646	792	2527	472	378	14.8	1532	716	K.25
Harrisburg	2302	5251	(9071)	404	687	864	3518	992	2860	20.1	1342	648	K.23
Philadelphia	2044	4923	(8896)	408	701	889	3661	1065	3170	17.1	1288	646	K.23
Pittsburgh	2773	5907	(5009)	392	642	790	2989	648	1040	19.0	1426	700	K.24
RHODE ISLAND													
Providence	2610	6022	(3631)	393	677	874	2756	693	1294	16.8	1459	684	K.24
SOUTH CAROLINA													
Charleston	435	2194	(23263)	467	796	925	5725	2005	5249	16.4	570	767	K.12
Columbia	694	2666	(21805)	467	816	953	5613	2110	8541	19.5	741	705	K.12
Greenville	907	3220	(14069)	459	814	971	4983	1400	3484	17.7	866	851	K.10
SOUTH DAKOTA													
Huron	4820	8351	(8677)	390	769	1044	2718	774	3739	24.5	1630	845	K.31
Pierre	4028	7358	(10444)	392	822	1147	3079	934	5262	24.2	1564	837	K.31
Rapid City	3672	7229	(8266)	394	819	1142	3581	863	3477	28.2	1530	570	K.29
Sioux Falls	4240	7683	(8638)	394	778	1078	2811	779	3029	20.2	1553	569	K.31
TENNESSEE													
Chattanooga	1232	3595	(17017)	444	738	869	4662	1541	5079	17.6	1030	684	K.20
Knoxville	1263	3818	(14214)	446	762	898	4435	1514	3840	17.8	1076	703	K.20
Memphis	1034	3259	(24804)	460	806	935	5319	2069	7807	19.2	869	651	K.22
Nashville	1165	3609	(16543)	443	749	863	4583	1552	5078	18.2	897	748	K.20

TABLE K.1 **Degree Days and Annual Average Insolation on Vertical Surfaces** (*continued*)

City	HDD50	HDD65	(CDH74)[a]	VSN	VSEW	VSS	CDD50	CDD65	CDH80	DR	NO HRS 8AM–4PM T < 55	NO HRS 8AM–4PM 55 ≤ T ≤ 69	ACP Table
TEXAS													
Abilene	792	2714	(31904)	494	924	1066	5968	2416	13206	21.5	760	648	K.13
Amarillo	1592	4331	(15718)	471	1013	1253	4113	1377	6763	23.9	1109	680	K.21
Austin	271	1735	(35180)	503	877	972	6873	2862	14093	19.3	564	664	K.13
Brownsville	35	642	(42529)	547	908	908	8531	3664	12218	14.8	191	422	K.16
Corpus Christi	106	889	(42515)	529	906	946	8200	3508	13109	17.2	249	543	K.16
Del Rio	186	1397	(42032)	511	903	1008	7376	3112	14870	19.8	474	732	K.13
El Paso	522	2605	(22966)	503	1133	1306	5617	2225	13224	21.3	660	735	K.13
Fort Worth	605	2354	(30148)	485	875	994	6174	2448	13682	20.5	673	772	K.13
Houston	195	1346	(30474)	490	805	883	7215	2891	10569	18.2	352	703	K.12
Kingsville	49	874	(42877)	527	881	922	8302	3652	15512	19.2	260	523	K.16
Laredo	65	842	(52560)	532	900	936	8827	4130	25225	21.4	286	598	—[c]
Lubbock	1173	3643	(18218)	488	1070	1267	4754	1749	9827	25.1	917	743	K.21
Lufkin	370	1846	(30370)	492	848	942	6667	2668	11737	21.5	478	681	K.12
Midland	634	2573	(24201)	504	1079	1247	5695	2159	11177	25.9	698	729	K.13
Port Arthur	167	1416	(31667)	497	824	900	6888	2662	8837	17.4	384	697	K.12
San Angelo	538	2110	(32735)	503	944	1076	6522	2619	14621	20.6	641	619	K.13
San Antonio	261	1579	(36179)	510	878	955	7170	3013	13841	20.1	462	690	K.13
Sherman	699	2708	(29686)	476	862	996	5844	2378	12065	20.2	785	721	K.13
Waco	488	2166	(36671)	495	874	972	6676	2879	15658	21.1	651	622	K.13
Wichita Falls	984	3049	(34510)	480	911	1077	5708	2299	14487	18.8	802	723	—[c]
UTAH													
Bryce Canyon	4709	9288	(31)	445	1063	1386	899	4	69	30.0	1660	841	K.33
Cedar City	2592	5888	(5036)	447	1054	1342	2802	624	3119	27.1	1392	629	K.26
Salt Lake City	2570	5975	(9898)	422	975	1266	3011	941	7030	29.1	1426	586	K.26
VERMONT													
Burlington	4211	7932	(2562)	382	698	925	2118	365	490	18.3	1697	637	K.31
VIRGINIA													
Norfolk	1185	3609	(13677)	443	792	964	4636	1586	4554	15.0	1014	685	K.20
Richmond	1322	3895	(12260)	430	745	923	4225	1323	4021	17.6	996	716	K.20
Roanoke	1520	4192	(9275)	433	763	946	3986	1183	3306	19.0	1148	713	K.20
WASHINGTON													
Olympia	1546	5550	(341)	351	619	819	1550	79	466	26.4	1577	985	K.18
Seattle/Tacoma	1382	5281	(1050)	350	621	828	1683	106	256	16.5	1700	982	K.18
Spokane	2983	6727	(3453)	363	758	1064	2094	363	1595	25.3	1669	640	K.25
Whidbey Island	1179	5274	(59)	344	630	878	1403	22	7	14.8	1671	1169	K.18
Yakima	2323	5877	(4118)	373	790	1091	2370	449	3285	31.2	1413	709	K.25
WEST VIRGINIA													
Charleston	1816	4587	(8790)	409	667	798	3712	1008	3054	20.8	1215	704	K.23
WISCONSIN													
Eau Claire	4751	8285	(3886)	376	683	923	2545	603	1898	18.2	1565	661	K.31
Green Bay	4310	8039	(2453)	380	696	947	2172	426	957	22.1	1604	651	K.31
La Crosse	3838	7243	(6795)	386	701	937	2786	716	2121	18.9	1568	644	K.29
Madison	4009	7466	(3343)	391	717	955	2559	542	1329	19.1	1511	658	K.31
Milwaukee	3586	7121	(3313)	396	724	941	2427	487	1013	17.1	1587	618	K.29
WYOMING													
Casper	3824	7617	(4370)	403	961	1343	2177	495	2699	29.8	1670	535	K.32
Cheyenne	3435	7218	(2087)	416	906	1267	1963	271	1040	26.4	1618	608	K.32
Rock Springs	4407	8391	(1043)	411	1012	1395	1698	207	702	29.1	1828	552	K.33
Sheridan	3605	7366	(4115)	387	806	1133	2074	360	2105	30.8	1650	574	K.30
OTHER LOCATIONS													
OUTSIDE U.S.A.													
Guantanamo Bay, CU	0	0	—	612	1045	1018	11071	5596	18452	15.5	0	17	K.5
Koror Island, PN	0	0	(70454)	662	890	827	11435	5960	14548	9.5	0	0	K.5
Kwajalein Island, PN	0	0	(72338)	678	961	888	11635	6160	16217	8.2	0	0	K.5
San Juan, PR	0	0	(55224)	608	963	931	10648	5173	11563	12.7	0	14	K.5
Wake Island, PN	0	0	(57637)	609	1002	977	10869	5394	10167	9.7	0	0	K.5

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[a]HDD50 Average annual heating degree days, base 50 F
HDD65 Average annual heating degree days, base 65 F
VSN Average annual insolation, vertical north facing surface, Btu/ft²-day
VSEW Average annual insolation, vertical east (west) facing surface, Btu/ft²-day
VSS Average annual insolation, vertical south facing surface, Btu/ft²-day
CDD50 Average annual cooling degree days, base 50 F
CDH80 Average annual cooling degree hours, base 80 F
DR Daily range in warmest month between day high and night low temperatures, F°
NO HRS 8 AM–4 PM Average annual hours at these temperatures during this time period

[b](CDH74) Average annual cooling degree hours, base 74 F, to nearest location listed. From Proposed BSR/ASHRAE Standard 90.2 P, *Energy Efficient Design of New Low-Rise Residential Buildings*.

[c]See ASHRAE/IES Standard 90.1-1989 for ACP table at this location.

TABLE K.2 ASHRAE/IES Standard 90.1-1989: Electric Lighting and Power Estimating

Part A. ***Prescriptive Unit Lighting Power Allowance (ULPA), W/ft² Gross Lighted Area of Total Building***[a]

Building Type or Space Activity	0 to 2000 ft²	2000 to 10,000 ft²	10,001 to 25,001 ft²	25,001 to 50,000 ft²	50,001 to 250,000 ft²	> 250,000 ft²
Food service						
Fast food cafeteria	1.50	1.38	1.34	1.32	1.31	
Leisure dining/bar	2.20	1.91	1.71	1.56	1.46	1.30
Offices	1.90	1.81	1.72	1.65	1.57	1.40
Retail[b]	3.30	3.08	2.83	2.50	2.28	1.50
Mall concourse	1.60	1.58	1.52	1.46	1.43	2.10
multistore service						1.40
Service establishment	2.70	2.37	2.08	1.92	1.80	
Garages	0.30	0.28	0.24	0.22	0.21	1.70
Schools						0.20
Preschool/elementary	1.80	1.80	1.72	1.65	1.57	
Jr. high/high school	1.90	1.90	1.88	1.83	1.76	1.50
Technical/vocational	2.40	2.33	2.17	2.01	1.84	1.70
Warehouse storage	0.80	0.66	0.56	0.48	0.43	1.70
						0.40

Part B. ***Average Receptacle Power Densities***

Building Type	W/ft²
1. Assembly	0.25
2. Office	0.75
3. Retail	0.25
4. Warehouse	0.10
5. School	0.50
6. Hotel or motel	0.25
7. Restaurant	0.10
8. Health	1.00
9. Multi-family	0.75

Part C. ***System Performance Unit Lighting Power Allowance, Common Activity Areas***

Area/Activity	UPD W/ft²	Note
Auditorium	1.6	c
Corridor	0.8	d
Classroom/lecture hall	2.0	
Electrical/mechanical equipment room		
General	0.7	d
Control rooms	1.5	d
Food service		
Fast food/cafeteria	1.3	
Leisure dining	2.5	e
Bar/lounge	2.5	e
Kitchen	1.4	
Recreation/lounge	0.7	
Stair		
Active traffic	0.6	
Emergency exit	0.4	
Toilet & washroom	0.8	
Garage		
Auto & pedestrial circulation area	0.3	
Parking area	0.2	
Laboratory	2.3	
Library		
Audio visual	1.1	
Stack area	1.5	
Card file & cataloging	1.6	
Reading area	1.9	
Lobby (general)		
Reception & waiting	1.0	
Elevator lobbies	0.8	
Atrium (multi-story)		
First 3 floors	0.7	
Each additional floor	0.2	
Locker room & shower	0.8	

TABLE K.2 ASHRAE/IES Standard 90.1-1989: Electric Lighting and Power Estimating (*continued*)

Area/Activity	UPD W/ft²	Note
Office category 1		
Enclosed offices, all open plan offices without partitions or with partitions[f] lower than 4.5 ft below the ceiling.		
Reading, typing and filing	1.8	g
Drafting	2.6	g
Accounting	2.1	g
Office category 2		
Open plan offices 900 ft² or larger with partitions[f] 3.5 to 4.5 ft below the ceiling.		
Offices less than 900 ft² shall use category 1.		
Reading, typing and filing	1.9	d
Drafting	2.9	d
Accounting	2.4	d
Office category 3		
Open plan offices 900 ft² or larger with partitions[f] higher than 3.5 ft below the ceiling. Offices less than 900 ft² shall use category 1.		
Reading, typing and filing	2.2	d
Drafting	3.4	d
Accounting	2.7	d
Common activity areas		
Conference/meeting room	1.8	c
Computer/office equipment	2.1	
Filing, inactive	1.0	
Mail room	1.8	
Shop (non-industrial)		
Machinery	2.5	
Electrical/electronic	2.5	
Painting	1.6	
Carpentry	2.3	
Welding	1.2	
Storage & warehouse		
Inactive storage	0.3	
Active storage, bulky	0.3	
Active storage, fine	1.0	
Material handling	1.0	
Unlisted space	0.2	

Part D. ***System Performance Unit Lighting Power Allowance, Specific Buildings***

Area/Activity	UPD W/ft²	Note
Airport, bus and rail station		
Baggage area	1.0	
Concourse/main thruway	0.9	
Ticket counter	2.5	
Waiting & lounge area	1.2	
Bank		
Customer area	1.1	
Banking activity area	2.8	
Barber & beauty parlor	2.0	
Church, synagogue, chapel		
Worship/congregational	2.5	
Preaching & sermon/choir	2.7	
Dormitory		
Bedroom	1.1	
Bedroom with study	1.4	
Study hall	1.8	
Fire & police department		
Fire engine room	0.7	
Jail cell	0.8	
Hospital/nursing home		
Corridor	1.3	d
Dental suite/examination/treatment	1.6	
Emergency	2.3	
Laboratory	1.9	
Lounge/waiting room	0.9	
Medical supplies	2.4	
Nursery	2.0	
Nurse station	2.1	
Occupational therapy/physical therapy	1.6	
Patient room	1.4	
Pharmacy	1.7	
Radiology	2.1	
Surgical & O.B. suites		
General area	2.1	
Operating room	7.0	
Recovery	2.3	

APPENDICES

TABLE K.2 **ASHRAE/IES Standard 90.1-1989: Electric Lighting and Power Estimating** ***(continued)***

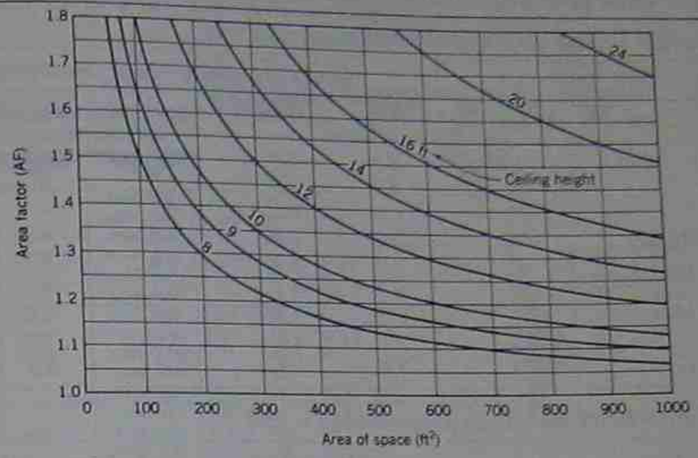
Area/Activity	*UPD W/ft²*	*Note*
Hotel/conference center		
Banquet room/multipurpose	2.4	c
Bathroom/powder room	1.2	
Guest room	1.4	
Public area	1.2	
Exhibition hall	2.6	
Conference/meeting	1.8	c
Lobby	1.9	
Reception desk	2.4	
Laundry		
Washing	0.9	
Ironing & sorting	1.3	
Museum & gallery		
General exhibition	1.9	
Inspection/restoration	3.9	
Storage (artifacts)		
Inactive	0.6	
Active	0.7	
Post office		
Lobby	1.1	
Sorting & mailing	2.1	
Service station/auto repair	1.0	
Theater		
Performance arts	1.5	
Motion picture	1.0	
Lobby	1.5	
Retail establishments (Merchandising & circulation area)		
Applicable to all lighting, including accent and display lighting, installed in merchandising and circulation areas		
Type A	5.6	h
Type B	3.2	h
Type C	3.3	h
Type D	3.1	h
Type E	2.8	h
Type F	2.7	h
Mall concourse	1.4	
Retail support areas		
Tailoring	2.1	
Dressing/fitting rooms	1.4	

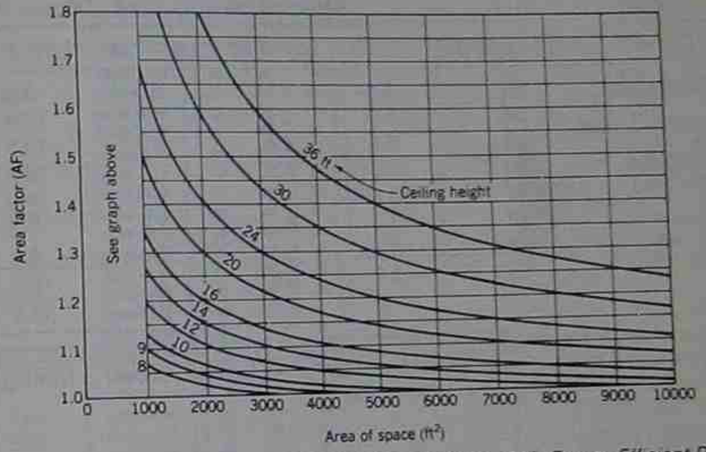
Part E. ***System Performance Unit Lighting Power Allowance, Indoor Athletic Areas***[f]

Area/Activity	*UPD W/ft²*	*Note*
Seating area, all sports	0.4	
Badminton		
Club	0.5	
Tournament	0.8	
Basketball/volleyball		
Intramural	0.8	
College	1.3	
Professional	1.9	
Bowling		
Approach area	0.5	
Lanes	1.1	
Boxing or wrestling (platform)		
Amateur	2.4	
Professional	4.8	
Gymnasium		
General exercising & recreation only	1.0	
Handball/racquetball/squash		
Club	1.3	
Tournament	2.6	
Hockey, ice		
Amateur	1.3	
College or professional	2.6	
Skating rink		
Recreational	0.6	
Exhibition/professional	2.6	
Swimming		
Recreational	0.9	
Exhibition	1.5	
Under water	1.0	
Tennis		
Recreational (class III)	1.3	
Club/college (class II)	1.9	
Professional (class I)	2.6	
Tennis, table	1.0	
Club	1.6	
Tournament		

TABLE K.2 **ASHRAE/IES Standard 90.1-1989: Electric Lighting and Power Estimating** ***(continued)***

Part F. ***Area Factors***





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[a]This prescriptive table is intended primarily for core and shell (i.e., speculative) buildings or during the preliminary design phase (i.e., when the space uses are less than 80% defined). The values in this table are not intended to represent the needs of all buildings within the types listed.

[b]Includes general, merchandising, and display lighting.

[c]A 1.5 power adjustment factor is applicable for multi-functional spaces.

[d]Area factor of 1.0 shall be used for these spaces.

[e]UPD includes lighting power required for clean-up purposes.

[f]Not less than 90% of all work stations shall be individually enclosed with partitions of at least the height described.

[g]Area factor shall not exceed 1.55.

[h]Retail establishment classifications:
Type A: jewelry merchandising
Type B: fine apparel and accessories, china, crystal and silver, art galleries
Type C: "warehouse type" display of general apparel, varieties, stationery, books, sporting goods, hobby, cameras, gifts, luggage
Type D: "department store type" display of general apparel, varieties, stationery, books, sporting goods, hobby, cameras, gifts, luggage
Type E: Food and miscellaneous: bakeries, hardware and housewares, grocery, appliances, furniture
Type F: Service establishments

Area factor of 1.0 shall be used for all indoor athletic spaces.

TABLE K.3 **ASHRAE/IES Standard 90.1-1989: Maximum % Skylight Area of Roof Area**

Part A. Skylight VLT (Visible Light Transmission) = 0.75

Building Location			Range of Lighting Power Density (W/ft²)				
HDD65	CDH80	Light Level (fc)	<1.00	1.01–1.50	1.51–2.00	2.01–2.50	>2.50
0–3000	0–10,000	30	2.3	3.1	3.9	4.7	4.7
		50	3.1	4.3	5.5	6.7	6.7
		70	4.3	5.5	6.7	7.9	7.9
0–3000	>10,000	30	2.2	2.8	3.4	4.0	4.0
		50	2.3	3.1	3.9	4.7	4.7
		70	2.9	4.1	5.3	6.5	6.5
>3000	All	30	2.3	3.4	4.5	5.6	5.6
		50	2.5	4.0	5.5	7.0	7.0
		70	2.8	4.6	6.4	8.2	8.2

Part B. Skylight VLT (Visible Light Transmission) = 0.50

Building Location			Range of Lighting Power Density (W/ft²)				
HDD65	CDH80	Light Level (fc)	<1.00	1.01–1.50	1.51–2.00	2.01–2.50	>2.50
0–3000	0–10,000	30	3.6	4.8	6.0	7.2	7.2
		50	4.8	6.6	8.4	10.2	10.2
		70	6.6	8.4	10.2	12.0	12.0
0–3000	>10,000	30	3.3	4.2	5.1	6.0	6.0
		50	3.6	4.8	6.0	7.2	7.2
		70	4.2	6.0	7.8	9.6	9.6
>3000	All	30	3.6	5.1	6.6	8.1	8.1
		50	3.9	6.0	8.1	10.2	10.2
		70	4.2	6.9	9.6	12.3	12.3

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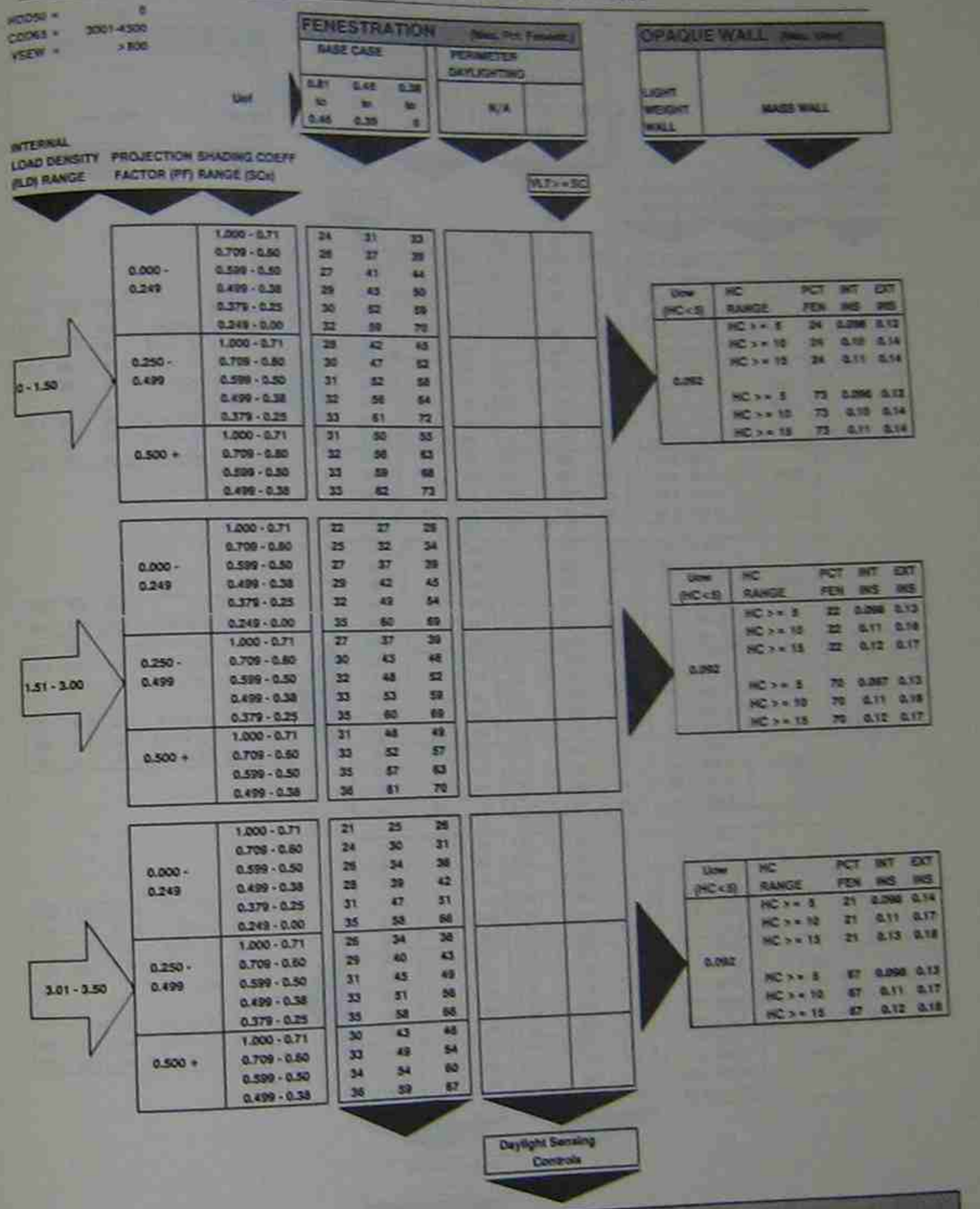
TABLE K.4 **ACP for Hawaii (Barbers Point, Hilo, Honolulu, Lihue)**

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989



OTHER CRITERIA					
	Minimum R-Value				Max U
WALL BELOW GRADE:	0			ROOF:	0.064
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.14
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.066
Horizontal	10	13	11		
Vertical	0	0	4		

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TABLE K.5 ACP for Puerto Rico (also Guantanamo Bay, CU; Kwajalein, Koror, Wake Islands)

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 0
CDD63 = >8500
VSEW = >845

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT> = SC

ILD	PF	SCx	LIGHT WEIGHT WALL			MASS WALL		
0 - 1.50	0.000 - 0.249	1.000 - 0.71	14	14		17	16	17
		0.709 - 0.60	19	18		21	21	22
		0.599 - 0.50	23	22		26	26	26
		0.499 - 0.38	29	28		33	32	33
		0.379 - 0.25	42	39		49	46	47
		0.249 - 0.00	81	72		96	82	85
	0.250 - 0.499	1.000 - 0.71	21	21		25	24	25
		0.709 - 0.60	28	27		33	31	32
		0.599 - 0.50	35	33		41	39	40
		0.499 - 0.38	45	42		53	49	51
		0.379 - 0.25	69	62		81	72	74
	0.500 +	1.000 - 0.71	30	29		35	33	34
		0.709 - 0.60	40	38		47	44	45
		0.599 - 0.50	50	47		60	55	56
		0.499 - 0.38	67	61		80	71	73
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	12	12		19	19	21
		0.709 - 0.60	16	15		25	24	26
		0.599 - 0.50	19	19		31	30	32
		0.499 - 0.38	24	23		40	38	40
		0.379 - 0.25	35	33		60	54	58
		0.249 - 0.00	66	60		100	93	100
	0.250 - 0.499	1.000 - 0.71	18	17		29	28	30
		0.709 - 0.60	23	23		39	37	39
		0.599 - 0.50	29	28		49	46	49
		0.499 - 0.38	37	35		65	59	62
		0.379 - 0.25	56	52		96	83	90
	0.500 +	1.000 - 0.71	25	24		42	39	42
		0.709 - 0.60	33	31		57	52	55
		0.599 - 0.50	41	39		73	66	69
		0.499 - 0.38	55	50		95	82	88
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	9	9		17	17	19
		0.709 - 0.60	12	12		23	22	25
		0.599 - 0.50	15	14		28	27	31
		0.499 - 0.38	18	18		36	34	38
		0.379 - 0.25	26	25		55	50	55
		0.249 - 0.00	49	46		100	86	96
	0.250 - 0.499	1.000 - 0.71	14	13		26	25	29
		0.709 - 0.60	18	17		35	33	37
		0.599 - 0.50	22	21		45	42	46
		0.499 - 0.38	28	27		60	54	59
		0.379 - 0.25	42	39		88	77	85
	0.500 +	1.000 - 0.71	19	18		38	36	40
		0.709 - 0.60	25	24		52	48	52
		0.599 - 0.50	31	30		68	61	66
		0.499 - 0.38	41	38		87	76	84

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
1.00	HC > = 5	14	1.00	1.00
	HC > = 10	14	1.00	1.00
	HC > = 15	14	1.00	1.00
	HC > = 5	96	1.00	1.00
	HC > = 10	96	1.00	1.00
	HC > = 15	96	1.00	1.00

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
1.00	HC > = 5	12	1.00	1.00
	HC > = 10	12	1.00	1.00
	HC > = 15	12	1.00	1.00
	HC > = 5	96	1.00	1.00
	HC > = 10	96	1.00	1.00
	HC > = 15	96	1.00	1.00

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
1.00	HC > = 5	9	1.00	1.00
	HC > = 10	9	1.00	1.00
	HC > = 15	9	1.00	1.00
	HC > = 5	96	1.00	1.00
	HC > = 10	96	1.00	1.00
	HC > = 15	96	1.00	1.00

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		0		ROOF: 0.057
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 1.8
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.43
Horizontal	0	0	0	
Vertical	0	0	0	

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TABLE K.6 ACP for Oakland, Point Mugu, and Sunnyvale, CA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1500
CDD63 = 0 - 300
VSEW = > 845
HDD65 = 1-3000

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT> = SC

ILD	PF	SCx	LIGHT WEIGHT WALL			MASS WALL		
0 - 1.50	0.000 - 0.249	1.000 - 0.71	24	25		29	28	29
		0.709 - 0.60	30	31		36	33	36
		0.599 - 0.50	34	36		43	39	43
		0.499 - 0.38	39	43		51	46	51
		0.379 - 0.25	47	54		63	57	66
		0.249 - 0.00	60	72		81	75	86
	0.250 - 0.499	1.000 - 0.71	34	36		36	39	42
		0.709 - 0.60	40	43		42	47	52
		0.599 - 0.50	45	50		47	54	61
		0.499 - 0.38	50	58		53	61	72
		0.379 - 0.25	59	70		61	74	91
	0.500 +	1.000 - 0.71	42	45		44	50	55
		0.709 - 0.60	49	55		51	59	68
		0.599 - 0.50	54	63		56	68	79
		0.499 - 0.38	60	71		61	74	92
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	19	20		26	27	28
		0.709 - 0.60	24	25		31	33	35
		0.599 - 0.50	28	29		35	38	41
		0.499 - 0.38	32	34		40	45	49
		0.379 - 0.25	40	44		49	56	64
		0.249 - 0.00	54	62		61	74	93
	0.250 - 0.499	1.000 - 0.71	27	28		35	38	40
		0.709 - 0.60	33	35		41	45	50
		0.599 - 0.50	38	41		46	52	59
		0.499 - 0.38	43	48		52	60	70
		0.379 - 0.25	52	60		60	72	88
	0.500 +	1.000 - 0.71	35	37		43	48	53
		0.709 - 0.60	41	45		50	57	68
		0.599 - 0.50	47	52		55	65	77
		0.499 - 0.38	53	60		61	72	89
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	17	17		25	26	27
		0.709 - 0.60	21	21		30	32	34
		0.599 - 0.50	24	25		34	37	40
		0.499 - 0.38	29	30		39	43	48
		0.379 - 0.25	38	39		47	54	63
		0.249 - 0.00	49	56		60	72	90
	0.250 - 0.499	1.000 - 0.71	24	25		34	36	39
		0.709 - 0.60	29	30		40	44	49
		0.599 - 0.50	34	36		45	50	57
		0.499 - 0.38	39	42		50	58	68
		0.379 - 0.25	48	53		58	69	86
	0.500 +	1.000 - 0.71	31	32		42	46	52
		0.709 - 0.60	37	40		48	55	64
		0.599 - 0.50	42	46		53	62	75
		0.499 - 0.38	48	54		59	70	87

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.14	HC > = 5	24	0.39	0.22
	HC > = 10	24	0.54	0.47
	HC > = 15	24	0.44	0.54
	HC > = 5	96	0.19	0.22
	HC > = 10	96	0.30	0.43
	HC > = 15	96	0.40	0.49

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.14	HC > = 5	19	0.22	0.22
	HC > = 10	19	0.45	0.56
	HC > = 15	19	0.62	0.79
	HC > = 5	93	0.20	0.22
	HC > = 10	93	0.35	0.49
	HC > = 15	93	0.45	0.57

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.14	HC > = 5	17	0.23	0.22
	HC > = 10	17	0.49	0.73
	HC > = 15	17	0.68	0.80
	HC > = 5	90	0.21	0.22
	HC > = 10	90	0.37	0.52
	HC > = 15	90	0.48	0.60

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		0		ROOF: 0.053
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 0.22
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.10
Horizontal	0	0	0	
Vertical	0	0	0	

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TABLE K.7 ACP for San Francisco and Santa Maria, CA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1-1000
CDD65 = 0- 300
VSEW = >845
HDD65 = 1-3000

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.81 to 0.46	0.45 to 0.39	0.38 to 0	0.81 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE | SHADING COEFF (SCx) | VLT >= SC

ILD	PF	SCx	LIGHT WEIGHT WALL			MASS WALL		
0 - 1.50	0.000 - 0.249	1.000 - 0.71	21	22	23	23	25	25
		0.709 - 0.60	26	28	28	28	31	31
		0.599 - 0.50	30	33	33	32	36	37
		0.499 - 0.38	35	39	40	37	43	44
		0.379 - 0.25	42	50	52	45	55	57
		0.249 - 0.00	55	72	76	57	77	82
	0.250 - 0.499	1.000 - 0.71	30	32	33	32	36	37
		0.709 - 0.60	35	40	40	38	44	45
		0.599 - 0.50	40	46	47	43	51	53
		0.499 - 0.38	46	55	56	48	60	63
		0.379 - 0.25	54	69	72	56	74	79
	0.500 +	1.000 - 0.71	38	43	43	40	47	48
		0.709 - 0.60	44	52	53	47	57	59
		0.599 - 0.50	49	60	62	52	65	69
		0.499 - 0.38	55	70	73	57	75	80
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	17	18	18	23	25	26
		0.709 - 0.60	21	22	22	28	31	32
		0.599 - 0.50	25	26	26	33	36	38
		0.499 - 0.38	29	31	32	38	43	45
		0.379 - 0.25	37	41	42	46	55	59
		0.249 - 0.00	51	61	63	60	77	84
	0.250 - 0.499	1.000 - 0.71	25	26	26	32	35	37
		0.709 - 0.60	30	32	32	39	43	46
		0.599 - 0.50	34	37	38	44	51	54
		0.499 - 0.38	40	45	45	49	60	64
		0.379 - 0.25	49	58	59	58	74	81
	0.500 +	1.000 - 0.71	32	34	34	41	47	49
		0.709 - 0.60	38	42	42	48	57	60
		0.599 - 0.50	43	49	50	53	65	70
		0.499 - 0.38	49	58	60	59	75	82
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	15	15	15	22	24	25
		0.709 - 0.60	18	19	19	27	29	31
		0.599 - 0.50	22	22	22	31	34	36
		0.499 - 0.38	26	27	27	36	41	44
		0.379 - 0.25	32	36	36	44	53	57
		0.249 - 0.00	45	53	54	57	73	82
	0.250 - 0.499	1.000 - 0.71	21	22	22	31	34	36
		0.709 - 0.60	26	27	27	37	42	44
		0.599 - 0.50	30	32	32	42	49	52
		0.499 - 0.38	35	38	39	47	57	62
		0.379 - 0.25	43	50	51	56	71	78
	0.500 +	1.000 - 0.71	27	29	29	39	44	48
		0.709 - 0.60	33	36	36	46	54	58
		0.599 - 0.50	38	42	43	51	63	68
		0.499 - 0.38	44	50	51	57	72	79

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.13	HC >= 5	21	0.17	0.21
	HC >= 10	21	0.27	0.36
	HC >= 15	21	0.36	0.38
	HC >= 5	82	0.17	0.21
	HC >= 10	82	0.24	0.34
	HC >= 15	82	0.33	0.38

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.13	HC >= 5	17	0.21	0.21
	HC >= 10	17	0.36	0.46
	HC >= 15	17	0.48	0.51
	HC >= 5	84	0.17	0.21
	HC >= 10	84	0.28	0.37
	HC >= 15	84	0.38	0.40

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.13	HC >= 5	15	0.21	0.21
	HC >= 10	15	0.37	0.48
	HC >= 15	15	0.52	0.56
	HC >= 5	82	0.17	0.21
	HC >= 10	82	0.29	0.37
	HC >= 15	82	0.39	0.41

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		7		ROOF:	0.048
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.21
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.064
Horizontal	11	9	8		
Vertical	6	5	4		

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TABLE K.8 ACP for El Toro, Long Beach, Los Angeles, and San Diego, CA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 301 - 1150
VSEW = > 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE | SHADING COEFF (SCx) | VLT >= SC

ILD	PF	SCx	LIGHT WEIGHT WALL			MASS WALL		
0 - 1.50	0.000 - 0.249	1.000 - 0.71	18	18		21	21	21
		0.709 - 0.60	23	23		28	28	28
		0.599 - 0.50	27	27		30	31	31
		0.499 - 0.38	33	33		36	37	38
		0.379 - 0.25	43	44		47	49	50
		0.249 - 0.00	64	67		70	73	75
	0.250 - 0.499	1.000 - 0.71	26	26		29	30	30
		0.709 - 0.60	33	33		36	37	38
		0.599 - 0.50	38	39		43	44	45
		0.499 - 0.38	46	47		51	52	53
		0.379 - 0.25	60	62		66	69	70
	0.500 +	1.000 - 0.71	35	35		39	39	40
		0.709 - 0.60	43	43		48	49	50
		0.599 - 0.50	50	52		56	58	59
		0.499 - 0.38	60	62		66	68	70
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	14	14		21	21	22
		0.709 - 0.60	18	18		26	26	27
		0.599 - 0.50	21	21		31	31	33
		0.499 - 0.38	26	26		37	37	39
		0.379 - 0.25	35	34		49	49	52
		0.249 - 0.00	54	54		72	74	78
	0.250 - 0.499	1.000 - 0.71	21	20		30	30	31
		0.709 - 0.60	26	26		37	37	39
		0.599 - 0.50	31	30		44	44	47
		0.499 - 0.38	37	37		53	53	56
		0.379 - 0.25	50	49		68	69	73
	0.500 +	1.000 - 0.71	27	27		39	39	42
		0.709 - 0.60	34	34		49	49	52
		0.599 - 0.50	41	41		58	58	62
		0.499 - 0.38	50	49		68	69	73
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	12	12		19	19	21
		0.709 - 0.60	15	15		24	24	26
		0.599 - 0.50	18	17		29	29	31
		0.499 - 0.38	21	21		35	35	38
		0.379 - 0.25	29	28		46	46	50
		0.249 - 0.00	45	44		69	70	75
	0.250 - 0.499	1.000 - 0.71	17	17		28	28	30
		0.709 - 0.60	21	21		35	34	38
		0.599 - 0.50	25	25		41	41	45
		0.499 - 0.38	31	30		49	50	54
		0.379 - 0.25	41	41		65	66	71
	0.500 +	1.000 - 0.71	22	22		37	37	40
		0.709 - 0.60	28	28		46	46	50
		0.599 - 0.50	34	33		54	55	59
		0.499 - 0.38	41	41		65	66	71

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.22	HC >= 5	18	0.37	0.37
	HC >= 10	18	0.62	0.76
	HC >= 15	18	0.80	0.80
	HC >= 5	75	0.35	0.37
	HC >= 10	75	0.57	0.70
	HC >= 15	75	0.75	0.78

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.22	HC >= 5	14	0.37	0.37
	HC >= 10	14	0.79	0.80
	HC >= 15	14	0.80	0.80
	HC >= 5	78	0.37	0.37
	HC >= 10	78	0.67	0.80
	HC >= 15	78	0.80	0.80

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.22	HC >= 5	12	0.37	0.37
	HC >= 10	12	0.80	0.80
	HC >= 15	12	0.80	0.80
	HC >= 5	75	0.37	0.37
	HC >= 10	75	0.69	0.80
	HC >= 15	75	0.80	0.80

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		0		ROOF:	0.10
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.37
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.17
Horizontal	0	0	0		
Vertical	0	0	0		

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TABLE K.9 ACP for Augusta, GA, Birmingham, AL, Cape Hatteras and Cherry Point, NC

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 1151 - 2000
VSEW = 560 - 845
HDD65 = 1 - 3000

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT >= SC

0 - 1.50

PF	SC	FEN	FEN	FEN
0.000 - 0.249	1.000 - 0.71	20	21	22 23 23
	0.709 - 0.60	24	25	27 28 29
	0.599 - 0.50	28	30	31 33 33
	0.499 - 0.38	33	35	35 39 39
	0.379 - 0.25	41	45	43 49 50
	0.249 - 0.00	54	63	57 67 69
0.250 - 0.499	1.000 - 0.71	28	29	30 32 33
	0.709 - 0.60	33	36	36 39 40
	0.599 - 0.50	38	41	41 45 46
	0.499 - 0.38	43	48	46 53 53
	0.379 - 0.25	52	60	55 65 66
0.500 +	1.000 - 0.71	35	38	38 41 42
	0.709 - 0.60	41	45	44 50 50
	0.599 - 0.50	46	52	49 57 58
	0.499 - 0.38	52	60	55 65 66

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.14	HC >= 5	20	0.17	0.23
	HC >= 10	20	0.22	0.31
	HC >= 15	20	0.29	0.34
	HC >= 5	69	0.16	0.22
	HC >= 10	69	0.20	0.27
	HC >= 15	69	0.25	0.29

1.51 - 3.00

PF	SC	FEN	FEN	FEN
0.000 - 0.249	1.000 - 0.71	15	16	21 22 23
	0.709 - 0.60	19	19	26 27 28
	0.599 - 0.50	22	23	29 32 33
	0.499 - 0.38	26	27	34 37 39
	0.379 - 0.25	33	35	42 47 50
	0.249 - 0.00	45	51	56 66 69
0.250 - 0.499	1.000 - 0.71	21	22	29 31 32
	0.709 - 0.60	26	27	35 38 39
	0.599 - 0.50	30	32	39 43 46
	0.499 - 0.38	35	38	45 51 53
	0.379 - 0.25	43	48	54 63 66
0.500 +	1.000 - 0.71	27	29	36 40 42
	0.709 - 0.60	33	35	43 48 50
	0.599 - 0.50	38	41	48 55 58
	0.499 - 0.38	43	48	54 63 66

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.14	HC >= 5	15	0.17	0.23
	HC >= 10	15	0.24	0.35
	HC >= 15	15	0.33	0.37
	HC >= 5	69	0.16	0.23
	HC >= 10	69	0.21	0.29
	HC >= 15	69	0.27	0.33

3.01 - 3.50

PF	SC	FEN	FEN	FEN
0.000 - 0.249	1.000 - 0.71	13	13	20 21 22
	0.709 - 0.60	16	16	24 25 27
	0.599 - 0.50	19	19	28 30 32
	0.499 - 0.38	22	23	32 35 38
	0.379 - 0.25	28	30	40 45 48
	0.249 - 0.00	40	44	53 62 67
0.250 - 0.499	1.000 - 0.71	16	19	27 29 31
	0.709 - 0.60	22	23	33 35 38
	0.599 - 0.50	26	27	37 41 44
	0.499 - 0.38	30	32	42 48 52
	0.379 - 0.25	38	41	51 59 64
0.500 +	1.000 - 0.71	23	24	34 37 40
	0.709 - 0.60	28	30	40 45 49
	0.599 - 0.50	32	35	45 52 56
	0.499 - 0.38	38	41	51 59 64

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.14	HC >= 5	13	0.17	0.23
	HC >= 10	13	0.25	0.35
	HC >= 15	13	0.34	0.37
	HC >= 5	67	0.16	0.22
	HC >= 10	67	0.22	0.30
	HC >= 15	67	0.27	0.33

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		0		ROOF: 0.069
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 0.23
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.19
Horizontal	0	0	0	
Vertical	0	0	0	

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TABLE K.10 ACP for Atlanta, GA, and Greenville, SC

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 1151 - 2000
VSEW = 560 - 845
HDD65 = > 3000

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.61 to 0.46	0.45 to 0.39	0.38 to 0	0.61 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT >= SC

0 - 1.50

PF	SC	FEN	FEN	FEN
0.000 - 0.249	1.000 - 0.71	16	16	17 17 18 19
	0.709 - 0.60	19	20	21 21 23 24
	0.599 - 0.50	22	24	25 24 27 28
	0.499 - 0.38	26	29	29 28 32 34
	0.379 - 0.25	32	38	39 35 42 44
	0.249 - 0.00	43	55	58 46 61 66
0.250 - 0.499	1.000 - 0.71	22	24	24 24 26 28
	0.709 - 0.60	26	29	30 29 33 34
	0.599 - 0.50	30	34	35 33 38 40
	0.499 - 0.38	35	41	42 37 45 48
	0.379 - 0.25	42	52	55 45 58 62
0.500 +	1.000 - 0.71	28	31	32 30 35 37
	0.709 - 0.60	33	38	39 38 43 45
	0.599 - 0.50	37	45	46 40 50 53
	0.499 - 0.38	42	53	55 45 58 63

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.13	HC >= 5	19	0.15	0.21
	HC >= 10	19	0.20	0.26
	HC >= 15	19	0.24	0.29
	HC >= 5	66	0.15	0.20
	HC >= 10	66	0.19	0.25
	HC >= 15	66	0.23	0.27

1.51 - 3.00

PF	SC	FEN	FEN	FEN
0.000 - 0.249	1.000 - 0.71	12	12	13 17 18 20
	0.709 - 0.60	15	16	16 21 22 25
	0.599 - 0.50	18	19	19 24 27 29
	0.499 - 0.38	21	22	23 28 32 35
	0.379 - 0.25	26	29	30 35 41 46
	0.249 - 0.00	37	44	46 47 61 68
0.250 - 0.499	1.000 - 0.71	17	18	18 24 26 29
	0.709 - 0.60	21	22	23 28 32 35
	0.599 - 0.50	24	26	27 32 38 42
	0.499 - 0.38	28	32	32 37 45 50
	0.379 - 0.25	35	41	43 45 57 65
0.500 +	1.000 - 0.71	22	24	24 30 34 38
	0.709 - 0.60	27	29	30 35 42 47
	0.599 - 0.50	31	35	35 40 49 55
	0.499 - 0.38	35	41	43 45 58 65

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.13	HC >= 5	12	0.16	0.21
	HC >= 10	12	0.22	0.31
	HC >= 15	12	0.29	0.34
	HC >= 5	66	0.16	0.21
	HC >= 10	66	0.20	0.28
	HC >= 15	66	0.26	0.31

3.01 - 3.50

PF	SC	FEN	FEN	FEN
0.000 - 0.249	1.000 - 0.71	10	10	10 16 16 19
	0.709 - 0.60	12	13	13 19 20 23
	0.599 - 0.50	14	15	15 22 24 28
	0.499 - 0.38	17	18	18 26 29 33
	0.379 - 0.25	22	24	25 32 38 44
	0.249 - 0.00	31	37	38 43 56 66
0.250 - 0.499	1.000 - 0.71	14	15	15 22 24 27
	0.709 - 0.60	17	18	18 26 29 34
	0.599 - 0.50	20	22	22 30 35 40
	0.499 - 0.38	24	26	26 34 41 48
	0.379 - 0.25	30	34	35 41 52 62
0.500 +	1.000 - 0.71	18	19	19 27 31 36
	0.709 - 0.60	22	24	24 32 38 44
	0.599 - 0.50	25	28	29 36 45 52
	0.499 - 0.38	30	34	35 41 53 62

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.13	HC >= 5	10	0.16	0.21
	HC >= 10	10	0.22	0.31
	HC >= 15	10	0.30	0.35
	HC >= 5	66	0.16	0.21
	HC >= 10	66	0.21	0.28
	HC >= 15	66	0.26	0.31

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		7		ROOF: 0.072
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 0.21
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.094
Horizontal	11	9	8	
Vertical	6	5	4	

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TABLE K.11 ACP for Red Bluff, Fresno, and Sacramento, CA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 1151 - 2000
VSEW = > 845

FENESTRATION (Max. Pct. Fenestr.)

Uof	BASE CASE			PERIMETER DAYLIGHTING		
	1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL | MASS WALL

VLT> = SC

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF) RANGE	SHADING COEFF (SCx)								
0 - 1.50	0.000 - 0.249	1.000 - 0.71	19	20	21	22	22	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
		0.709 - 0.60	24	25	26	27	28	0.14	HC > = 5	19	0.17	0.22
		0.599 - 0.50	28	29	30	32	33		HC > = 10	19	0.23	0.31
		0.499 - 0.38	33	35	35	38	39		HC > = 15	19	0.30	0.38
		0.379 - 0.25	41	45	44	49	50					
		0.249 - 0.00	56	65	59	69	70		HC > = 5	70	0.17	0.22
	0.250 - 0.499	1.000 - 0.71	27	29	30	32	32		HC > = 10	70	0.22	0.29
		0.709 - 0.60	33	35	36	39	39		HC > = 15	70	0.27	0.31
		0.599 - 0.50	38	41	41	45	46					
		0.499 - 0.38	44	49	47	53	54					
		0.379 - 0.25	54	62	57	66	68					
	0.500 +	1.000 - 0.71	35	38	38	41	42					
		0.709 - 0.60	42	46	45	50	51					
		0.599 - 0.50	48	54	51	58	59					
		0.499 - 0.38	55	63	57	67	68					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	15	15	20	21	22	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
		0.709 - 0.60	18	19	25	26	27	0.14	HC > = 5	15	0.18	0.22
		0.599 - 0.50	22	23	29	30	32		HC > = 10	15	0.24	0.32
		0.499 - 0.38	26	27	34	36	38		HC > = 15	15	0.32	0.37
		0.379 - 0.25	33	35	42	47	49					
		0.249 - 0.00	47	53	58	67	70		HC > = 5	70	0.17	0.22
	0.250 - 0.499	1.000 - 0.71	21	22	28	30	31		HC > = 10	70	0.22	0.30
		0.709 - 0.60	26	27	34	37	39		HC > = 15	70	0.28	0.33
		0.599 - 0.50	30	32	39	43	45					
		0.499 - 0.38	36	38	46	51	53					
		0.379 - 0.25	45	50	55	64	67					
	0.500 +	1.000 - 0.71	28	29	36	39	41					
		0.709 - 0.60	34	36	43	48	50					
		0.599 - 0.50	39	42	49	56	59					
		0.499 - 0.38	45	50	56	65	68					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	13	13	19	20	21	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
		0.709 - 0.60	16	16	23	24	26	0.14	HC > = 5	13	0.18	0.22
		0.599 - 0.50	19	19	27	29	31		HC > = 10	13	0.24	0.34
		0.499 - 0.38	22	23	32	34	37		HC > = 15	13	0.32	0.37
		0.379 - 0.25	29	31	40	44	48					
		0.249 - 0.00	42	46	55	64	68		HC > = 5	68	0.17	0.22
	0.250 - 0.499	1.000 - 0.71	18	19	27	28	30		HC > = 10	68	0.23	0.31
		0.709 - 0.60	22	23	32	35	37		HC > = 15	68	0.29	0.34
		0.599 - 0.50	26	27	37	41	44					
		0.499 - 0.38	31	33	43	48	52					
		0.379 - 0.25	39	43	53	61	66					
	0.500 +	1.000 - 0.71	24	25	34	37	40					
		0.709 - 0.60	29	31	41	45	49					
		0.599 - 0.50	34	36	47	53	57					
		0.499 - 0.38	40	43	53	61	66					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max U-0
WALL BELOW GRADE:	0		ROOF:	0.059
UNHEATED SLAB			WALL ADJACENT TO UNCOND SPACE:	0.22
ON GRADE:	24"	36"	48"	
Horizontal	0	0	0	FLOOR OVER UNCOND. SPACE:
Vertical	0	0	0	

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TABLE K.12 ACP for Louisiana, Mississippi, Charleston and Columbia, SC, Macon and Savannah, GA, Mobile and Montgomery, AL, Houston, Lufkin, and Port Arthur TX

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 2001 - 3250
VSEW = 560 - 845
HDD65 = 1 - 3000

FENESTRATION (Max. Pct. Fenestr.)

Uof	BASE CASE			PERIMETER DAYLIGHTING		
	1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL | MASS WALL

VLT> = SC

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF) RANGE	SHADING COEFF (SCx)								
0 - 1.50	0.000 - 0.249	1.000 - 0.71	19	19	21	22	22	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
		0.709 - 0.60	23	24	26	27	27	0.15	HC > = 5	19	0.17	0.24
		0.599 - 0.50	27	28	30	32	32		HC > = 10	19	0.23	0.33
		0.499 - 0.38	32	34	36	38	38		HC > = 15	19	0.30	0.38
		0.379 - 0.25	41	44	45	49	50					
		0.249 - 0.00	59	68	63	72	73		HC > = 5	73	0.17	0.24
	0.250 - 0.499	1.000 - 0.71	26	27	29	31	31		HC > = 10	73	0.22	0.30
		0.709 - 0.60	32	34	35	38	38		HC > = 15	73	0.28	0.33
		0.599 - 0.50	38	40	41	44	45					
		0.499 - 0.38	44	47	48	53	54					
		0.379 - 0.25	55	61	60	67	69					
	0.500 +	1.000 - 0.71	34	36	38	40	41					
		0.709 - 0.60	41	44	46	49	50					
		0.599 - 0.50	48	52	52	58	59					
		0.499 - 0.38	56	61	60	68	69					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	15	15	21	21	23	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
		0.709 - 0.60	18	18	26	27	28	0.15	HC > = 5	15	0.17	0.24
		0.599 - 0.50	22	22	30	31	33		HC > = 10	15	0.24	0.35
		0.499 - 0.38	26	27	36	38	40		HC > = 15	15	0.34	0.39
		0.379 - 0.25	34	35	46	49	52					
		0.249 - 0.00	49	53	65	72	76		HC > = 5	76	0.17	0.24
	0.250 - 0.499	1.000 - 0.71	21	21	29	30	32		HC > = 10	76	0.23	0.33
		0.709 - 0.60	26	26	36	38	40		HC > = 15	76	0.30	0.36
		0.599 - 0.50	30	31	42	45	47					
		0.499 - 0.38	36	37	49	53	56					
		0.379 - 0.25	46	49	61	68	72					
	0.500 +	1.000 - 0.71	27	28	38	40	42					
		0.709 - 0.60	33	35	46	49	52					
		0.599 - 0.50	39	41	53	58	61					
		0.499 - 0.38	46	49	61	68	72					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	12	12	19	20	22	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
		0.709 - 0.60	15	15	24	25	27	0.15	HC > = 5	12	0.17	0.24
		0.599 - 0.50	18	18	28	29	32		HC > = 10	12	0.25	0.35
		0.499 - 0.38	22	22	33	35	38		HC > = 15	12	0.34	0.39
		0.379 - 0.25	28	29	43	46	50					
		0.249 - 0.00	42	45	61	68	73		HC > = 5	73	0.17	0.24
	0.250 - 0.499	1.000 - 0.71	17	17	27	28	31		HC > = 10	73	0.23	0.33
		0.709 - 0.60	21	22	33	35	38		HC > = 15	73	0.31	0.37
		0.599 - 0.50	25	26	39	42	45					
		0.499 - 0.38	30	31	46	50	54					
		0.379 - 0.25	39	41	57	64	69					
	0.500 +	1.000 - 0.71	23	23	36	37	41					
		0.709 - 0.60	28	29	43	46	50					
		0.599 - 0.50	33	34	50	54	59					
		0.499 - 0.38	39	41	57	64	69					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max U-0
WALL BELOW GRADE:	0		ROOF:	0.065
UNHEATED SLAB			WALL ADJACENT TO UNCOND SPACE:	0.24
ON GRADE:	24"	36"	48"	
Horizontal	0	0	0	FLOOR OVER UNCOND. SPACE:
Vertical	0	0	0	

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TABLE K.13 ACP for Apalachicola, Daytona Beach, Jacksonville, Tallahassee, and Tampa, FL, Bakersfield, CA, Abilene, Austin, Del Rio, El Paso, Fort Worth, Midland, San Angelo, San Antonio, Sherman, and Waco, TX

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 2001 - 3250
VSEW = > 845
CDH80 = 0 - 18000
HDD65 = 1 - 3000

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL | MASS WALL

VLT>=SC

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF)	SHADING COEFF RANGE (SCx)					
0 - 1.50	0.000 - 0.249	1.000 - 0.71	17	18	19	19	20
		0.709 - 0.60	22	22	23	24	25
		0.599 - 0.50	25	26	27	29	29
		0.499 - 0.38	30	32	33	34	35
		0.379 - 0.25	39	42	42	45	46
		0.249 - 0.00	56	63	59	67	68
	0.250 - 0.499	1.000 - 0.71	25	26	27	28	29
		0.709 - 0.60	31	32	33	35	35
		0.599 - 0.50	36	38	38	41	42
		0.499 - 0.38	42	45	45	49	50
		0.379 - 0.25	53	59	57	64	65
	0.500 +	1.000 - 0.71	33	34	35	37	38
		0.709 - 0.60	40	42	43	46	47
		0.599 - 0.50	46	50	49	54	55
		0.499 - 0.38	54	60	57	64	65
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	14	14	19	19	20
		0.709 - 0.60	17	18	23	24	25
		0.599 - 0.50	21	21	27	28	30
		0.499 - 0.38	25	26	32	34	36
		0.379 - 0.25	32	34	42	45	47
		0.249 - 0.00	48	52	60	67	70
	0.250 - 0.499	1.000 - 0.71	20	20	27	28	29
		0.709 - 0.60	25	26	33	34	36
		0.599 - 0.50	29	30	38	40	43
		0.499 - 0.38	35	37	45	49	51
		0.379 - 0.25	45	49	57	63	67
	0.500 +	1.000 - 0.71	26	27	35	37	39
		0.709 - 0.60	33	34	42	45	48
		0.599 - 0.50	38	40	49	53	56
		0.499 - 0.38	45	49	57	64	67
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	12	12	17	18	19
		0.709 - 0.60	15	15	22	22	24
		0.599 - 0.50	18	18	25	26	29
		0.499 - 0.38	21	22	30	32	35
		0.379 - 0.25	28	29	39	42	45
		0.249 - 0.00	42	45	57	64	68
	0.250 - 0.499	1.000 - 0.71	17	18	25	26	28
		0.709 - 0.60	21	22	31	32	35
		0.599 - 0.50	25	26	36	38	41
		0.499 - 0.38	30	32	43	46	49
		0.379 - 0.25	39	42	54	60	64
	0.500 +	1.000 - 0.71	23	23	33	35	37
		0.709 - 0.60	28	29	40	43	46
		0.599 - 0.50	33	35	47	51	54
		0.499 - 0.38	39	42	54	60	65

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.15	HC >= 5	17	0.17	0.23
	HC >= 10	17	0.21	0.30
	HC >= 15	17	0.27	0.33
	HC >= 5	68	0.17	0.23
	HC >= 10	68	0.21	0.30
	HC >= 15	68	0.25	0.33

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.15	HC >= 5	14	0.17	0.24
	HC >= 10	14	0.22	0.32
	HC >= 15	14	0.30	0.33
	HC >= 5	70	0.17	0.23
	HC >= 10	70	0.21	0.30
	HC >= 15	70	0.27	0.33

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.15	HC >= 5	12	0.17	0.24
	HC >= 10	12	0.23	0.33
	HC >= 15	12	0.30	0.38
	HC >= 5	68	0.17	0.23
	HC >= 10	68	0.21	0.30
	HC >= 15	68	0.27	0.33

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max U0	
WALL BELOW GRADE:		0			0.058
UNHEATED SLAB				ROOF:	
ON GRADE:	24"	36"	48"	WALL ADJACENT TO UNCOND SPACE:	0.24
Horizontal	0	0	0	FLOOR OVER	
Vertical	0	0	0	UNCOND. SPACE:	0.11

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TABLE K.14 ACP for Tucson, AZ, China Lake and Daggett, CA, and Las Vegas, NV

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1000
CDD65 = 2001 - 3250
VSEW = > 845
CDH80 = > 18000

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL | MASS WALL

VLT>=SC

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF)	SHADING COEFF RANGE (SCx)					
0 - 1.50	0.000 - 0.249	1.000 - 0.71	17	17	18	19	19
		0.709 - 0.60	21	22	23	23	24
		0.599 - 0.50	25	26	27	28	29
		0.499 - 0.38	30	31	32	34	35
		0.379 - 0.25	39	42	42	45	46
		0.249 - 0.00	59	65	63	70	71
	0.250 - 0.499	1.000 - 0.71	24	25	26	27	28
		0.709 - 0.60	30	31	33	34	35
		0.599 - 0.50	36	37	39	41	42
		0.499 - 0.38	43	45	46	49	50
		0.379 - 0.25	55	61	59	66	67
	0.500 +	1.000 - 0.71	32	34	35	37	37
		0.709 - 0.60	40	42	43	46	47
		0.599 - 0.50	47	50	51	55	56
		0.499 - 0.38	56	61	60	66	67
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	14	14	18	18	20
		0.709 - 0.60	17	17	23	23	25
		0.599 - 0.50	20	21	27	28	30
		0.499 - 0.38	25	25	33	34	36
		0.379 - 0.25	33	34	43	45	48
		0.249 - 0.00	50	54	55	71	75
	0.250 - 0.499	1.000 - 0.71	20	20	26	27	29
		0.709 - 0.60	25	25	33	34	36
		0.599 - 0.50	29	30	39	41	43
		0.499 - 0.38	35	37	47	50	52
		0.379 - 0.25	47	50	61	67	70
	0.500 +	1.000 - 0.71	26	27	35	37	39
		0.709 - 0.60	33	34	44	46	49
		0.599 - 0.50	39	41	51	55	58
		0.499 - 0.38	47	50	61	67	70
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	12	12	17	17	19
		0.709 - 0.60	15	15	21	22	24
		0.599 - 0.50	17	18	25	26	28
		0.499 - 0.38	21	22	31	32	35
		0.379 - 0.25	28	29	40	43	46
		0.249 - 0.00	44	45	61	67	72
	0.250 - 0.499	1.000 - 0.71	17	17	25	25	28
		0.709 - 0.60	21	22	31	32	35
		0.599 - 0.50	25	26	37	38	42
		0.499 - 0.38	30	32	44	47	51
		0.379 - 0.25	40	43	57	63	68
	0.500 +	1.000 - 0.71	22	23	33	34	37
		0.709 - 0.60	28	29	41	43	47
		0.599 - 0.50	33	35	49	52	56
		0.499 - 0.38	40	42	58	63	68

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.16	HC >= 5	17	0.19	0.24
	HC >= 10	17	0.23	0.29
	HC >= 15	17	0.28	0.31
	HC >= 5	71	0.19	0.24
	HC >= 10	71	0.24	0.29
	HC >= 15	71	0.28	0.31

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.16	HC >= 5	14	0.19	0.24
	HC >= 10	14	0.24	0.30
	HC >= 15	14	0.29	0.32
	HC >= 5	75	0.19	0.24
	HC >= 10	75	0.24	0.30
	HC >= 15	75	0.29	0.32

Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.16	HC >= 5	12	0.19	0.24
	HC >= 10	12	0.23	0.29
	HC >= 15	12	0.28	0.32
	HC >= 5	72	0.19	0.24
	HC >= 10	72	0.24	0.30
	HC >= 15	72	0.29	0.33

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max U0	
WALL BELOW GRADE:		0			0.048
UNHEATED SLAB				ROOF:	
ON GRADE:	24"	36"	48"	WALL ADJACENT TO UNCOND SPACE:	0.26
Horizontal	0	0	0	FLOOR OVER	
Vertical	0	0	0	UNCOND. SPACE:	0.12

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TABLE K.15 ACP for Miami and West Palm Beach, FL

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1500
CDD65 = 3701 - 6500
VSEW = > 845
CDH80 = 0 - 18000

Use

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uval)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE (SCx) | VLT>=SC

ILD	PF	SCx	LIGHT WEIGHT WALL	MASS WALL	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	14	14	17	16	17	1.00	HC >= 5	14	1.00	1.00
		0.709 - 0.60	18	18	22	21	22		HC >= 10	14	1.00	1.00
		0.599 - 0.50	23	22	27	26	27		HC >= 15	14	1.00	1.00
		0.499 - 0.38	29	28	34	33	34					
		0.379 - 0.25	42	40	50	47	49		HC >= 5	90	1.00	1.00
		0.249 - 0.00	84	75	100	87	90		HC >= 10	90	1.00	1.00
	0.250 - 0.499	1.000 - 0.71	21	21	25	25	25		HC >= 15	90	1.00	1.00
		0.709 - 0.60	28	27	33	32	33	1.00				
		0.599 - 0.50	35	34	42	40	41					
		0.499 - 0.38	46	43	55	51	53					
		0.379 - 0.25	71	64	86	78	79					
	0.500 +	1.000 - 0.71	30	29	36	34	35					
		0.709 - 0.60	40	38	49	46	47					
		0.599 - 0.50	52	49	63	58	60					
		0.499 - 0.38	70	64	85	75	78					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	12	12	20	19	21		HC >= 5	12	1.00	1.00
		0.709 - 0.60	16	15	26	25	27		HC >= 10	12	1.00	1.00
		0.599 - 0.50	19	19	32	31	33		HC >= 15	12	1.00	1.00
		0.499 - 0.38	24	23	41	39	42					
		0.379 - 0.25	35	33	62	57	60		HC >= 5	98	1.00	1.00
		0.249 - 0.00	68	61	100	98	100		HC >= 10	98	1.00	1.00
	0.250 - 0.499	1.000 - 0.71	18	17	30	29	31		HC >= 15	98	1.00	1.00
		0.709 - 0.60	23	23	41	38	41	1.00				
		0.599 - 0.50	29	28	52	48	51					
		0.499 - 0.38	38	36	68	62	65					
		0.379 - 0.25	58	53	100	87	95					
	0.500 +	1.000 - 0.71	25	24	44	41	44					
		0.709 - 0.60	33	32	60	55	58					
		0.599 - 0.50	43	40	76	69	73					
		0.499 - 0.38	57	52	100	87	94					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	9	9	18	17	20		HC >= 5	9	1.00	1.00
		0.709 - 0.60	12	11	23	22	26		HC >= 10	9	1.00	1.00
		0.599 - 0.50	14	14	29	28	32		HC >= 15	9	1.00	1.00
		0.499 - 0.38	18	18	38	35	40					
		0.379 - 0.25	26	25	57	52	57		HC >= 5	92	1.00	1.00
		0.249 - 0.00	50	46	100	90	100		HC >= 10	92	1.00	1.00
	0.250 - 0.499	1.000 - 0.71	13	13	27	26	30		HC >= 15	92	1.00	1.00
		0.709 - 0.60	18	17	37	35	39	1.00				
		0.599 - 0.50	22	21	47	44	48					
		0.499 - 0.38	28	27	63	57	62					
		0.379 - 0.25	43	40	92	81	90					
	0.500 +	1.000 - 0.71	19	18	40	37	42					
		0.709 - 0.60	25	24	55	50	55					
		0.599 - 0.50	32	30	71	65	69					
		0.499 - 0.38	42	39	91	80	89					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value					Max Uo
WALL BELOW GRADE:		0		ROOF:	0.074
UNHEATED SLAB				WALL ADJACENT TO	
ON GRADE:	24"	36"	48"	UNCOND SPACE:	1.5
Horizontal	0	0	0	FLOOR OVER	
Vertical	0	0	0	UNCOND. SPACE:	0.40

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TABLE K.16 ACP for Orlando, FL, Brownsville, Corpus Christi, and Kingsville, TX

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1 - 1500
CDD65 = 3251 - 3700
VSEW = > 845
CDH80 = 0 - 18000

Use

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uval)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE (SCx) | VLT>=SC

ILD	PF	SCx	LIGHT WEIGHT WALL	MASS WALL	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	15	15	19	17	18	0.34	HC >= 5	15	0.41	0.51
		0.709 - 0.60	20	19	25	24	25		HC >= 10	15	0.53	0.63
		0.599 - 0.50	24	23	31	30	32		HC >= 15	15	0.62	0.67
		0.499 - 0.38	29	29	38	37	40					
		0.379 - 0.25	41	40	55	52	56		HC >= 5	86	0.43	0.59
		0.249 - 0.00	74	70	97	88	95		HC >= 10	86	0.57	0.70
	0.250 - 0.499	1.000 - 0.71	22	22	29	28	30		HC >= 15	86	0.66	0.78
		0.709 - 0.60	28	28	38	37	39					
		0.599 - 0.50	35	33	47	45	48					
		0.499 - 0.38	45	43	61	57	60					
		0.379 - 0.25	65	62	87	79	86					
	0.500 +	1.000 - 0.71	31	30	41	39	42					
		0.709 - 0.60	45	39	54	51	54					
		0.599 - 0.50	50	48	67	64	67					
		0.499 - 0.38	65	61	86	79	85					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	13	12	19	19	21		HC >= 5	12	0.42	0.52
		0.709 - 0.60	16	16	25	24	26		HC >= 10	12	0.54	0.65
		0.599 - 0.50	20	19	31	30	32		HC >= 15	12	0.64	0.69
		0.499 - 0.38	24	24	38	37	40					
		0.379 - 0.25	34	33	55	52	56		HC >= 5	97	0.44	0.58
		0.249 - 0.00	61	58	97	88	95		HC >= 10	97	0.61	0.76
	0.250 - 0.499	1.000 - 0.71	19	18	29	28	30		HC >= 15	97	0.75	0.80
		0.709 - 0.60	24	23	38	37	39	0.34				
		0.599 - 0.50	29	29	47	45	48					
		0.499 - 0.38	37	36	61	57	60					
		0.379 - 0.25	54	51	87	79	86					
	0.500 +	1.000 - 0.71	25	25	41	39	42					
		0.709 - 0.60	33	32	54	51	54					
		0.599 - 0.50	41	40	58	64	67					
		0.499 - 0.38	53	50	86	79	85					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	10	10	18	17	20		HC >= 5	10	0.41	0.51
		0.709 - 0.60	13	13	23	22	25		HC >= 10	10	0.53	0.63
		0.599 - 0.50	16	15	28	27	31		HC >= 15	10	0.62	0.67
		0.499 - 0.38	19	19	35	34	38					
		0.379 - 0.25	27	26	51	48	53		HC >= 5	90	0.44	0.57
		0.249 - 0.00	48	45	89	81	90		HC >= 10	90	0.60	0.74
	0.250 - 0.499	1.000 - 0.71	15	14	27	26	29		HC >= 15	90	0.73	0.80
		0.709 - 0.60	19	18	35	33	37	0.34				
		0.599 - 0.50	23	23	43	41	46					
		0.499 - 0.38	29	28	58	52	58					
		0.379 - 0.25	42	40	80	74	81					
	0.500 +	1.000 - 0.71	20	20	37	36	40					
		0.709 - 0.60	26	25	50	47	52					
		0.599 - 0.50	32	31	64	59	64					
		0.499 - 0.38	41	39	79	73	80					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value					Max Uo
WALL BELOW GRADE:		0		ROOF:	0.063
UNHEATED SLAB				WALL ADJACENT TO	
ON GRADE:	24"	36"	48"	UNCOND SPACE:	0.82
Horizontal	0	0	0	FLOOR OVER	
Vertical	0	0	0	UNCOND. SPACE:	0.28

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TABLE K.17 ACP for Phoenix, AZ

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD65 = 1 - 1999
CDD65 = 2001 - 3795
VIEW = > 845
CDH80 = > 1800

Glaz

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER SKYLIGHTING		
1.15 to 0.82	0.81 to 0	N/A	1.15 to 0.82	0.81 to 0	0.81 to 0

OPAQUE WALL (Max. Uval)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | PLT x =SC

ILD	PF	SCx	PLT		
0 - 1.00	0.500 - 0.249	1.000 - 0.71	15	15	17
		0.709 - 0.60	19	19	21
		0.599 - 0.50	23	23	26
		0.499 - 0.38	29	29	32
		0.379 - 0.25	40	40	44
		0.249 - 0.00	65	65	75
	0.250 - 0.499	1.000 - 0.71	22	22	25
		0.709 - 0.60	29	29	32
		0.599 - 0.50	35	35	38
		0.499 - 0.38	43	43	48
		0.379 - 0.25	62	62	69
	0.500 +	1.000 - 0.71	31	31	34
		0.709 - 0.60	40	39	44
		0.599 - 0.50	49	49	54
		0.499 - 0.38	62	62	69
1.01 - 2.00	0.500 - 0.249	1.000 - 0.71	13	13	17
		0.709 - 0.60	16	16	22
		0.599 - 0.50	20	19	27
		0.499 - 0.38	24	24	34
		0.379 - 0.25	34	33	47
		0.249 - 0.00	58	57	80
	0.250 - 0.499	1.000 - 0.71	19	18	26
		0.709 - 0.60	24	24	34
		0.599 - 0.50	29	29	41
		0.499 - 0.38	36	36	52
		0.379 - 0.25	52	51	75
	0.500 +	1.000 - 0.71	25	25	36
		0.709 - 0.60	33	33	47
		0.599 - 0.50	41	40	59
		0.499 - 0.38	52	51	75
2.01 - 3.00	0.500 - 0.249	1.000 - 0.71	11	10	15
		0.709 - 0.60	13	13	20
		0.599 - 0.50	16	16	23
		0.499 - 0.38	20	20	31
		0.379 - 0.25	28	28	44
		0.249 - 0.00	48	47	77
	0.250 - 0.499	1.000 - 0.71	15	15	24
		0.709 - 0.60	20	20	31
		0.599 - 0.50	24	24	38
		0.499 - 0.38	30	30	49
		0.379 - 0.25	43	43	71
	0.500 +	1.000 - 0.71	21	21	34
		0.709 - 0.60	27	27	44
		0.599 - 0.50	34	33	55
		0.499 - 0.38	42	42	71
3.01 - 3.50	0.500 - 0.249	1.000 - 0.71	10	9	13
		0.709 - 0.60	12	12	17
		0.599 - 0.50	14	14	19
		0.499 - 0.38	18	18	26
		0.379 - 0.25	25	25	37
		0.249 - 0.00	42	41	65
	0.250 - 0.499	1.000 - 0.71	13	13	20
		0.709 - 0.60	17	17	26
		0.599 - 0.50	21	21	32
		0.499 - 0.38	26	26	40
		0.379 - 0.25	37	37	58
	0.500 +	1.000 - 0.71	18	18	28
		0.709 - 0.60	23	23	36
		0.599 - 0.50	29	29	45
		0.499 - 0.38	37	37	58

Glaz (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.24	HC >= 5	15	0.28	0.34
	HC >= 10	15	0.36	0.41
	HC >= 15	15	0.41	0.45
	HC >= 5	77	0.26	0.31
	HC >= 10	77	0.34	0.39
	HC >= 15	77	0.44	0.48

Glaz (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.24	HC >= 5	13	0.28	0.34
	HC >= 10	13	0.36	0.41
	HC >= 15	13	0.41	0.45
	HC >= 5	86	0.25	0.30
	HC >= 10	86	0.36	0.44
	HC >= 15	86	0.44	0.47

Glaz (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.24	HC >= 5	10	0.28	0.34
	HC >= 10	10	0.34	0.40
	HC >= 15	10	0.40	0.43
	HC >= 5	82	0.23	0.27
	HC >= 10	82	0.36	0.44
	HC >= 15	82	0.44	0.46

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		0		0.040
UNHEATED SLAB				
ON GRADE:	24"	36"	48"	
Horizontal	0	0	0	
Vertical	0	0	0	

ROOF:	0.048
WALL ADJACENT TO UNCOND SPACE:	0.43
FLOOR OVER UNCOND. SPACE:	0.19

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TABLE K.18 ACP for Astoria, Portland, and Salem, OR, Olympia, Seattle, and Whidbey Island, WA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD65 = 1001 - 1750
CDD65 = 0 - 505
VIEW = 500 - 845

Glaz

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER SKYLIGHTING	
0.81 to 0.46	0.45 to 0.26	0.26 to 0	N/A	

OPAQUE WALL (Max. Uval)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | PLT x =SC

ILD	PF	SCx	PLT		
0 - 1.00	0.500 - 0.249	1.000 - 0.71	34	31	33
		0.709 - 0.60	36	37	39
		0.599 - 0.50	37	41	44
		0.499 - 0.38	39	45	50
		0.379 - 0.25	50	53	59
		0.249 - 0.00	62	59	75
	0.250 - 0.499	1.000 - 0.71	38	42	45
		0.709 - 0.60	39	47	52
		0.599 - 0.50	41	53	58
		0.499 - 0.38	52	56	64
		0.379 - 0.25	63	61	72
	0.500 +	1.000 - 0.71	51	50	55
		0.709 - 0.60	52	56	63
		0.599 - 0.50	53	59	68
		0.499 - 0.38	63	62	73
1.01 - 2.00	0.500 - 0.249	1.000 - 0.71	22	27	28
		0.709 - 0.60	25	32	34
		0.599 - 0.50	27	37	39
		0.499 - 0.38	29	42	45
		0.379 - 0.25	42	49	54
		0.249 - 0.00	55	60	69
	0.250 - 0.499	1.000 - 0.71	27	27	39
		0.709 - 0.60	30	43	46
		0.599 - 0.50	32	48	52
		0.499 - 0.38	33	53	59
		0.379 - 0.25	35	60	69
	0.500 +	1.000 - 0.71	31	46	49
		0.709 - 0.60	33	52	57
		0.599 - 0.50	35	57	63
		0.499 - 0.38	36	61	75
2.01 - 3.50	0.500 - 0.249	1.000 - 0.71	21	25	26
		0.709 - 0.60	24	30	31
		0.599 - 0.50	26	34	36
		0.499 - 0.38	28	39	42
		0.379 - 0.25	31	47	51
		0.249 - 0.00	35	58	66
	0.250 - 0.499	1.000 - 0.71	25	34	36
		0.709 - 0.60	29	40	43
		0.599 - 0.50	31	45	49
		0.499 - 0.38	33	51	56
		0.379 - 0.25	35	58	66
	0.500 +	1.000 - 0.71	30	43	46
		0.709 - 0.60	33	49	54
		0.599 - 0.50	34	54	60
		0.499 - 0.38	36	59	67

Glaz (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.052	HC >= 5	34	0.098	0.13
	HC >= 10	34	0.10	0.14
	HC >= 15	34	0.11	0.14
	HC >= 5	73	0.098	0.13
	HC >= 10	73	0.10	0.14
	HC >= 15	73	0.11	0.14

Glaz (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.052	HC >= 5	33	0.098	0.13
	HC >= 10	33	0.11	0.16
	HC >= 15	33	0.12	0.17
	HC >= 5	70	0.097	0.13
	HC >= 10	70	0.11	0.16
	HC >= 15	70	0.12	0.17

Glaz (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.052	HC >= 5	21	0.098	0.14
	HC >= 10	21	0.11	0.17
	HC >= 15	21	0.13	0.18
	HC >= 5	67	0.098	0.13
	HC >= 10	67	0.11	0.17
	HC >= 15	67	0.12	0.18

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		0		0.064
UNHEATED SLAB				
ON GRADE:	24"	36"	48"	
Horizontal	16	13	11	
Vertical	8	6	4	

ROOF:	0.064
WALL ADJACENT TO UNCOND SPACE:	0.14
FLOOR OVER UNCOND. SPACE:	0.066

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TABLE K.19 ACP for Asheville, NC, and Medford, OR

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDDS = 1001 - 1750
CDDS = 501 - 1150
VSEW = 560 - 845

Uof

FENESTRATION (Max. Pct. Fenestr.)					
BASE CASE			PERIMETER DAYLIGHTING		
0.61 to 0.46	0.45 to 0.39	0.38 to 0	0.61 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)	
LIGHT WEIGHT WALL	MASS WALL

VLT >= SC

INTERNAL LOAD DENSITY (LD) RANGE	PROJECTION FACTOR (PF) RANGE	SHADING COEFF (SC)					
		1.000 - 0.71	20	24	25	22	26	27
		0.709 - 0.60	24	29	30	25	31	33
	0.000 - 0.249	0.599 - 0.50	28	34	35	27	36	38
		0.499 - 0.38	29	39	41	30	41	44
		0.379 - 0.25	33	47	51	33	50	55
		0.249 - 0.00	38	61	69	36	63	72
		1.000 - 0.71	27	34	35	28	37	39
	0.250 - 0.499	0.709 - 0.60	30	41	43	31	43	47
		0.599 - 0.50	33	46	49	33	49	53
0 - 1.50		0.499 - 0.38	35	53	57	35	54	61
		0.379 - 0.25	38	61	69	38	63	72
		1.000 - 0.71	32	43	46	32	46	50
	0.500 +	0.709 - 0.60	35	51	55	35	53	59
		0.599 - 0.50	37	57	62	37	59	67
		0.499 - 0.38	39	63	70	39	65	74

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.10	HC >= 5	20	0.11	0.16
	HC >= 10	20	0.13	0.18
	HC >= 15	20	0.15	0.19
	HC >= 5	74	0.11	0.14
	HC >= 10	74	0.13	0.17
	HC >= 15	74	0.14	0.18

		1.000 - 0.71	18	20	20	22	27	28
		0.709 - 0.60	21	25	25	26	32	34
	0.000 - 0.249	0.599 - 0.50	24	29	30	29	37	40
		0.499 - 0.38	27	34	35	32	43	46
		0.379 - 0.25	32	42	45	36	52	58
		0.249 - 0.00	39	58	63	41	67	77
		1.000 - 0.71	24	29	29	29	37	40
	0.250 - 0.499	0.709 - 0.60	28	35	36	32	44	46
		0.599 - 0.50	31	40	42	35	50	56
1.51 - 3.00		0.499 - 0.38	34	46	49	38	57	64
		0.379 - 0.25	38	56	61	41	66	76
		1.000 - 0.71	29	37	39	34	47	52
	0.500 +	0.709 - 0.60	33	44	47	37	55	62
		0.599 - 0.50	36	50	54	39	61	70
		0.499 - 0.38	39	57	62	41	67	78

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.10	HC >= 5	18	0.11	0.15
	HC >= 10	18	0.14	0.21
	HC >= 15	18	0.17	0.23
	HC >= 5	78	0.11	0.15
	HC >= 10	78	0.13	0.19
	HC >= 15	78	0.15	0.20

		1.000 - 0.71	16	18	18	22	26	27
		0.709 - 0.60	19	22	22	25	31	33
	0.000 - 0.249	0.599 - 0.50	22	25	26	28	36	39
		0.499 - 0.38	25	30	31	31	42	45
		0.379 - 0.25	29	38	40	35	51	57
		0.249 - 0.00	36	52	57	40	65	75
		1.000 - 0.71	22	25	26	28	36	39
	0.250 - 0.499	0.709 - 0.60	25	31	32	31	43	47
		0.599 - 0.50	28	35	37	34	49	54
3.01 - 3.50		0.499 - 0.38	31	41	43	36	55	63
		0.379 - 0.25	36	51	55	40	64	75
		1.000 - 0.71	26	33	34	33	46	51
	0.500 +	0.709 - 0.60	30	39	41	36	53	60
		0.599 - 0.50	33	45	48	38	59	68
		0.499 - 0.38	36	51	55	40	65	76

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.10	HC >= 5	16	0.11	0.15
	HC >= 10	16	0.14	0.22
	HC >= 15	16	0.16	0.24
	HC >= 5	76	0.11	0.15
	HC >= 10	76	0.13	0.19
	HC >= 15	76	0.15	0.20

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		9		ROOF: 0.063
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 0.15
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.064
Horizontal	15	13	10	
Vertical	7	6	4	

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TABLE K.20 ACP for Charlotte, Greensboro, and Raleigh, NC, Chattanooga, Knoxville, and Nashville, TN, Norfolk, Richmond, and Roanoke, VA, and Patuxent, MD

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDDS = 1001 - 1750
CDDS = 1151 - 2000
VSEW = 560 - 845

Uof

FENESTRATION (Max. Pct. Fenestr.)					
BASE CASE			PERIMETER DAYLIGHTING		
0.61 to 0.46	0.45 to 0.39	0.38 to 0	0.61 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)	
LIGHT WEIGHT WALL	MASS WALL

VLT >= SC

INTERNAL LOAD DENSITY (LD) RANGE	PROJECTION FACTOR (PF) RANGE	SHADING COEFF (SC)					
		1.000 - 0.71	16	18	18	18	20	20
		0.709 - 0.60	20	22	22	21	24	25
	0.000 - 0.249	0.599 - 0.50	23	26	26	24	28	30
		0.499 - 0.38	26	30	31	28	33	35
		0.379 - 0.25	32	39	41	34	43	44
		0.249 - 0.00	41	56	59	43	60	66
		1.000 - 0.71	22	25	25	24	28	29
	0.250 - 0.499	0.709 - 0.60	27	31	32	29	34	36
		0.599 - 0.50	30	36	37	32	40	42
0 - 1.50		0.499 - 0.38	34	42	44	36	46	50
		0.379 - 0.25	40	53	57	42	58	63
		1.000 - 0.71	28	33	34	30	36	38
	0.500 +	0.709 - 0.60	33	45	47	35	44	47
		0.599 - 0.50	36	46	48	38	51	55
		0.499 - 0.38	40	54	57	42	58	64

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.11	HC >= 5	16	0.12	0.16
	HC >= 10	16	0.14	0.18
	HC >= 15	16	0.16	0.19
	HC >= 5	66	0.12	0.16
	HC >= 10	66	0.14	0.17
	HC >= 15	66	0.15	0.18

		1.000 - 0.71	13	14	14	18	20	21
		0.709 - 0.60	16	17	17	22	24	27
	0.000 - 0.249	0.599 - 0.50	19	21	21	25	29	31
		0.499 - 0.38	22	25	25	29	34	37
		0.379 - 0.25	28	32	33	35	44	49
		0.249 - 0.00	37	47	49	45	63	70
		1.000 - 0.71	19	20	20	25	28	31
	0.250 - 0.499	0.709 - 0.60	22	25	25	29	35	38
		0.599 - 0.50	26	29	30	33	40	45
1.51 - 3.00		0.499 - 0.38	30	35	36	37	47	53
		0.379 - 0.25	36	45	46	44	59	67
		1.000 - 0.71	24	26	27	31	37	41
	0.500 +	0.709 - 0.60	28	32	33	36	45	50
		0.599 - 0.50	32	38	39	40	52	58
		0.499 - 0.38	36	45	47	44	60	68

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.11	HC >= 5	13	0.12	0.17
	HC >= 10	13	0.15	0.21
	HC >= 15	13	0.18	0.22
	HC >= 5	70	0.12	0.15
	HC >= 10	70	0.14	0.19
	HC >= 15	70	0.16	0.20

		1.000 - 0.71	11	12	12	17	18	20
		0.709 - 0.60	14	14	15	20	23	23
	0.000 - 0.249	0.599 - 0.50	16	17	17	23	27	30
		0.499 - 0.38	19	21	21	27	32	36
		0.379 - 0.25	24	27	28	33	41	47
		0.249 - 0.00	32	40	42	42	58	68
		1.000 - 0.71	16	17	17	23	26	29
	0.250 - 0.499	0.709 - 0.60	19	21	21	27	32	36
		0.599 - 0.50	22	24	25	31	38	43
3.01 - 3.50		0.499 - 0.38	25	29	30	35	44	51
		0.379 - 0.25	31	38	39	40	55	65
		1.000 - 0.71	20	22	22	29	34	39
	0.500 +	0.709 - 0.60	24	27	28	33	42	48
		0.599 - 0.50	27	32	33	37	48	56
		0.499 - 0.38	31	38	39	41	56	65

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.11	HC >= 5	11	0.12	0.17
	HC >= 10	11	0.15	0.22
	HC >= 15	11	0.18	0.23
	HC >= 5	68	0.12	0.16
	HC >= 10	68	0.14	0.19
	HC >= 15	68	0.16	0.20

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:		8		ROOF: 0.063
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 0.17
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.074
Horizontal	13	11	9	
Vertical	7	6	4	

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TABLE K.21 ACP for Albuquerque, Roswell, Truth or Consequences, and Tucumcari, NM, Oklahoma City, OK, Amarillo and Lubbock, TX

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1001 - 1750
CDD65 = 1151 - 2000
VSEW = > 845

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.81 to 0.46	0.45 to 0.39	0.38 to 0	0.81 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT >= SC

ILD	PF	SC								
0 - 1.50	0.000 - 0.249	1.000 - 0.71	14	15	16	15	17	17	0.10	HC >= 5 / 10 / 15
		0.709 - 0.60	17	19	19	18	21	22		
		0.599 - 0.50	19	22	23	20	24	25		
		0.499 - 0.38	22	26	27	23	28	30		
		0.379 - 0.25	26	33	35	28	36	38		
		0.249 - 0.00	33	47	50	35	49	55		
	0.250 - 0.499	1.000 - 0.71	19	22	23	21	24	26		
		0.709 - 0.60	23	27	28	24	30	31		
		0.599 - 0.50	26	32	33	27	34	37		
		0.499 - 0.38	29	37	39	30	40	43		
		0.379 - 0.25	33	46	49	34	49	54		
	0.500 +	1.000 - 0.71	24	29	30	26	32	34		
		0.709 - 0.60	28	35	37	29	38	41		
		0.599 - 0.50	31	41	43	32	44	47		
		0.499 - 0.38	34	47	50	35	50	55		
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	11	12	12	15	16	18	0.10	HC >= 5 / 10 / 15
		0.709 - 0.60	14	15	15	18	20	22		
		0.599 - 0.50	16	18	18	20	23	26		
		0.499 - 0.38	19	21	22	23	28	31		
		0.379 - 0.25	23	27	28	28	35	40		
		0.249 - 0.00	31	39	42	35	49	57		
	0.250 - 0.499	1.000 - 0.71	16	17	18	20	24	26		
		0.709 - 0.60	19	22	22	24	29	32		
		0.599 - 0.50	22	25	26	27	33	37		
		0.499 - 0.38	25	30	31	30	39	44		
		0.379 - 0.25	30	38	40	35	48	55		
	0.500 +	1.000 - 0.71	20	23	24	25	31	35		
		0.709 - 0.60	24	28	29	29	37	42		
		0.599 - 0.50	27	33	34	32	43	49		
		0.499 - 0.38	30	38	40	35	49	57		
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	10	10	10	14	15	17	0.10	HC >= 5 / 10 / 15
		0.709 - 0.60	12	13	13	16	18	21		
		0.599 - 0.50	14	15	15	19	22	25		
		0.499 - 0.38	16	18	18	21	26	29		
		0.379 - 0.25	20	23	24	26	33	38		
		0.249 - 0.00	27	34	35	33	46	54		
	0.250 - 0.499	1.000 - 0.71	13	15	15	19	22	25		
		0.709 - 0.60	16	18	18	22	26	30		
		0.599 - 0.50	19	21	22	25	31	36		
		0.499 - 0.38	21	25	26	28	36	42		
		0.379 - 0.25	26	32	34	32	44	53		
	0.500 +	1.000 - 0.71	17	19	20	23	29	33		
		0.709 - 0.60	20	24	24	27	34	40		
		0.599 - 0.50	23	28	29	30	39	46		
		0.499 - 0.38	26	33	34	32	45	54		

Uow (HC<5) | HC RANGE | PCT FEN | INT INS | EXT INS

Uow	HC RANGE	PCT FEN	INT INS	EXT INS
0.10	HC >= 5	14	0.11	0.16
	HC >= 10	14	0.14	0.20
	HC >= 15	14	0.16	0.21
	HC >= 5	55	0.11	0.16
	HC >= 10	55	0.14	0.19
	HC >= 15	55	0.16	0.21

Uow	HC RANGE	PCT FEN	INT INS	EXT INS
0.10	HC >= 5	11	0.12	0.16
	HC >= 10	11	0.15	0.22
	HC >= 15	11	0.18	0.24
	HC >= 5	57	0.12	0.16
	HC >= 10	57	0.14	0.20
	HC >= 15	57	0.17	0.22

Uow	HC RANGE	PCT FEN	INT INS	EXT INS
0.10	HC >= 5	10	0.12	0.16
	HC >= 10	10	0.15	0.23
	HC >= 15	10	0.19	0.25
	HC >= 5	54	0.12	0.16
	HC >= 10	54	0.14	0.21
	HC >= 15	54	0.17	0.22

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE: UNHEATED SLAB		8		ROOF:	0.039
ON GRADE:	24"	36"	48"	WALL ADJACENT TO UNCOND SPACE:	0.18
Horizontal	14	12	10	FLOOR OVER UNCOND. SPACE:	0.070
Vertical	7	6	4		

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TABLE K.22 ACP for Fort Smith, AR, Tulsa, OK, and Memphis, TN

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1001 - 1750
CDD65 = 2001 - 3250
VSEW = 560 - 845

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.81 to 0.46	0.45 to 0.39	0.38 to 0	0.81 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT >= SC

ILD	PF	SC								
0 - 1.50	0.000 - 0.249	1.000 - 0.71	14	15	15	16	17	17	0.12	HC >= 5 / 10 / 15
		0.709 - 0.60	17	19	19	19	21	22		
		0.599 - 0.50	20	22	22	22	25	26		
		0.499 - 0.38	24	26	27	26	29	31		
		0.379 - 0.25	30	35	36	32	38	41		
		0.249 - 0.00	41	52	54	43	57	62		
	0.250 - 0.499	1.000 - 0.71	20	21	22	22	24	25		
		0.709 - 0.60	24	27	27	26	30	31		
		0.599 - 0.50	28	31	32	30	35	37		
		0.499 - 0.38	32	38	39	35	42	44		
		0.379 - 0.25	39	49	51	42	54	58		
	0.500 +	1.000 - 0.71	25	28	29	28	32	33		
		0.709 - 0.60	30	35	36	33	39	41		
		0.599 - 0.50	34	41	43	37	46	49		
		0.499 - 0.38	39	49	51	42	54	58		
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	11	11	11	15	16	18	0.12	HC >= 5 / 10 / 15
		0.709 - 0.60	13	14	14	19	20	22		
		0.599 - 0.50	16	17	17	22	24	27		
		0.499 - 0.38	19	20	20	25	29	32		
		0.379 - 0.25	24	27	27	32	38	43		
		0.249 - 0.00	34	41	42	43	56	65		
	0.250 - 0.499	1.000 - 0.71	15	16	16	21	23	26		
		0.709 - 0.60	19	20	20	26	29	32		
		0.599 - 0.50	22	24	24	29	34	38		
		0.499 - 0.38	26	29	29	34	41	46		
		0.379 - 0.25	32	38	39	41	53	61		
	0.500 +	1.000 - 0.71	20	21	22	27	31	35		
		0.709 - 0.60	24	27	27	32	38	43		
		0.599 - 0.50	28	32	32	37	45	51		
		0.499 - 0.38	32	38	39	42	53	61		
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	9	9	9	14	14	17	0.12	HC >= 5 / 10 / 15
		0.709 - 0.60	11	11	11	17	18	21		
		0.599 - 0.50	13	14	14	20	21	25		
		0.499 - 0.38	15	16	17	23	26	30		
		0.379 - 0.25	20	22	22	29	34	40		
		0.249 - 0.00	28	33	34	39	51	61		
	0.250 - 0.499	1.000 - 0.71	12	13	13	19	21	24		
		0.709 - 0.60	15	16	16	23	26	30		
		0.599 - 0.50	18	19	20	27	31	36		
		0.499 - 0.38	21	23	24	31	37	43		
		0.379 - 0.25	27	31	32	37	48	57		
	0.500 +	1.000 - 0.71	16	17	17	24	28	32		
		0.709 - 0.60	20	22	22	29	34	40		
		0.599 - 0.50	23	26	26	33	40	48		
		0.499 - 0.38	27	31	31	37	48	57		

Uow (HC<5) | HC RANGE | PCT FEN | INT INS | EXT INS

Uow	HC RANGE	PCT FEN	INT INS	EXT INS
0.12	HC >= 5	14	0.13	0.17
	HC >= 10	14	0.15	0.20
	HC >= 15	14	0.17	0.21
	HC >= 5	62	0.13	0.16
	HC >= 10	62	0.15	0.19
	HC >= 15	62	0.17	0.21

Uow	HC RANGE	PCT FEN	INT INS	EXT INS
0.12	HC >= 5	11	0.13	0.17
	HC >= 10	11	0.15	0.21
	HC >= 15	11	0.18	0.23
	HC >= 5	65	0.13	0.17
	HC >= 10	65	0.15	0.21
	HC >= 15	65	0.18	0.22

Uow	HC RANGE	PCT FEN	INT INS	EXT INS
0.12	HC >= 5	9	0.13	0.18
	HC >= 10	9	0.15	0.22
	HC >= 15	9	0.18	0.23
	HC >= 5	61	0.13	0.17
	HC >= 10	61	0.15	0.21
	HC >= 15	61	0.18	0.22

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE: UNHEATED SLAB		8		ROOF:	0.057
ON GRADE:	24"	36"	48"	WALL ADJACENT TO UNCOND SPACE:	0.18
Horizontal	12	10	9	FLOOR OVER UNCOND. SPACE:	0.082
Vertical	7	5	4		

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TABLE K.23 ACP for Delaware, New Jersey, Washington, DC, Baltimore, MD, Boston, MA, New York, NY, Columbus and Dayton, OH, Covington, KY, Charleston, WV, Harrisburg and Philadelphia, PA, and Lewiston, ID

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1751 - 2600
CDD65 = 501 - 1150
VSEW = 560 - 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
Uof					
0.68 to 0.46	0.45 to 0.39	0.38 to 0	0.68 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) | SHADING COEFF RANGE (SCx) | VLT >= SC

ILD	PF	SC	LIGHT WEIGHT WALL	MASS WALL	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	22	23	0.089	HC >= 5	22	0.095	0.11
		0.709 - 0.60	26	27		HC >= 10	22	0.10	0.12
		0.599 - 0.50	28	29		HC >= 15	22	0.11	0.13
		0.499 - 0.38	31	32					
		0.379 - 0.25	35	36		HC >= 5	71	0.094	0.11
		0.249 - 0.00	40	40		HC >= 10	71	0.10	0.12
	0.250 - 0.499	1.000 - 0.71	25	27		HC >= 15	71	0.10	0.12
		0.709 - 0.60	30	32					
		0.599 - 0.50	34	36					
		0.499 - 0.38	39	41					
		0.379 - 0.25	47	48					
		0.249 - 0.00	58	59					
	0.500 +	1.000 - 0.71	26	28					
		0.709 - 0.60	32	34					
		0.599 - 0.50	36	39					
		0.499 - 0.38	42	45					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	19	24	0.089	HC >= 5	19	0.096	0.12
		0.709 - 0.60	23	28		HC >= 10	19	0.10	0.14
		0.599 - 0.50	26	30		HC >= 15	19	0.11	0.15
		0.499 - 0.38	29	34					
		0.379 - 0.25	34	38		HC >= 5	74	0.094	0.11
		0.249 - 0.00	41	44		HC >= 10	74	0.10	0.12
	0.250 - 0.499	1.000 - 0.71	22	24		HC >= 15	74	0.10	0.13
		0.709 - 0.60	26	28					
		0.599 - 0.50	30	33					
		0.499 - 0.38	33	37					
		0.379 - 0.25	41	43					
		0.249 - 0.00	46	49					
	0.500 +	1.000 - 0.71	26	31					
		0.709 - 0.60	30	35					
		0.599 - 0.50	33	37					
		0.499 - 0.38	36	40					
		0.379 - 0.25	41	43					
		0.249 - 0.00	55	55					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	17	23	0.089	HC >= 5	17	0.096	0.12
		0.709 - 0.60	21	27		HC >= 10	17	0.10	0.14
		0.599 - 0.50	23	30		HC >= 15	17	0.12	0.15
		0.499 - 0.38	27	33					
		0.379 - 0.25	32	37		HC >= 5	73	0.094	0.11
		0.249 - 0.00	39	43		HC >= 10	73	0.10	0.12
	0.250 - 0.499	1.000 - 0.71	23	30		HC >= 15	73	0.10	0.13
		0.709 - 0.60	27	34					
		0.599 - 0.50	30	34					
		0.499 - 0.38	34	43					
		0.379 - 0.25	38	46					
		0.249 - 0.00	50	52					
	0.500 +	1.000 - 0.71	29	35					
		0.709 - 0.60	33	40					
		0.599 - 0.50	36	45					
		0.499 - 0.38	42	51					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		9		ROOF:	0.050
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.14
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.054
Horizontal	16	14	11		
Vertical	8	6	4		

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TABLE K.24 ACP for Connecticut, Rhode Island, Allentown, Pittsburgh, and Scranton, PA, Akron, Toledo, and Youngstown, OH, Fort Wayne, Indianapolis, and South Bend, IN, Detroit, MI, Chicago and Moline IL, Burlington, IA, and Omaha, NE

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 2501 - 3200
CDD65 = 501 - 1150
VSEW = 560 - 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
Uof					
0.68 to 0.46	0.45 to 0.39	0.38 to 0	0.68 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) | SHADING COEFF RANGE (SCx) | VLT >= SC

ILD	PF	SC	LIGHT WEIGHT WALL	MASS WALL	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	22	23	0.082	HC >= 5	22	0.085	0.10
		0.709 - 0.60	25	25		HC >= 10	22	0.091	0.11
		0.599 - 0.50	27	27		HC >= 15	22	0.095	0.11
		0.499 - 0.38	29	30					
		0.379 - 0.25	32	32		HC >= 5	64	0.085	0.098
		0.249 - 0.00	36	36		HC >= 10	64	0.089	0.10
	0.250 - 0.499	1.000 - 0.71	26	28		HC >= 15	64	0.092	0.10
		0.709 - 0.60	31	31					
		0.599 - 0.50	33	32					
		0.499 - 0.38	34	34					
		0.379 - 0.25	37	36					
	0.500 +	1.000 - 0.71	32	32					
		0.709 - 0.60	34	34					
		0.599 - 0.50	36	35					
		0.499 - 0.38	37	37					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	19	23	0.082	HC >= 5	19	0.086	0.10
		0.709 - 0.60	23	26		HC >= 10	19	0.093	0.12
		0.599 - 0.50	25	29		HC >= 15	19	0.10	0.12
		0.499 - 0.38	28	31					
		0.379 - 0.25	32	34		HC >= 5	67	0.085	0.10
		0.249 - 0.00	37	39		HC >= 10	67	0.090	0.11
	0.250 - 0.499	1.000 - 0.71	25	29		HC >= 15	67	0.094	0.11
		0.709 - 0.60	29	32					
		0.599 - 0.50	31	34					
		0.499 - 0.38	34	36					
		0.379 - 0.25	37	39					
	0.500 +	1.000 - 0.71	30	33					
		0.709 - 0.60	33	36					
		0.599 - 0.50	35	37					
		0.499 - 0.38	38	39					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	18	23	0.082	HC >= 5	18	0.086	0.11
		0.709 - 0.60	21	26		HC >= 10	18	0.094	0.12
		0.599 - 0.50	23	28		HC >= 15	18	0.10	0.13
		0.499 - 0.38	26	31					
		0.379 - 0.25	30	34		HC >= 5	67	0.085	0.10
		0.249 - 0.00	36	38		HC >= 10	67	0.090	0.11
	0.250 - 0.499	1.000 - 0.71	23	28		HC >= 15	67	0.095	0.11
		0.709 - 0.60	26	31					
		0.599 - 0.50	29	33					
		0.499 - 0.38	32	35					
		0.379 - 0.25	35	38					
	0.500 +	1.000 - 0.71	28	32					
		0.709 - 0.60	31	35					
		0.599 - 0.50	33	36					
		0.499 - 0.38	36	38					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		10		ROOF:	0.053
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.13
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.048
Horizontal	17	14	11		
Vertical	8	6	4		

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TABLE K.25 ACP for Erie, PA, Redmond, OR, Spokane and Yakima, WA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1751 - 3200
CDD65 = 0 - 500
VSEW = 560 - 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING	
0.68 to 0.46	0.45 to 0.39	0.38 to 0	N/A	

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT >= SC

ILD	PF	SCx	BASE CASE	PERIMETER DAYLIGHTING	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	22 28 30		0.060	HC >= 5	22	0.084	0.10
		0.709 - 0.60	23 32 35			HC >= 10	22	0.091	0.12
		0.599 - 0.50	24 35 39			HC >= 15	22	0.097	0.13
		0.499 - 0.38	25 37 43						
		0.379 - 0.25	25 40 48			HC >= 5	59	0.083	0.10
		0.249 - 0.00	26 42 52			HC >= 10	59	0.090	0.11
	0.250 - 0.499	1.000 - 0.71	27 38 42			HC >= 15	59	0.095	0.12
		0.709 - 0.60	27 41 47						
		0.599 - 0.50	27 43 51						
		0.499 - 0.38	27 45 54						
		0.379 - 0.25	27 46 56						
	0.500 +	1.000 - 0.71	29 44 51						
		0.709 - 0.60	29 47 55						
		0.599 - 0.50	28 48 58						
		0.499 - 0.38	28 48 59						
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	20 24 25		0.060	HC >= 5	20	0.085	0.11
		0.709 - 0.60	23 28 30			HC >= 10	20	0.095	0.13
		0.599 - 0.50	24 32 34			HC >= 15	20	0.10	0.14
		0.499 - 0.38	26 35 39						
		0.379 - 0.25	28 40 45			HC >= 5	58	0.084	0.11
		0.249 - 0.00	30 46 54			HC >= 10	58	0.093	0.13
	0.250 - 0.499	1.000 - 0.71	26 33 35			HC >= 15	58	0.10	0.13
		0.709 - 0.60	28 37 41						
		0.599 - 0.50	29 41 46						
		0.499 - 0.38	30 44 50						
		0.379 - 0.25	31 48 56						
	0.500 +	1.000 - 0.71	29 40 44						
		0.709 - 0.60	30 44 50						
		0.599 - 0.50	31 47 54						
		0.499 - 0.38	32 49 58						
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	19 22 23		0.060	HC >= 5	19	0.085	0.11
		0.709 - 0.60	21 26 27			HC >= 10	19	0.096	0.13
		0.599 - 0.50	23 29 31			HC >= 15	19	0.10	0.14
		0.499 - 0.38	25 33 36						
		0.379 - 0.25	27 38 42			HC >= 5	54	0.084	0.11
		0.249 - 0.00	30 44 52			HC >= 10	54	0.094	0.13
	0.250 - 0.499	1.000 - 0.71	24 30 32			HC >= 15	54	0.10	0.14
		0.709 - 0.60	26 35 38						
		0.599 - 0.50	28 38 42						
		0.499 - 0.38	29 41 47						
		0.379 - 0.25	31 46 53						
	0.500 +	1.000 - 0.71	27 37 40						
		0.709 - 0.60	29 41 46						
		0.599 - 0.50	30 44 50						
		0.499 - 0.38	31 47 54						

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value					Max Uo
WALL BELOW GRADE:	10			ROOF:	0.054
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.12
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.047
Horizontal	17	14	11		
Vertical	8	6	4		

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TABLE K.26 ACP for Colorado Springs, Denver, and Pueblo, CO, Boise, ID, Goodland, KS, Clayton, NM, Lovelock, Reno, Tonopah, and Winnemucca, NV, Cedar City and Salt Lake City, UT, and Mount Shasta, CA

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 1751 - 3200
CDD65 = 0 - 1150
VSEW = > 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.68 to 0.46	0.45 to 0.39	0.38 to 0	0.68 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION SHADING COEFF FACTOR (PF) RANGE (SCx) | VLT >= SC

ILD	PF	SCx	BASE CASE	PERIMETER DAYLIGHTING	Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	22 24 25	23 26 27	0.062	HC >= 5	22	0.092	0.12
		0.709 - 0.60	25 29 31	26 31 33		HC >= 10	22	0.10	0.15
		0.599 - 0.50	27 33 35	28 35 38		HC >= 15	22	0.12	0.16
		0.499 - 0.38	30 38 41	30 39 43					
		0.379 - 0.25	33 45 49	33 46 52		HC >= 5	58	0.090	0.12
		0.249 - 0.00	37 54 62	37 55 63		HC >= 10	58	0.10	0.14
	0.250 - 0.499	1.000 - 0.71	29 35 36	29 37 39		HC >= 15	58	0.11	0.15
		0.709 - 0.60	32 40 43	32 42 46					
		0.599 - 0.50	34 45 49	34 48 52					
		0.499 - 0.38	36 50 55	36 51 56					
		0.379 - 0.25	38 56 64	38 56 66					
	0.500 +	1.000 - 0.71	34 43 47	34 45 50					
		0.709 - 0.60	36 49 54	36 51 56					
		0.599 - 0.50	38 54 60	38 55 63					
		0.499 - 0.38	39 58 66	39 58 68					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	19 20 21	23 26 28	0.062	HC >= 5	19	0.094	0.13
		0.709 - 0.60	22 25 25	26 31 33		HC >= 10	19	0.11	0.17
		0.599 - 0.50	25 29 30	29 36 39		HC >= 15	19	0.13	0.18
		0.499 - 0.38	28 33 35	32 41 45					
		0.379 - 0.25	32 41 44	36 48 54		HC >= 5	71	0.091	0.12
		0.249 - 0.00	39 52 58	40 58 68		HC >= 10	71	0.10	0.15
	0.250 - 0.499	1.000 - 0.71	25 29 30	30 37 40		HC >= 15	71	0.11	0.16
		0.709 - 0.60	29 35 36	33 43 47					
		0.599 - 0.50	32 39 42	38 47 54					
		0.499 - 0.38	35 44 48	38 52 60					
		0.379 - 0.25	39 52 58	41 59 69					
	0.500 +	1.000 - 0.71	31 37 39	35 46 51					
		0.709 - 0.60	34 43 46	38 52 59					
		0.599 - 0.50	37 48 52	40 56 66					
		0.499 - 0.38	40 54 59	41 60 71					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	17 18 18	22 26 27	0.062	HC >= 5	17	0.094	0.13
		0.709 - 0.60	20 22 23	26 31 33		HC >= 10	17	0.11	0.18
		0.599 - 0.50	22 26 26	28 35 38		HC >= 15	17	0.13	0.19
		0.499 - 0.38	25 30 31	31 39 44					
		0.379 - 0.25	30 37 39	35 47 53		HC >= 5	70	0.091	0.12
		0.249 - 0.00	36 48 53	40 57 67		HC >= 10	70	0.10	0.15
	0.250 - 0.499	1.000 - 0.71	23 26 26	29 36 39		HC >= 15	70	0.12	0.16
		0.709 - 0.60	26 31 32	32 42 46					
		0.599 - 0.50	29 35 37	35 46 52					
		0.499 - 0.38	32 40 43	37 51 59					
		0.379 - 0.25	36 48 52	40 57 68					
	0.500 +	1.000 - 0.71	28 33 34	34 45 50					
		0.709 - 0.60	32 39 41	37 50 58					
		0.599 - 0.50	34 44 47	39 54 65					
		0.499 - 0.38	37 49 53	41 59 70					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value					Max Uo
WALL BELOW GRADE:	10			ROOF:	0.051
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.13
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.049
Horizontal	17	14	11		
Vertical	8	6	4		

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TABLE K.27 ACP for Springfield, IL, Evansville, IN, Lexington and Louisville, KY, Columbia, St. Louis, and Springfield, MO, and Topeka, KS

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD65 = 1751 - 3200
CDD65 = 1151 - 2000
VSEW = 560 - 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.81 to 0.46	0.45 to 0.39	0.38 to 0	0.81 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE | SHADING COEFF (SC+) | VLT >= SC

ILD	PF	SC+	0.38	0.45	0.81	VLT >= SC
0 - 1.50	0.000 - 0.249	1.000 - 0.71	17	19	19	18 / 20 / 21
		0.709 - 0.60	20	23	23	21 / 25 / 26
		0.599 - 0.50	22	27	27	24 / 29 / 31
		0.499 - 0.38	25	31	32	27 / 34 / 36
		0.379 - 0.25	30	39	41	31 / 42 / 46
		0.249 - 0.00	37	54	58	38 / 57 / 63
	0.250 - 0.499	1.000 - 0.71	22	26	27	24 / 29 / 30
		0.709 - 0.60	26	32	33	27 / 35 / 37
		0.599 - 0.50	29	37	39	30 / 40 / 43
		0.499 - 0.38	32	43	45	33 / 46 / 50
		0.379 - 0.25	36	52	57	37 / 56 / 62
	0.500 +	1.000 - 0.71	27	34	36	29 / 37 / 40
		0.709 - 0.60	31	41	43	32 / 44 / 48
		0.599 - 0.50	34	47	50	35 / 50 / 55
		0.499 - 0.38	37	53	57	38 / 56 / 63
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	14	15	15	18 / 21 / 22
		0.709 - 0.60	17	19	19	22 / 25 / 27
		0.599 - 0.50	19	22	22	25 / 30 / 32
		0.499 - 0.38	22	26	27	28 / 35 / 38
		0.379 - 0.25	27	33	35	33 / 44 / 49
		0.249 - 0.00	35	47	50	40 / 59 / 68
	0.250 - 0.499	1.000 - 0.71	19	21	22	25 / 29 / 32
		0.709 - 0.60	23	26	27	28 / 36 / 39
		0.599 - 0.50	26	31	32	31 / 41 / 46
		0.499 - 0.38	29	36	38	34 / 47 / 53
		0.379 - 0.25	34	45	48	39 / 57 / 66
	0.500 +	1.000 - 0.71	24	26	29	30 / 38 / 42
		0.709 - 0.60	28	34	35	33 / 45 / 51
		0.599 - 0.50	31	39	41	36 / 51 / 58
		0.499 - 0.38	34	46	48	39 / 58 / 67
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	12	13	13	17 / 19 / 21
		0.709 - 0.60	14	16	16	20 / 24 / 26
		0.599 - 0.50	17	19	19	23 / 28 / 31
		0.499 - 0.38	19	22	23	26 / 33 / 37
		0.379 - 0.25	24	29	30	31 / 41 / 47
		0.249 - 0.00	31	41	43	38 / 56 / 66
	0.250 - 0.499	1.000 - 0.71	16	18	18	23 / 28 / 31
		0.709 - 0.60	20	22	23	27 / 33 / 38
		0.599 - 0.50	22	26	27	29 / 38 / 44
		0.499 - 0.38	25	31	32	32 / 44 / 51
		0.379 - 0.25	30	39	41	37 / 54 / 64
	0.500 +	1.000 - 0.71	21	24	24	28 / 36 / 40
		0.709 - 0.60	24	29	30	31 / 42 / 49
		0.599 - 0.50	27	34	35	34 / 48 / 56
		0.499 - 0.38	30	39	41	37 / 55 / 65

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.093	HC >= 5	14	0.10	0.13
	HC >= 10	14	0.11	0.15
	HC >= 15	14	0.12	0.16
	HC >= 5	68	0.099	0.12
	HC >= 10	68	0.11	0.14
	HC >= 15	68	0.11	0.14

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.093	HC >= 5	12	0.10	0.13
	HC >= 10	12	0.11	0.15
	HC >= 15	12	0.12	0.17
	HC >= 5	66	0.099	0.12
	HC >= 10	66	0.11	0.14
	HC >= 15	66	0.11	0.14

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		9		ROOF:	0.058
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.14
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.057
Horizontal	16	13	11		
Vertical	8	6	4		

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TABLE K.28 ACP for Dodge City, KS, and Grand Junction, CO

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD65 = 1751 - 3200
CDD65 = 1151 - 2000
VSEW = > 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.81 to 0.46	0.45 to 0.39	0.38 to 0	0.81 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE | SHADING COEFF (SC+) | VLT >= SC

ILD	PF	SC+	0.38	0.45	0.81	VLT >= SC
0 - 1.50	0.000 - 0.249	1.000 - 0.71	15	17	17	16 / 19 / 19
		0.709 - 0.60	18	21	21	19 / 23 / 24
		0.599 - 0.50	20	24	25	21 / 26 / 28
		0.499 - 0.38	22	28	30	23 / 30 / 32
		0.379 - 0.25	26	35	38	27 / 37 / 41
		0.249 - 0.00	31	47	52	32 / 49 / 56
	0.250 - 0.499	1.000 - 0.71	20	24	25	21 / 26 / 28
		0.709 - 0.60	23	29	31	24 / 32 / 34
		0.599 - 0.50	25	34	36	26 / 36 / 39
		0.499 - 0.38	28	39	42	29 / 41 / 45
		0.379 - 0.25	31	47	51	32 / 49 / 55
	0.500 +	1.000 - 0.71	24	32	33	25 / 34 / 37
		0.709 - 0.60	27	37	40	28 / 40 / 44
		0.599 - 0.50	30	42	45	30 / 45 / 50
		0.499 - 0.38	32	48	52	32 / 50 / 56
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	12	13	14	16 / 18 / 20
		0.709 - 0.60	15	17	17	19 / 22 / 24
		0.599 - 0.50	17	20	20	21 / 26 / 28
		0.499 - 0.38	19	23	24	23 / 30 / 34
		0.379 - 0.25	23	29	31	27 / 37 / 42
		0.249 - 0.00	30	41	44	33 / 50 / 58
	0.250 - 0.499	1.000 - 0.71	17	19	20	21 / 26 / 29
		0.709 - 0.60	20	24	24	24 / 31 / 35
		0.599 - 0.50	22	27	29	26 / 35 / 40
		0.499 - 0.38	25	32	34	29 / 41 / 47
		0.379 - 0.25	29	40	43	33 / 49 / 57
	0.500 +	1.000 - 0.71	21	25	26	25 / 33 / 37
		0.709 - 0.60	24	30	32	28 / 39 / 45
		0.599 - 0.50	27	35	37	30 / 44 / 51
		0.499 - 0.38	29	40	43	33 / 50 / 58
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	11	11	12	15 / 17 / 19
		0.709 - 0.60	13	14	14	17 / 21 / 23
		0.599 - 0.50	15	17	17	20 / 24 / 27
		0.499 - 0.38	17	20	20	22 / 28 / 32
		0.379 - 0.25	21	25	27	26 / 35 / 41
		0.249 - 0.00	27	36	38	31 / 47 / 56
	0.250 - 0.499	1.000 - 0.71	15	16	17	20 / 24 / 27
		0.709 - 0.60	17	20	21	23 / 29 / 33
		0.599 - 0.50	19	24	24	25 / 33 / 39
		0.499 - 0.38	22	28	29	27 / 38 / 45
		0.379 - 0.25	26	35	37	31 / 48 / 55
	0.500 +	1.000 - 0.71	18	22	22	24 / 31 / 36
		0.709 - 0.60	21	26	27	26 / 37 / 43
		0.599 - 0.50	24	30	32	29 / 41 / 49
		0.499 - 0.38	26	35	37	31 / 47 / 56

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.090	HC >= 5	15	0.097	0.12
	HC >= 10	15	0.11	0.14
	HC >= 15	15	0.12	0.15
	HC >= 5	56	0.097	0.12
	HC >= 10	56	0.10	0.14
	HC >= 15	56	0.11	0.15

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.090	HC >= 5	12	0.098	0.13
	HC >= 10	12	0.11	0.16
	HC >= 15	12	0.13	0.17
	HC >= 5	58	0.097	0.12
	HC >= 10	58	0.11	0.15
	HC >= 15	58	0.12	0.16

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.090	HC >= 5	11	0.099	0.13
	HC >= 10	11	0.11	0.16
	HC >= 15	11	0.13	0.17
	HC >= 5	56	0.097	0.12
	HC >= 10	56	0.11	0.14
	HC >= 15	56	0.12	0.15

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		9		ROOF:	0.053
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE:	0.14
ON GRADE:	24"	36"	48"	FLOOR OVER UNCOND. SPACE:	0.053
Horizontal	16	14	11		
Vertical	8	6	4		

Source: Adapted with permission from ASHRAE/IES Standard 90.1-1989, *Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*, © 1989 by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga.

TABLE K.29 ACP for Albany, Buffalo, Rochester, and Syracuse, NY, Grand Rapids, MI, La Crosse and Milwaukee, WI, Des Moines and Sioux City, IA, Grand Island, NE, Rapid City, SD, and Billings, MT

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 3201 - 4000
CDD65 = 501 - 1150
VSEW = 560 - 845

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING		
0.68 to 0.46	0.45 to 0.39	0.38 to 0	0.68 to 0.46	0.45 to 0	0.38 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

VLT>=SC

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF)	SHADING COEFF RANGE (SCx)						Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	22	26	28	22	27	29	0.076	HC >= 5	22	0.079	0.095
		0.709 - 0.60	24	31	33	24	31	34		HC >= 10	22	0.085	0.10
		0.599 - 0.50	25	34	37	25	34	38		HC >= 15	22	0.089	0.10
		0.499 - 0.38	27	37	42	27	37	42					
		0.379 - 0.25	29	42	48	28	41	48		HC >= 5	59	0.079	0.093
		0.249 - 0.00	31	46	56	30	47	55		HC >= 10	59	0.084	0.10
	0.250 - 0.499	1.000 - 0.71	26	35	38	26	35	39		HC >= 15	59	0.087	0.10
		0.709 - 0.60	28	39	44	28	39	45					
		0.599 - 0.50	29	42	48	29	42	48					
		0.499 - 0.38	30	45	52	30	44	52					
		0.379 - 0.25	32	49	57	31	47	56					
	0.500 +	1.000 - 0.71	29	41	46	29	41	48					
		0.709 - 0.60	31	45	52	30	44	52					
		0.599 - 0.50	32	47	55	30	46	55					
		0.499 - 0.38	32	50	59	31	48	57					
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	20	23	24	22	27	29	0.076	HC >= 5	20	0.080	0.10
		0.709 - 0.60	22	27	29	25	32	35		HC >= 10	20	0.087	0.11
		0.599 - 0.50	24	31	33	26	35	39		HC >= 15	20	0.093	0.11
		0.499 - 0.38	27	34	37	28	39	43					
		0.379 - 0.25	30	40	45	31	44	50		HC >= 5	60	0.079	0.093
		0.249 - 0.00	33	48	55	33	50	59		HC >= 10	60	0.084	0.10
	0.250 - 0.499	1.000 - 0.71	25	31	33	27	36	40		HC >= 15	60	0.087	0.10
		0.709 - 0.60	27	36	39	29	40	46					
		0.599 - 0.50	29	39	43	30	43	50					
		0.499 - 0.38	31	43	48	31	46	54					
		0.379 - 0.25	33	48	55	33	50	59					
	0.500 +	1.000 - 0.71	28	37	41	30	42	49					
		0.709 - 0.60	31	42	47	31	45	54					
		0.599 - 0.50	32	45	51	32	48	57					
		0.499 - 0.38	34	49	56	33	50	60					
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	18	21	21	22	27	29	0.076	HC >= 5	18	0.080	0.10
		0.709 - 0.60	21	25	26	24	31	34		HC >= 10	18	0.088	0.11
		0.599 - 0.50	23	28	30	26	35	39		HC >= 15	18	0.094	0.12
		0.499 - 0.38	25	32	34	28	38	43					
		0.379 - 0.25	28	38	41	30	43	50		HC >= 5	60	0.079	0.094
		0.249 - 0.00	32	46	52	33	50	59		HC >= 10	60	0.084	0.10
	0.250 - 0.499	1.000 - 0.71	23	28	30	26	35	39		HC >= 15	60	0.088	0.10
		0.709 - 0.60	26	33	35	28	39	45					
		0.599 - 0.50	28	36	40	30	42	50					
		0.499 - 0.38	29	40	44	31	45	54					
		0.379 - 0.25	32	45	52	33	49	58					
	0.500 +	1.000 - 0.71	27	34	37	29	41	48					
		0.709 - 0.60	29	39	43	31	45	53					
		0.599 - 0.50	31	42	48	32	47	57					
		0.499 - 0.38	32	46	52	33	50	60					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:	10			0.049
UNHEATED SLAB				
ON GRADE:	24'	36'	48'	
Horizontal	18	15	11	
Vertical	8	6	4	

ROOF:	
WALL ADJACENT TO UNCOND SPACE:	0.12
FLOOR OVER UNCOND. SPACE:	0.044

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TABLE K.30 ACP for Portland, ME, Concord, NH, Binghampton, NY, Flint and Traverse City, MI, Great Falls, Helena, and Missoula, MT, and Sheridan, WY

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 3201 - 4000
CDD65 = 0 - 500
VSEW = 560 - 845

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING	
0.58 to 0.46	0.45 to 0.29	0.28 to 0	N/A	

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

VLT>=SC

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF)	SHADING COEFF RANGE (SCx)						Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0 - 1.50	0.000 - 0.249	1.000 - 0.71	20	27	32				0.072	HC >= 5	20	0.075	0.092
		0.709 - 0.60	21	30	39					HC >= 10	20	0.080	0.10
		0.599 - 0.50	21	31	44					HC >= 15	20	0.084	0.10
		0.499 - 0.38	21	33	49								
		0.379 - 0.25	22	35	57					HC >= 5	72	0.075	0.094
		0.249 - 0.00	22	36	64					HC >= 10	72	0.080	0.10
	0.250 - 0.499	1.000 - 0.71	23	34	46					HC >= 15	72	0.085	0.11
		0.709 - 0.60	23	36	53								
		0.599 - 0.50	23	37	59								
		0.499 - 0.38	23	38	64								
		0.379 - 0.25	23	38	69								
	0.500 +	1.000 - 0.71	24	38	57								
		0.709 - 0.60	24	39	64								
		0.599 - 0.50	24	40	69								
		0.499 - 0.38	23	39	72								
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	19	24	27				0.072	HC >= 5	19	0.075	0.098
		0.709 - 0.60	21	27	33					HC >= 10	19	0.082	0.11
		0.599 - 0.50	22	30	38					HC >= 15	19	0.086	0.11
		0.499 - 0.38	23	32	43								
		0.379 - 0.25	24	36	52					HC >= 5	68	0.075	0.099
		0.249 - 0.00	26	40	64					HC >= 10	68	0.082	0.11
	0.250 - 0.499	1.000 - 0.71	23	31	38					HC >= 15	68	0.089	0.12
		0.709 - 0.60	24	34	45								
		0.599 - 0.50	25	37	51								
		0.499 - 0.38	26	39	57								
		0.379 - 0.25	26	41	66								
	0.500 +	1.000 - 0.71	25	36	49								
		0.709 - 0.60	26	39	56								
		0.599 - 0.50	26	41	62								
		0.499 - 0.38	27	42	68								
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	18	22	24				0.072	HC >= 5	18	0.075	0.10
		0.709 - 0.60	20	25	30					HC >= 10	18	0.083	0.11
		0.599 - 0.50	21	28	34					HC >= 15	18	0.090	0.12
		0.499 - 0.38	22	31	40								
		0.379 - 0.25	24	35	49					HC >= 5	64	0.075	0.10
		0.249 - 0.00	26	39	61					HC >= 10	64	0.083	0.11
	0.250 - 0.499	1.000 - 0.71	22	29	35					HC >= 15	64	0.090	0.12
		0.709 - 0.60	23	32	42								
		0.599 - 0.50	24	35	47								
		0.499 - 0.38	25	37	53								
		0.379 - 0.25	26	40	62								
	0.500 +	1.000 - 0.71	24	34	45								
		0.709 - 0.60	25	37	52								
		0.599 - 0.50	26	39	58								
		0.499 - 0.38	27	41	64								

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:	11			0.049
UNHEATED SLAB				
ON GRADE:	24'	36'	48'	
Horizontal	18	15	11	
Vertical	8	6	4	

ROOF:	
WALL ADJACENT TO UNCOND SPACE:	0.11
FLOOR OVER UNCOND. SPACE:	0.040

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TABLE K.31 ACP for Bangor, ME, Burlington, VT, Massena, NY, Alpena, MI, Eau Claire, Green Bay, and Madison, WI, Mason City, IA, Minneapolis and Rochester, MN, Huron, Pierre, and Sioux Falls, SD, Cut Bank, Dillon, Lewistown, and Miles, MT

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 4001 - 5000
CDD65 = 0 - 1150
VSEW = 580 - 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING	
0.68 to 0.46	0.45 to 0.29	0.28 to 0	N/A	

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF)	SHADING COEFF RANGE (SCx)	VLT >= SC					
0 - 1.50	0.000 - 0.249	1.000 - 0.71	19	27	32			
		0.709 - 0.60	20	29	39			
		0.599 - 0.50	20	31	44			
		0.499 - 0.38	20	32	49			
		0.379 - 0.25	20	32	55			
		0.249 - 0.00	19	32	60			
	0.250 - 0.499	1.000 - 0.71	22	34	46			
		0.709 - 0.60	22	35	54			
		0.599 - 0.50	21	36	59			
		0.499 - 0.38	21	36	63			
		0.379 - 0.25	20	35	66			
	0.500 +	1.000 - 0.71	23	38	58			
		0.709 - 0.60	22	38	64			
		0.599 - 0.50	21	37	68			
		0.499 - 0.38	21	36	70			
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	18	23	27			
		0.709 - 0.60	20	27	32			
		0.599 - 0.50	21	29	37			
		0.499 - 0.38	22	31	42			
		0.379 - 0.25	23	34	50			
		0.249 - 0.00	24	37	60			
	0.250 - 0.499	1.000 - 0.71	22	30	38			
		0.709 - 0.60	23	33	45			
		0.599 - 0.50	24	35	50			
		0.499 - 0.38	24	37	56			
		0.379 - 0.25	24	38	63			
	0.500 +	1.000 - 0.71	24	35	49			
		0.709 - 0.60	24	37	55			
		0.599 - 0.50	25	39	60			
		0.499 - 0.38	25	40	65			
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	17	21	24			
		0.709 - 0.60	19	25	29			
		0.599 - 0.50	20	27	34			
		0.499 - 0.38	21	29	39			
		0.379 - 0.25	22	33	47			
		0.249 - 0.00	24	36	57			
	0.250 - 0.499	1.000 - 0.71	21	28	34			
		0.709 - 0.60	22	31	41			
		0.599 - 0.50	23	33	46			
		0.499 - 0.38	24	35	51			
		0.379 - 0.25	24	37	59			
	0.500 +	1.000 - 0.71	23	33	44			
		0.709 - 0.60	24	36	51			
		0.599 - 0.50	24	37	56			
		0.499 - 0.38	25	38	61			

Daylight Sensing Controls

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.065	HC >= 5	19	0.067	0.078
	HC >= 10	19	0.069	0.082
	HC >= 15	19	0.071	0.083
	HC >= 5	70	0.067	0.083
	HC >= 10	70	0.071	0.094
	HC >= 15	70	0.075	0.097

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.065	HC >= 5	18	0.067	0.086
	HC >= 10	18	0.072	0.099
	HC >= 15	18	0.076	0.10
	HC >= 5	65	0.067	0.087
	HC >= 10	65	0.072	0.10
	HC >= 15	65	0.077	0.10

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.065	HC >= 5	17	0.067	0.087
	HC >= 10	17	0.073	0.10
	HC >= 15	17	0.077	0.10
	HC >= 5	61	0.068	0.088
	HC >= 10	61	0.073	0.10
	HC >= 15	61	0.077	0.10

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		12			ROOF: 0.045
UNHEATED SLAB					WALL ADJACENT TO UNCOND SPACE: 0.10
ON GRADE:	24"	36"	48"		FLOOR OVER UNCOND. SPACE: 0.040
Horizontal	18	15	11		
Vertical	8	6	4		

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TABLE K.32 ACP for North Platte and Scottsbluff, NE, Casper and Cheyenne, WY, Pocatello, ID, Elko and Ely, NV

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD50 = 3201 - 4000
CDD65 = 0 - 1150
VSEW = > 845

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING	
0.68 to 0.46	0.45 to 0.29	0.28 to 0	0.68 to 0.46	0.45 to 0	0.28 to 0

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

Uof

INTERNAL LOAD DENSITY (ILD) RANGE	PROJECTION FACTOR (PF)	SHADING COEFF RANGE (SCx)	VLT >= SC					
0 - 1.50	0.000 - 0.249	1.000 - 0.71	19	26	30	19	26	32
		0.709 - 0.60	20	28	36	19	29	38
		0.599 - 0.50	20	30	41	19	30	43
		0.499 - 0.38	20	32	46	19	31	48
		0.379 - 0.25	20	33	53	19	32	54
		0.249 - 0.00	20	33	60	19	32	57
	0.250 - 0.499	1.000 - 0.71	23	34	44	22	34	47
		0.709 - 0.60	23	36	52	21	35	55
		0.599 - 0.50	22	37	57	21	36	60
		0.499 - 0.38	22	37	62	21	35	64
		0.379 - 0.25	21	37	67	20	34	66
	0.500 +	1.000 - 0.71	24	39	56	22	38	60
		0.709 - 0.60	23	39	64	22	38	67
		0.599 - 0.50	23	39	68	21	37	71
		0.499 - 0.38	22	39	71	21	36	71
1.51 - 3.00	0.000 - 0.249	1.000 - 0.71	18	22	24	20	27	32
		0.709 - 0.60	20	25	30	21	30	38
		0.599 - 0.50	21	28	34	22	32	44
		0.499 - 0.38	22	31	40	23	34	50
		0.379 - 0.25	23	34	48	23	36	57
		0.249 - 0.00	25	38	59	24	38	64
	0.250 - 0.499	1.000 - 0.71	22	30	35	24	35	47
		0.709 - 0.60	24	33	42	24	37	55
		0.599 - 0.50	24	35	48	24	38	61
		0.499 - 0.38	25	37	54	25	39	66
		0.379 - 0.25	26	40	62	25	40	70
	0.500 +	1.000 - 0.71	25	35	48	25	40	60
		0.709 - 0.60	26	38	53	25	41	68
		0.599 - 0.50	26	40	59	25	41	73
		0.499 - 0.38	26	41	65	25	41	75
3.01 - 3.50	0.000 - 0.249	1.000 - 0.71	16	19	21	20	26	31
		0.709 - 0.60	18	23	26	21	30	38
		0.599 - 0.50	20	25	30	22	32	43
		0.499 - 0.38	21	28	35	23	34	49
		0.379 - 0.25	23	32	43	24	36	57
		0.249 - 0.00	25	36	55	25	38	64
	0.250 - 0.499	1.000 - 0.71	21	27	31	23	35	45
		0.709 - 0.60	22	30	37	24	37	53
		0.599 - 0.50	23	32	43	24	38	60
		0.499 - 0.38	24	35	48	25	39	68
		0.379 - 0.25	25	38	58	25	40	70
	0.500 +	1.000 - 0.71	23	32	41	25	39	58
		0.709 - 0.60	24	35	48	25	40	67
		0.599 - 0.50	25	37	53	25	40	72
		0.499 - 0.38	26	39	58	26	41	74

Daylight Sensing Controls

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.073	HC >= 5	19	0.076	0.098
	HC >= 10	19	0.083	0.11
	HC >= 15	19	0.088	0.11
	HC >= 5	71	0.078	0.10
	HC >= 10	71	0.084	0.11
	HC >= 15	71	0.091	0.12

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.073	HC >= 5	18	0.077	0.10
	HC >= 10	18	0.087	0.13
	HC >= 15	18	0.096	0.13
	HC >= 5	75	0.078	0.10
	HC >= 10	75	0.086	0.12
	HC >= 15	75	0.094	0.13

Uow (HC < 5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.073	HC >= 5	16	0.077	0.11
	HC >= 10	16	0.088	0.13
	HC >= 15	16	0.097	0.14
	HC >= 5	74	0.078	0.10
	HC >= 10	74	0.086	0.12
	HC >= 15	74	0.093	0.13

OTHER CRITERIA

Minimum R-Value				Max Uo	
WALL BELOW GRADE:		11			ROOF: 0.049
UNHEATED SLAB					WALL ADJACENT TO UNCOND SPACE: 0.11
ON GRADE:	24"	36"	48"		FLOOR OVER UNCOND. SPACE: 0.041
Horizontal	18	15	11		
Vertical	8	6	4		

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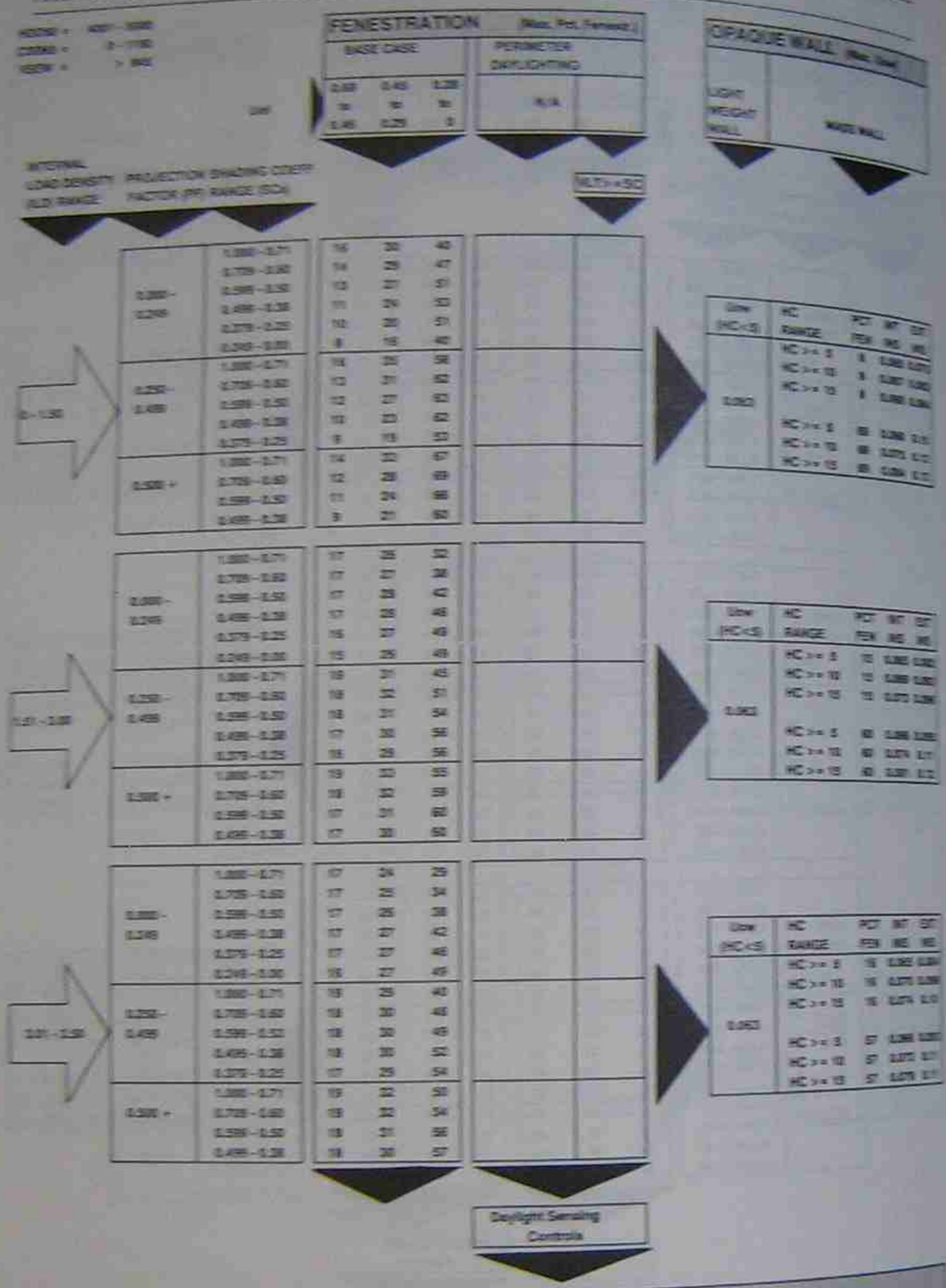
APPENDICES

TABLE K.33 ACP for Eagle, CO, Rock Springs, WY, and Bryce Canyon, UT

Alternate Component Package for ASHRAE/IES Standard 90.1-1989



OTHER CRITERIA					
Minimum R-Value					Max U-V
WALL BELOW GRADE: UNHEATED SLAB		12		ROOF:	0.042
ON GRADE:	24"	36"	48"	WALL ADJACENT TO UNCOND SPACE:	0.10
Horizontal	10	15	11	FLOOR OVER UNCOND. SPACE:	0.042
Vertical	8	6	4		

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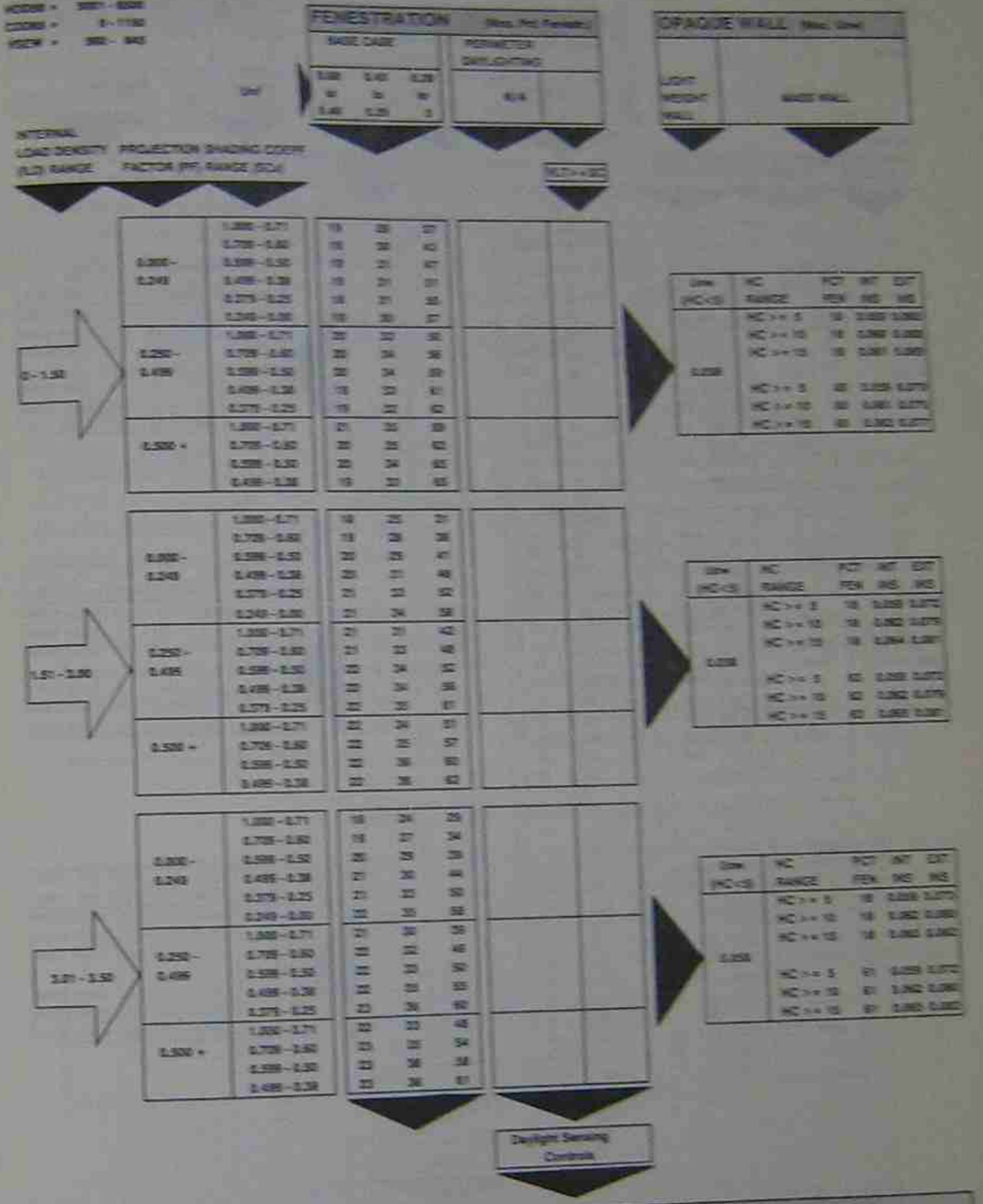
TABLE K.34 ACP for Caribou, ME, Sault St. Marie, MI, Duluth and International Falls, MN, Bismarck, Fargo, and Minot, ND, and Glasgow, MT

Alternate Component Package for ASHRAE/IES Standard 90.1-1989



OTHER CRITERIA					
Minimum R-Value					Max U-V
WALL BELOW GRADE: UNHEATED SLAB		12		ROOF:	0.042
ON GRADE:	24"	36"	48"	WALL ADJACENT TO UNCOND SPACE:	0.10
Horizontal	10	15	11	FLOOR OVER UNCOND. SPACE:	0.042
Vertical	8	6	4		

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TABLE K.35 **ACP for Adak, Anchorage, Annette Island, Juneau, Kodiak, and Yakutat, AK**

Alternate Component Package, for ASHRAE/IES Standard 90.1-1989

HDD65 = 2501 - 8500
CDD65 = < 100
VSEW = < 960

Uof

FENESTRATION (Max. Pct. Fenestr.)

BASE CASE			PERIMETER DAYLIGHTING	
0.68 to 0.46	0.45 to 0.29	0.28 to 0	N/A	

OPAQUE WALL (Max. Uow)

LIGHT WEIGHT WALL	MASS WALL

INTERNAL LOAD DENSITY (ILD) RANGE | PROJECTION FACTOR (PF) RANGE (SCx) | SHADING COEFF

VLT>=SC

0 - 1.50

PF	SC			Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.000 - 0.249	1.000 - 0.71	17	29	45	0.058	HC >= 5	12	0.059	0.072
	0.709 - 0.60	16	29	50		HC >= 10	12	0.060	0.080
	0.599 - 0.50	15	28	53		HC >= 15	12	0.061	0.085
	0.499 - 0.38	14	27	55					
	0.379 - 0.25	13	25	53		HC >= 5	63	0.059	0.080
	0.249 - 0.00	12	22	48		HC >= 10	63	0.062	0.094
0.250 - 0.499	1.000 - 0.71	16	31	57		HC >= 15	63	0.064	0.10
	0.709 - 0.60	15	29	60					
	0.599 - 0.50	15	28	60					
	0.499 - 0.38	14	26	58					
	0.379 - 0.25	13	24	54					
0.500 +	1.000 - 0.71	16	30	63					
	0.709 - 0.60	15	28	63					
	0.599 - 0.50	14	26	60					
	0.499 - 0.38	13	25	57					

1.51 - 3.00

PF	SC			Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.000 - 0.249	1.000 - 0.71	17	27	39	0.058	HC >= 5	15	0.059	0.076
	0.709 - 0.60	17	28	44		HC >= 10	15	0.061	0.088
	0.599 - 0.50	17	28	48		HC >= 15	15	0.063	0.093
	0.499 - 0.38	16	28	50					
	0.379 - 0.25	16	27	52		HC >= 5	58	0.059	0.079
	0.249 - 0.00	15	26	51		HC >= 10	58	0.061	0.092
0.250 - 0.499	1.000 - 0.71	18	30	50		HC >= 15	58	0.064	0.10
	0.709 - 0.60	17	30	54					
	0.599 - 0.50	17	29	56					
	0.499 - 0.38	16	28	56					
	0.379 - 0.25	16	27	55					
0.500 +	1.000 - 0.71	17	31	57					
	0.709 - 0.60	17	30	58					
	0.599 - 0.50	16	29	58					
	0.499 - 0.38	16	28	57					

3.01 - 3.50

PF	SC			Uow (HC<5)	HC RANGE	PCT FEN	INT INS	EXT INS
0.000 - 0.249	1.000 - 0.71	20	30	41	0.058	HC >= 5	18	0.059	0.078
	0.709 - 0.60	20	31	47		HC >= 10	18	0.061	0.091
	0.599 - 0.50	19	32	51		HC >= 15	18	0.063	0.096
	0.499 - 0.38	19	32	55					
	0.379 - 0.25	19	32	58		HC >= 5	65	0.059	0.080
	0.249 - 0.00	18	31	59		HC >= 10	65	0.061	0.094
0.250 - 0.499	1.000 - 0.71	20	34	53		HC >= 15	65	0.064	0.10
	0.709 - 0.60	20	34	58					
	0.599 - 0.50	20	34	61					
	0.499 - 0.38	19	33	63					
	0.379 - 0.25	19	32	63					
0.500 +	1.000 - 0.71	20	35	61					
	0.709 - 0.60	20	34	64					
	0.599 - 0.50	19	34	65					
	0.499 - 0.38	19	33	65					

Daylight Sensing Controls

OTHER CRITERIA

Minimum R-Value				Max Uo
WALL BELOW GRADE:	13			ROOF: 0.041
UNHEATED SLAB				WALL ADJACENT TO UNCOND SPACE: 0.10
ON GRADE:	24'	36'	48'	FLOOR OVER UNCOND. SPACE: 0.040
Horizontal	16	15	11	
Vertical	8	6	4	

Source: Adapted with permission from ASHRAE/IES Standard 90.1-1989, *Energy Efficient Design of New Buildings Except Low-Rise Residential Buildings*, © 1989 by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga.

K.2 Low-Rise Residential Design Criteria for Energy Conservation

The following criteria are taken from ASHRAE Standard 90A–1980, *Energy Conservation in New Building Design*. This standard is frequently updated; series 90.1 deals with all buildings except low-rise residential; series 90.2 deals with low-rise residential buildings.

An important basis of these criteria is the concept of an average U value for all portions of vertical walls, called $U_{overall}$ walls or U_o walls; similarly, an average roof U value is called U_o roofs. This value is calculated in the same way as any other weighted average:

$$U_o \text{ walls} = \frac{(U_{\text{opaque wall}} \times A_{\text{opaque wall}}) + (U_{\text{window}} \times A_{\text{window}}) + \cdots}{A_o \text{ walls}}$$

where A_o includes *all* the areas of all vertical exposed surfaces (walls, windows, doors, etc.)—in other words, the sum of all the areas listed in the numerator of the equation. Note that *each* wall component that is thermally different from other wall components is treated separately in the equation; thus ($U_{\text{wall}} \times A_{\text{wall}}$) might become ($U_{\text{masonry wall}} \times A_{\text{masonry wall}}$) plus ($U_{\text{frame wall}} \times A_{\text{frame wall}}$), and so on.

Similarly,

$$U_o \text{ roofs} = \frac{(U_{\text{opaque roof}} \times A_{\text{opaque roof}}) + (U_{\text{skylight}} \times A_{\text{skylight}}) + \cdots}{A_o \text{ roofs}}$$

where A_o roofs is, again, the sum of all horizontal or sloped surface areas, from the numerator.

Residential (type A) buildings. This includes detached one- and two-family dwellings (A_1) and multifamily dwellings that are *three stories or less* (A_2). (For four or more floors, see ASHRAE Standard 90.1-1989.)

Roof/ceiling: Figure K.2 shows the *maximum* value of U_o roofs for buildings of type A_1 and A_2 that are heated and/or mechanically cooled. For heating degree days, see Appendix B. There is an exception for "cathedral" ceilings, where the finished interior surface is essentially the exposed underside of the structural roof deck. In this case, for any geographic location, U_o roofs maximum = 0.08 Btu/ft²-h-°F (0.45 W/m²-°C; units are interchangeable with W/m²-K).

Walls: Figure K.3 shows the *maximum* value of U_o walls for buildings of types A_1 and A_2

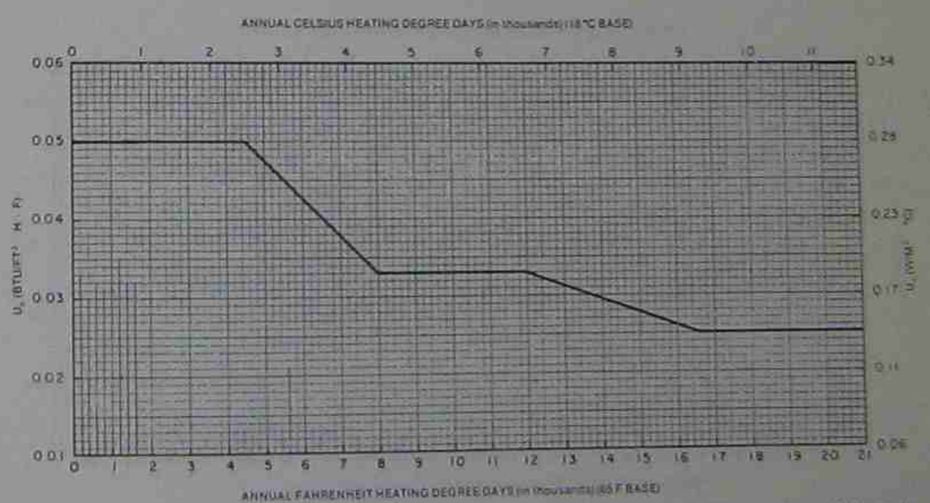

Fig. K.2 U_o values for roofs/ceilings, type A_1 and A_2 (small residential) buildings. Copyright © by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga. Reprinted by permission from ASHRAE Standard 90A-1980.

APPENDICES

that are heated and/or mechanically cooled. In the special case of warmer climates below 500 heating degree days Fahrenheit (278 DD Celsius), buildings that are mechanically cooled have a maximum U_o wall as follows: type A_1, 0.30 Btu/ft²-h-°F (1.70 W/m²-°C); type A_2, 0.38 Btu/ft²-h-°F (2.15 W/m²-°C).

Slab floors on grade: Figure K.4 shows the minimum required thermal resistance (*R* value) for *perimeter insulation*, which extends downward from the top of the slab for a minimum distance of 24 in. (0.6 m). Alternatively, such insulation should extend from the top of the slab to the bottom, then horizontally below the slab for a minimum distance of 24 in. (0.6 m).

Exposed floors. Two conditions are covered here. Heated and/or mechanically cooled spaces with floors that are exposed to *exterior* conditions should have, at maximum, a floor U_o as shown in Fig. K.2 (same as for roofs). However, for floors over protected, but unheated spaces, the maximum U_o is as shown in Fig. K.5.

Infiltration. Air leakage rates are based on a pressure differential equivalent to the effect of a 25-mph (11.1-m/s) wind. Technically, this is a pressure differential of 1.57 lb/ft² (75 Pa).

Windows should have a maximum air infiltration rate of 0.5 cfm per foot (7.74×10^{-4} m³/s per meter) of sash crack.

Doors for residential living units should have a maximum air infiltration rate of 0.5 cfm per square foot (2.54×10^{-3} m³/s per square meter) of door area.

Doors for other usages should have a maximum air infiltration rate of 11 cfm per linear foot (1.7×10^{-2} m³/s per linear meter) of door crack.

Other joints in the exterior envelope that can be sources of air leakage (around window and door frames, between walls and foundation, walls and roof, at utility penetrations, etc.) should be caulked, gasketed, weather stripped, or otherwise sealed.

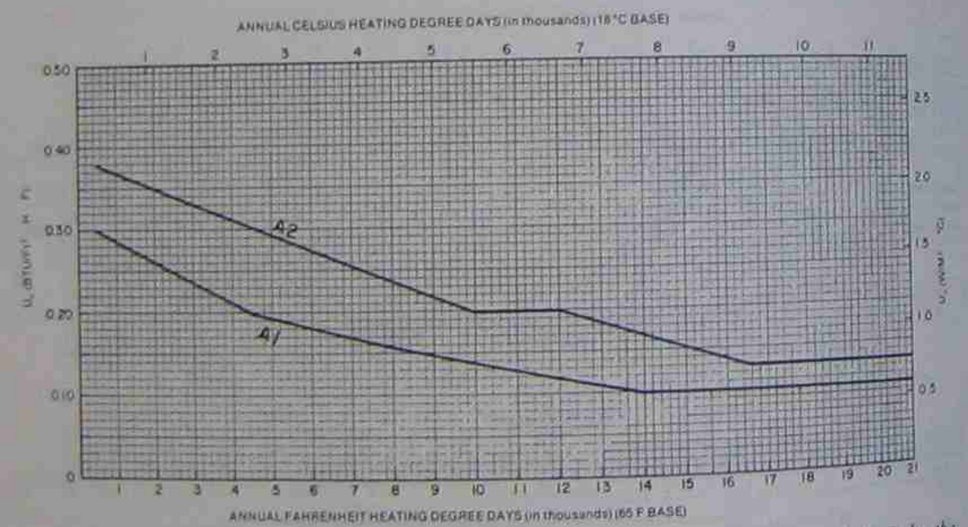

Fig. K.3 U_o values for walls, type A_1 and A_2 (small residential) buildings. Copyright © by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga. Reprinted by permission from ASHRAE Standard 90A-1980.

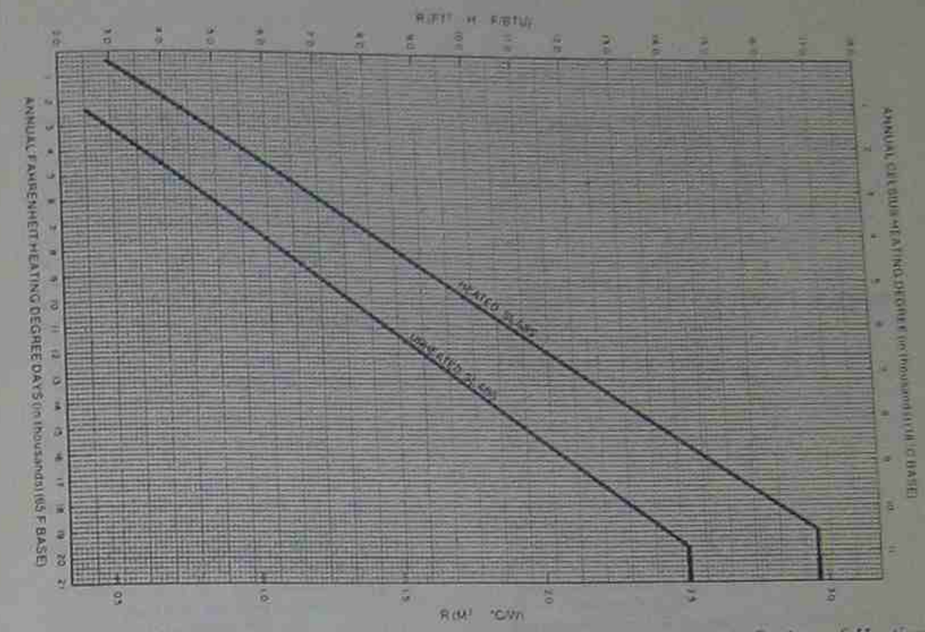

Fig. K.4 R values for slab floors on grade. Copyright © by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga. Reprinted by permission from ASHRAE Standard 90A-1980.

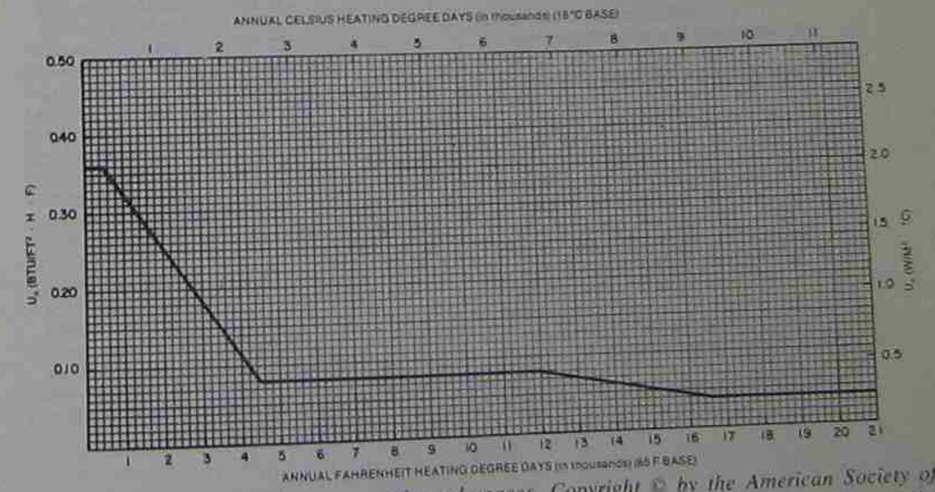

Fig. K.5 U_o values for floors over unheated spaces. Copyright © by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga. Reprinted by permission from ASHRAE Standard 90A-1980.

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Understanding Building Automation Systems

Direct Digital Control
Energy Management
Life Safety
Security/Access Control
Lighting
Building Management Programs

Reinhold A. Carlson, PE
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696
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Foreword

For nearly twenty years, I have had the opportunity to participate in the building automation systems industry as a consulting engineer who represented users, builders, contractors, and vendors. More recently I have been a part of a successful vendor team whose goal is to listen to customers and others within the marketplace, to ensure that future products and services are compatible with needs.

Since building automation systems utilize computers and perform complex control functions, such systems have developed an air of "magic" about them. The perception of magical forces within the systems themselves and within the industry has been reinforced by the rapid changes in a technology whose time constant is significantly shorter than the expected life of the buildings in which these systems are installed.

The level of confusion in such a rapidly changing industry has peaked, and we are now ready to recognize that the application of automated control technology to buildings is a valid engineering discipline. Furthermore, we should now be ready to understand and integrate building automation systems and disciplines into the construction process as a matter of course.

These requirements all derive their impetus from users whose expectations regarding the need for control centralization have matured along with their building operations expertise.

This book, authored by technically competent individuals who also exhibit a strong historical perspective and an end-user orientation, takes stock of current technology and industry practices. It is both an excellent text and an important reference tool. It is broad in scope, covering monitoring and control of fire safety, security, lighting and energy management functions, as well as traditional HVAC control. It is also very specific with regard to system applications, layout methodology, and estimation. Despite the historically rapid change in technology, the concepts and practices presented will not change and will serve us well for the long term.

Part One

Capabilities and Overview of BAS

A Building Automation System is a tool in the hands of building operations personnel, to provide more effective and efficient control over all building systems. Historically, environmental control systems for large buildings have been pneumatic. These systems are capable of maintaining acceptable environmental conditions in a building and can perform some relatively complex control sequences. However, since they are hardware-intensive, the initial installation costs and maintenance requirements can be substantial. There are also the problems of limited accuracy, mechanical wear, and inflexibility. In recent years, the integration of building systems such as heating, ventilating, and air-conditioning, lighting, fire safety, and security has proven economically advantageous, while simplifying system interaction. To determine the value of applying a Building Automation System to a particular building, one must first understand the capabilities offered by such a system. The objective of Part I of this book is to give the reader an overview of these systems, their capabilities, and the software programs associated with them.

Chapter One

Development of Building Automation Systems

The post World War II era introduced new concepts in architectural design. Radical changes in the building envelope occurred, resulting in the employment of more exterior glass, lighter construction, non-opening windows, and a strong emphasis on interior comfort conditions. While these changes enhanced the aesthetic value of the new buildings, they presented a difficult challenge for the engineer responsible for the design of the heating, ventilating, and air-conditioning system. Artificial means of introducing outdoor air for ventilation became mandatory to meet both the needs of occupants and the new ventilation codes. Mechanical refrigeration was introduced to compensate for internal heat build-up. Additional heating and cooling capacity became necessary to offset the temperature of ventilation air being introduced into the building. These requirements were satisfied by installing large, built-up, central heating, ventilating, and air-conditioning systems. The central units were installed in mechanical equipment rooms at various locations in the building where they conditioned air or water, which was ducted or piped to occupied spaces.

With these new central systems governing the building environment, automatic control became an extremely important consideration. No longer was a single, centrally located thermostat adequate to control the heat supplied to an entire building. The open window approach to cooling and ventilating buildings was a thing of the past. To meet the demand for more comfortable, well ventilated, cleaner environmental conditions in buildings, automatic temperature control manufacturers developed pneumatic and electronic control systems with year-round capabilities. Control devices were designed for increased sensitivity, and automatic control systems became more sophisticated. Environmental control engineering reached a level of major importance in the design of new buildings.

Local Control Panels

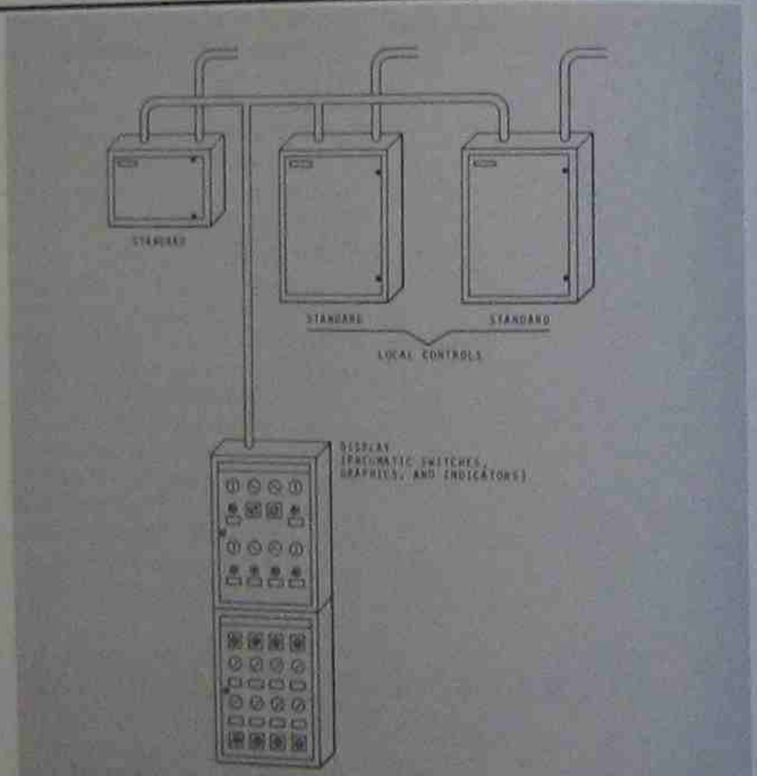
With the proliferation of mechanical systems in buildings, and the increased complexity of automatic control systems, another need became apparent. Building maintenance and operating personnel spent a considerable amount of their time walking through various mechanical equipment rooms checking the equipment, reading temperatures, and

adjusting control settings. Automatic temperature control manufacturers recognized the need for centralization – both for convenience and also as a timesaving measure.

Initially, local control panels, as shown in Figure 1.1, were installed in individual mechanical rooms. These panels contained switches, pilot lights, thermometers, time clocks and appurtenances necessary to control and monitor equipment in the room. This arrangement provided a one-stop location for maintenance personnel to evaluate system status and adjust control set points.

Centralized Control and Monitoring Panels

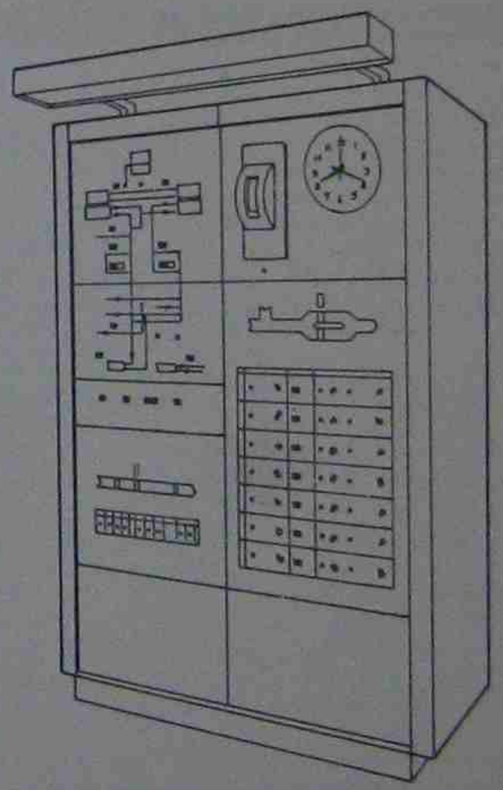
In the early 1950s the first centralized building control centers were developed. These were freestanding, hard-wired and pneumatically piped panels. These panels contained the switches, pilot lights, and other control devices from multiple mechanical rooms. From a central location, building maintenance and operating personnel could start and stop equipment throughout the building, read temperatures at various locations, and make control set point adjustments. Graphic displays of floor layouts, mechanical systems, or piping schematics were mounted on the panel face. This gave the operator an indication of temperature sensor locations and mechanical system layout. A typical control center and sample graphic displays are shown in Figures 1.2 and 1.3.



Local Control Panel

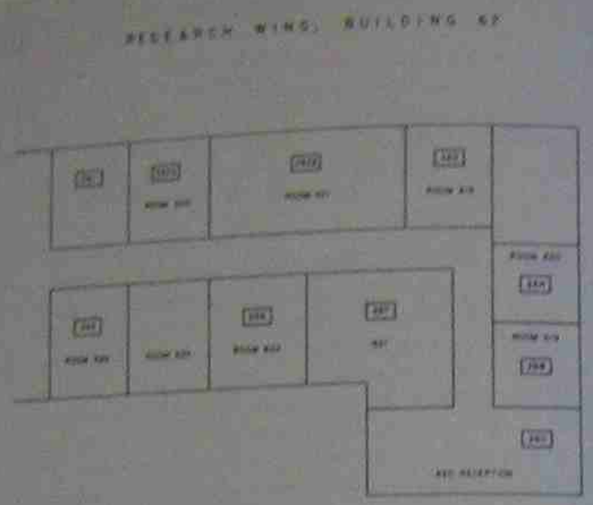
Figure 1.1

Although these systems performed their required tasks, they also had significant limitations. The initial installation cost was high due to the requirement to wire and pneumatically pipe all functions from the remote mechanical rooms back to the central panel. Expansion capabilities were also limited due to the wiring and piping burden, and the space requirements of the massive central control center panel. The systems did, however, provide some positive benefits to building maintenance and operating personnel in the form of a means by which to monitor and control building temperatures and mechanical equipment from a central location. Maintenance personnel were no longer required to walk through buildings checking mechanical equipment rooms, and could instead put their time to more effective use performing preventive maintenance.



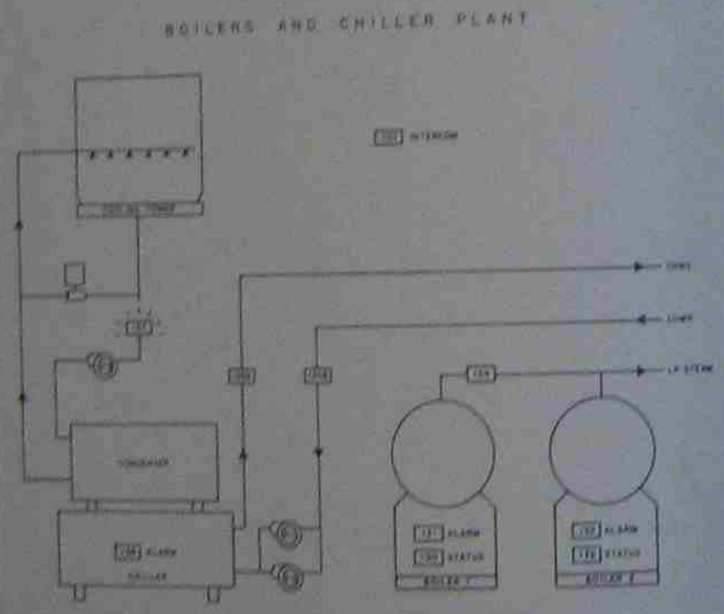
Centralized Control and Monitoring Panel

Figure 1.2



Typical Building Floor Plan

Figure 1.3a



Typical Boiler and Chiller Plant

Figure 1.3b

Centralized Multiplexing Systems

In the 1960s, multiplexing was introduced to the Building Automation System. Multiplexing was a switching technology similar to that used by the telephone companies. Remote switching panels were strategically located throughout a building, and served as junction panels for temperature sensors, control set point adjustment, fan and pump start/stop wiring, etc.. These panels were connected to a central console via a multi-conductor cable. Enhancements included a slide projector and projection screen built into the console. A typical centralized multiplexing system is shown in Figure 1.4.

The projector slides could display building floor layouts; piping schematics; or heating, ventilating and air-conditioning system layouts. They could also indicate temperature sensor locations, fan and pump start/stop locations, and other pertinent data. Examples of these slides are shown in Figure 1.5. Other accessories mounted in the console included a printer to record alarms and generate run status printouts, and a recorder to document multiple temperature, humidity, or pressure points.

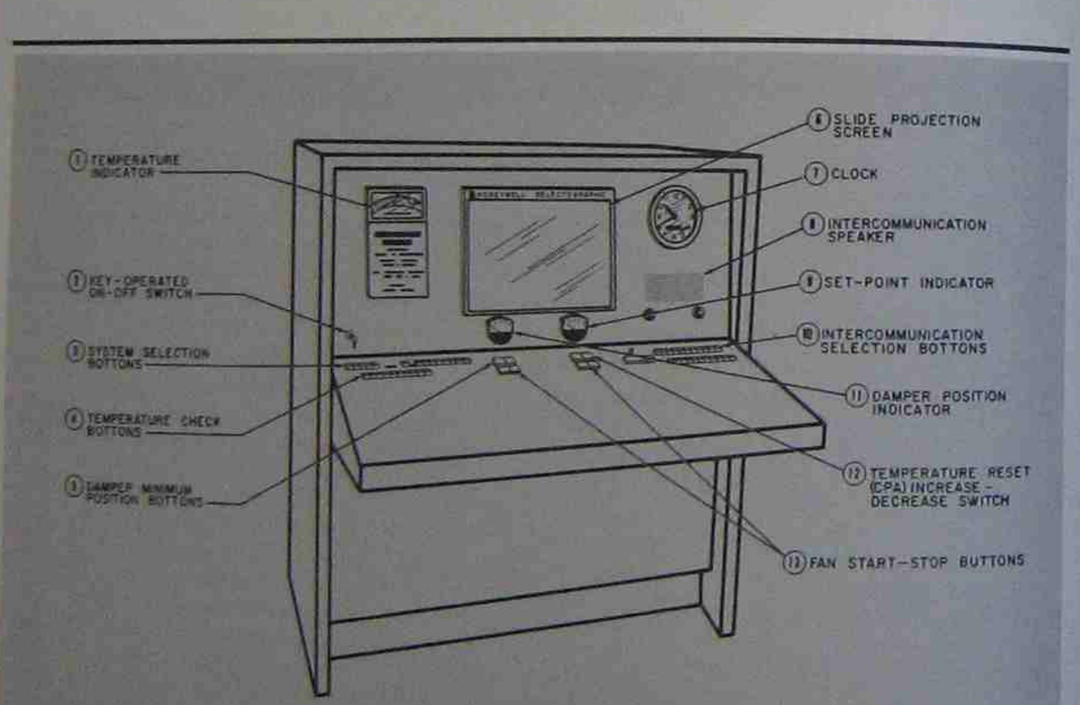
Computerized Systems

In the early 1970s the introduction of solid state electronics and digital transmission revolutionized the development of the Building Automation System. Computer technology using serial transmission was employed, thereby reducing the transmission loop wiring connecting the central system with remote junction panels from 80–96 conductors to a single pair. Solid state logic technology replaced noisy, electromechanical relays, and digital type sensors replaced thermocouples for temperature sensing. Data could be transmitted over transmission loop wiring at speeds up to 50 kilobits per second. The central processing unit had memory storage capability for alarm limits, time-based programming, and equipment status alarms. Digital readout of temperatures, equipment status and alarms, and printers for hard copy printout of data and alarms were featured. Operator's terminals with full color CRT displays were added.

During this period, new software packages were developed at a rapid rate. Fire and security alarm capabilities, patrol tour, card access, and lighting control software programs were included. Software programs could also be customized to the building owner's needs. These were the first "intelligent," software-driven, Building Automation Systems and the first step toward the integrated building.

The application of minicomputers to building automation and management was a major development. Increased memory capability and flexibility of system architecture made this a logical step. These computers, as shown in Figure 1.6, had the ability to perform all building automation requirements as well as generate numerous management reports. They could be installed with multiple CRT's, operator's terminals, and printers. Full English language printouts and multi-colored video displays were common. Although this technology was considered state-of-the-art, it was necessary to adapt general purpose computer software to building automation strategies. Hardware was expensive and operating personnel required a high level of training. Consequently, these systems found their application primarily in large building complexes where high paybacks on energy and manpower savings could be realized.

When the energy crisis developed in the late 1970s, the need for energy conservation in buildings became imperative. Many new programs and strategies were developed to save energy through more efficient operation of energy-consuming systems in buildings. Terms such as: *optimum start-stop*, *duty cycle*, *chiller optimization*, *reheat reduction*, and *load shedding* became common amongst building design and operating engineers. All of these programs were included as standard software offerings with computerized Building Automation Systems. The major automatic temperature control manufacturers embarked on development programs to enhance and expand their systems to incorporate the concepts of building and energy management into one system. A major breakthrough in cost, flexibility, and capability took place with the advent of the personal computer (PC). These systems provided a memory capacity far greater than that of any of their predecessors. They were also user-friendly, providing menu-driven selection of system graphics and points, English language descriptors and action messages, status and historical logs. PC's also make a wealth of third party software available to building operations people. Their features include: word processing, spreadsheets, maintenance management, energy audits, and bar charting. Dynamic system graphic displays provide the operator increased detail of system status and alarm condition at a glance. Programming and reprogramming of



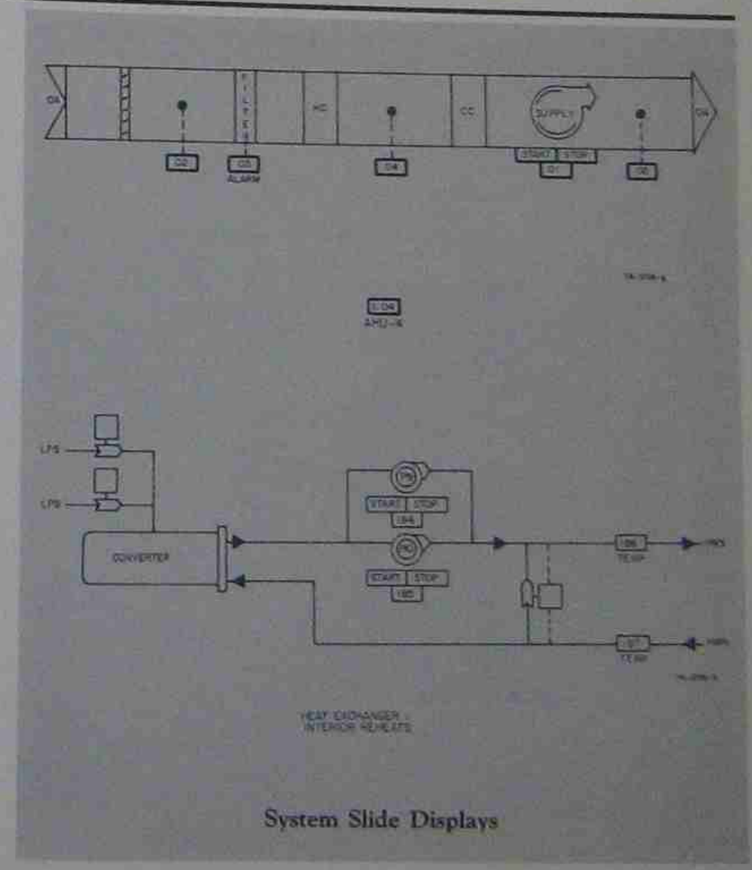
Centralized Multiplexing System

Figure 1.4

building functions can be performed by operators with little or no prior knowledge or training in computer operations. Hardware has also reached new levels of reliability and performance at reduced cost. Hard disk and diskette-drives with enhanced memory capacity, and high resolution color graphic monitors with mouse-driven pointers are featured by most system manufacturers. A great variety of high speed English language printers are also available.

Distributed Processing Systems

The introduction of the PC to the Building Automation Systems marketplace triggered the development of distributed processing systems through Direct Digital Control (DDC). Previously, the central computer was primarily an automation and energy management system with monitoring capability. The local pneumatic or electric control system provided all control functions. The remote panels, which were connected to the central computer via a two-wire transmission loop, served essentially as junction boxes for sensors and equipment control relays. The panels had no "intelligence," or automatic control capability.



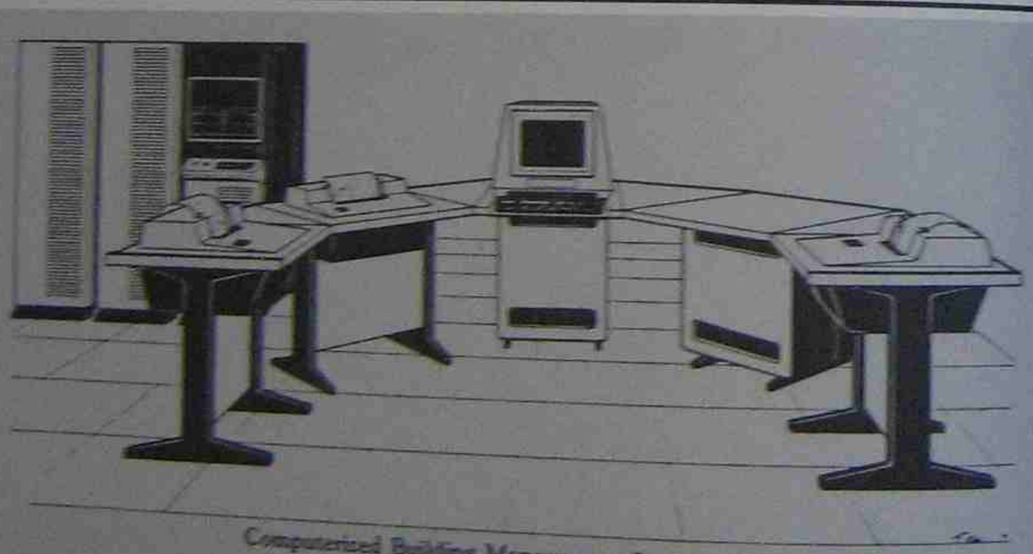
System Slide Displays

Figure 1.5

Microprocessor-based control technology, developed in the early 1960s, gave birth to "intelligent," remote panels called direct digital control (DDC) controllers. These are software-driven controllers which contain heating, ventilating, and air-conditioning control strategies and functions formerly performed by pneumatic or electric control hardware. They also contain all energy management programs originally resident in the central computer. These DDC controllers are wired in parallel on a two-wire communications bus to the PC. The controllers communicate with one another and with the host PC over a communications bus. The host PC can now generate management reports from information supplied to it by the network of controllers. Program changes, set point adjustments, temperature readouts, off-normal alarms, and management reports take place at the host PC. The combination of the PC, communications bus, DDC controllers, and remote sensors and actuators make up the Building Automation System of the late 1980s. A layout of this type of system is shown in Figure 1.7.

Integrated Building Systems

Other building systems, such as lighting, fire alarm, security, and access control can be readily integrated into a Building Automation System. This integration can take two forms. First, the existing, or new stand-alone fire/security system can transmit redundant alarm or status information to the local DDC controller. The host PC can display alarm data, action messages, and if desired, take action through event-initiated programs. This form of integration is usually applied to buildings where the existing fire or security system is functional.



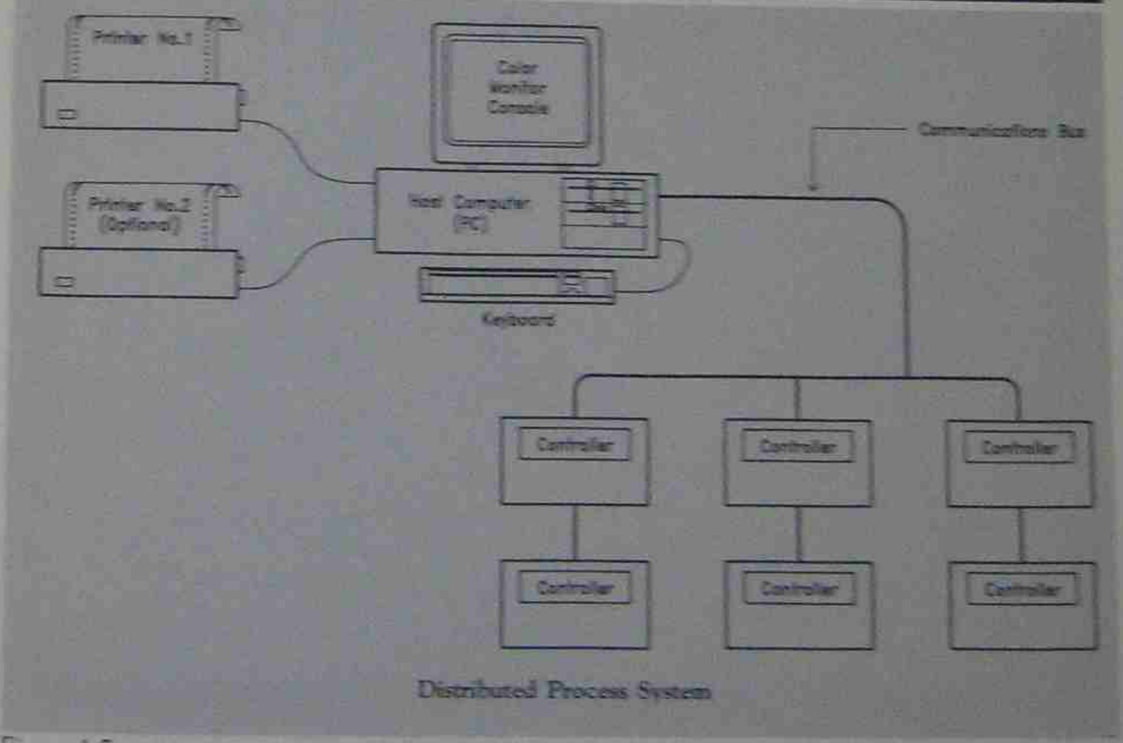
Computerized Building Management System

Figure 1.6

Under a total integrated system, the host PC directly serves all of the building systems over communications buses. The fire security controllers can stand alone and function effectively even if the communications bus is severed or the host PC fails. Software integration and sharing of information by all controllers (HVAC, lighting, fire, security) provide a truly comprehensive mode of building control. A layout of an integrated system is shown in Figure 1.8.

Future Trends and Concepts

The Building Automation System is a tool to be used for more effective and efficient management of building operating systems. These BAS's can create optimum environmental conditions in a building while consuming minimum energy. Lighting control, fire and security protection can also be integrated into the system. The future will see continued developments in distributed processing, with the emphasis on networking systems, to facilitate communications between controllers. Systems will become even more user-friendly, with improved dynamic graphics, and window techniques where an operator can observe operations simultaneously. Software programs to



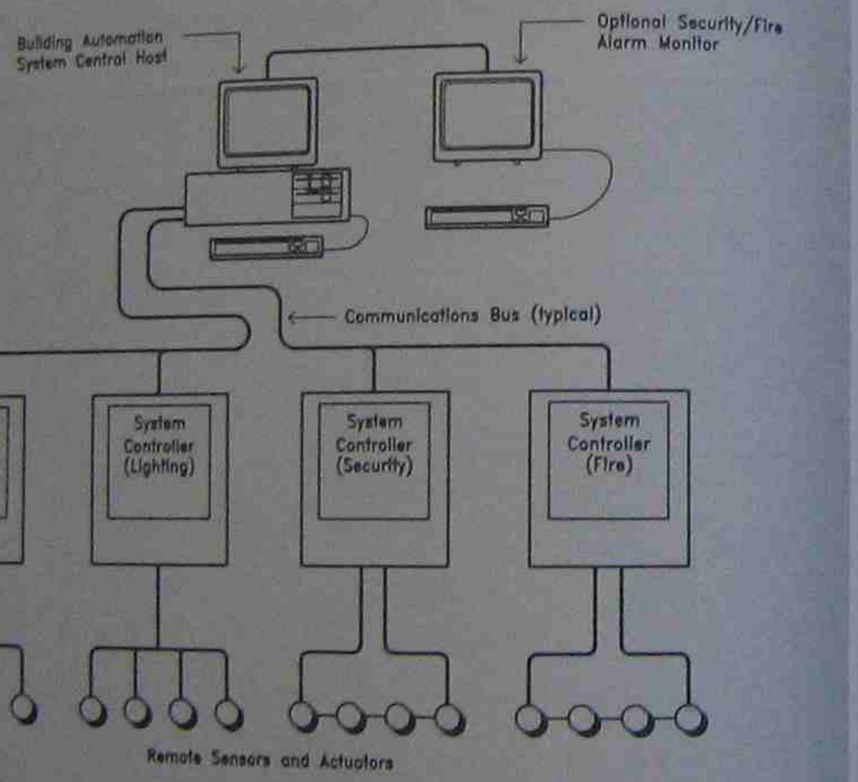
Distributed Process System

Figure 1.7

generate dynamic management reports and historical equipment information will be continually improved. This will allow building owners to constantly monitor the efficiency of various building systems. Software programs will also be developed to provide a history, on a year-by-year basis, of energy consumption in a building by building system or by floor or tenant area.

Pneumatic and electric control systems in older buildings will eventually be replaced with DDC systems. Even today, HVAC units are shipped from the manufacturer with their own attached DDC controllers. These controllers can be networked to a central PC which will control the entire building.

The concept of the intelligent building has been the subject of many technical papers in the past few years. The thought of integrating all building systems and subsystems into one comprehensive Building



Integrated Building System

Figure 1.8

Automation System is exciting. There is no question that a building could be managed and operated more effectively and efficiently if this could be accomplished.

Historically, the integration of all building systems and subsystems under one Building Automation System has not yet occurred. One major reason is that most of these systems are manufactured, installed, and serviced by different vendors. Therefore, HVAC control systems, lighting control, fire safety systems, security and access, telecommunications, office automation, information management, and many other building systems are not compatible with one another. Some companies have taken steps to integrate some of these systems, but there are numerous compatibility questions to be addressed before in-depth integration becomes a reality. Cost is another major barrier to the intelligent building concept. Manufacturers will be required to risk large capital investments to develop a common language, or standard or open protocol, which will allow diverse digital processors to communicate with one another. However, if the demand is great enough and building owners are truly interested in system compatibility and integration, then manufacturers will undoubtedly invest the capital.

In the near future, varying degrees of systems integration will continue. This book will explore some basic steps toward integration of building systems, their control and management.

Chapter Two

Distributed Process Systems

In the original computerized Building Automation Systems all automation, energy management and control processes were performed by the central, host computer. Local control of HVAC equipment was accomplished by traditional pneumatic or electric control system. The development of microelectronic technology and the microprocessor has had a major impact on the control of all building systems, including HVAC, lighting, and life safety. These chip-sized digital computers have become comprehensive controllers and have replaced the conventional pneumatic and electric control systems. They are reliable, flexible, and provide an accuracy of control previously unachievable by traditional control systems. The processes formerly performed by the central computer are now distributed to these intelligent, microprocessor-based controllers. These include energy management programs, off-normal alarms, event-initiated programs, and time-based programs. Through a communications language, or protocol, the controllers (distributed processors) can "talk" to one another, or share data transmitted over a communications bus from a central host computer.

The communication bus can be connected to a central host computer (PC) shown in Figure 2.1. From this central computer, set points can be changed, programs revised, alarms received and documented, and management reports generated. If there is no central computer, the controllers can operate as stand-alone control systems.

Direct Digital Control

Conventional pneumatic and electric control systems consist primarily of sensors, controllers, and actuators. The sensor basically senses or measures the controlled variable (temperature, humidity, pressure, flow). The controller receives a signal from the sensor and compares this data to its set point. It then operates the actuator (damper actuator, valve actuator, pneumatic electric switch) to compensate for the disparity between set point and actual control point. This controller/actuator team can work in one of two ways: it can develop a modulating or proportioning action, which means that the actuator can assume any position in its travel, proportional to the deviation between set point and control point; or, the action can be two-position, which means that the actuator will assume one of two positions (on-off, open-closed) on a preset deviation between set point and

control point. This sensor/controller/actuator arrangement is called a control loop (Figure 2.2).

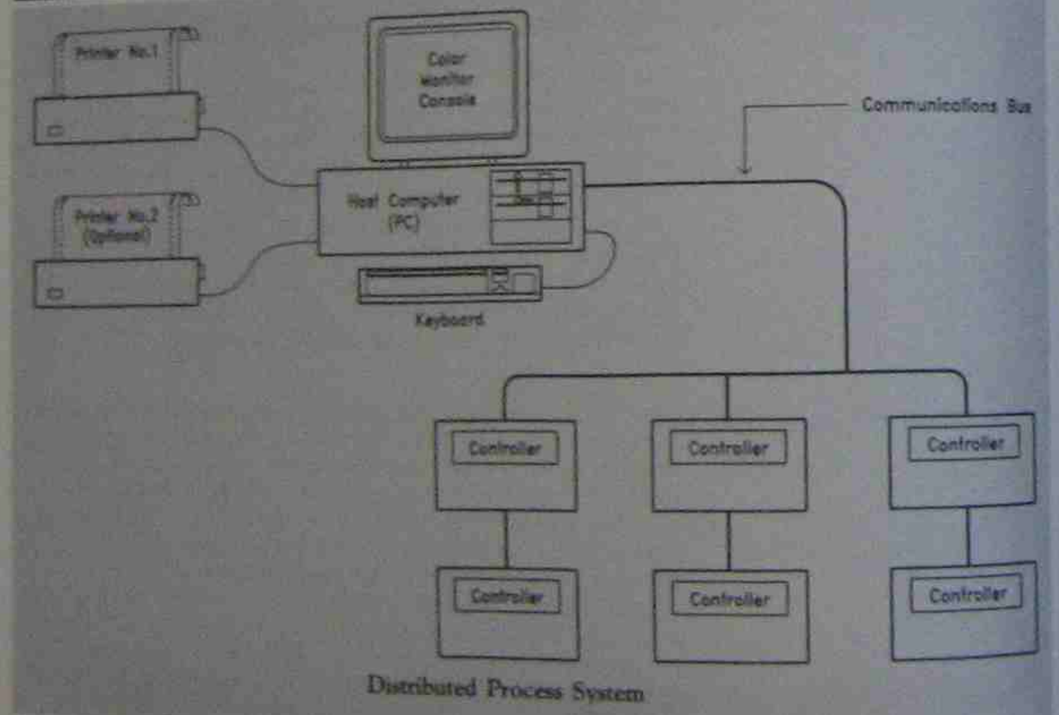
In an HVAC system, these control loops occur frequently. Dampers may be controlled in a modulating or two-position mode; chilled water and hot water valves may be modulated; direct expansion cooling may be cycled in a two-position manner; VAV boxes may use both modes of control.

The controller in a Direct Digital Control (DDC) system is a digital computer. Based on the information it receives from a sensor or a switch, the controller can take any number of programmed actions, within the framework of various software programs. All of the control loops mentioned above are incorporated in the controller's software capabilities, as are many other control strategies and programs.

DDC offers numerous benefits over pneumatic and electric control systems. While electric and pneumatic control devices require periodic adjustment, calibration, and maintenance, digital computers have no moving parts and therefore require minimum maintenance. Once the sensors are in place, control loops can be changed or made interactive with no new wiring, piping, or devices. A centrally located PC can be linked to the DDC controllers, thereby providing the operator access to temperatures, set points, alarms, energy management programs, and other pertinent information. Accuracy of control is a feature of DDC control that is very difficult, if not impossible, to match with conventional controls.

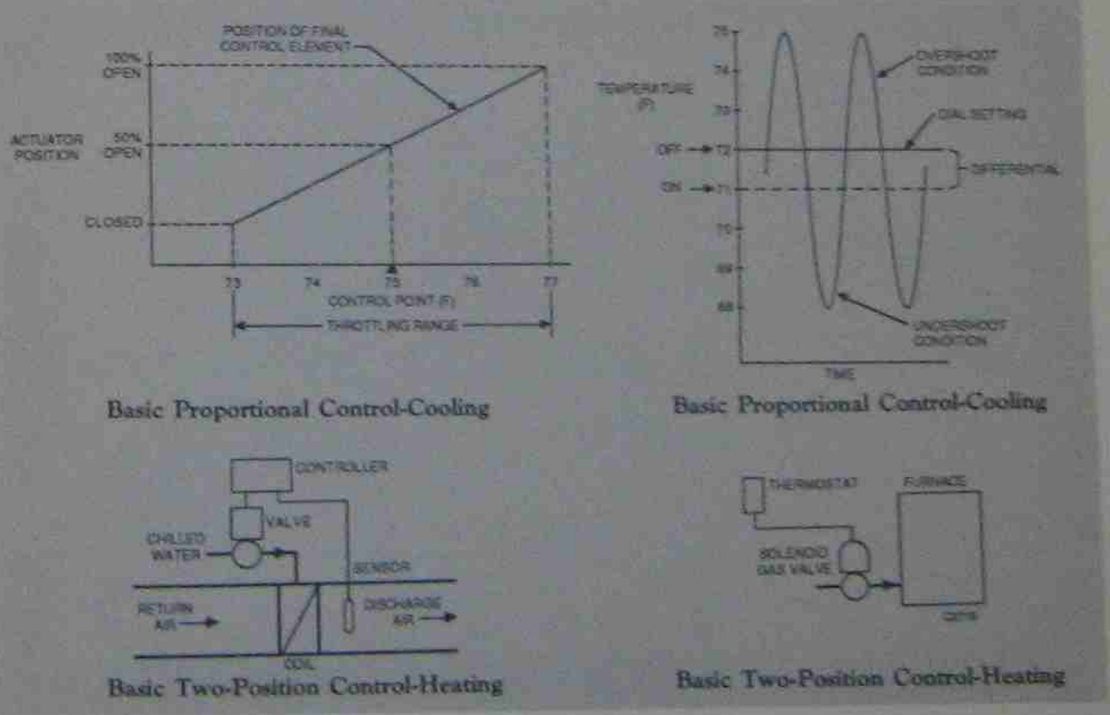
Modulating or proportional control has an inherent problem called *offset*. Offset is defined as a sustained deviation between the set point of a control and the actual control point. With DDC control, the offset can be eliminated entirely through software programs, a difficult feat with pneumatic and electric controls.

DDC controllers have input connections to remote input devices, such as sensors or contact closure devices (switches). They also have output connections to controlled devices, such as valve actuators, damper actuators, fans, pumps, etc. Input and output devices can be analog or digital. An analog input device could be a temperature, pressure, or humidity sensor which sends a continuously varying input signal to the DDC controller. A digital input is a two-posinon (0 and 1), on-off



Distributed Process System

Figure 2.1



Basic Proportional Control-Cooling

Basic Proportional Control-Cooling

Basic Two-Position Control-Heating

Basic Two-Position Control-Heating

Figure 2.2

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signal, such as a switch action. An analog output is a variable output which could be 0–10 volts, 4–20 MA, or 3–13 pounds for pneumatically-controlled actuators. A digital output is a two-mode output which is either on or off. This switching action could control a fan, pump, or lights.

Ventilation Control

DDC control loops used for ventilation purposes or atmospheric cooling can provide the following control sequences:

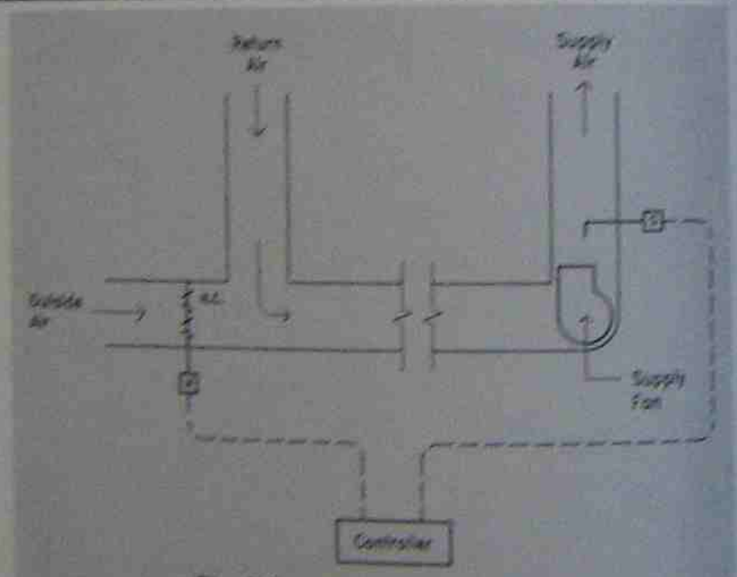
- Fixed quantity of outdoor air
- Mixed air control
- Economizer control of mixed air

Fixed Quantity of Outdoor Air

When the HVAC unit fan is energized, the outdoor air damper will go to the full open position. When the fan is de-energized, the damper will go to the closed position (Figure 2.3).

Mixed Air Control

When the unit fans are energized, the damper control system will also be energized. A temperature sensor located in the mixed air will modulate the outdoor and return air dampers to maintain mixed air temperature. A minimum outdoor air damper position can be preset to provide minimum ventilation. When the unit fans are de-energized, the outdoor air damper will fully close and the return air damper will fully open. If an exhaust damper is installed, it will modulate in unison with the outdoor air damper (Figure 2.4).



Fixed Quantity of Outdoor Air

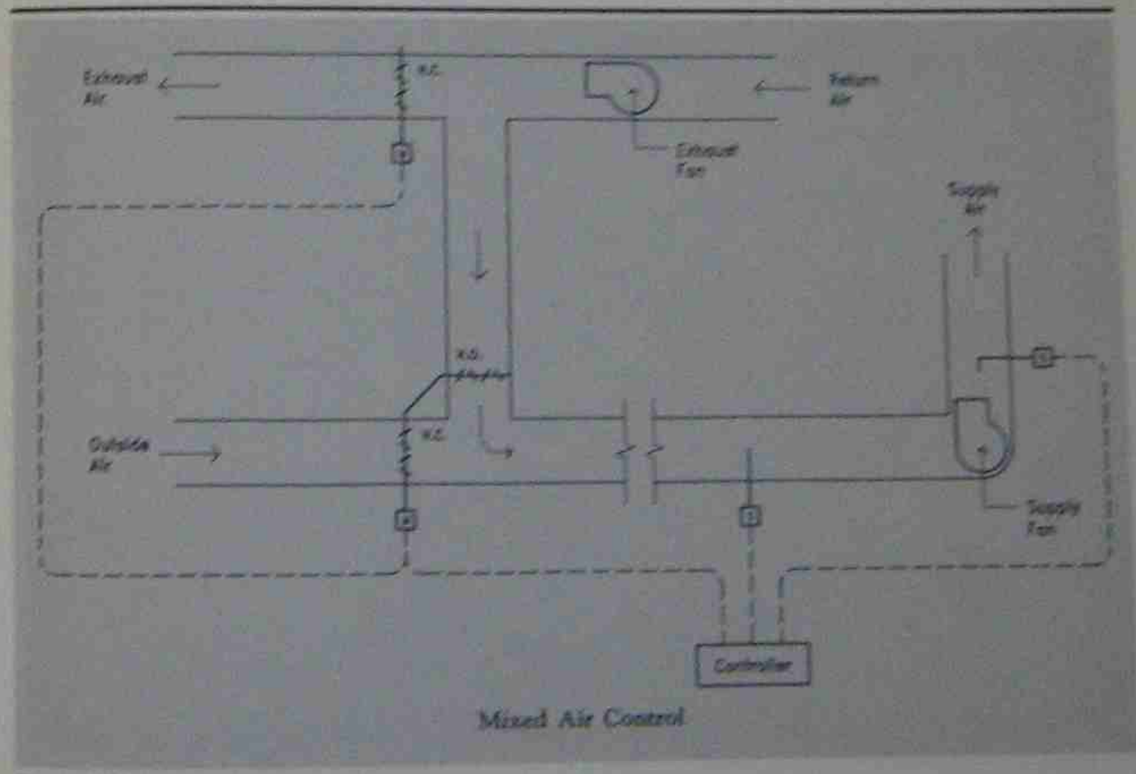
Figure 2.3

Economizer Control of Mixed Air

When the unit fans are energized, the damper control system will also be energized. A mixed air sensor will modulate the outdoor and return air dampers to maintain mixed air temperature. A minimum outdoor air damper position can be preset to provide minimum ventilation. An outdoor air sensor will return the fresh air damper to minimum position, when outdoor air temperature exceeds a preset level. When the unit fans are de-energized, the outdoor air damper will fully close and the return air damper will fully open. If an exhaust damper is installed, it will modulate in unison with the outdoor air damper. If it is desirable to reset the mixed air temperature upward as outdoor air temperature decreases, this can be accomplished through software programming. The outdoor air and mixed air sensors are already in place to accomplish this (Figure 2.5).

Heating Control

Numerous DDC control loops and strategies are available for heating applications. Software programs are available for reset, sequencing, discharge, or space control.



Mixed Air Control

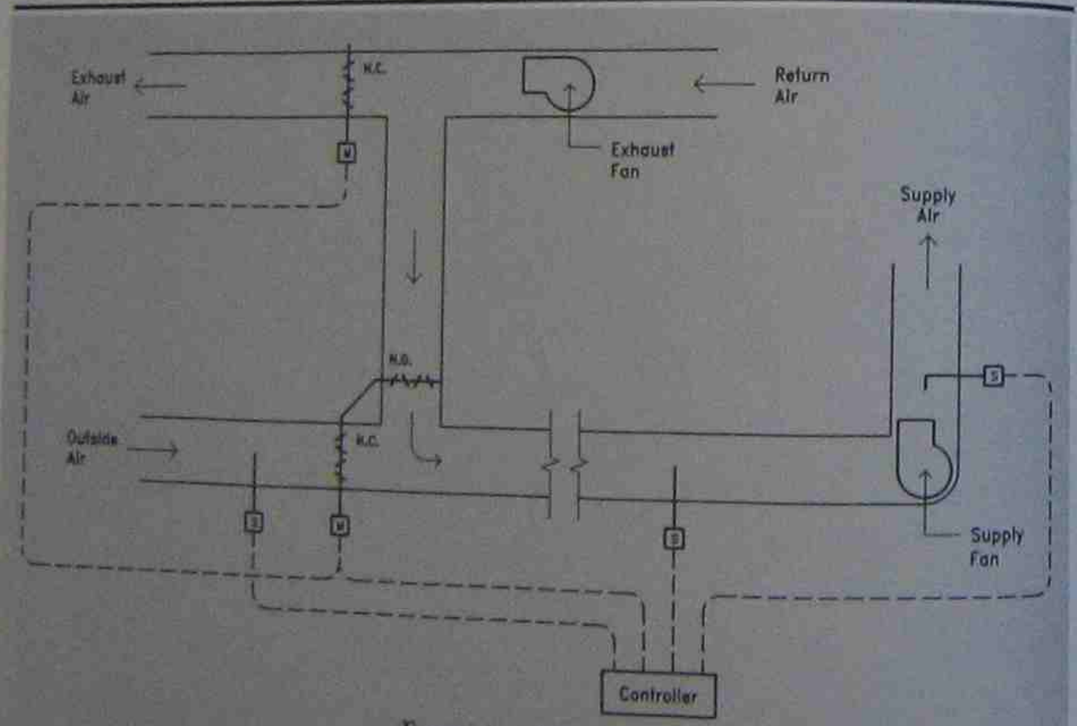
Figure 2.4

Constant Temperature Hot Water Control (Boiler)

A sensor installed in the system supply water will modulate a three-way mixing valve to maintain its set point. The valve will mix boiler water with return water. This mixture is then pumped to the system. If the system has two-way control valves on all space heating units (radiation or heating coils), provision should be made for a differential bypass valve and sensor across the pump. As the two-way control valves close, the pressure difference across the pump will increase. The differential pressure sensor will sense this increase, and through the DDC controller, modulate the bypass valve toward the open position (Figure 2.6).

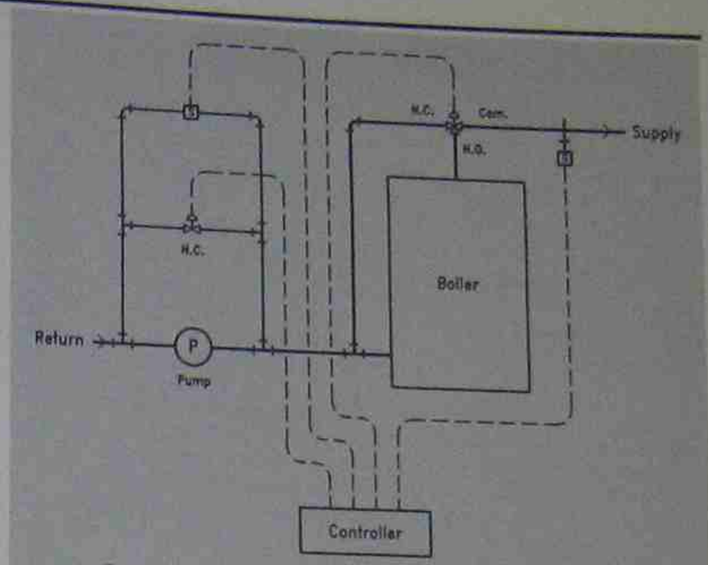
Constant Temperature Hot Water Control (Heat Exchanger)

The control loop for a heat exchanger is identical to that given above for boilers except that the three-way mixing valve will be replaced by a normally closed, two-way valve in the steam supply to the heat exchanger (Figure 2.7).



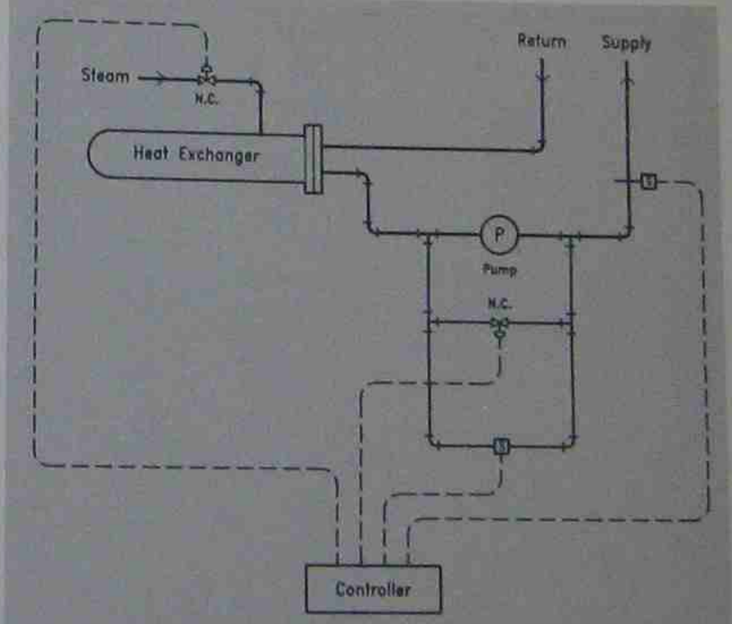
Economizer Control

Figure 2.5



Constant Temperature Hot Water Control (Boiler)

Figure 2.6



Constant Temperature Hot Water Control (Heat Exchanger)

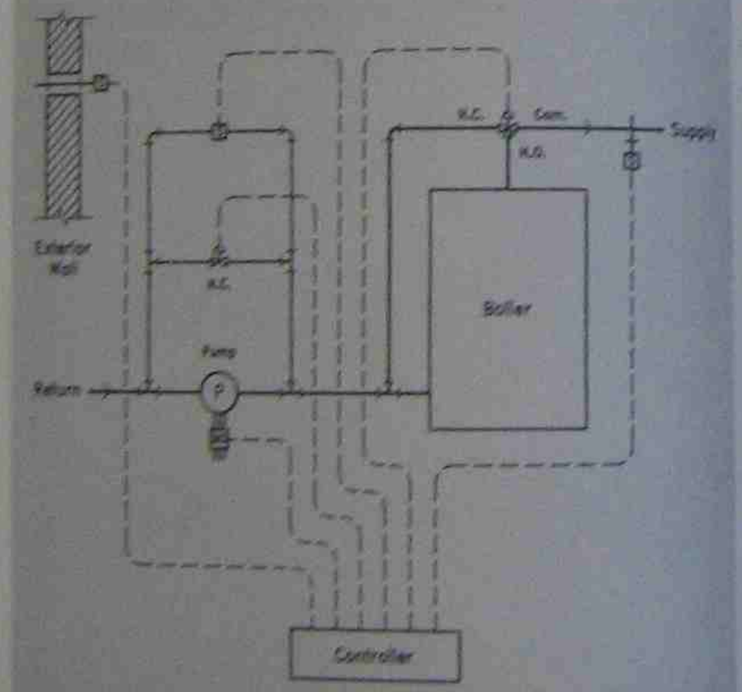
Figure 2.7

Hot Water Reset Control (Boiler)

The addition of an outdoor air sensor to the control loop described above for *constant temperature hot water (boiler)* will, with the help of an appropriate software program, allow reset of the discharge water temperature as a function of outdoor air temperature. A digital output point wired from the DDC controller to the pump magnetic starter will provide a means of shutting down the pump at a predetermined outdoor air temperature, when heat is no longer required (Figure 2.8).

Hot Water Reset Control (Heat Exchanger)

The addition of an outdoor air sensor to the previously described control loop for *constant temperature hot water (heat exchanger)* will allow the reset of discharge water temperature as a function of outdoor air temperature. Again, a digital output point from the DDC controller to the pump magnetic starter will provide a means of shutting down the pump at a predetermined outdoor air temperature, when heat is no longer required (Figure 2.9).



Hot Water Reset Control (Boiler)

Figure 2.8

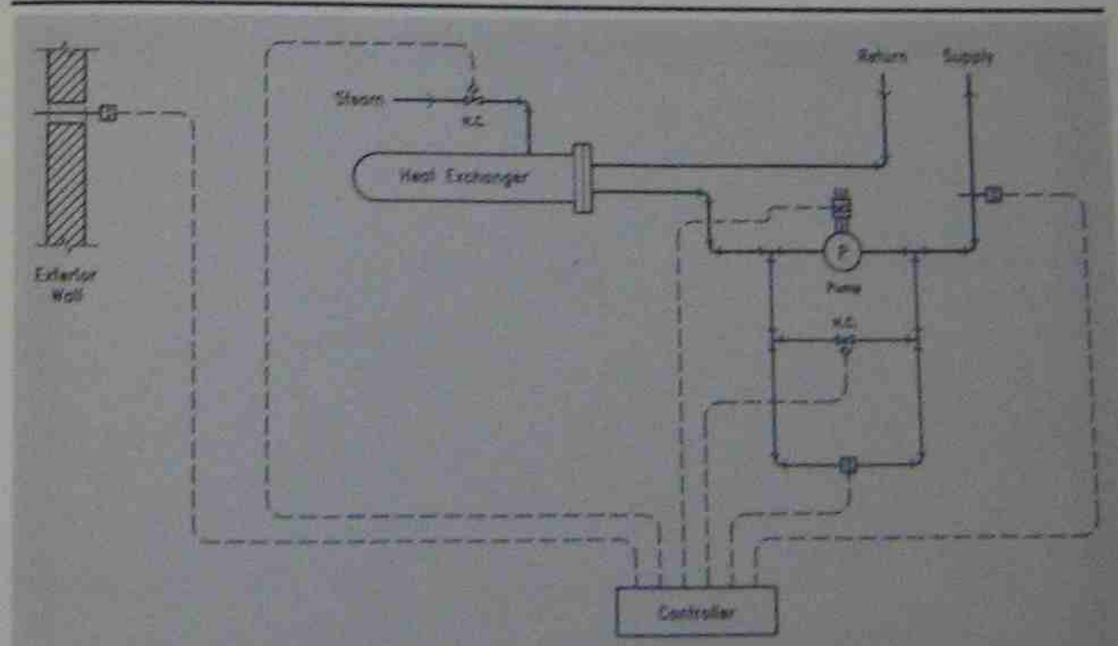
Discharge Air Control (HVAC) – Heating

A duct-mounted sensor on the discharge side of the heating coil will modulate a control valve in the steam or hot water supply to the heating coil in order to maintain its set point. If there is any possibility that air entering the coil could be below 32°F, a low temperature safety controller should be installed on the discharge side of the heating coil. Prompted by the proper software program, the controller would initiate corrective action if a potential coil freeze-up situation should occur.

If electric heat is utilized, the same control loop is used. However, the analog output to a modulating control valve is replaced with multiple digital outputs to control stages of electric heat. If it is desirable to modulate the electric heat through a SCR (Silicon Controlled Rectifier) control, the analog output may be used in a manner similar to the modulating valve application (Figure 2.10).

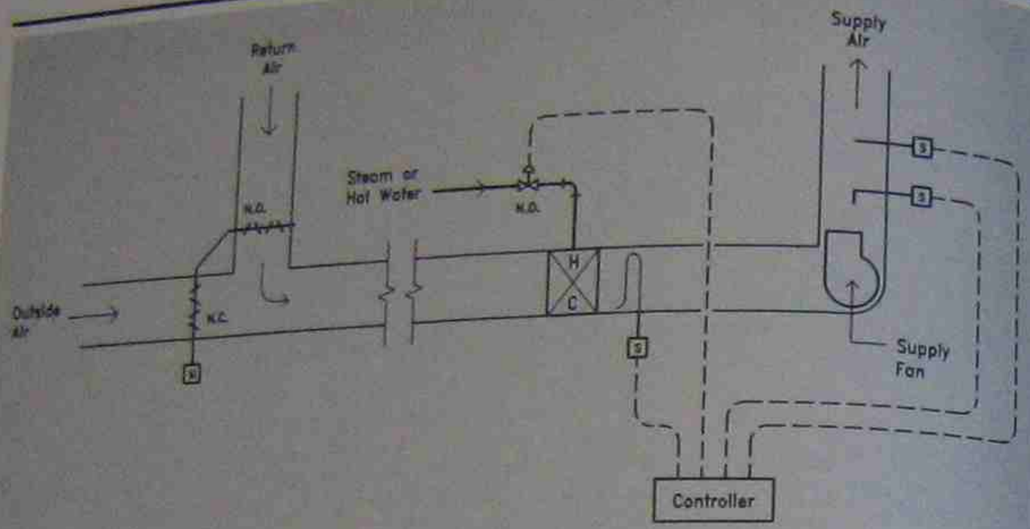
Discharge Air Reset Control (HVAC) – Heating

Adding an outdoor air temperature sensor to any of the control loops described above will provide reset capability. Reset programs are available in the DDC controller to raise or lower the setting of the discharge air sensor to compensate for changes in outdoor air temperature (Figure 2.11).



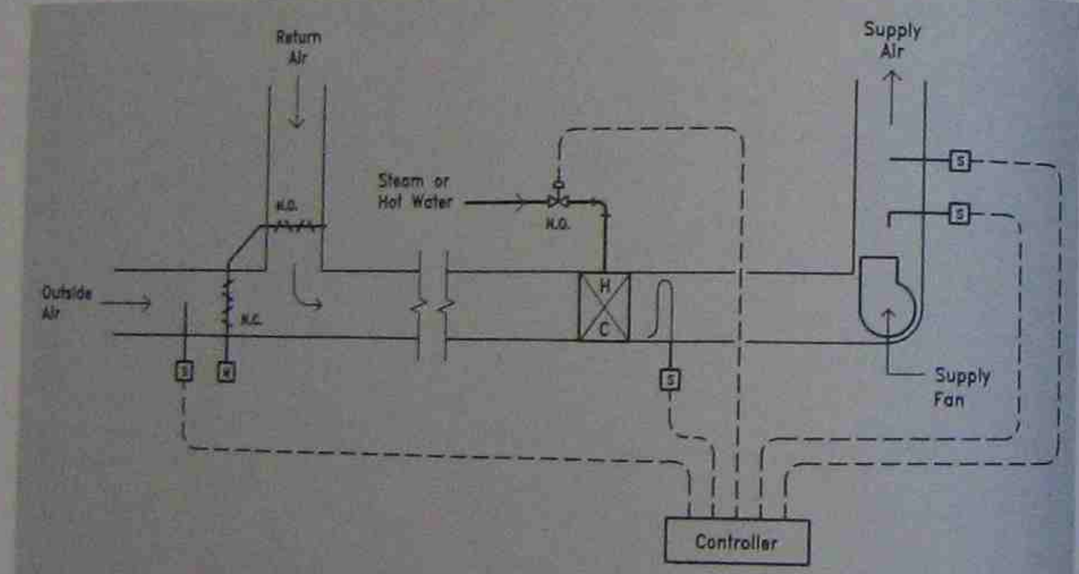
Hot Water Reset Control (Heat Exchanger)

Figure 2.9



Discharge Air Control – Heating

Figure 2.10



Discharge Air Reset Control – Heating

Figure 2.11

Space Temperature Control (HVAC) – Heating

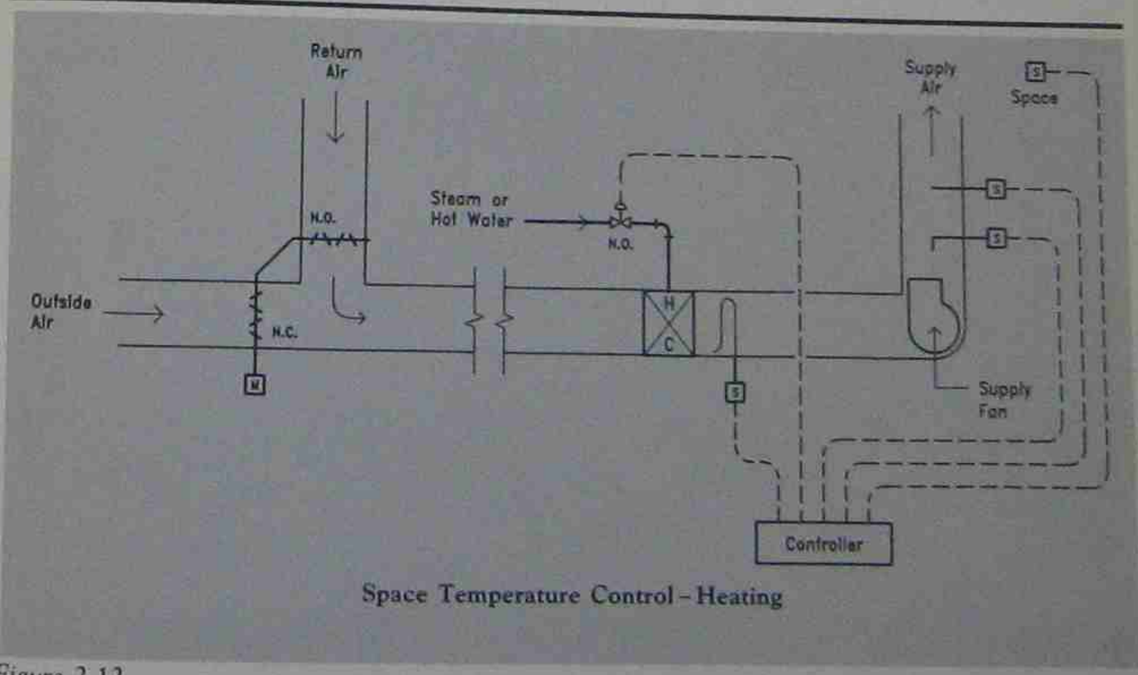
A space temperature sensor may be installed to act as a primary controller in the applications described above. This space sensor could control the heat output of the heating coil or electric heating elements directly, with the discharge air sensor acting as a low limit. The space sensor may also reset the discharge air sensor as a function of space temperature (Figure 2.12).

Cooling/Dehumidification Control

Software programs for the control of cooling and dehumidification are a component of direct digital controllers. The following are some of the programs available to control these elements:

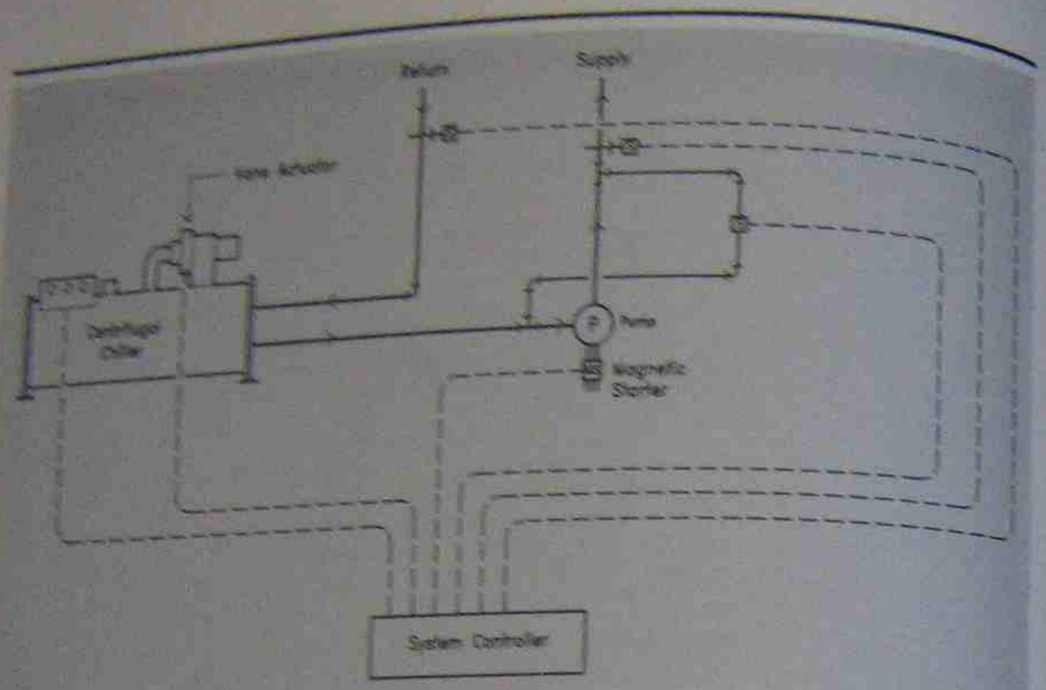
Chilled Water Control (Centrifugal/Reciprocating)

A sensor installed in the chiller water supply will maintain its set point by modulating an actuator which positions the inlet vanes on a centrifugal chiller. Control of these chillers can be enhanced by installing a sensor in the return water to reset the discharge water sensor set point. Under light load conditions, the discharge water temperature can be increased to reduce the load on the chiller (See Figure 2.13).

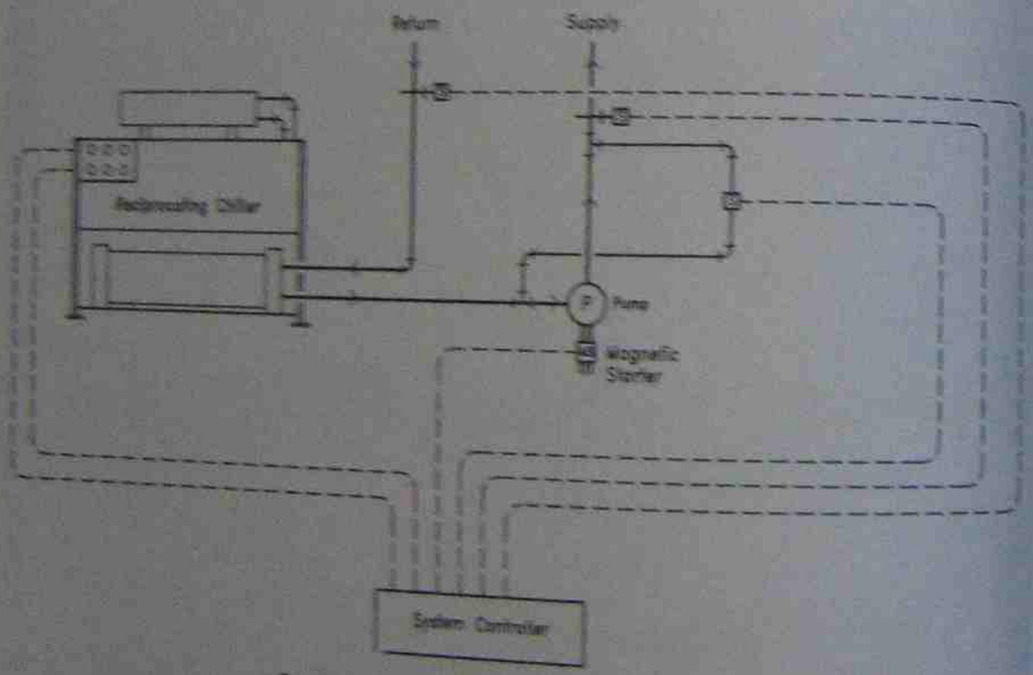


Space Temperature Control – Heating

Figure 2.12



Centrifugal Chiller Control



Reciprocating Chiller Control (2-Stage)

Figure 2.13

Reciprocating chillers require digital output control rather than analog output, as in the case of the centrifugal chillers. Reciprocating chillers operate in two position stages by sequencing multiple compressors, or unloaders, as the load changes. Here again, a return water sensor can be utilized to reset the discharge water sensor as the load changes (See Figure 2.13).

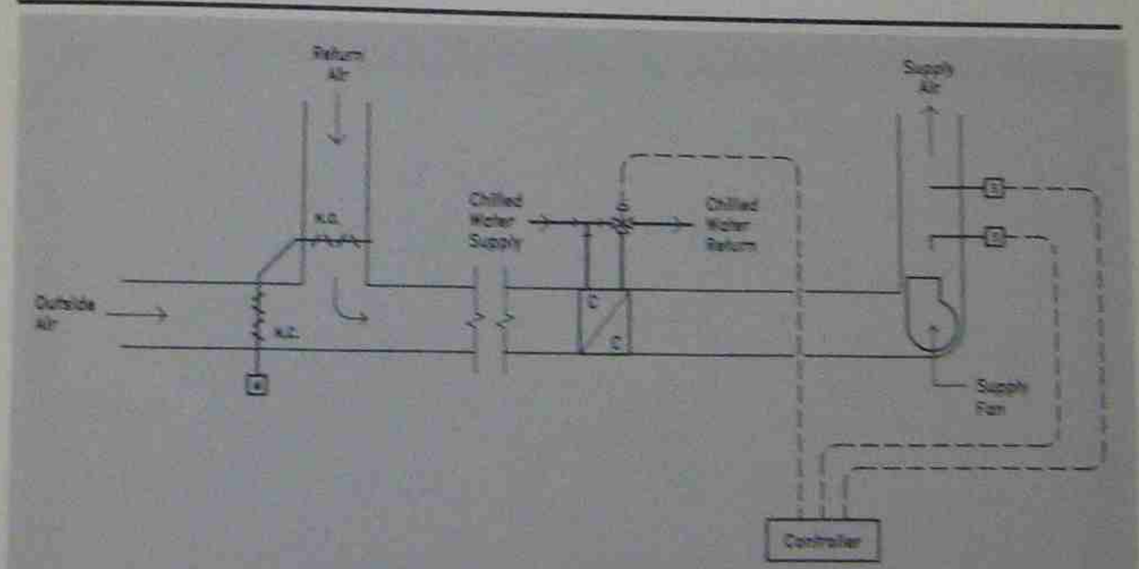
Discharge Air Control (HVAC) – Cooling

A duct-mounted sensor on the discharge side of the chilled water coil will modulate a control valve in the chilled water supply to the coil, to maintain its set point. The control valve may be a three-way or two-way type. In either case, it will require an analog output from the DDC controller. (Figure 2.14).

If direct expansion (DX) cooling is used, discharge air control is not recommended. This would result in short cycling of the compressor due to the large temperature drop when the system compressor is energized. The best application would be control from a space or a return air temperature sensor.

Discharge Air Reset Control (HVAC) – Cooling

Adding an outdoor air temperature sensor to the control loops described above will provide reset capability. Reset programs are available in the DDC controller to vary the setting of the discharge air sensor to compensate for fluctuations in outdoor air temperature.



Discharge Air Control – Cooling

Figure 2.14

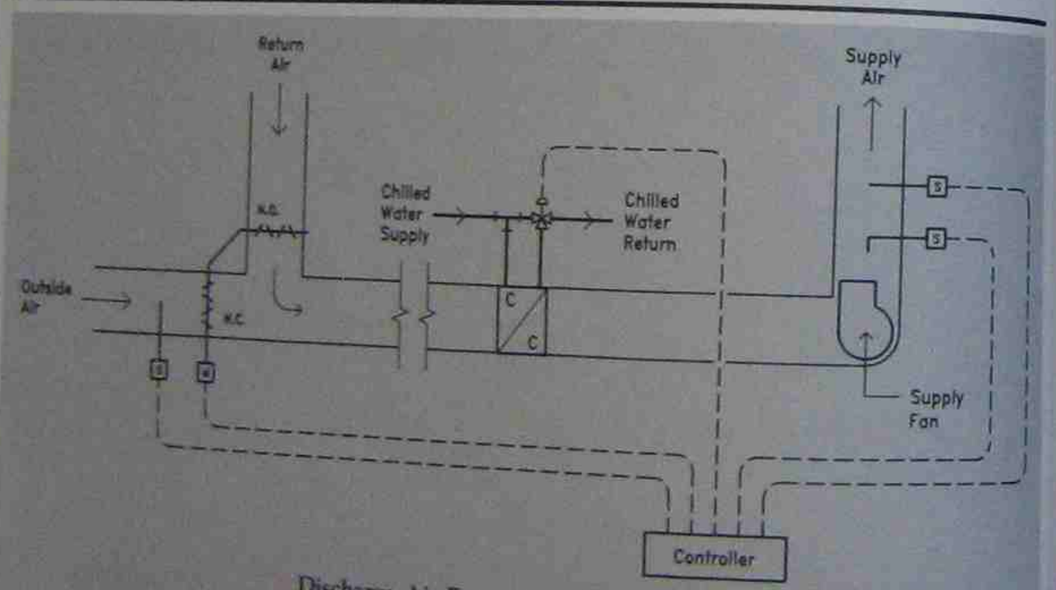
A space temperature sensor or multiple sensors may also be used to reset the discharge sensor set point. This will vary the discharge air temperature as a function of load in the space. In the case of multiple sensors, the area with the greatest cooling requirements will reset the discharge sensor. Averaging of sensor readings is not recommended *(Figure 2.15)*.

Space Temperature Control – Cooling

A space temperature sensor may replace the discharge sensor to control the chilled water control valve. If direct expansion cooling is used, a space temperature sensor may be applied to cycle the compressor through a digital output point *(Figure 2.16)*.

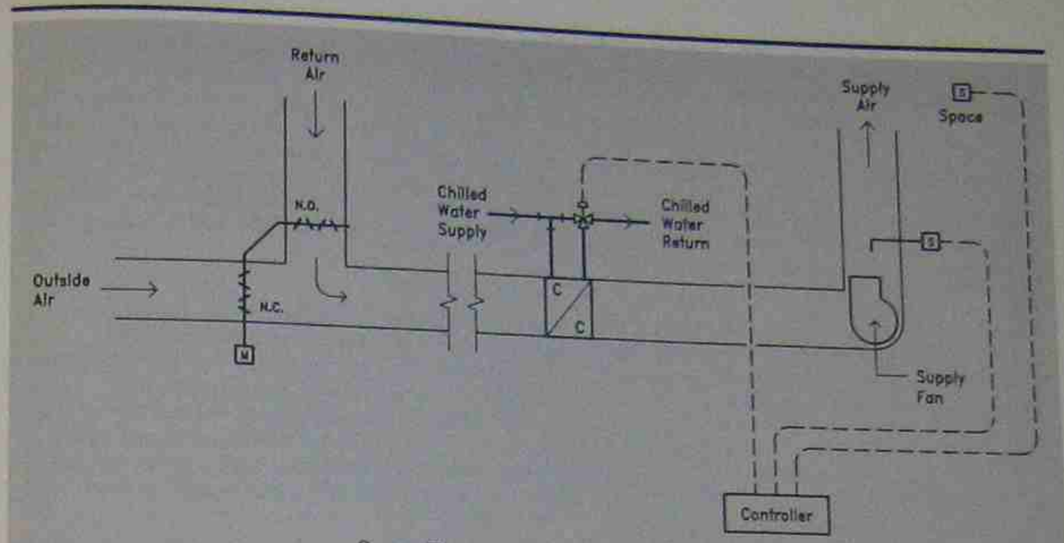
Dehumidification Control

Dehumidification can be accomplished by the use of a chilled water coil or a direct expansion coil. In the case of the chilled water coil, a space humidity sensor will modulate, or "two position" a control valve in the chilled water supply. A reheat coil should be provided to reheat the air after dehumidification. The space temperature sensor which controls the reheat coil may also modulate the chilled water valve for space cooling requirements. If direct expansion dehumidification is used, the space humidity sensor will cycle the compressor in a two-position manner. Here again, some method of reheat should be provided to maintain space comfort conditions *(See Figure 2.17)*.



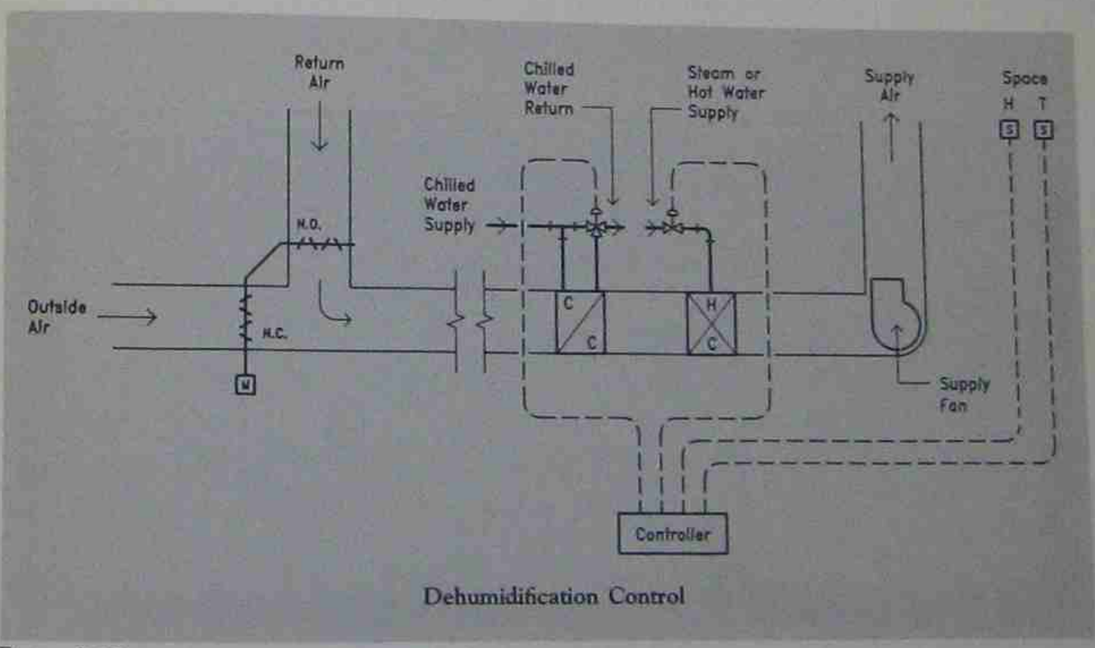
Discharge Air Reset Control – Cooling

Figure 2.15



Space Temperature Control – Cooling

Figure 2.16



Dehumidification Control

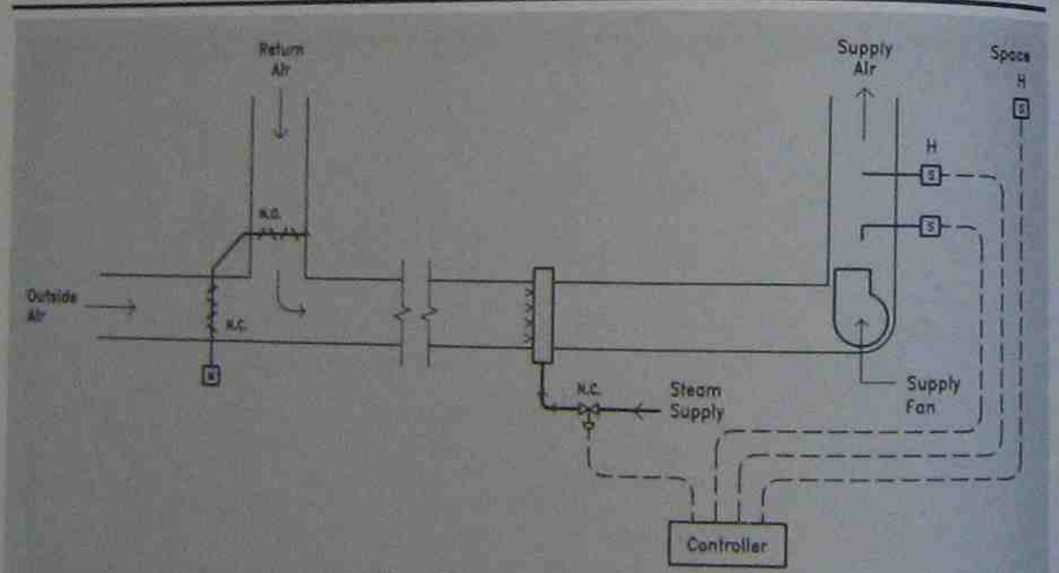
Figure 2.17

Humidification Control

A space humidity sensor maintains space relative humidity by modulating the valve on a steam humidifier. A high limit, duct-mounted, humidity sensor located downstream of the humidifier will override the space sensor and modulate the steam valve if relative humidity in the discharge duct reaches its set point. Some humidifiers require a two-position rather than modulating control mode. In this case, a digital output point from the DDC controller is used. When the unit supply fan is de-energized, the humidifier will shut down (See Figure 2.18).

Heating/Cooling Sequencing

A single space temperature sensor, or duct-mounted, discharge air sensor may be used to control the heating coil valve and chilled water coil valve in sequence. As an energy savings feature, a deadband (or zero-energy band) may be programmed, using appropriate software, between the heating and cooling modes. During this deadband both valves are closed. Although this practice may widen the temperature swings within the space, these ranges could be limited to acceptable levels for comfort, with appreciable energy savings (See Figure 2.19).



Humidification Control

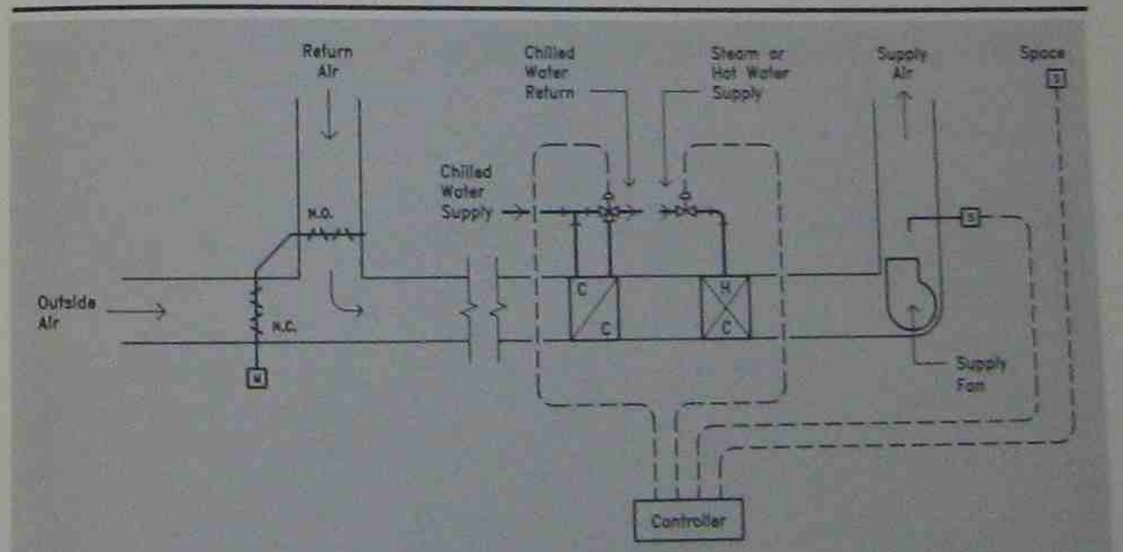
Figure 2.18

Humidification/Dehumidification Sequencing

A single space humidity sensor may be used to control the humidification and dehumidification process. When space relative humidity exceeds the setting of the humidity sensor, the cooling coil valve modulates open to provide dehumidification. When relative humidity falls below the space sensor set point, the humidifier steam valve modulates toward the open position, subject to the override action of the discharge high limit humidity sensor. As mentioned under *Dehumidification Control*, a reheat coil is necessary to maintain comfort conditions during dehumidification (See Figure 2.20).

Static Pressure Control

The control of static pressure inside a building, or in variable air volume system supply ducts, can be accomplished in two ways: (1) modulating fan inlet vane dampers or (2) variable speed drives. For static pressure control in variable air volume (VAV) systems, the static pressure sensor is located in the main supply duct to the terminal units. This sensor will maintain supply duct static pressure by modulating the system fan inlet vanes (See Figure 2.21), or by modulating fan speed, through a variable speed drive. Variable frequency drives provide excellent fan speed control, and most are designed for 3-15 pound, or 4-20 milliamp inputs, which fall within the scope of most DDC



Heating – Cooling Sequencing

Figure 2.19

controllers. For direct building static pressure control, the sensor is located in the space and is referenced to a location outside the building. Space static pressure is maintained by controlling return fan inlet vanes or by variable speed drive on the return fan.

Energy Management Programs – HVAC

In a distributed process system, the energy management programs formerly performed by the central computer, are now resident in the intelligent, microprocessor-based DDC controllers. The energy management programs described below are traditional, well-proven programs which have become standards in the industry. Most DDC systems also have the capability of custom-designed programs to operate HVAC systems in an energy efficient manner.

Duty Cycle Program

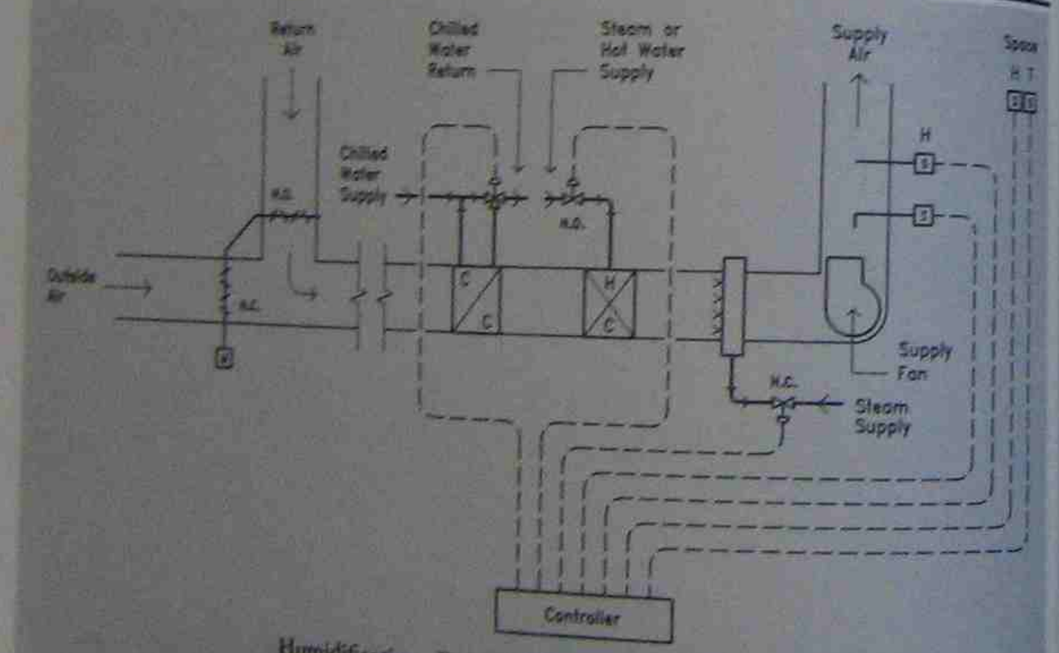
The purpose of a duty cycle program is to reduce energy consumption by periodically shutting down energy-consuming systems. Shutdown periods can be on a fixed cycle rate, or on a variable cycle rate, a choice that will depend on space and outdoor air temperature. An additional benefit of this program is its tendency to reduce electrical demand, if properly applied. Under the duty cycle program, an HVAC system is shut down for short periods of time and the space temperature is allowed to drift within limits that do not jeopardize comfort. During the shutdown period, no fan electrical energy is consumed, and ventilation air need not be heated or cooled, since the system is not operating, and the outdoor air damper is closed.

Fixed time duty cycling means that the HVAC system will be on for fixed periods of time, and off for fixed periods of time during the duty cycle period. Different areas of a building could have different cycling requirements due to internal loads, sun loads, or building construction. With space temperature compensated duty cycling, the "on" and "off" periods are varied according to feedback from a space temperature sensor. When space temperature is within programmed comfort limits, the "off" periods are extended and the "on" periods shortened. As space comfort limits are approached, the reverse will occur. This is clearly a more effective means of achieving maximum energy savings, while maintaining optimum comfort conditions, than fixed time duty cycling.

Existing HVAC systems that have space thermostats which cycle the fan and the heating/cooling source simultaneously are not good candidates on a return on investment basis for a duty cycle program, since duty cycling is already taking place. Figure 2.22 shows a typical duty cycle schedule.

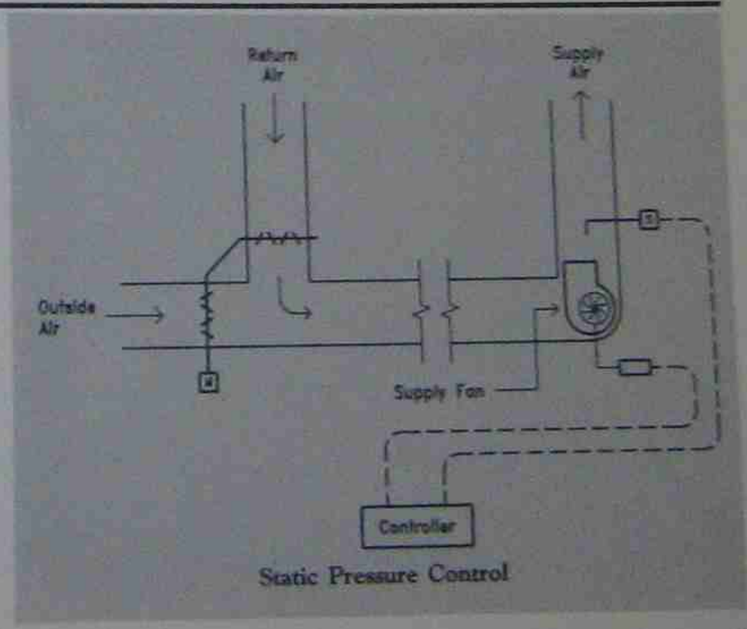
Power Demand Limiting Program

The power demand program controls electrical loads in buildings in order to eliminate demand peaks that result in costly demand charges. The controller monitors electrical demand, compares it with preprogrammed target limits, and sheds loads to limit peaks.



Humidification – Dehumidification Sequencing

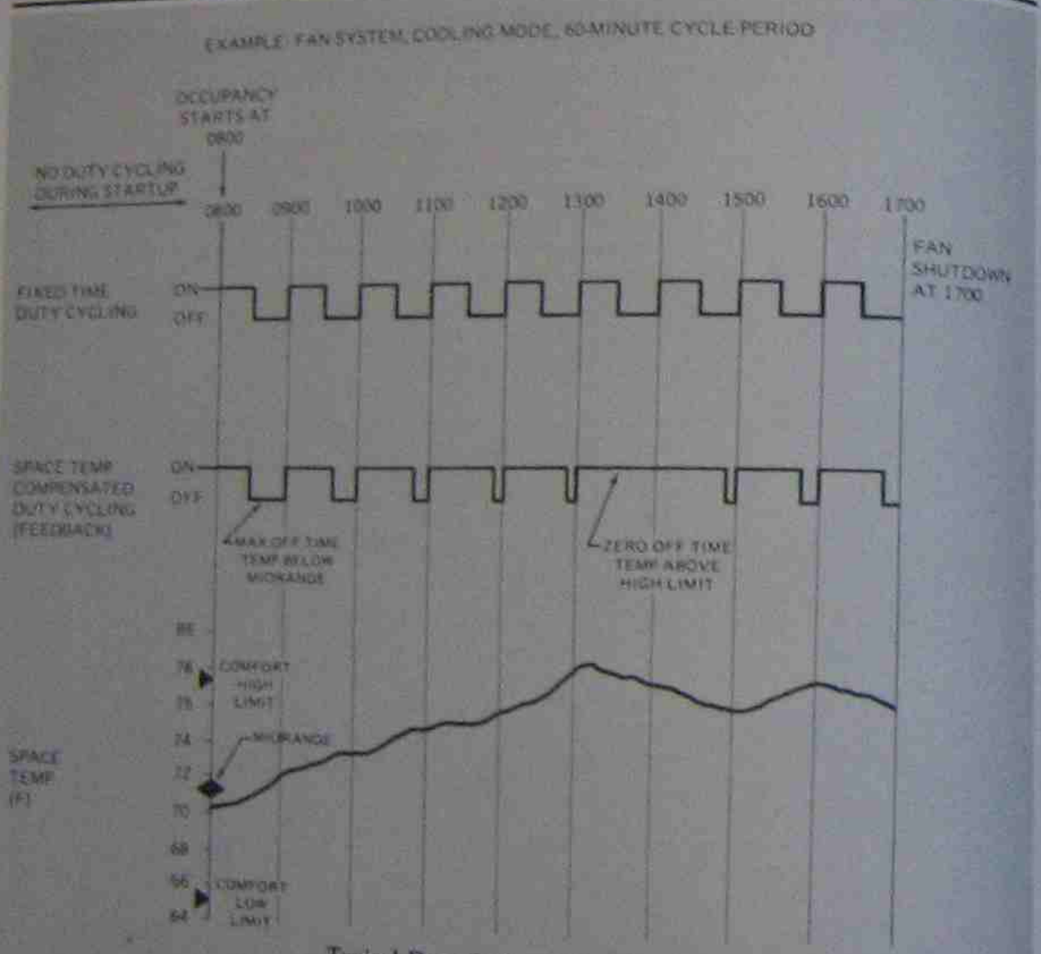
Figure 2.20



Static Pressure Control

Figure 2.21

The electrical loads in the building should be prioritized. As the building electrical demand approaches the preprogrammed limit, the lowest priority loads will be shed in sequence. Low priority loads are those that supply electric devices that the occupants can do without for short periods of time. If the demand continues to increase, the controller will begin to shed the second priority loads. If building demand continues to increase, an alarm may sound at the central computer, at which point the operator can manually shed loads from the terminal. Figure 2.23 gives an indication of how energy savings are achieved with this program.



Typical Duty Cycling Schedule

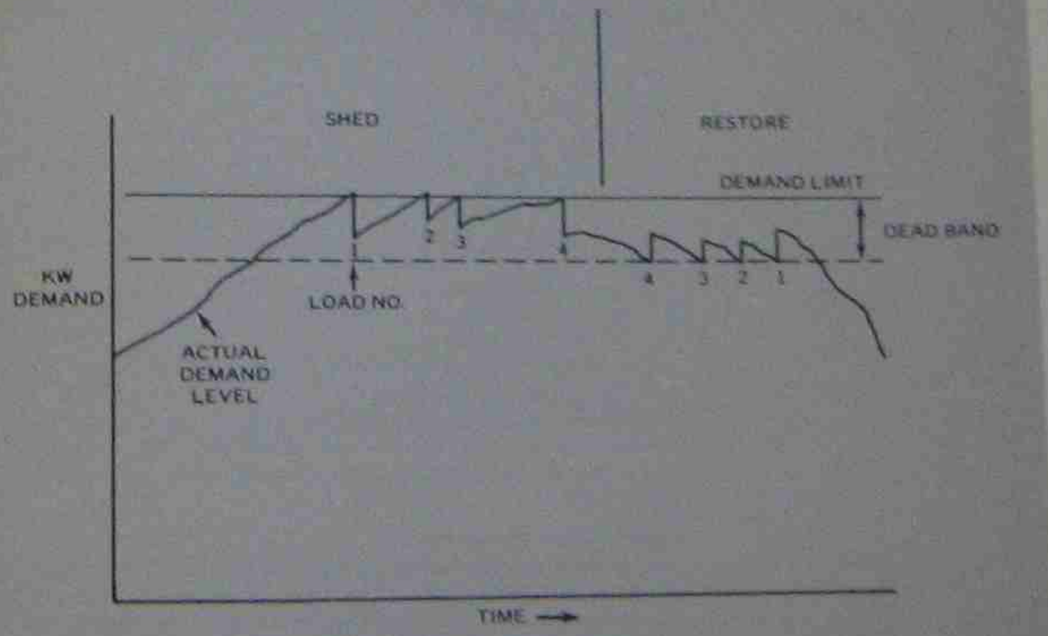
Figure 2.22

Time of Day Program

The Time of Day Program is basically a time clock function which provides for shutdown of energy-consuming loads based on time only. It can shut down boilers, chillers, or HVAC units at the end of the building occupancy periods, and reactivate them prior to the next occupancy period. If this program is used to shut down heating equipment in areas where extremely low temperatures may be experienced, provision should be made to override the program in the event that space temperatures reach dangerously low levels.

Optimum Start/Stop Program

This program conserves energy while maintaining comfort when HVAC systems are started in the morning and shut down at the end of the day. Comfort levels and occupancy times are programmed into the controller. HVAC system startup prior to anticipated occupancy is delayed until the last possible moment, yet timed to have the building or zone up to programmed comfort levels at occupancy time. Shutdown of the HVAC systems takes place prior to the end of the programmed occupancy period, and the building is allowed to coast into vacancy.



Power Demand Control Operation

Figure 2.23

The optimized startup and shutdown times take into consideration space temperature, outdoor air temperature, the preprogrammed space comfort conditions, occupancy times, and the heat loss/heat gain characteristics of the building or zone. Figure 2.24 shows some typical optimum start and optimum stop graphs.

Unoccupied Space Temperature Setback Program

The Unoccupied Space Temperature Setback Program, or night cycle program, has a twofold purpose: energy conservation and building protection. It can be applied to buildings or zones that are subject to temperature or humidity extremes, although it was developed primarily for heating applications.

This program reduces energy consumption by maintaining reduced building temperatures during unoccupied periods in the heating season. The reduced temperatures are kept within limits that will protect the contents of the building. The program can maintain outdoor air dampers on HVAC systems in the closed position whenever the fan is cycled to satisfy the reduced temperature setting. During the cooling season, the night cycle program allows building or zone temperatures to drift to higher levels during unoccupied periods. The HVAC systems may be cycled to maintain a high limit temperature or, if there is no anticipated danger to the building contents, the HVAC systems may remain in the de-energized state during the entire period. Figure 2.25 shows typical night cycle program curves for the heating seasons.

Unoccupied Night Purge Program (Summer Only)

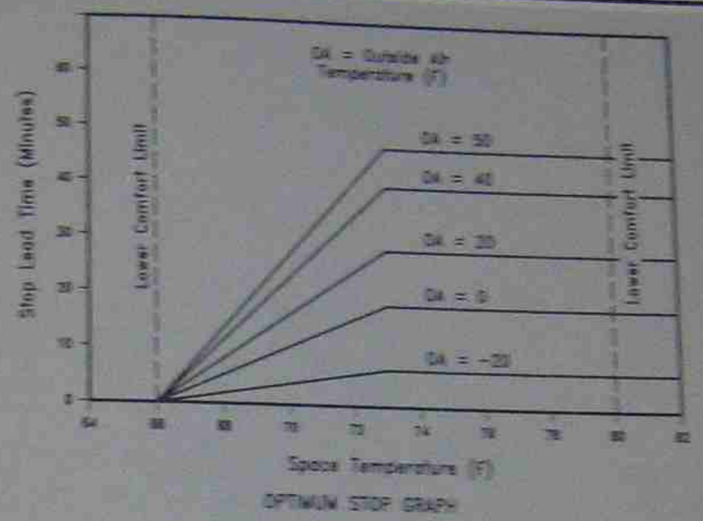
This program can provide free atmospheric cooling shortly before the time of occupancy, thereby delaying the startup of mechanical cooling and reducing electrical consumption. A few hours prior to occupancy, the program begins monitoring indoor and outdoor conditions (temperature and dewpoint). If the need for cooling is detected, and outdoor air conditions are suitable, the program will energize the HVAC unit fan and open the outdoor air damper 100%. The exhaust fan will also be energized. This purging of the building will continue until the space temperature and dewpoint reach preprogrammed limits, at which time the fans will be de-energized. With the building pre-cooled, startup of mechanical cooling equipment and HVAC systems in preparation for occupancy can be delayed (See Figure 2.26).

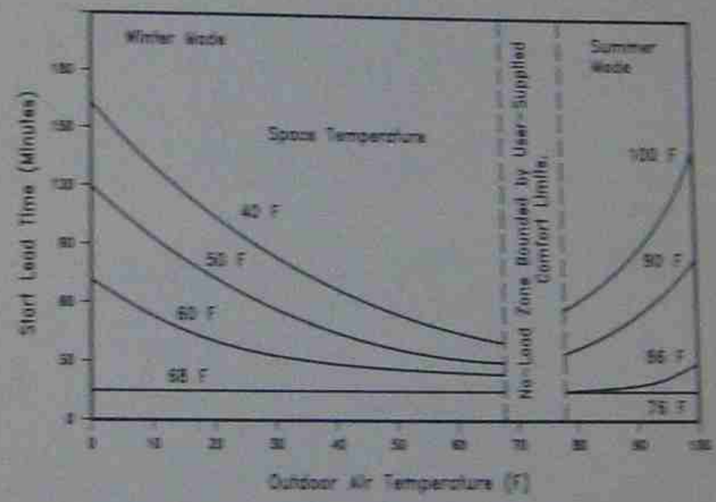
Enthalpy Program

The purpose of the enthalpy program is to reduce energy consumption for cooling, by selecting either return air or outdoor air, based on which has the lowest total heat (enthalpy). The program constantly monitors outdoor air and return air temperature, and relative humidity, or dewpoint. It will then operate the mixing dampers to use outdoor air or return air, whichever has the lowest total heat. This minimizes the load on the mechanical refrigeration, thereby saving on energy (See Figure 2.27).

Load Reset Program

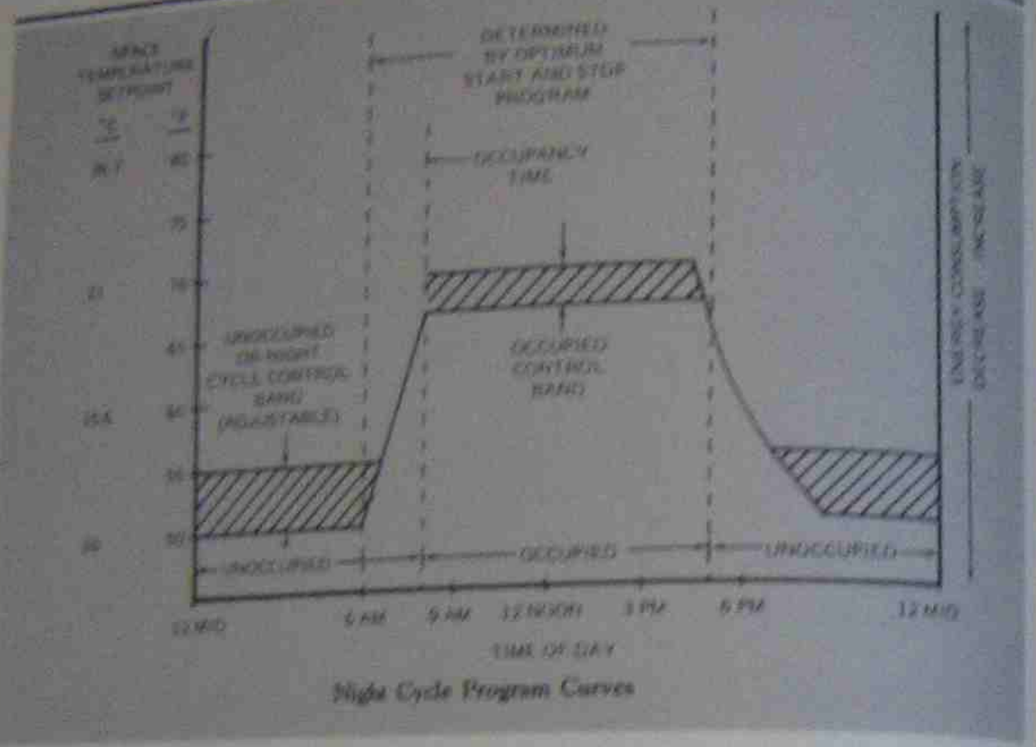
This program can save energy by adjusting HVAC system supply air temperature to just satisfy the zone with the greatest heating/cooling requirement. It applies to HVAC systems employing heating and cooling simultaneously. It may also be applied to chillers and hot water systems.





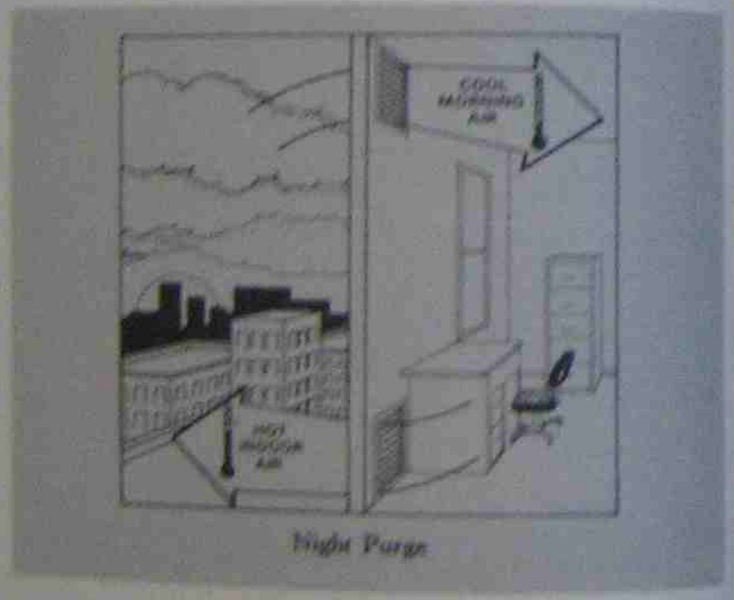
Optimum Stop and Start Graphs

Figure 2.24



Night Cycle Program Curves

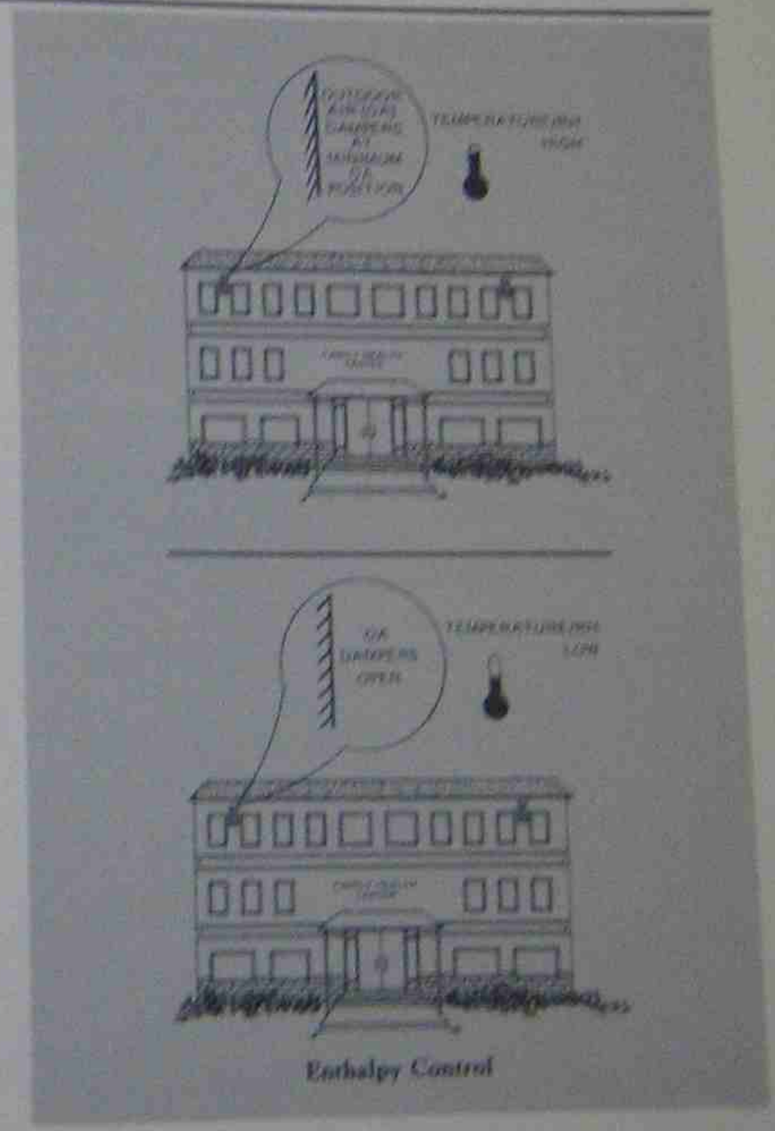
Figure 2.25



Night Purge

Figure 2.26

In reheat systems, space sensors in every zone monitor zone temperatures. This information is fed to the program, and the HVAC unit discharge air temperature is reset accordingly. This same reset strategy is applied to the hot and cold deck of a dual duct system and multizone units. The program may also be applied to reset chiller discharge water temperature as a function of outdoor air, or zone requirements, or to a hot water heater, or heat exchanger. Figure 2.28 gives an overview of the load reset program.



Enthalpy Control

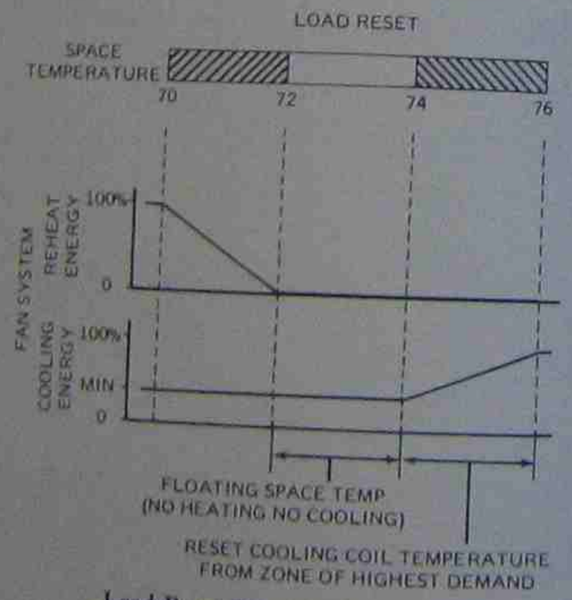
Figure 2.27

Zero-Energy Band Program

This program applies to HVAC systems that have heating and cooling capabilities. It eliminates energy waste resulting from simultaneous heating and cooling of air delivered to the space. The space comfort range is divided into three categories: heat, zero-energy band, and cool. These categories are adjustable and may be set as desired by the building occupant. At the lower end of the comfort range is the heating region. When the space temperature enters this region, the heating source is energized. At the upper end of the comfort range is the cooling region. When space temperature is in this region, the cooling source is energized. Between the heating and cooling regions is the zero-energy band, within which region both heating and cooling sources are off.

The zero-energy band program interacts with the load reset program. When the space temperature is outside of the heating and cooling regions, the heating and cooling sources are de-energized. The program, however, continues to monitor space temperatures and perform load reset. The heating and cooling remain de-energized until the space temperature re-enters one of these regions.

When an HVAC system, such as a multizone unit, serves different exposures (north and south), or different internal loads (interior and exterior), temperatures from zone to zone may vary considerably. The program constantly scans zone space temperatures and makes cooling decisions based on the highest temperature, and heating decisions based on the lowest temperature. This ensures that all zones will remain in the comfort range (See Figure 2.29).



Load Reset Program Overview

Figure 2.28

Energy Management – Lighting

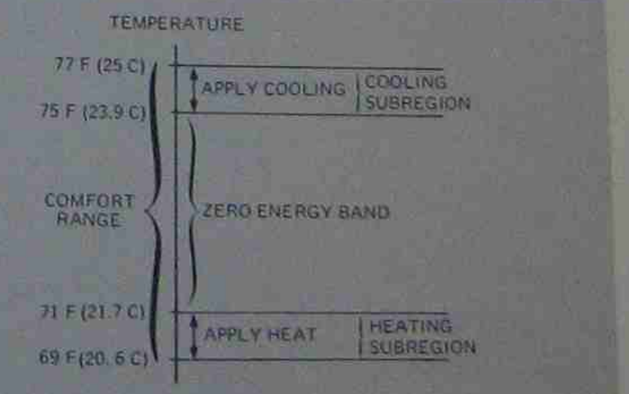
Lighting control falls into two basic categories: (1) simple on/off for occupied/unoccupied control, and (2) actual control of lighting levels in a building during occupied periods.

Centralized control of lighting is most conveniently accomplished when it is designed into new building electrical systems. Contactors can be installed ahead of lighting circuit breaker panels for each floor, zone, or area of a building. Emergency lights, wall outlets, and non-lighting circuits can be tied into circuit breaker panels not under control of the lighting program.

Adapting lighting control to existing buildings is not always economically feasible. Frequently, the existing circuit breaker panels carry a mixture of loads, such as lighting, wall outlets, exhaust fans, etc. This would require removing the lighting circuits and wiring them through a contactor to a new circuit breaker panel. Another option would be to install a low voltage lighting control system. The final decision would have to be made on the basis of economy and return on investment.

Occupied – Unoccupied Program

Programmed lighting applies the basic on/off, or occupied/unoccupied programming strategy to building lighting systems. It ensures the owner that lights automatically turn off at the end of normal occupied periods. Program override capability is available for unusual or



Zero-Energy Band Program

Figure 2.29

overtime periods of occupancy. This override can be applied only to the zones to be occupied, thereby leaving all other zones or floors in the unoccupied mode.

Lighting Level Control

Lighting level control complements the occupied/unoccupied program described above. It controls the level of lighting during occupied periods. There are two methods of controlling lighting levels. The first method uses multiple lamp fixtures to provide different light levels. Two- or four-lamp fixtures are divided into two circuits to provide either one half capacity or full-on lighting levels. Three lamp fixtures can provide one third, two thirds, or full-on lighting levels.

The second method applies primarily to fluorescent lighting and is most effective in open landscape lighting design. Ambient lighting through windows or skylights is also a requirement to supplement the artificial lighting. Under this program, an ambient light sensor measures the total light in the space (daylight and artificial light), and increases or decreases artificial light levels to maintain total light levels according to predetermined standards (See Figure 2.30). These lighting control programs can reduce overlighting, reduce energy consumption and demand charges, and reduce air-conditioning costs.

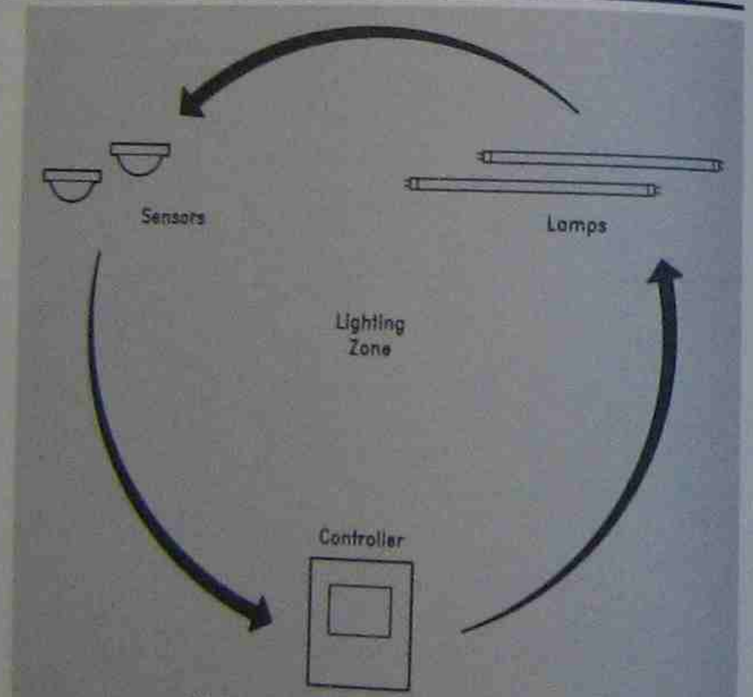


Figure 2.30 Lighting Control Block Diagram

Fire Safety Systems

Stand-alone fire alarm systems can be integrated into a distributed process system, thereby providing enhanced alarm capabilities and fire safety programs. This is particularly advantageous to the existing building which may have an existing, functioning, in-house fire alarm system. In a new building, the owner or engineer may want to totally integrate the fire safety system into the Building Automation System, or may prefer to install a stand-alone fire alarm system with redundant alarming into the BAS. In both cases, the stand-alone system and the totally integrated system, the benefits are substantial. Life safety and asset protection are probably two of the major benefits to be derived from either option. The subject of fire safety systems will not be covered in detail in this book; however, a general overview of capabilities will be offered. The reader should consult current NFPA Standards, local building codes, and local authorities having jurisdiction over fire safety systems before proceeding with system design.

Detection Methods

Alarm initiating devices for fire alarm systems can be manual pull stations, heat detectors, or sprinkler system waterflow switches. Smoke detection systems may consist of area or duct smoke detectors. These may be either ionization or photoelectric type units. Flame detectors in the form of infrared sensors are also available. These sensors respond to infrared radiation which is emitted from a flickering flame. National Fire Protection Association standard 72E contains guidelines for the placement of detection system elements.

Annunciation and Alarm

Upon actuation of any alarm initiating device, any or all of the following annunciation and/or alarm conditions may occur:

- An English language announcement of the alarm and an indication of its zone or detector location will appear on the host computer CRT. An audible alarm will sound, and the alarm condition will flash on the CRT to notify the operator of the emergency. Emergency action instructions will be displayed on the CRT screen for the operator's information.
- The host computer printer will document the alarm by type, zone, or actual detector location, time and date.
- The municipal alarm system will be actuated.
- Audible and visual alarm devices will be activated throughout the building. They will remain active until the alarm initiating device is reset and the system is returned to normal through the host computer terminal.
- Prerecorded voice action messages may be broadcast to building occupants over speakers located throughout the building. These may be specific instructions directing building occupants to safe locations.
- Preprogrammed smoke control procedures can be initiated. Such procedures could involve the activation of HVAC fans, exhaust fans, and dampers to clear smoke from the fire location and pressurize adjacent areas to prevent smoke migration. Self-closing smoke and fire doors may also be released.
- The elevator call system may be disabled and all elevators returned to the ground floor for manual operation by firefighters. If the fire is in a ground floor zone, the elevators can be returned to another floor.

- Prerecorded voice messages can be transmitted to elevators.
- Doors which are locked by the access control (security) system may be programmed to unlock to provide occupant egress. This function may also be performed by the operator from the host computer terminal.

Building Security/Access Control

Access control systems can be integrated into the distributed process system along with HVAC and fire alarm systems. These access control systems control personnel access to secured areas or the entire building. Credit card-sized access cards with a coded magnetic stripe or barium ferrite layer are assigned to authorized personnel. Cards may allow the cardholder access to a specific room, through specific doors, and within certain established time limits. If the access control system is applied to elevator control, the cardholder's access may be limited to specific floors.

When the card is inserted, or swiped (passed through a card reader), the system reads the ID number on the card in conjunction with the location, the time, and the day. This data is compared with the preprogrammed, valid information stored in memory. If the comparison is positive, indicating an authorized entry or exit, a signal is sent to activate the appropriate door strike. The host computer printer will document the card ID number, card reader location, and time of day. If there is not a match with the preprogrammed conditions, the door will remain locked and a printout will occur indicating the reason why access or egress was denied. For additional security, an electronic keypad may be installed to act in concert with the card reader. In this case, the cardholder must enter a four-digit ID number and insert the card to obtain authorized entry. This prevents unauthorized use of stolen or lost cards.

In most systems, if the host computer fails or the communications bus to the access control panel fails, the access control panel will maintain control. It will also store all card activity, alarms, time, and day information in memory. When communication with the host computer is restored, all stored information will be uploaded for documentation purposes.

If any door designated for card reader access is operated without the use of a valid card, an alarm condition will display on the host computer CRT and printer for operator action.

Central Host Computer

The complete distributed process system consists of the following:

- A central host PC as the operator interface
- Distributed processors (controllers)
- Remote sensors, detectors and actuators

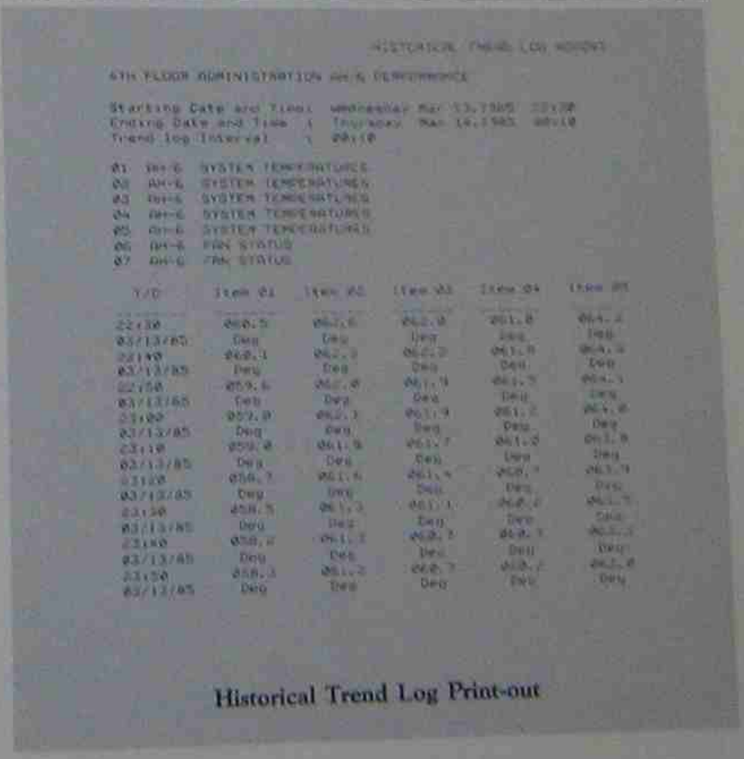
The distributed processors (controllers) connect directly to the remote sensors, actuators, and detectors to provide constant control functions, energy management strategies, and fire/security monitoring. The processors contain software programs that accept information from these remote devices, process the information, and perform control functions. The processors communicate with one another over a communications bus by means of a common language, or protocol. Although these processors are intelligent, and can perform their functions on a stand-alone basis, the central personal computer can provide high level system monitoring, control, alarming, and management reporting. In summary, the central PC provides user-friendly operator interface capabilities.

Building Management Programs

Most distributed process systems have standard application packages and optional software programs which enhance the capability of the personal computer as a building operations tool. These application packages and programs provide reports and documentation to assist building owners and operation personnel in managing building systems in the safest and most cost effective manner.

Historical Data

The building operator may initiate a program which will store or retrieve information relating to a specific point, or group of points. He/she can manually request a printout of the information, or program an automatic printout of the reports on a regular, periodic basis. The reports may include alarms, return-to-normal, points in trouble, or point status (temperature, humidity, on/off, etc.). These reports allow the operator to recognize trends and, in many cases, predict a malfunction before it occurs. A sample of a historical trend log printout is shown in Figure 2.31.



Historical Trend Log Print-out

Figure 2.31

Action Messages

Preprogrammed messages that print and display on the CRT are an important feature when a point goes into alarm or trouble. Regardless of the operator's skill level, this feature provides an element of support in emergency situations. This is extremely important for fire and security applications.

Energy Audit Program

Under this program, a building owner may use a spreadsheet format to convert specified measured data (kilowatt hours, cubic feet of gas, gallons of oil, etc.) into logical management reports. The output can be a simple listing of energy consumption data for a given period, or the raw values may be converted to management-related terms, such as kilowatt hours per square foot, or cubic feet of gas per degree day. This allows building owners or managers to better understand the energy requirements of their building and the effectiveness of their energy management strategies (See Figure 2.32).

Material Inventory

A material inventory program provides a convenient method of inventory control for the building maintenance or facilities department. This program can track material quantity, cost, usage, and if desired, it

PARKWAY BUILDING
320,000 SQ FT

BUILDING ENERGY AUDIT
REPORT FOR MARCH 1991

THIS MONTH

	1990	1991	% CHANGE
ELECTRICITY			
KWH	790,435	649,330	-18
KWH COST ($)	45,924	44,090	-4
PEAK DEMAND (KW)	3,525	3,201	-9
DEMAND COST ($)	14,226	16,645	17
#2 FUEL OIL			
GALLONS	10,567	9,141	-13
TOTAL COST ($)	11,663	8,958	-23
MILLION BTU	1,471	1,286	-13
TOTAL ENERGY			
COST ($)	57,587	53,048	-8
MILLION BTU	4,168	3,495	-16
PERFORMANCE			
HTG DEGREE DAYS	891	849	-5
CLG DEGREE DAYS	0	0	0
BTU/SQ FT	12,944	10,854	-16

Energy Auditor Print-Out

Figure 2.32

can monitor material location. Inventory minimum levels can be preprogrammed into the computer. When levels drop below these levels, a reorder printout will be generated. This ensures that materials and parts are always available when needed (See Figure 2.33).

Maintenance Management Program

The maintenance management program is a valuable tool for facilities management personnel. This program documents the required maintenance tasks, the level of skill required for each, and the tools and materials necessary to perform each task. Scheduling of preventive maintenance activities can be based on either calendar time or equipment run time or event occurence. Preventive maintenance printouts may be generated on a daily basis. These printouts or work orders include the following information:

- Purpose of maintenance task and instructions
- Description of piece of equipment
- Type of worker required (electrician, mechanic, etc.)
- Normal time requirement to perform task
- Materials and tools required to perform task

1991/05/20

MAINTENANCE MANAGER

MATERIALS TO REORDER

MATERIAL ID	UNIT	QUANTITY ON HAND	COST ON HAND	QUANTITY TO REORDER	ESTIMATED PRICE
MAT01	EA	150.00	$ 200.00	200.00	$ 2.00
MAT04	EA	2.00	$ 250.00	10.00	$150.00
MAT05	EA	150.00	$ 200.00	200.00	$ 2.00
MAT06		5.00	$ 170.00	30.00	$ 34.00
MAT09	DOZ	12.50	$4,200.00	25.00	$350.00

*** END OF REPORT ***

1991/05/20

MAINTENANCE MANAGER

MATERIALS ON ORDER

MATERIAL ID	UNIT	QUANTITY ON HAND	COST ON HAND	QUANTITY TO REORDER	ESTIMATED PRICE
MAT02	EA	150.00	$ 200.00	200.00	$ 2.00
MAT07	EA	5,000.00	$50,000.00	50.00	$10.00
MAT10	GAL	13.50	$ 1,100.00	25.00	$40.50

*** END OF REPORT ***

Inventory Control Report

Figure 2.33

After completion of the task, the actual time and materials used are entered into the system. The program will track ongoing costs for each item (task, materials, skill) on a monthly, yearly, or lifetime total basis. A printout of incomplete tasks can be generated to check work in progress. This information assists supervisors in determining workload and scheduling personnel.

To protect sensitive data that may be stored in the maintenance management program, operator access can be limited to different levels. For instance, a lower level operator may have access to work orders and management reports only, whereas a higher level operator can not only access this data, but also modify maintenance information in memory. (See Figure 2.34).

Color Graphics and Annunciation

Color graphic software presents graphic displays of HVAC system schematics, building floor layouts, bar charts, or graphs. This is a convenient way of presenting pertinent information in a multi-colored, logical format for the system operator. The multiple colors can give greater meaning to graphic displays and emphasize critical data. For example, normal point status might be displayed in green, and alarm status displayed in red. The operator can call up a system graphic and review large amounts of data relating to that graphic. The data is dynamic in nature, which means that it changes as actual changes occur.

With most systems, the operator can create custom graphic displays while the system is operational. The operator selects standard symbols and HVAC system diagrams from a library of multicolored graphics. Standard libraries contain HVAC equipment symbols for items such as fans, pumps, dampers, valves, sensors, etc. Fire and security symbols display fire and smoke detectors, manual stations, bells and horns, card readers, etc. Floor plans, piping schematics, and ductwork layouts are also available.

Selected analog data can be programmed to create graphs or bar charts. This is beneficial to building owners and operations personnel in comparing past and present performance. Dynamic graphs and bar charts for selected points can be displayed on an ongoing basis. This provides the operator with up-to-the-minute system information and trends so that corrective action can be taken if required.

Voice Communications

Most manufacturers now offer off-site voice communications capability. This means that a building owner or authorized person can dial in to the host computer from a remote touchtone telephone, and request information or change point settings. The caller must have a valid password to enter the system. The password will be requested verbally when the proper telephone number is dialed. The caller then enters the password through the touchtone pad. The caller may then request the status of a specific point (through a code entered through the touchtone pad) and the requested information will be returned verbally, along with the point action message. If the caller wishes to make a set point change, he/she can do so on the same call. Access to specific points can be restricted to specific password holders.

```
                    WORK ORDER NUMBER 87 - 13 - B
          PRINTED BY HONEYWELL, INC. MAINTENANCE MANAGER on 08/11/87
                                FOR
                           "SAMPLE SYSTEM"

EMERGENCY WORK ORDER    (CT SMA # 03001)

Complete by:
    08/12/87

Work Order Purpose:
    fan system periodic maintenance

To be performed on:
    23.01     SUPPLY FAN STATUS

Performer:
    mechanic

Task Purpose:
    replace belt

Instructions:
    turn off power- remove belt
    install belt- turn on power

Estimated completion time:
    45  minutes

Materials Required:
    1   unit(s) of fan belt

Tools Required:
    wrench

================================================================================

COMPLETION INFORMATION

Yes   No

___   ___   Took Estimated minutes to complete.
            If no, how many? __________

___   ___   Used Estimated material quantity.
            If no, how much? __________

COMMENTS:


_____________________________________  ____________  _________
Name                                   Date          Time
```

Maintenance Task Print-Out

Figure 2.34

ST. GEORGE
COLLEGE OF TAFE
LIBRARY

Dial In/Out Function

In most systems, two-way communications are possible between the host computer and the DDC controllers over voice grade telephone lines. Through the use of modems, controllers located in remote buildings can direct dial the host computer to report off-normal alarms. The host computer can periodically dial the remote controllers and request the transmission of all point data and alarms.

Building owners or facilities personnel who have a compatible PC and software, at a remote location can monitor and operate the Building Automation System at their building. They can verify HVAC system operation and make adjustments to set points from the remote location. This off-site monitoring and control is an attractive feature to many who are responsible for building operations.

Chapter Three

System Architecture

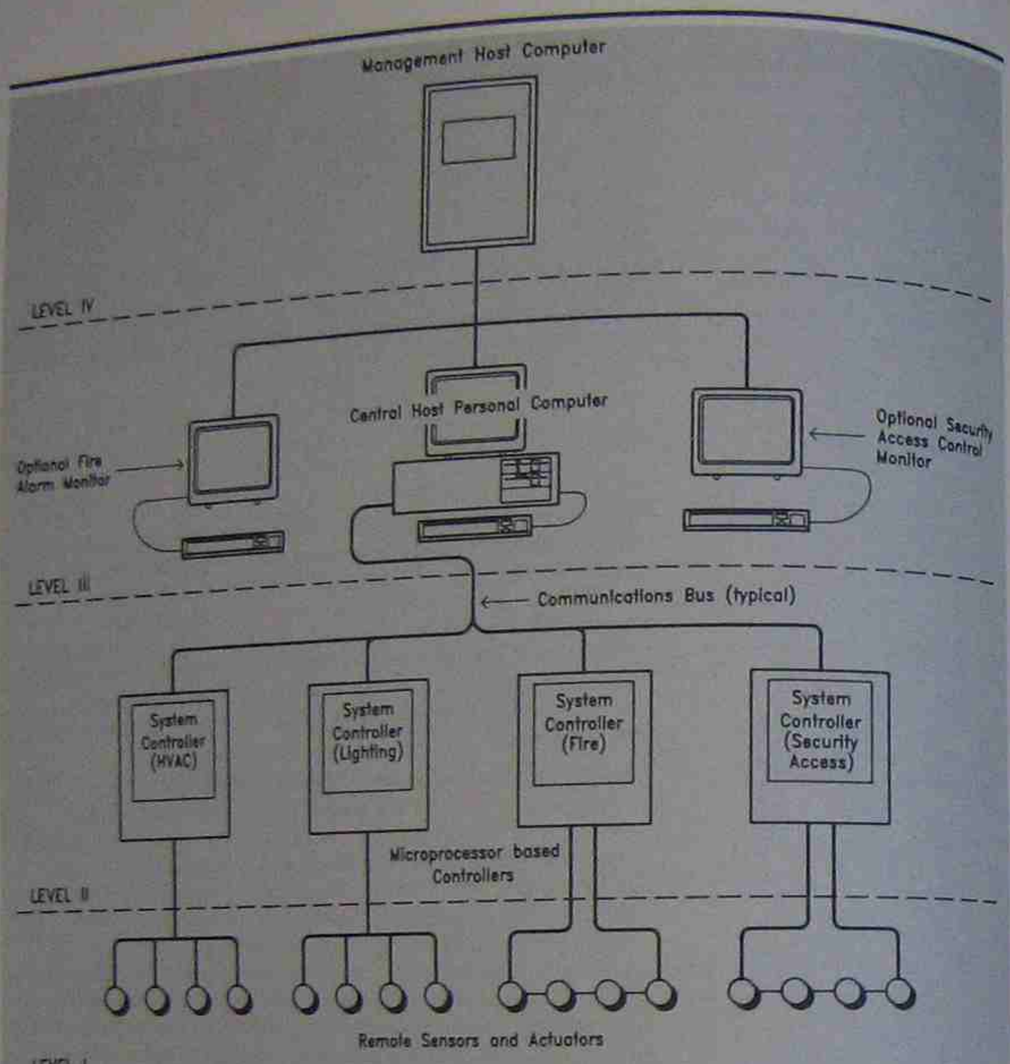
Building Automation Systems centralize the operation, monitoring, and management of building systems, such as heating, ventilating, air-conditioning (HVAC), lighting, fire safety, and security-access. The goal of these systems is to provide a comfortable and healthy environment for building occupants, reduce energy costs, and maintain a high level of life safety and security. These systems enable building owners and operations personnel to operate their facilities more efficiently, while making the most effective use of maintenance and operations staff.

The first Building Automation Systems (BAS) were basically electro-mechanical, whereby sensors and controlled devices were hard-wired or piped to a large central control panel. Over the past 25 years, however, these systems have become computerized. Today, a BAS consists of *remote sensors and actuators*, *microprocessor-based controllers*, an optional *central host computer* (PC), and an optional *management host computer*. The remote sensors (Level I) sample the building environment and transmit pertinent data to the controllers. The controllers (Level II) perform Direct Digital Control (DDC) functions and energy management strategies by controlling remote actuation devices. Building management reporting, monitoring, and access to system data can be accomplished through the controllers, the central host PC (Level III), or an optional management host computer (Level IV). These BAS components are illustrated in Figure 3.1 and described in detail in the following sections.

Remote Sensors and Actuators (Level I)

The sensors, actuators, and controlled devices that are connected to Level II controllers are known as points. Points are classified by their input or output function as follows:

- Digital inputs (DI)
- Digital outputs (DO)
- Analog inputs (AI)
- Analog outputs (AO)



Building Automation System Architecture

Figure 3.1

Digital Inputs (DI)

A *digital input* point is an external sensor that sends a two-state, on-off, or two-position signal to a controller. An example of this would be electrical switch contacts, which are either open or closed. Low-temperature detection controllers, high-temperature detection controllers, duct smoke detectors, or duct static pressure sensors are all considered digital input points. The duct static pressure sensor shown in Figure 3.2 has built-in switch contacts that close when the duct static pressure exceeds its setting, and open when the duct static pressure drops below its setting. This device is a digital input sensor used to signal the controller that a fan is or is not operating.

Digital Outputs (DO)

A *digital output* point is the two-position switching action of switch contacts residing in the controller. This switching action makes or breaks an external electrical circuit. The circuit could be wired to turn lights on or off, or to start and stop an electrical motor such as a supply fan for an air handling unit shown in Figure 3.3.

Analog Inputs (AI)

An *analog input* point is an external device that sends a proportional or variable signal to the controller. Examples may be a humidity sensor, water or duct airflow sensors, or a space temperature sensor, as shown in Figure 3.4. Unlike digital input points, analog input signals are sent over the entire range of the sensing device. Most controllers will accept analog input signals of 2 to 10 volts DC (VDC), 4 to 20 milliAmp (MA), or a variable resistance.

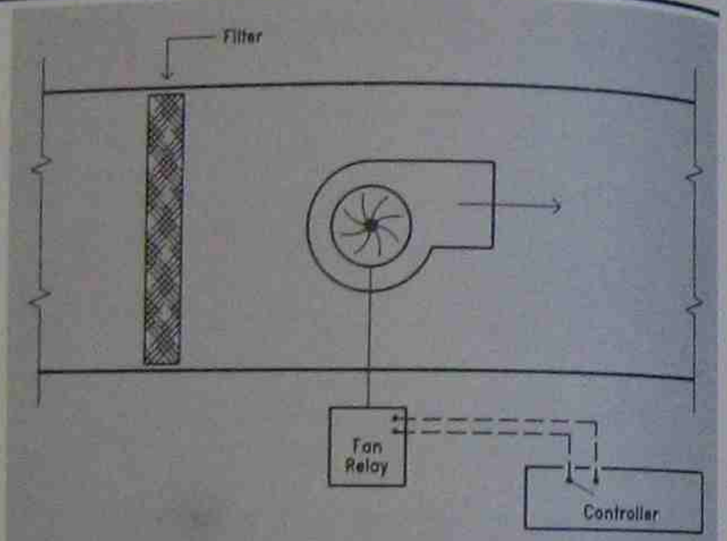
Static Pressure Sensor (DI)

Figure 3.2

Analog Outputs (AO)

An *analog output* point is a proportional, variable signal sent by the controller to modulate an external control device. The analog output signal can be 2 to 10 VDC, 4 to 20 MA, or 3 to 15 pounds per square inch gauge (PSIG) air pressure. The external controlled device could be a variable frequency drive, a damper actuator, or a valve actuator, as shown in Figure 3.5.

A typical example of a basic five point control system, using the four types of points employed by direct digital control systems, is shown in Figure 3.6.

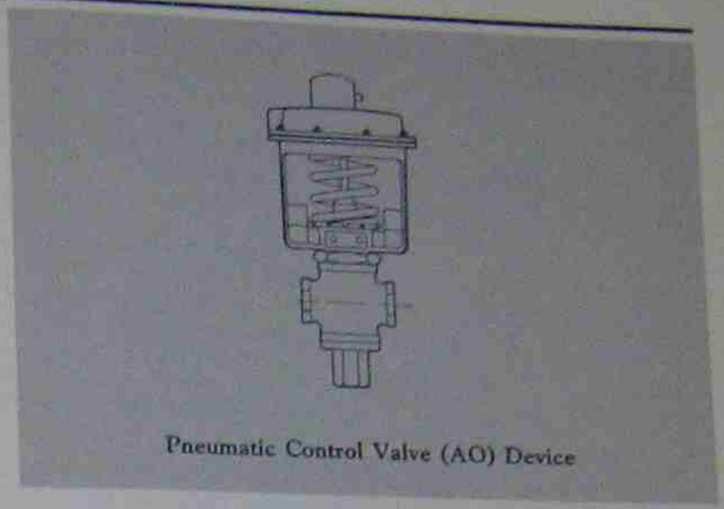


Digital Output (DO) Point Starting and Stopping an Air Handling Unit Supply Fan

Figure 3.3

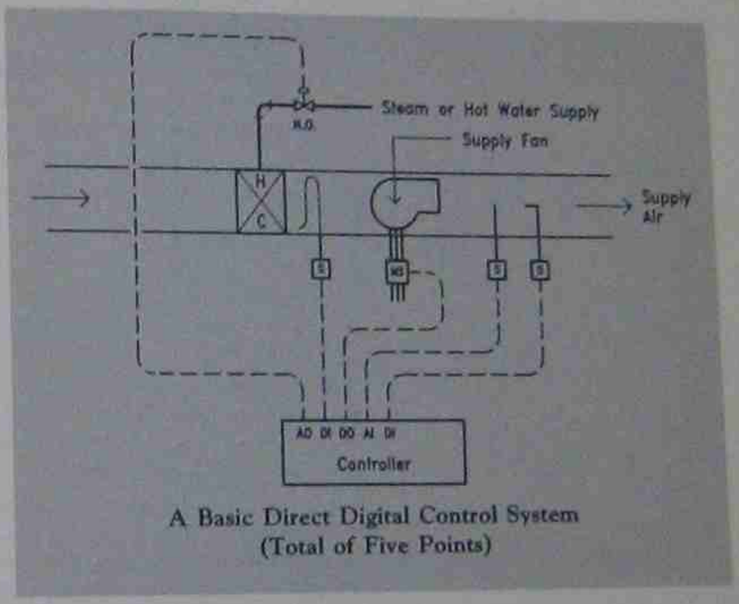
Analog Input (AI) Space Temperature Sensor

Figure 3.4



Pneumatic Control Valve (AO) Device

Figure 3.5



A Basic Direct Digital Control System (Total of Five Points)

Figure 3.6

The sequence of operation for this system would be as follows:

1. The controller energizes the supply fan magnetic starter (MS) by a digital output point.
2. A digital input point – a static pressure sensor located in the supply air duct – closes its switching contacts in response to an increase in static pressure, indicating to the controller that the fan is operating.
3. An analog input point – a temperature sensor located in the supply air duct – sends a variable input signal to the controller.
4. The controller maintains its setting by sending an analog output signal to modulate the automatic control valve.
5. If the heating coil discharge air temperature drops below the low temperature detection sensor setting, the sensor opens its contacts, sending a digital input signal to the controller. The controller sends a digital output signal to stop the fan, and an analog output signal to open the automatic control valve.

Microprocessor-Based Controllers (Level II)

In general terms, a controller receives a signal from a sensor (Level I), compares the signal with a preset set point, and determines if corrective action is necessary. Corrective action is in the form of an output signal to modulate or two-position an actuator or controlled device (Level I).

Controllers are microprocessor-based. Since their software programs are in digital form, the controllers perform direct digital control. Microprocessor-based controllers can be used as stand-alone controllers or can be incorporated into a Building Automation System.

Microprocessor-based controllers offer a more flexible and accurate means of control than traditional electric, electronic, and pneumatic control systems. Through the use of software programs, the controllers can provide a variety of HVAC control functions, energy management programs, and other building management functions. Revisions to control sequences can be readily accomplished without major hardware changes, simply by changing the program software.

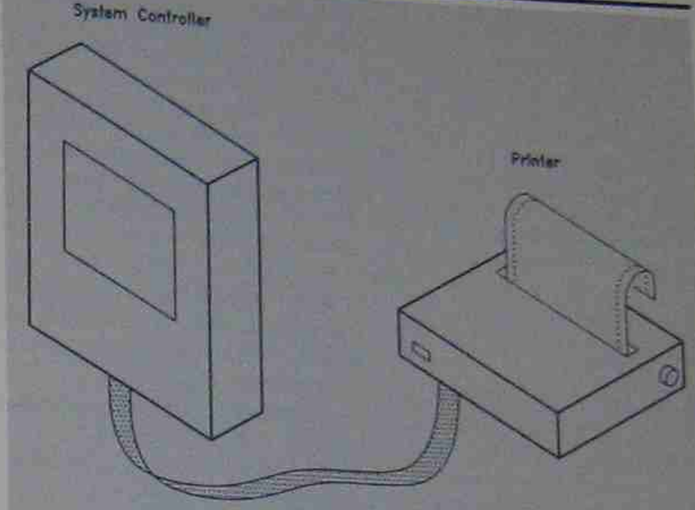
Since the controllers are microelectronic, they contain no moving parts and, therefore, their maintenance requirements are minimal. The controllers are reliable, and most manufacturers include self-diagnostic features to notify maintenance personnel of any malfunctions.

In addition, most Level II controllers are provided with a communication port or channel for connection to a remote or portable operator's terminal, printer, or telephone modem. Figure 3.7 illustrates a printer connected to a Level II system controller.

In general, most manufacturers offer two basic types of controllers: *zone controllers* and *system controllers*. These are illustrated in Figure 3.8 and described in the next sections.

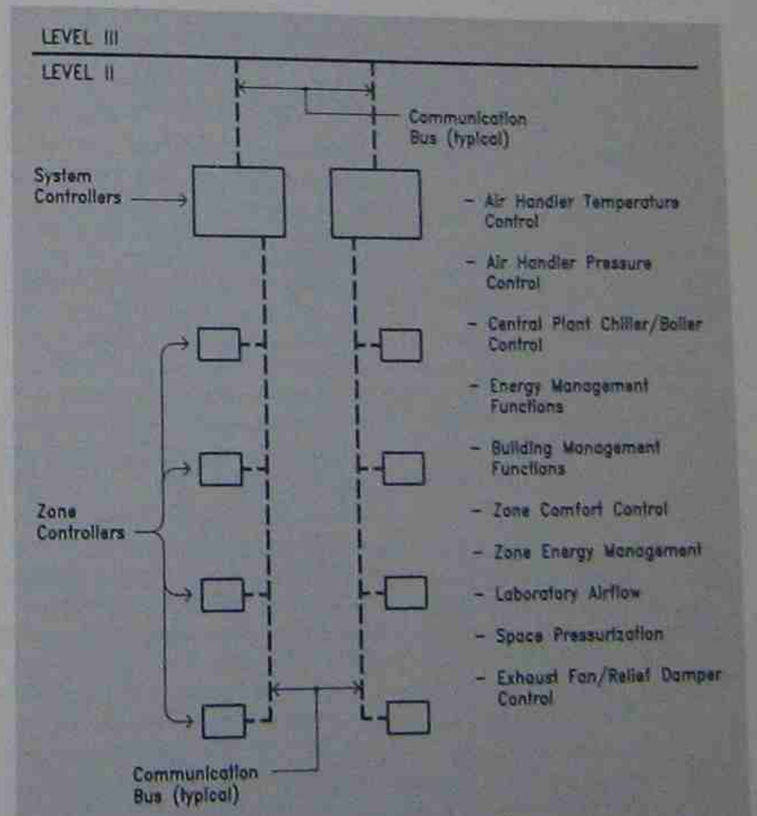
Zone Controllers

Zone controllers typically control HVAC terminal units, such as variable air volume (VAV) terminal units, fan-coil units, heat pumps, smaller air handlers, packaged heating/cooling units, and laboratory fume hoods. Usually these controllers have relatively few connected Level I points and standardized control sequences, and are designed for specific applications. For example, a VAV terminal unit zone controller is frequently packaged with an internal damper actuator (Level I), and has only the required point capacity to meet the specific application. The DDC software program is resident in the controller.



Printer Connected to a Level II System Controller

Figure 3.7



Zone and System Controllers

Figure 3.8

In general, the controller has a communication port, or channel, connected to a portable operator terminal for use during initial setup and for subsequent adjustments. A communications bus enables the networking of zone controllers, allowing Level I point information to be shared with other system controllers and with a central host PC (Level III). (Communication buses are discussed in more detail later.) For example, a system level controller can use space temperature values from a zone controller as inputs to perform optimum start, optimum stop, night setback, and night purge programs. A Level III central host PC can use the same Level I point information, in text or graphic display form, as data for trend reports, alarms, and historical logs and files.

Typical Point Data

For a typical VAV terminal unit controller, the following Level I point and DDC program information is generally available for display or program use:

- Airflow in cubic feet per minute (CFM)
- Set point temperature
- Deviation from set point (offset)
- Space temperature
- Duct air temperature
- Damper position
- Reheat stages energized (for electric and/or fan reheat coils)
- Hot water valve position (for hot water reheat coils)
- BTU per hour added to or removed from the space
- Maximum/minimum CFM set point

Other types of zone controllers provide different information, depending on the application.

System Controllers

System controllers have a greater capacity than zone controllers in terms of the number of Level I points, DDC loops, and control programs. System controllers are usually applied to major mechanical HVAC equipment, such as large built-up air handlers, central VAV systems, and central heating and chiller plants. Other types of system controllers are designed to monitor individual or multiple zones of fire alarms, unauthorized intrusion alarms, or to provide access or lighting control. They can provide smoke containment or evacuation programs, emergency occupant evacuation control, or can control personnel movement through card reader access.

Controllers at this level interface with controlled equipment (Level I) directly through Level I sensors and actuators, or indirectly through communications links with other system or zone controllers. System controllers typically have a communications port or channel to accept a portable operator's terminal during initial setup, and for subsequent adjustments. When the system controllers are linked to a Level III central host PC, changes to the controller software program can be made as follows:

- Software program changes are performed at the Level III central host PC and down-line loaded to the system controllers over the communications bus.
- Software program changes are performed at the system controller and are up-loaded to a Level III central host PC.

Level I point information, processed by system controllers, is used directly by the resident DDC, EMS (Energy Management System), and Time/Event software programs. The information is accessible, either through a keyboard access and display permanently mounted on the system controller door, or a portable operator's terminal. This information can be communicated to other system controllers and to a Level III central host PC. Programmed parameters (such as set points, commands, and overrides) and Level I point values associated with DDC and other resident programs can also be read and adjusted through a local keyboard and display, a portable operator's terminal, or a Level III central host PC. However, system controllers will continue to operate as programmed on a stand-alone basis should the communications link with other system controllers or the Level III central host PC be lost.

Communications Bus

The communications bus links controllers to one another as well as to a Level III central host PC. The most common communications bus media are twisted shielded copper *(called hard-wire)*, *direct-dial telephone lines*, and *fiber optic cable*. Some factors to consider when selecting a medium are the signal to be transmitted, cost, geographic layout, and the possibility of electrical interference.

Hard-Wire

Twisted shielded copper conductors (hard-wire), ranging in size from 16 to 24 gauge, is the most commonly used and the most economical choice for single building applications. Communications bus lengths of up to 4,000 feet are common, without the use of auxiliary extenders or repeaters. When repeaters are used, extension of three to four times this distance are possible. The two most common communications bus wiring configurations are daisy chain (Figure 3.9) and star (Figure 3.10).

Direct-Dial Telephone Lines

Common carrier direct-dial telephone lines can link distant buildings. Dial-up to a single remote Level II system controller is possible with the proper telephone modems, as shown in Figure 3.11.

Fiber Optic Cable

A fiber optic communications bus is particularly well-suited to installations in an environment that interferes with its communications, such as areas subject to radio frequency interference (RFI) generated by electrical power lines or electrical storms. The disadvantages of fiber optic transmission are high material and installation costs and the absence of established guidelines for this technology.

Central Host Personal Computer (Level III)

The central cost personal computer acts as an operator-machine interface. It provides an operator with a way to access program information, point information, and management reports, and to change programs when necessary. It also allows the operator to monitor equipment status, receive alarms, and take corrective action when alarms occur.

The PC consists of an operator terminal with color CRT, self-prompting system access, memory expansion capability, and communication boards. The PC also contains plug-in function boards and multiple communication ports or channels to accommodate peripheral devices such as a telephone modem and local or remote terminals and printers.

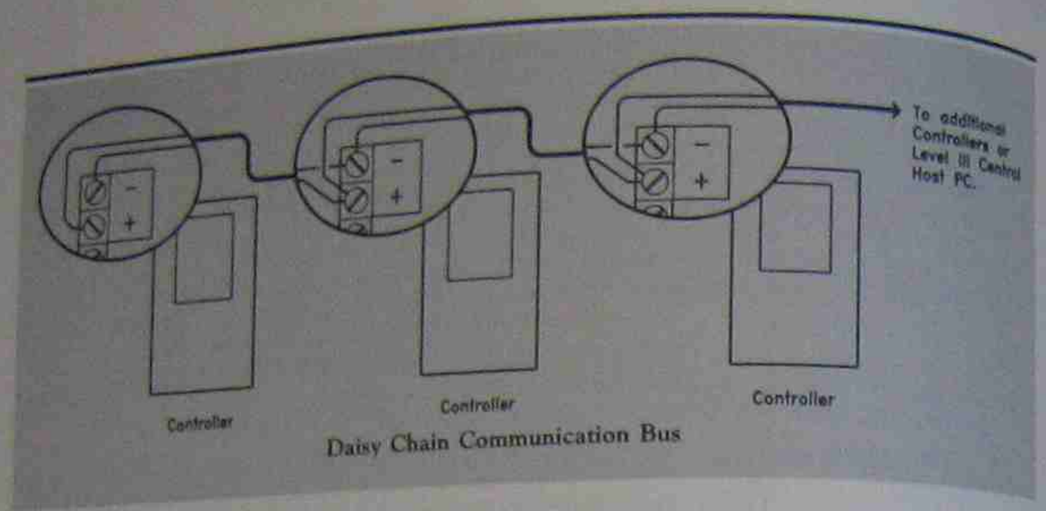


Figure 3.9

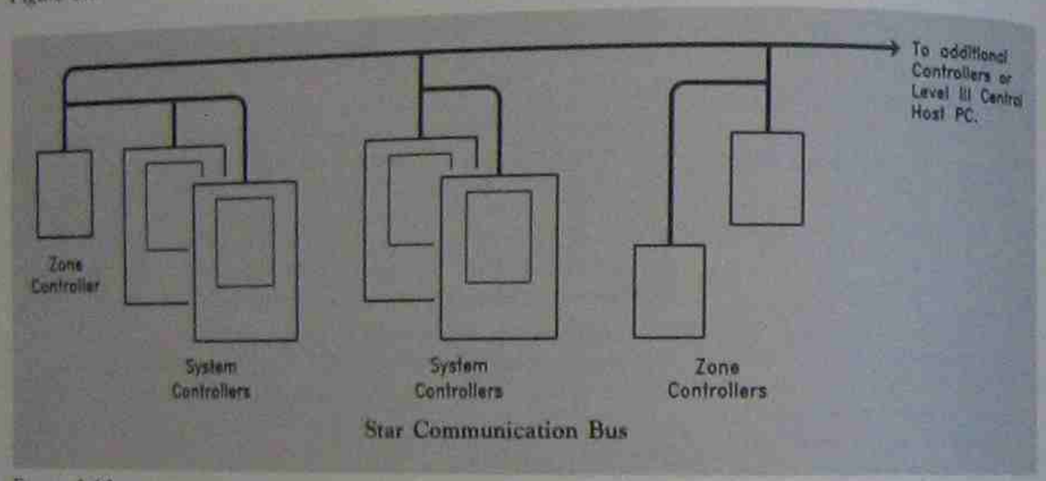


Figure 3.10

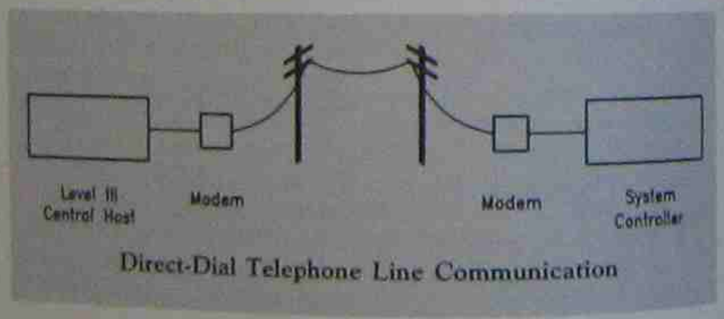


Figure 3.11

Some application software features are as follows:

- *Multiple level access codes*: Operators are authorized access to specific levels of programming. This prevents unauthorized tampering with software or system operation. It also ensures that only authorized personnel will have access to proprietary information.
- *Customized programming capability*: Custom programs can be written for specific sequences and applications. The programs can be entered through the PC operator's terminal and down-line loaded to specific system controllers.
- *Custom colorgraphic displays*: The CRT can display multicolored, dynamic layouts of HVAC systems, piping diagrams, lighting systems, fire/smoke detectors, and floor layouts. It can also display dynamic bar charts and graphs to provide building management personnel with an ongoing picture of building costs, energy consumption, or mechanical equipment efficiencies.
- *Automatic or manually requested log report printouts*: The system can be programmed to periodically print logs of:
  - –All points status
  - –All points in alarm
  - –Single point status – to observe trends
  - –Unacknowledged alarms
  - –Energy consumption
  - –Building access time and access card number
  - –Historical trends
- *Maintenance Management Program*: Preventive maintenance can be scheduled, based on run time of equipment, calendar time, or an event occurrence. Work orders will show estimated task time, tools required, and classification of worker.
- *Customized Reporting Program*: Point and controller information can be assigned to report and display, along with action messages for the operator, at specific CRTs and printers. Security and fire points can be designated for one CRT and printer, and HVAC-related points to another CRT and printer.
- *Software integration of building systems*: Interactive software programs can integrate HVAC, fire alarm, security, access control, and lighting systems.

Management Host Computer (Level IV)

Level III central host PCs are the most commonly used as an operator-machine interface to a BAS. However, Level IV management host computers may be used for applications, such as campuses with multiple buildings or complexes with multiple remote facilities. Each of the buildings may have its own independent central host PC.

Another example is a single building organization that is using its PC extensively. If facility management wishes to change programs or request management reports, this may be extremely difficult when the system is so actively used.

In the case of multiple buildings with separate PCs, there may be a need by facility management for a centrally located PC to receive management reports and/or critical alarms. The Level IV management host computer fills these needs.

Management host computers are at the top of the BAS hierarchy. They are used to manage and execute commands to lower level devices. In general, their primary role is to retrieve, archive, and process building point information, such as energy consumption, operating costs, and alarm activity. This information allows the computer to generate customized reports, such as graphs, bar charts, and spreadsheets necessary for the long-term management and operation of the building. At this level, facility management personnel can access any or, in some cases, all system point information, and execute commands to operate the system.

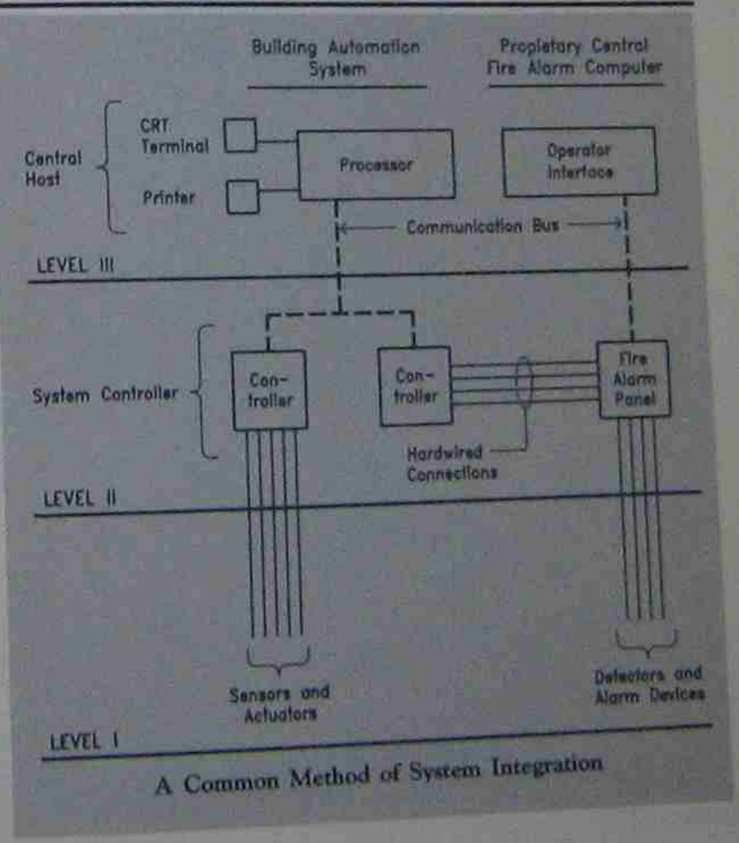
A powerful personal computer (PC) can be adequate for the management host computer function. Depending on the requirements for memory size, networking, and data processing (such as processing speed), software compatibility and capability, a mini-computer might be used, with hard disk storage. Peripheral devices, such as terminals, keyboards, CRTs, and printers are the same as those listed for a Level III central host. The software used for management Level IV and central host Level III computers is also identical, with the exception that the management level reports and graphic capability needs of Level IV are more comprehensive than those required for Level III. Many management level applications can be integrated into the Level III central host computer. However, in the case of BAS applications in extensive and/or diverse facilities or campuses, certain management functions may necessitate a Level IV computer. Some of these management functions and duties may include:

- The up or down transfer (within the BAS hierarchy) of operator authority and assignments during regular or unattended periods of building operations.
- Logging and reporting of any changes to BAS, DDC, EMS, or any other software programs identified by operators.
- Reports and summaries, over any user-defined time period, of all acknowledged and unacknowledged alarms; and facility management information, such as energy consumption, heating and/or cooling plant efficiency.
- Historical reports of all alarm occurrences and their return to normal.
- Archiving of all system controller DDC, EMS, and other software programs on back-up storage media.
- Facility cost allocations and accounting of energy consumption to specific buildings, systems, departments, or tenants.
- Daily reports of all BAS hardware, firmware, software, and equipment failures and their return to normal.
- Operator and maintenance means to oversee, and fine tune a facility's most critical systems on a dynamic basis.
- Segregated alarms pertaining to a facility's most critical systems.

Integrating Other Building Systems

A building owner or manager may wish to integrate other building systems, such as fire alarm, security, access control, and lighting control, with his HVAC systems. There are two methods of integrating these systems into the Building Automation architecture. Fire alarm, security, and access control systems are basically stand-alone systems. They each have the equivalent of a controller, Level I sensors, and actuators. These systems have central alarm panels which are connected to remote sensors, detectors, and alarm devices. The central panels are considered controllers (Level II), while the sensors, detectors, and alarms are Level I devices. Figure 3.12 shows how a stand-alone fire alarm system can be integrated with an HVAC system, with all point information displayed and accessible at the central host personal computer (Level III).

In this example, the fire alarm panel contains auxiliary alarm contacts and status contacts (digital outputs) which are hard-wired to a standard system controller as digital inputs. In the event of an alarm, the auxiliary contacts close, signalling the alarm condition to the system controller. The system controller can initiate preprogrammed smoke containment or evacuation programs, or building occupant evacuation procedures. The fire alarm panel displays the alarm, and if it is connected to a proprietary central fire alarm computer, the alarm will be displayed there also. The system controller also communicates the alarm to the BAS central host computer. The central host printer generates a printout of the alarm information and the CRT presents a display of alarm information for operator action.



A Common Method of System Integration

Figure 3.12

This method of integrating HVAC and other building systems applies primarily to existing buildings. Many of these buildings have up-to-date, functioning fire, security, or access control systems. If a BAS is to be installed, it may be advantageous, from a building management standpoint, to integrate these systems with the HVAC systems.

Figure 3.13 illustrates another method of integrating building systems. HVAC zone and system controllers are linked to the central host computer by a communications bus. Another communications bus connects the fire or security controller to the host computer. These controllers are designed specifically as fire alarm, security, or access controllers. They have their own resident software programs so that if the host computer malfunctions or the communications bus is severed, they will continue to operate, as programmed, in a stand-alone manner.

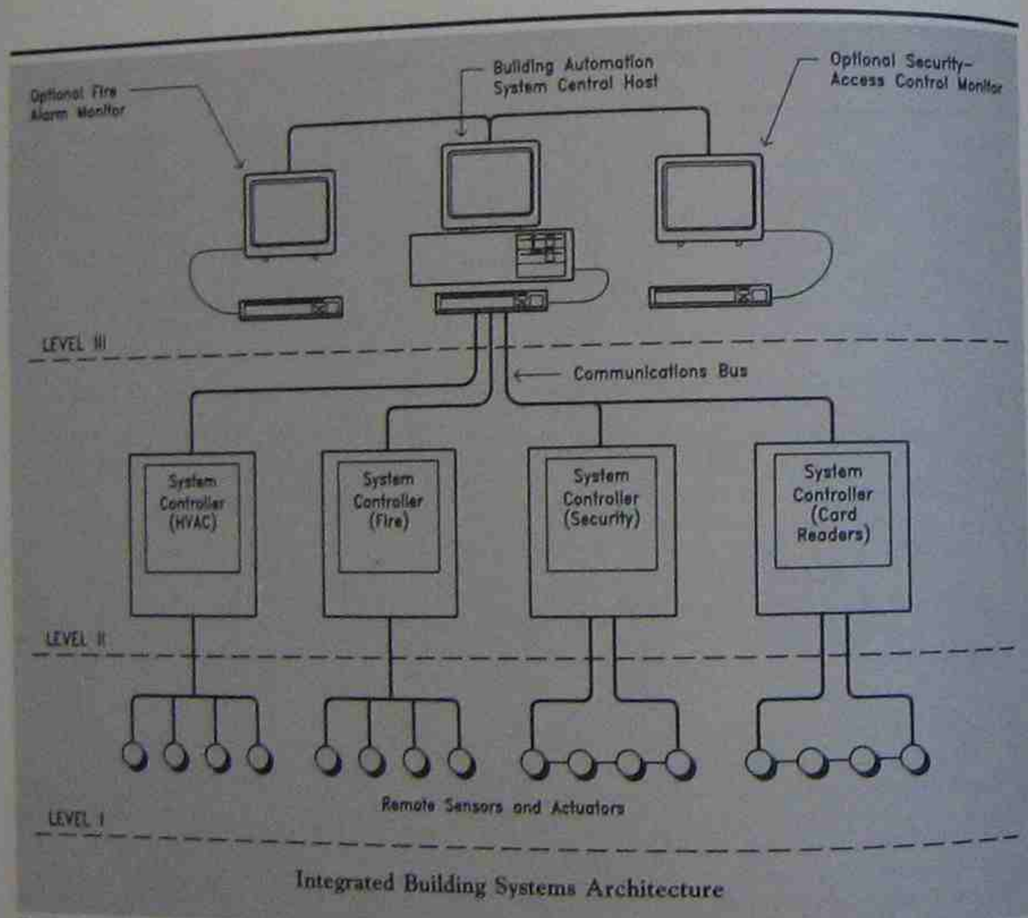


Figure 3.13

The information transmitted by the HVAC, fire, security, and access controllers to the central host can be segregated for monitoring and management purposes. The HVAC operator terminal and printer, therefore, can be located apart from the fire or security terminal and printer. In many buildings, operator terminals and printers are installed in both the security office and the maintenance office. Information transmitted by the controllers is prioritized as security or HVAC and displayed only at the appropriate location. Also, access by the operator's terminal to security and fire alarm controllers and point information can only be obtained from the security office, and access to HVAC information can only be obtained from the maintenance office. A third operator terminal could be installed at a selected location to receive all alarms and building management information. Management reports, such as energy audits, alarm logs, budget reports, and utility consumption reports, could also be generated at this location.

Although hardware and software information for building systems (HVAC, fire, security, access control, lighting) can be separated physically, they can also be integrated through interactive software programs. HVAC and lighting programs can interact for occupancy control; HVAC and fire alarm programs can work together for smoke evacuation, building evacuation, and stair tower pressurization: lighting and security programs can interact to automatically illuminate a zone when an intrusion alarm is initiated.

Part Two

Applications

The proper application of a Building Automation System requires careful planning as well as an understanding of what can be achieved by installing such a system. In an existing building with an old, obsolete HVAC control system, serious consideration should be given to the installation of a Direct Digital Control (DDC) system as a first step. The DDC system can act as a stand-alone control system, but can also be connected to a central computer in the future. The energy management programs available in the DDC software can provide some financial return to partially offset the initial investment. If central control and integration of other building systems (fire, security, access control, and lighting) are important, the central computer can be installed with the DDC system to accomplish these goals.

For new buildings, DDC is state-of-the-art for HVAC control systems. It provides flexibility, accuracy of control, and dependability. Connecting the DDC system to a central computer provides the option of integrating all building systems. It also offers the building owner and his operating staff numerous programs to assist them in monitoring and managing energy consumption and operating costs. The integration of building systems during the initial construction of a new building is the least expensive approach.

Chapter Four

Direct Digital Control (DDC)

For many years, computers have been used to monitor, supervise, and carry out energy management strategies on heating, ventilating, and air-conditioning systems. Pneumatic and electric control systems provided space temperature control and local loop control at the HVAC units. These control systems, although not energy efficient, did provide an acceptable level of comfort and, with a preventive maintenance program, a reasonable degree of reliability. The central computer, although expensive and complicated, gave building owners and operating personnel some management and control over energy-consuming systems in their buildings.

The advent of microelectronic technology revolutionized the automatic control industry. Microprocessor-based controllers could be installed in a mechanical equipment room and could perform the control loop functions previously assigned to conventional pneumatic, electric, and electronic control systems. They could also provide energy management and monitoring programs formerly performed by the central mainframe, or minicomputer. The introduction of the microprocessor reduced costs, increased reliability, improved accuracy, and provided a flexibility of control previously unachievable with conventional controls. Maintenance requirements were also dramatically reduced.

HVAC systems maintain comfort conditions in a building or building zone through the action of several *control loops*. A control loop consists of a sensor (for temperature, pressure, or humidity), a controller, and a final control element.

The sensor monitors the controlled variable and sends an input signal to the controller. The controller compares this signal to a preprogrammed set point. If the signal deviates from the set point, the controller sends an output signal to the final control element. The final control element then varies the controlled process to correct the deviation.

Input signals to the DDC controller take one of two forms: digital or analog. A digital input (DI) signal is a two-position signal, such as a switching action, where contacts are in either the closed or open position. This could be a signal from auxiliary contacts on a motor starter to indicate that the starter is energized. An analog input (AI) signal is a continuously changing input, such as a signal from a temperature or humidity sensor.

Output signals from a controller are also either digital or analog. A digital output (DO) signal is a two-position mode of control similar to a switching action. This mode of control would be used to start or stop a fan, or to control lighting in an on-off manner. An analog output (AO) signal is a variable output signal that can be used to modulate a valve or damper motor.

When all required remote sensors and controlled devices have been connected to the controller, the software programs for the appropriate control loops can be activated. Set points, reset schedules, sequencing, alarm limits, operating schedules, interlocks, and many other control options can now be programmed to create a fully operating control system. Modifications or revisions to control sequences, settings, or programs, can be made from an operator's terminal, without interfering with system operation.

Since energy management programs are also included in the controller memory, they too can be activated, if desired. In many cases, the sensors and the controlled devices connected to the controller for control loop purposes may be utilized for energy management programs as well.

The application of direct digital control to any system should be approached systematically. First, determine what control loops are required to create the desired environmental conditions. Include any energy management programs and monitoring requirements that you wish to accomplish. Next, make a schematic layout of the HVAC system and all its controlled devices, such as control valves, motorized dampers, magnetic starters, lighting contactors, relays, and so forth. Add sensors and other input devices in their appropriate locations. Extend all sensors, input devices, and controlled devices to a central location and label them digital inputs (DI), analog inputs (AI), digital outputs (DO), or analog outputs (AO).

Ventilation Control

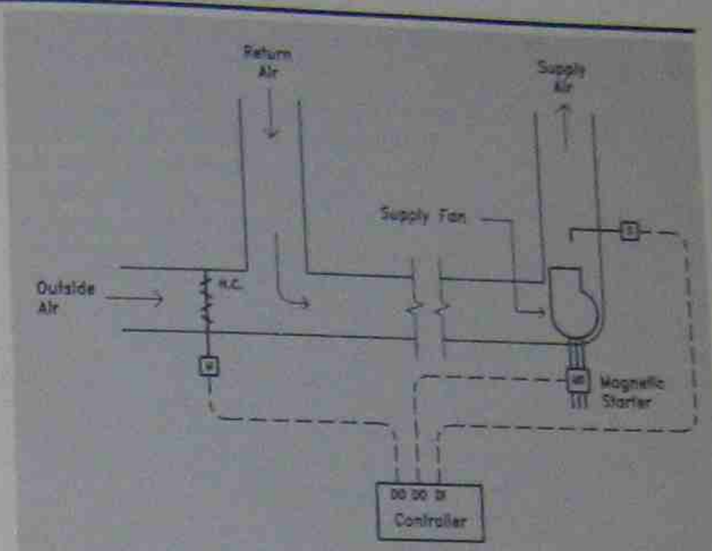
DDC control loops for damper operation are available to provide ventilation requirements or to utilize outdoor air for cooling. The following are some of the more common programs.

Fixed Quantity of Outdoor Air

This control loop provides a fixed minimum amount of outside air for ventilation whenever the HVAC fan is energized. The minimum outdoor air damper moves to the full-open position when the fan is energized. When the fan is de-energized, the damper returns to the closed position. (See Figure 4.1)

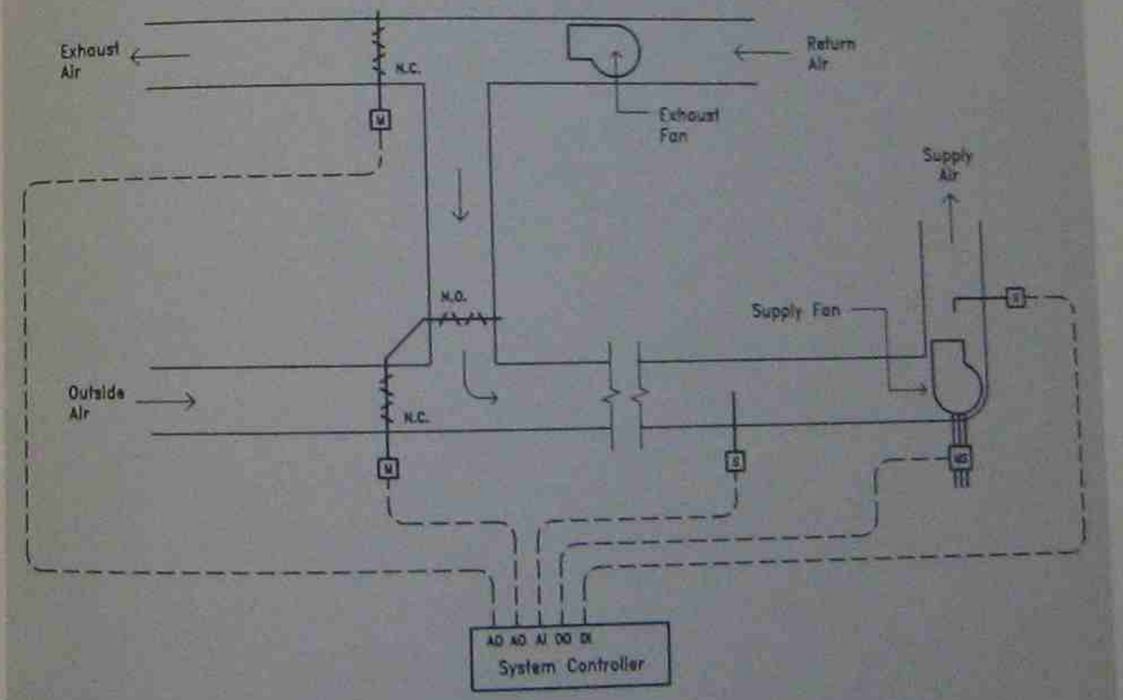
Mixed Air Control

When the HVAC unit fan is energized, as sensed by a static pressure sensor, the damper control system becomes energized. A temperature sensor located in the mixed air modulates the outdoor and return air dampers to maintain mixed air temperature. A minimum outdoor air damper position can be set at the controller to ensure that minimum ventilation requirements will be met. If the system has an exhaust or relief damper, it will modulate in unison with the outdoor air damper. When the unit fan is de-engergized, the damper control system becomes de-energized, the outdoor air damper closes, and the return air damper opens. (See Figure 4.2)



Fixed Quantity of Outdoor Air

Figure 4.1



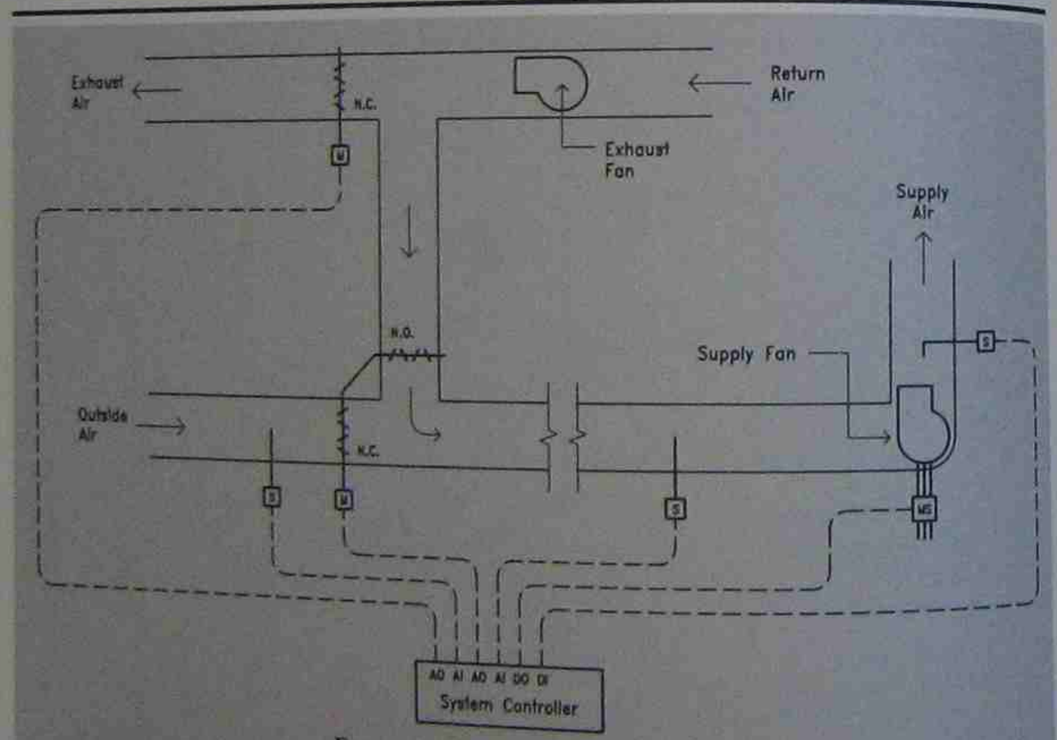
Mixed Air Control

Figure 4.2

Economizer Control of Mixed Air

The economizer control system provides a means of cooling a building using outdoor air, thereby saving energy that would otherwise be consumed if mechanical cooling were utilized. The basic concept for economizer control of mixed air is the same as for mixed air control (previously described), but also uses a system of dampers, temperature and humidity sensors, and actuators, to maximize the use of outdoor air for cooling.

A sensor mounted in the mixed air modulates the outdoor and return air dampers to maintain mixed air at a suitable temperature for cooling (usually 55°F). A minimum outdoor air damper position can be set at the controller to maintain minimum ventilation requirements. An outdoor air sensor returns the outdoor air damper to the minimum position when outdoor air temperature increases to a level at which it is no longer suitable for cooling (usually 65°F). If the system has an exhaust or relief damper, it will modulate in unison with the outdoor air damper to avoid overpressurization of the building. When the unit fan is de-energized, the outdoor air damper closes, and the return air damper opens.



Economizer Control of Mixed Air

Figure 4.3

With sensors already installed in the mixed air and outdoor air, the controller can be programmed to reset the mixed air temperature at a higher level as outdoor air temperature decreases. This is an energy saving measure, since the mixed air must be heated before it is discharged into the building. Figure 4.3 shows the arrangement for either standard economizer or reset control.

Heating Control

There are numerous software strategies for heating applications. Programs are available to reset temperatures as a function of outdoor air temperature, for sequencing heating with cooling, or simply to control heat from discharge air or space temperature.

Constant Temperature Hot Water Control (Boiler)

A sensor installed in the system supply maintains water temperature by one of two methods: The controller can, through a digital output point, direct-fire the oil, gas, or electric source of heat. Or, the boiler can be maintained at a constant water temperature and a three-way control valve can be modulated, mixing boiler and return water to maintain supply water temperature. If the space heating units (radiation or heating coils) have two-way control valves, a differential bypass valve and sensor should be installed. As the two-way control valves close during low-load conditions, the pressure difference across the pump will increase. The differential pressure sensor will sense the increase and, through the controller, modulate the bypass valve toward the open position to maintain a constant pressure across the system. (See Figures 4.4 and 4.5)

Constant Temperature Hot Water Control (Heat Exchanger)

Constant temperature discharge control from a steam to hot water heat exchanger is accomplished by using a sensor in the discharge water that modulates a control valve in the steam supply. A normally-closed steam valve is recommended for this application. If the pump fails, the differential pressure sensor will sense the drop in pressure difference and close the steam valve. The differential pressure sensor will also maintain a constant pressure difference across the system by modulating the pump bypass valve as system two-way control valves close during load-low conditions. (See Figure 4.6)

Hot Water Reset Control (Boiler)

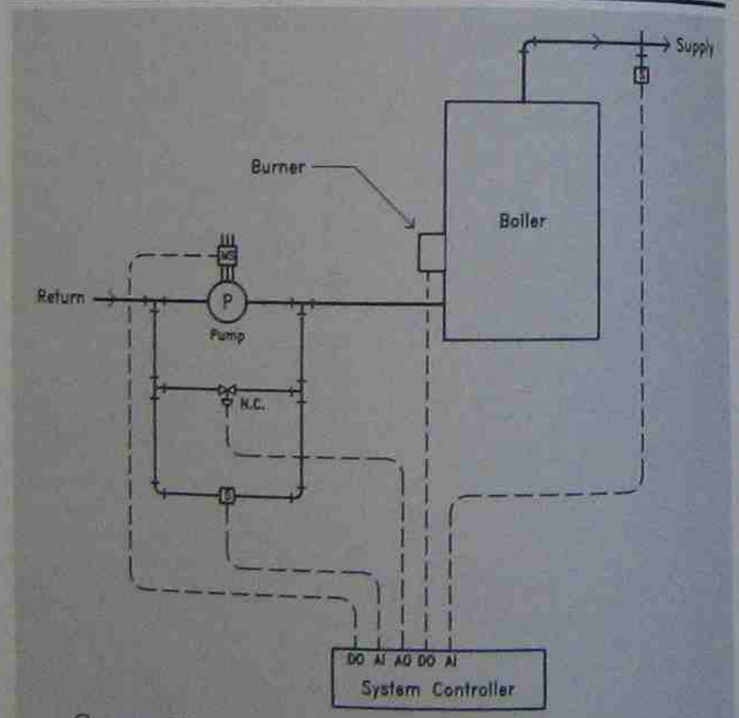
The addition of an outdoor air sensor to the control loop previously described for the constant temperature hot water control (boiler) will convey outdoor temperature information to the controller, which (through software programs) will then reset the discharge water temperature as a function of outdoor air temperature. This measure saves energy as well as wear on seats and discs of control valves located on radiation and heating coils. The outdoor air sensor can also shut down the system supply pump at a predetermined outdoor air temperature when heating is no longer required. (See Figures 4.7 and 4.8.)

Hot Water Reset Control (Heat Exchanger)

Again, the addition of an outdoor air sensor to the control loop previously described for constant temperature hot water control (boiler) will (through controller software programs) reset the discharge water temperature as a function of outdoor air temperature for the heat exchanger. This is an energy saving program and also saves wear on seats and discs of control valves located on radiation and heating coils. Again, the outdoor air sensor can shut down the system supply pump at a predetermined outdoor air temperature when heating is no longer required. (See Figure 4.9.)

Discharge Air Control (HVAC) – Heating

This control loop provides for a constant discharge air temperature. A duct-mounted sensor on the discharge side of the supply fan modulates a control valve in the steam or hot water supply to the heating coil to maintain the controller set point. If there is a chance that air could enter the heating coil at or below 32°F, a low-temperature safety controller should be installed on the discharge side of the heating coil. This controller, through software programs, can initiate corrective action if a coil freeze-up situation occurs. (See Figure 4.10.)



Constant Temperature Hot Water Control (Direct Fire)

Figure 4.4

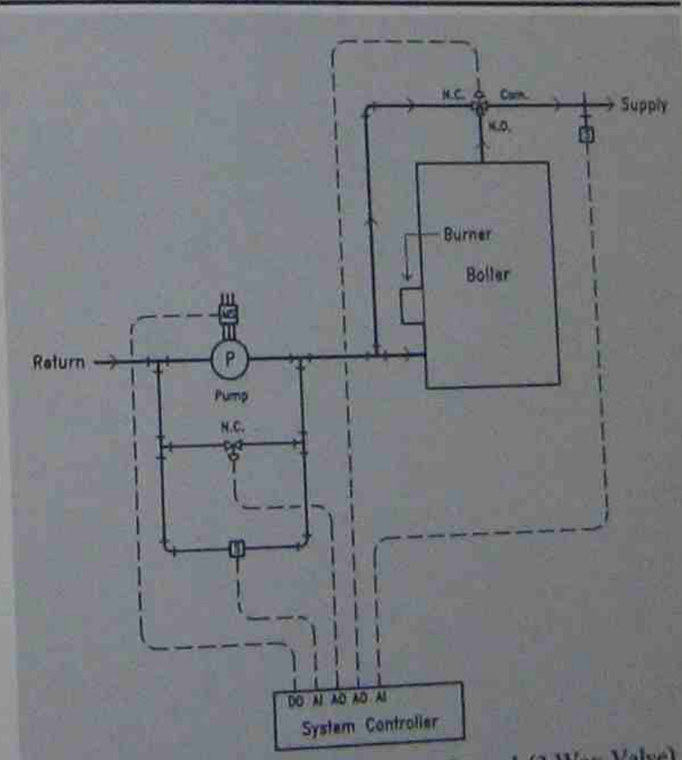
If electric heat is utilized, the same control loop may be used except that the analog output to the control valve will be replaced with multiple digital outputs to control multiple stages of electric heat. If modulated electric heat is desired, an SCR (Silicon Control Rectifier) control may be installed, which can be controlled from an analog output similar to the control valve.

Discharge Air Reset Control (HVAC) – Heating

The addition of an outdoor air temperature sensor, operating in concert with a discharge air sensor, provides reset capability. The controller can receive signals from the two sensors and reset the discharge air sensor as a function of outdoor air temperature. (See Figure 4.11)

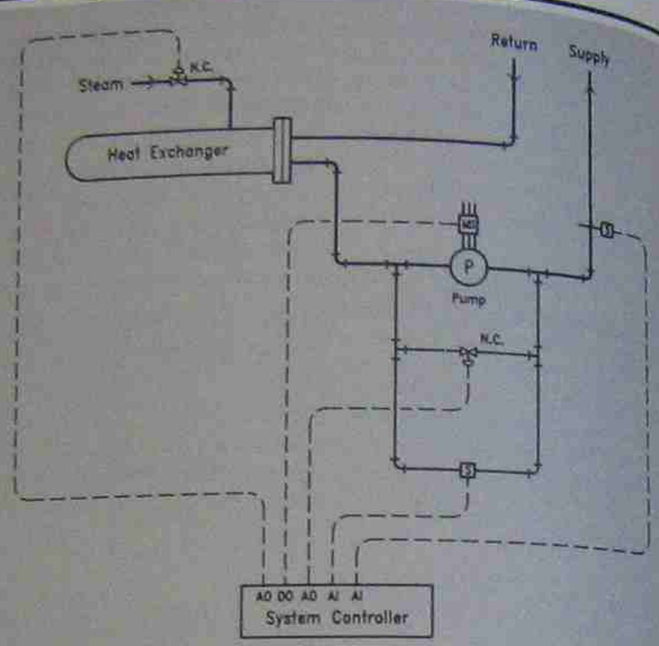
Space Temperature Control (HVAC) – Heating

A space temperature sensor acts as a primary sensor for an HVAC system. The sensor modulates a control valve in the steam or hot water supply to a heating coil, or cycles several stages of electric heat through



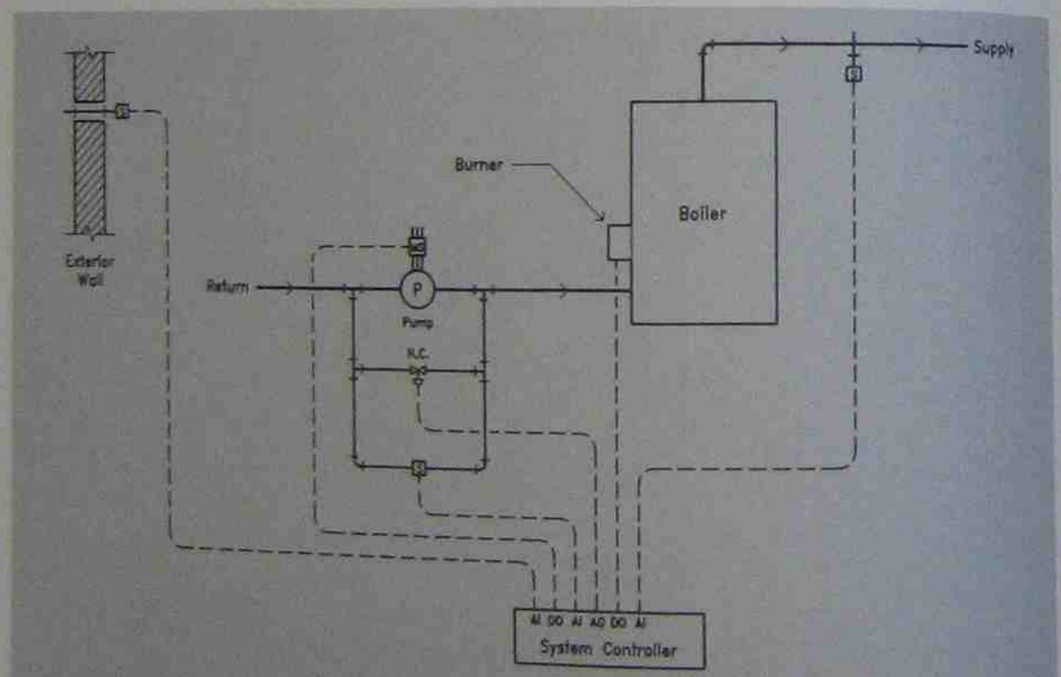
Constant Temperature Hot Water Control (3-Way Valve)

Figure 4.5



Constant Temperature Hot Water Control (Heat Exchanger)

Figure 4.6



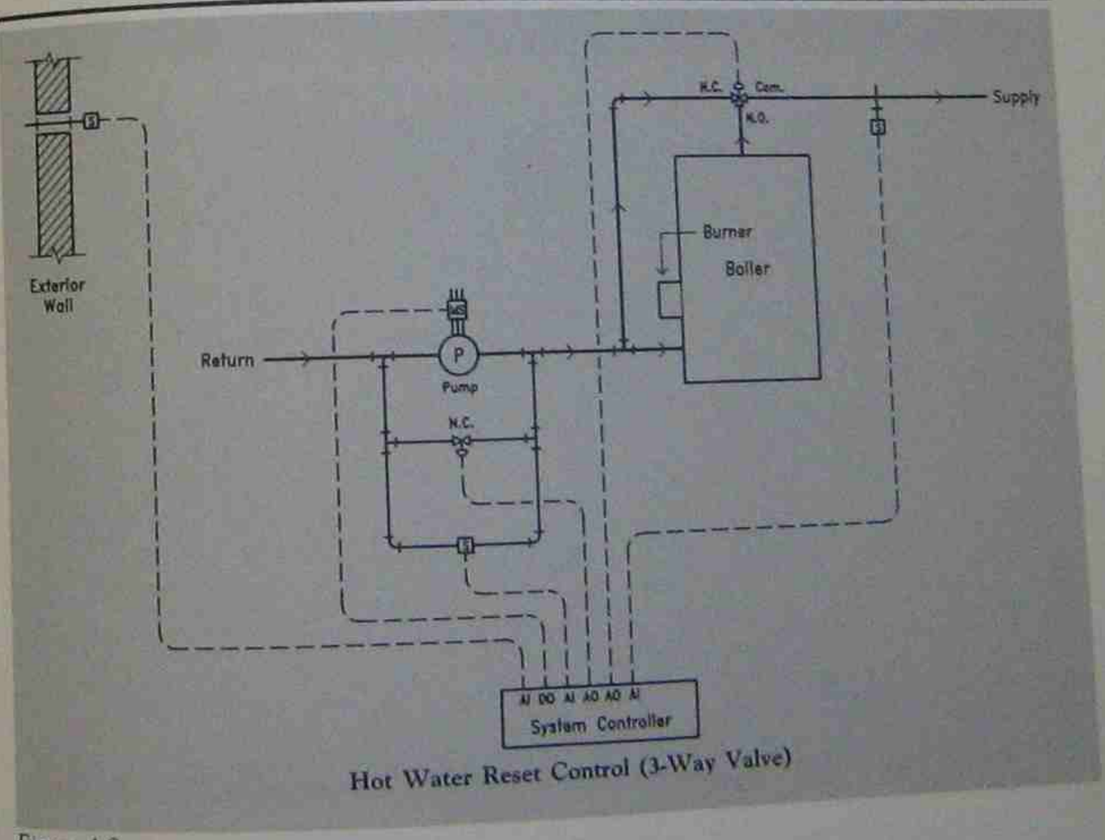
Hot Water Reset Control (Direct Fire)

Figure 4.7

multiple digital outputs. The discharge air sensor acts as a discharge low limit to maintain a minimum discharge air temperature. A reset software program can be applied so that the space sensor resets the discharge air temperature according to a predetermined schedule. Regardless of which strategy is applied, the layout will be as shown in Figure 4.12.

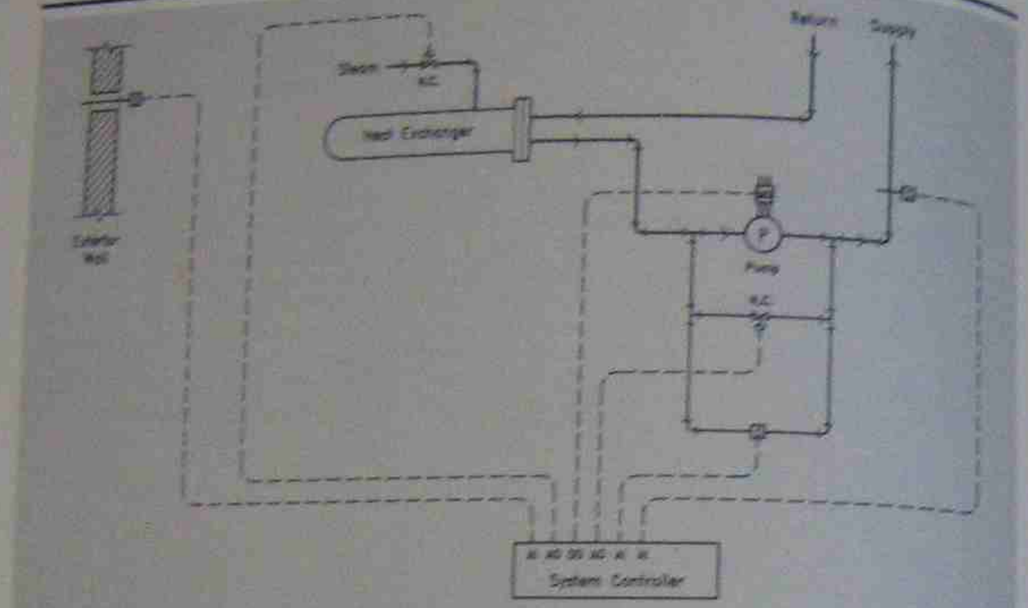
Cooling/Heating, Humidification/ Dehumidification Control

Included in Direct Digital Controllers are software programs for cooling control similar to those used for heating control, as discussed earlier in this chapter. The layout for discharge air control, in the case of a chilled water coil, is identical to Figure 4.10 in this chapter. If the source of cooling is a direct expansion coil, discharge control is not recommended. This could short cycle the compressor due to the large temperature drop when the compressor system is energized. The best application would be to control from a space sensor or a return air sensor. Discharge air reset control and space temperature control for chilled water cooling applications are the same as shown in Figures 4.11 and 4.12, respectively.



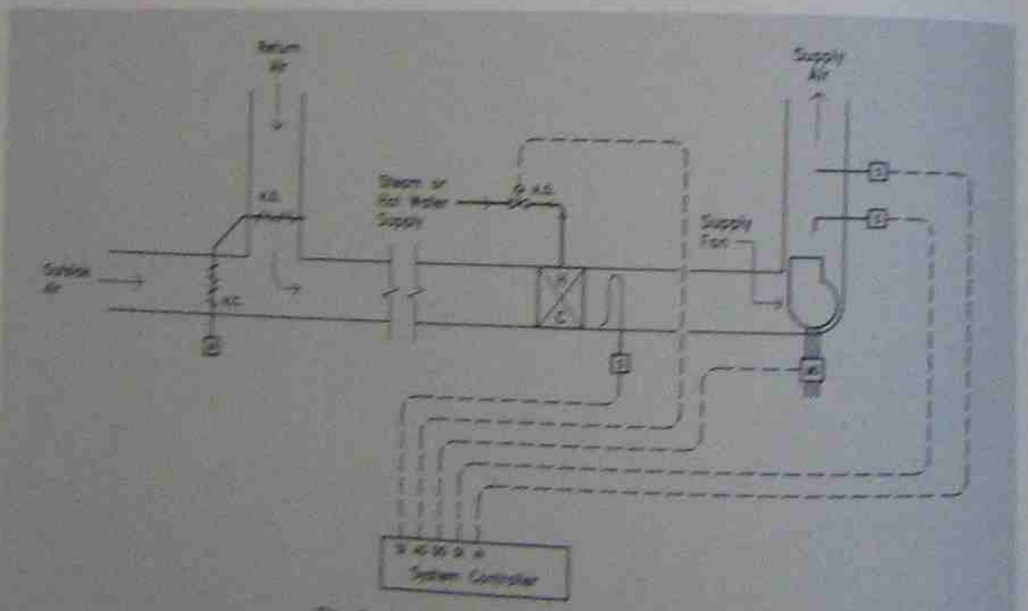
Hot Water Reset Control (3-Way Valve)

Figure 4.8



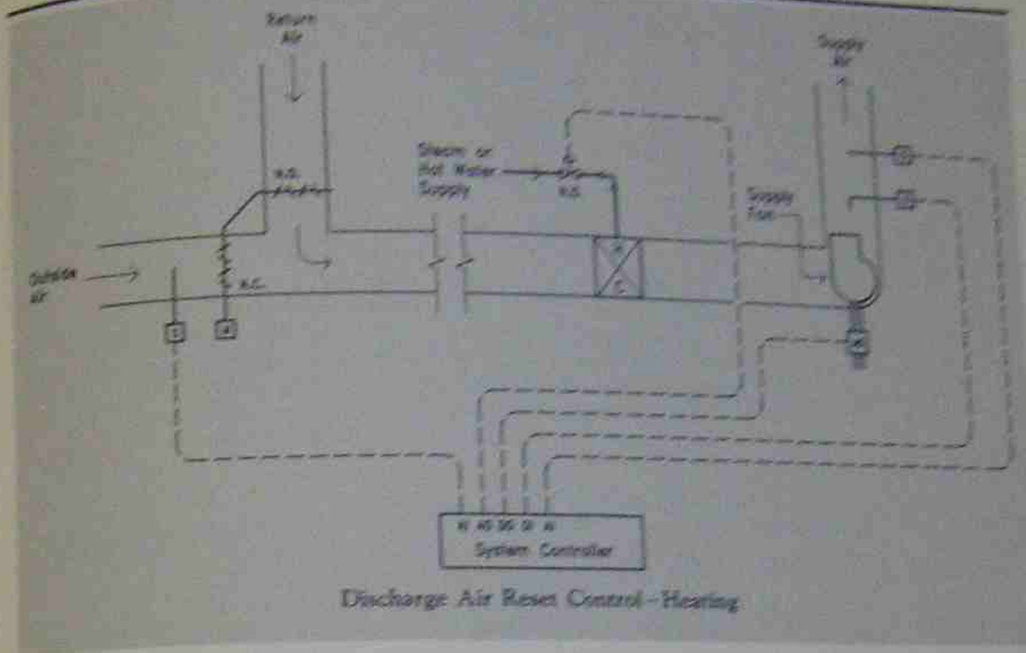
Hot Water Reset Control (Heat Exchanger)

Figure 4.9



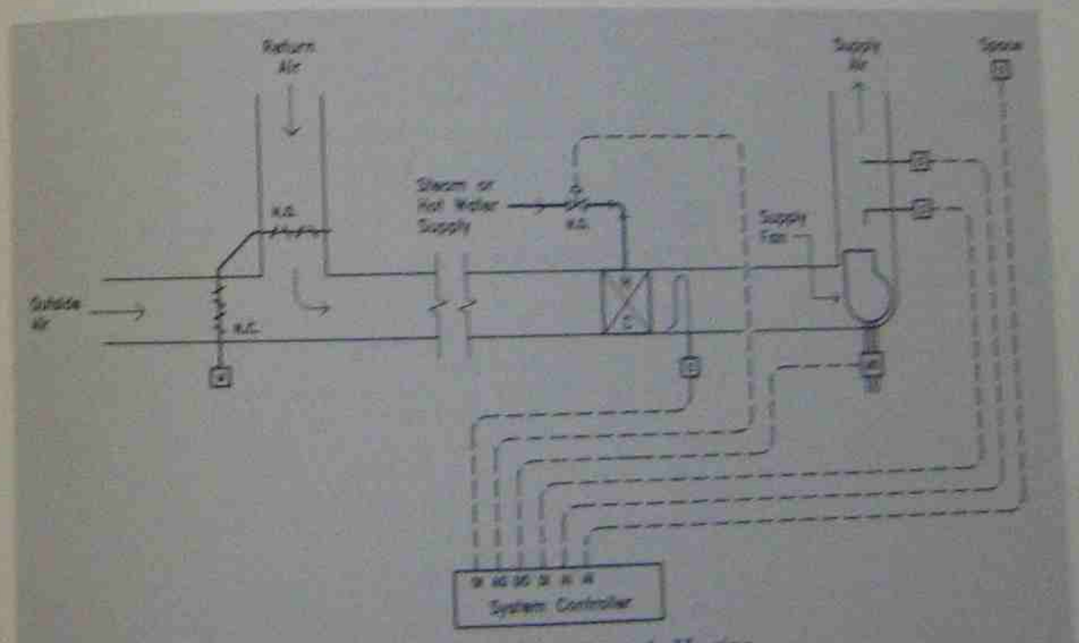
Discharge Air Control - Heating

Figure 4.10



Discharge Air Reset Control - Heating

Figure 4.11



Space Temperature Control - Heating

Figure 4.12

Chilled Water Control (Centrifugal/Reciprocating)

Centrifugal refrigeration machines are controlled by a sensor installed in the system's chilled water supply. The sensor, through the controller, modulates the inlet vane actuator to maintain chiller discharge water temperature. The chilled water pump is started from a digital output point. A differential pressure sensor, installed across the pump, enables the chiller to operate through a digital output point when water flow has been established. An outdoor air sensor (dry bulb or dewpoint) or a return water sensor can be installed to reset the discharge water sensor setting. This reduces energy consumption by decreasing the pressure rise across the compressor.

Reciprocating chillers are also controlled by a sensor in the chilled water supply. However, the controller operates the compressors in a two-position manner through digital output points. Multi-stage chillers will have multiple digital output points. Like the centrifugal system, the chilled water pump for the reciprocating chiller is energized from a digital output point, and uses the same operating principles. Figure 4.13 shows the control loops for centrifugal and reciprocating chillers.

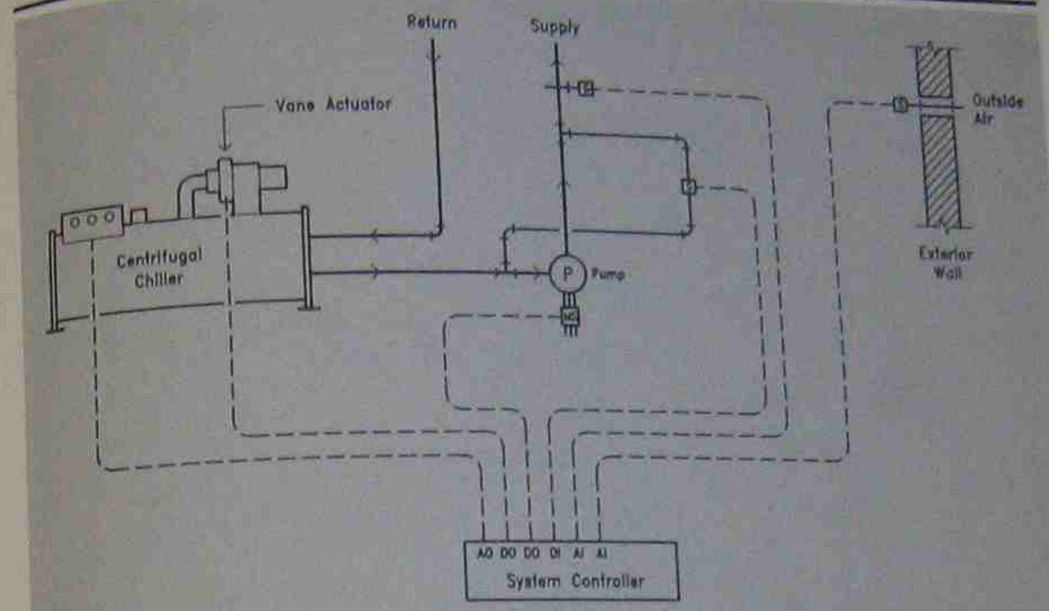
Dehumidification Control

Dehumidification control can be accomplished by means of a chilled water coil or a direct expansion (DX) coil. In the case of a chilled water coil, a space humidity sensor modulates, or two-positions, a control valve in the supply to the chilled water coil. A reheat coil should be installed downstream from the chilled water coil to reheat the dehumidified air. A space temperature sensor modulates the chilled water coil valve and reheat coil valve in sequence to maintain space temperature conditions. The space humidity sensor overrides the temperature sensor and opens the chilled water coil valve if space relative humidity exceeds its setting. The space temperature sensor maintains its set point by modulating the reheat coil valve.

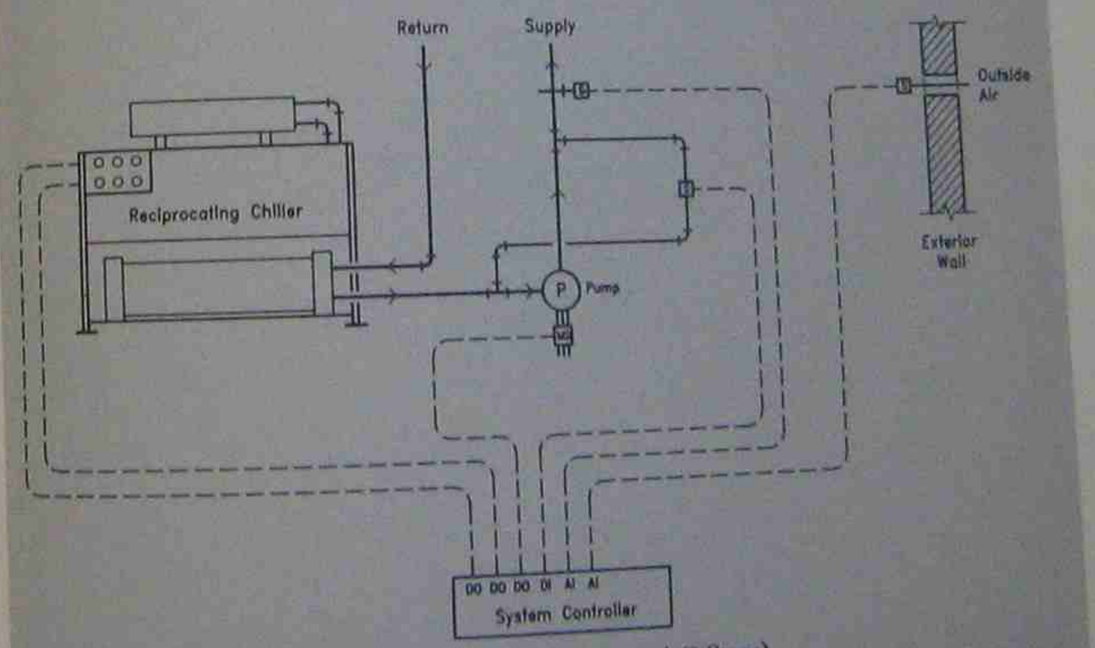
If direct expansion dehumidification is used, the control sequence will be identical to that for chilled water, except that the compressor will be cycled through a digital output point. Figure 4.14 shows the layout for this application.

Humidification Control

A space humidity sensor maintains space relative humidity by modulating a control valve on a steam humidifier. A high-limit, duct-mounted humidity sensor located downstream from the humidifier overrides the space sensor and maintains 85% to 90% relative humidity in the supply duct. This prevents over-humidification and condensation in the supply duct. Some humidifiers require a two-position mode of control which would necessitate a digital output point. When the unit supply fan is de-energized, as sensed by a static pressure sensor, the humidifier becomes inoperable. The humidification control loop is shown in Figure 4.15.

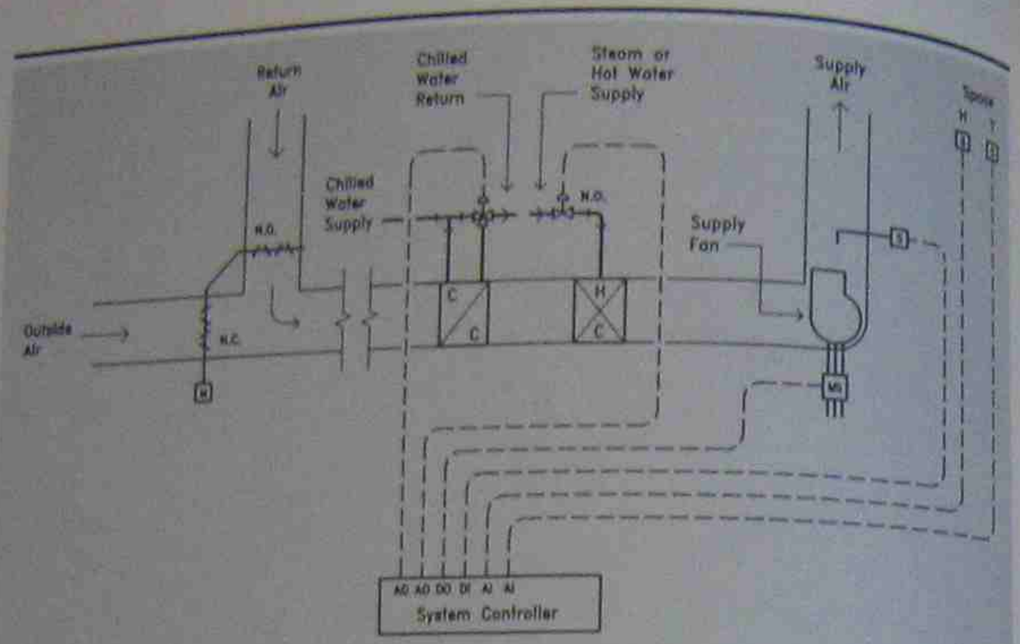


Centrifugal Chiller Control



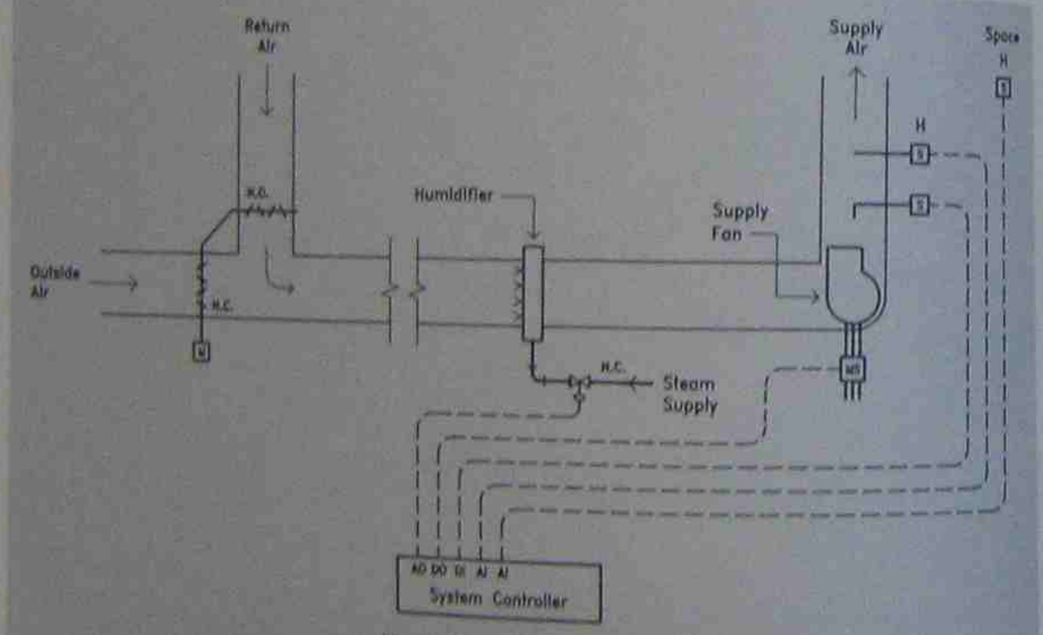
Reciprocating Chiller Control (2-Stage)

Figure 4.13



Dehumidification Control

Figure 4.14



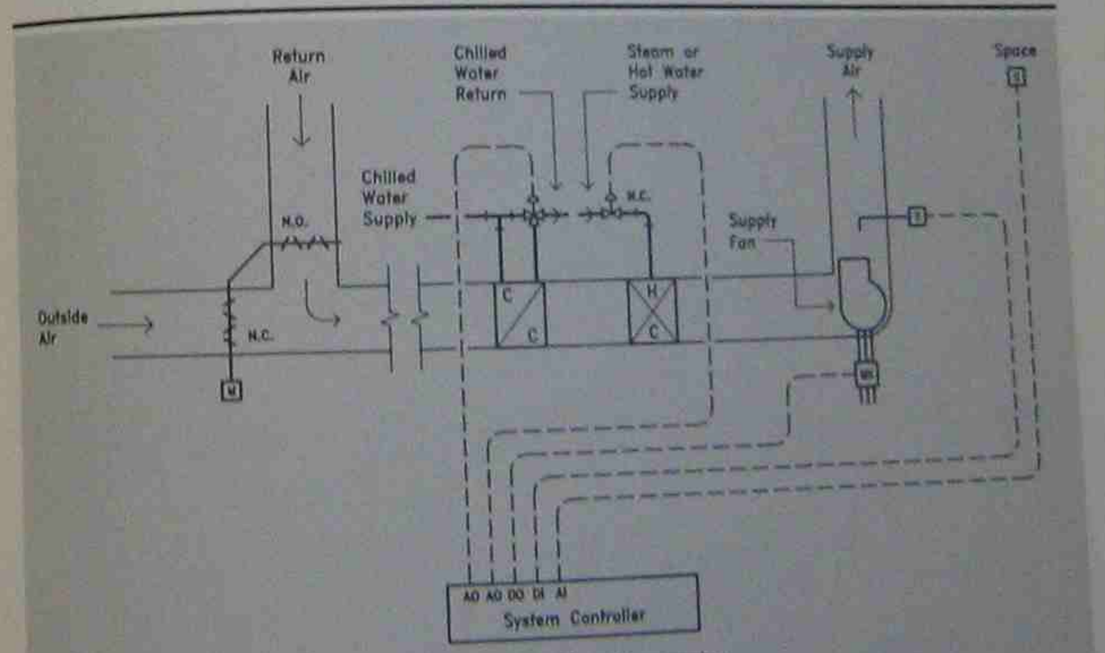
Humidification Control

Figure 4.15

Heating–Cooling Sequencing

A space temperature sensor, or duct-mounted discharge air sensor may be used to control the heating coil valve in sequence with the chilled water coil valve. As an energy saving feature, most DDC controllers have a *deadband program*. This means that an adjustable number of degrees can be programmed between the heating and cooling modes. During this deadband, both the heating and cooling coil valves will be closed, and no energy will be consumed. Although this will result in wider-than-normal temperature swings in the space, these swings can be limited to acceptable comfort levels. Figure 4.16 shows the heating-cooling sequencing control loop, with hot water or steam for heating and chilled water for cooling.

When direct expansion cooling and electric heat are controlled, the same sequencing control software is used. However, the heating and cooling control outputs will change to digital outputs, as required by the number of stages of electric heat and direct expansion cooling. When the supply fan is de-energized, as sensed by the static pressure sensor, the direct expansion cooling and the electric heat will be inoperable.



Heating–Cooling Sequencing

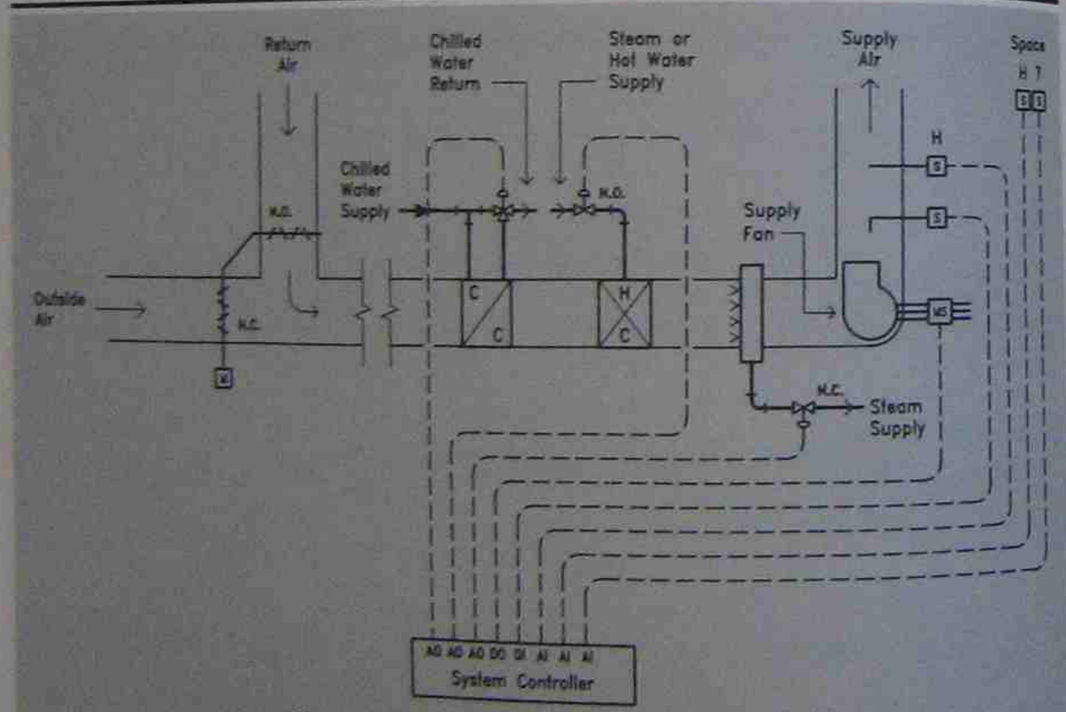
Figure 4.16

Humidification – Dehumidification Sequencing

This control loop employs the same basic software programming as the heating-cooling sequencing. A space humidity sensor modulates the humidifier steam valve in sequence with the chilled water valve to maintain space relative humidity. As mentioned under *Dehumidification Control*, a reheat coil is necessary to prevent subcooling during the dehumidification cycle. The space temperature sensor controls the heating coil valve and the cooling coil valve, in sequence, to maintain space temperature conditions. Figure 4.17 displays the layout for this control system.

Static Pressure Control

Static pressure can be controlled by two methods: 1) by modulating fan inlet vane dampers, or 2) through variable speed drives on the fan motor. In variable air volume (VAV) systems, the static pressure sensor is located in the main supply duct to the terminal units. The sensor, through the controller, maintains supply duct static pressure by modulating the system fan inlet vanes, or by modulating the fan speed through a variable speed drive. (Figure 4.18 shows the layout for controlling inlet vanes to maintain duct static pressure in a variable air volume system.)



Humidification – Dehumidification Sequencing

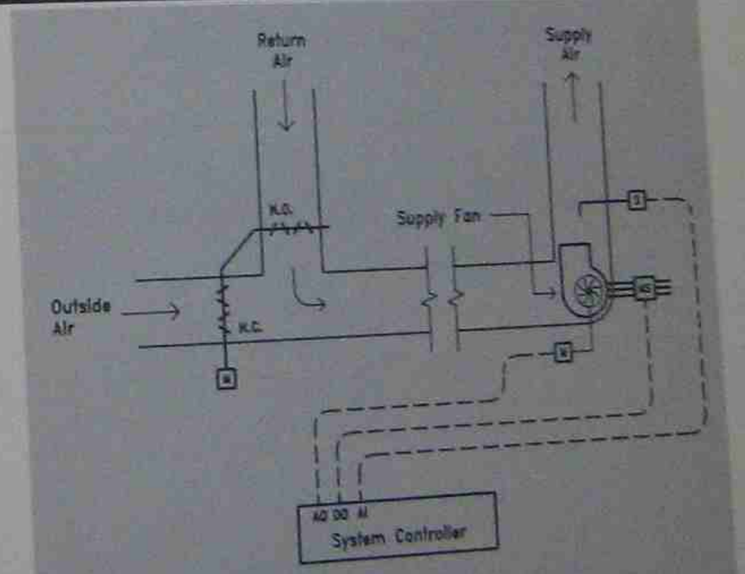
Figure 4.17

Variable speed drives provide excellent fan speed control and are usually designed for 3 to 15 pounds, 4 to 20 milliamps, or 2 to 12 VDC inputs. These inputs fall within the scope of most DDC controller output capabilities. For direct building or floor static pressure control, the sensor is located in the space and is referenced to an appropriate location outside the building. With the VAV system, the controller either modulates the return air fan inlet vanes or controls a variable speed drive to maintain static pressure in the space.

Variable Air Volume System Terminal Box Control

Most variable air volume systems supply air at approximately 55°F year-round. With a decrease in space temperature, the space sensor, through the zone controller, throttles the VAV box, thereby reducing the volume of cool air entering the space and allowing the space temperature to increase. Areas located around the perimeter of the building may require reheat coils or radiation to maintain space temperature during severe winter periods.

VAV systems require some form of static pressure control at the fan. This is necessary to compensate for periods in which a large number of VAV box dampers in the system move to the closed position, resulting in an increase in static pressure in the supply duct. See the section titled *Static Pressure Control* and Figure 4.18 in this chapter for an explanation of this control loop.



Duct Static Pressure Control

Figure 4.18

Pressure Independent – Cooling Only

In cooling-only applications, the space sensor (through the controller) regulates the airflow regardless of variations in supply duct pressure. The minimum and maximum airflow that are needed (as sensed by an airflow sensor) to ensure ventilation requirements are met during low-load conditions and prevent excessive delivery of cool air during periods of high-demand. Figure 4.19 shows this application.

Cooling and Electric Reheat

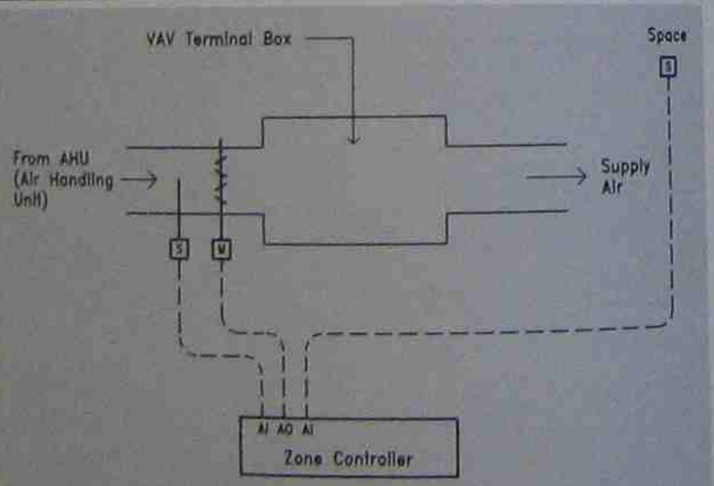
When electric reheat is included in the terminal box, an adjustable deadband can be programmed between the cooling and heating cycles. On a drop in space temperature, the sensor modulates the damper toward the preset minimum position. The damper will remain at the minimum position throughout the desired deadband. On a continued drop in space temperature, the electric heat will be energized in stages. (See Figure 4.20.)

Cooling and Hot Water Reheat

This application is identical to that outlined in the section *Cooling and Electric Reheat*, except that the stages of electric heat are replaced with a modulating valve controlling a hot water coil. The adjustable deadband also applies to this application. (See Figure 4.21.)

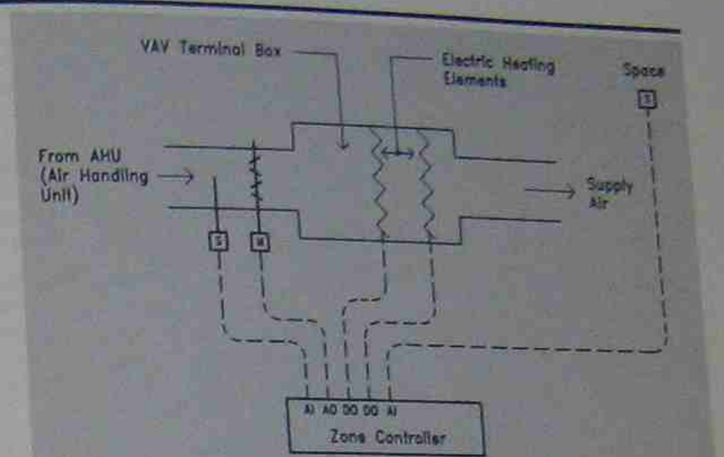
Fan-Powered Return Air Heat

In this application, the cooling volume damper is sequenced with the return air fan. Upon a decrease in space temperature, the space sensor, through the zone controller, modulates the cooling damper to the minimum position. The damper will remain at this minimum position throughout the adjustable deadband. Upon a continued drop in space temperature, the return air fan will be energized. (See Figure 4.22.)



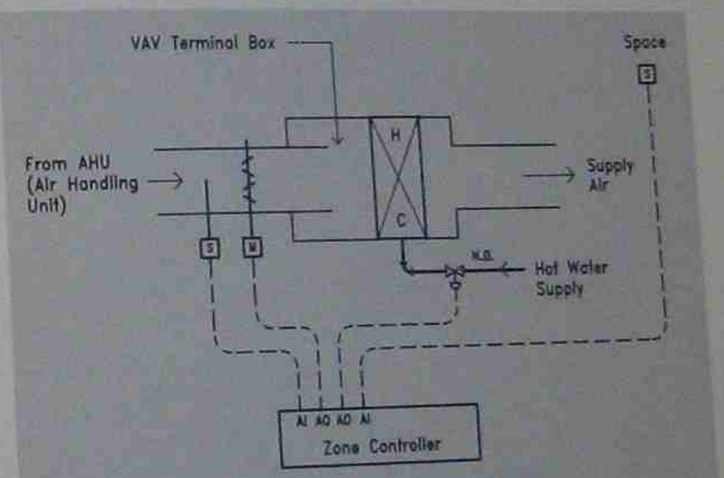
VAV Terminal Box Control – Cooling Only

Figure 4.19



Cooling and Electric Reheat

Figure 4.20



Cooling and Hot Water Reheat

Figure 4.21

Fan-Powered Return Air and Electric Heat

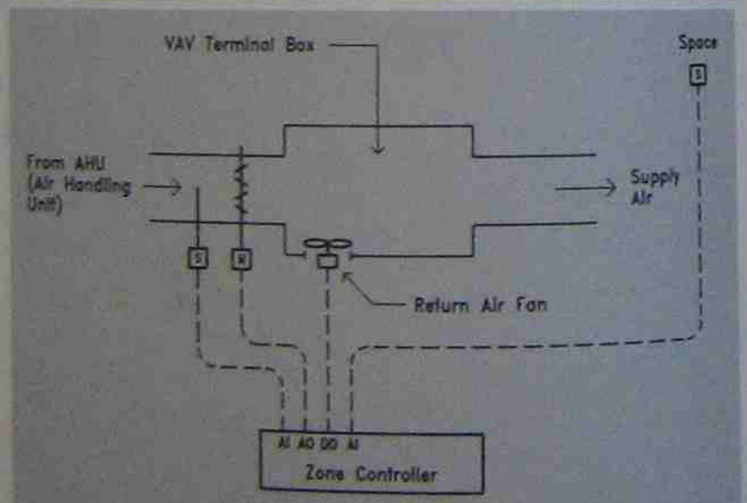
In this application, the electric heat stages and the return air fan are sequenced with the cooling damper. Upon a drop in space temperature, the space sensor causes the cooling damper to modulate to the minimum position. The damper will continue at the minimum position as long as conditions remain within the adjustable deadband range. With a continued drop in space temperature, the damper will adjust to a new heating minimum position, and the return air fan will be energized. On a call for additional heat, the stages of electric heat will be cycled on in sequence. This is shown in Figure 4.23.

Fan-Powered Return Air and Hot Water Heat

This application is identical to that outlined in the section *Fan-Powered Return Air and Electric Heat*, except that the stages of electric heat are replaced with a modulating valve-controlled hot water coil. The adjustable deadband applies to this application as well. (See Figure 4.24.)

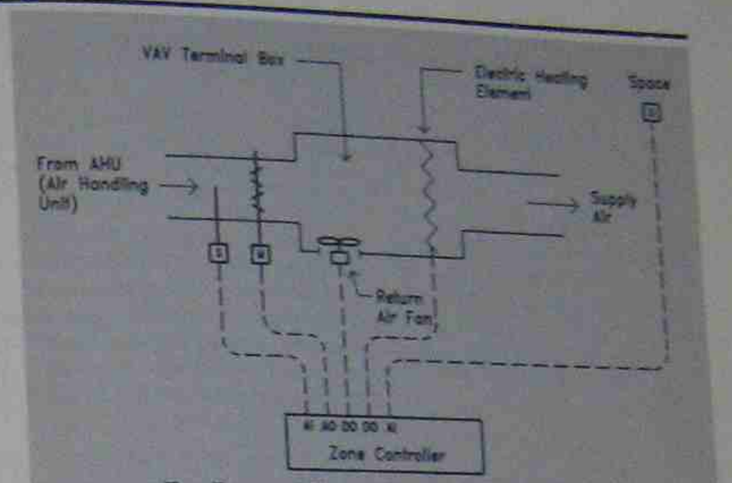
Night Temperature Setback/Setup and Morning Warm-Up/Cool-Down for Variable Air Volume Systems

When a single HVAC unit supplies multiple zones, night temperature setback or setup is traditionally accomplished by cycling the unit fan from a centrally located night thermostat. Morning warm-up or cool-down is traditionally controlled from a space thermostat or return air controller. If the zones have different occupancy schedules, energy is wasted under this method of control. This is because the system operates as one large zone, resulting in the heating or cooling of unoccupied zones.



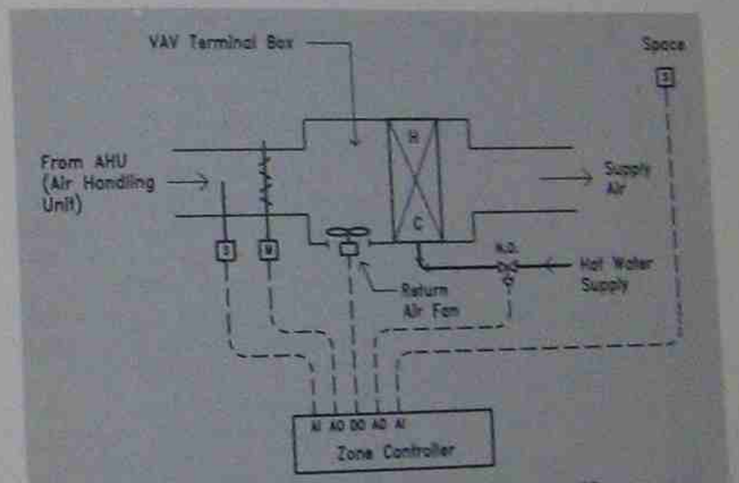
Fan-Powered Return Air Heat

Figure 4.22



Fan-Powered Return Air and Electric Heat

Figure 4.23



Fan-Powered Return Air and Hot Water Heat

Figure 4.24

With direct digital control, the VAV controller for each zone can be programmed for the appropriate occupied/unoccupied schedule and unoccupied setback/setup temperatures. Another DDC benefit is the ability to provide warm-up or cool-down on a zone-by-zone basis. When a zone controller switches from the unoccupied to the occupied mode, the VAV box will switch to the full heat or full cooling position until the space temperature reaches the occupied setting of the space sensor. Control will then revert to the space sensor.

A Typical HVAC Unit DDC System

Figure 4.25 depicts a DDC System applied to a typical heating, ventilating, and air-conditioning unit. The control system is made up of several control loops discussed in this chapter: economizer control of mixed air, heating-cooling sequencing, and humidification-dehumidification sequencing. The next step is to activate the appropriate software programs to accomplish the required sequence of operation as follows.

When the unit fan is energized, as sensed by a static pressure sensor in the supply duct, the damper control system becomes activated. A mixed air sensor maintains mixed air temperature (55°F) by modulating the outdoor air, return air, and exhaust dampers. When outdoor air temperature exceeds the setting of the outdoor air sensor, the outdoor and exhaust air dampers return to the minimum open position as programmed at the controller. The return air damper takes the corresponding open position.

A space temperature sensor, through the controller, maintains the space temperature by modulating the heating coil valve in sequence with the chilled water coil valve. A space humidity sensor, through the controller, maintains space humidity. Upon a drop in space relative humidity, the humidifier steam valve modulates toward the open position, subject to a duct-mounted high-limit humidity sensor. With a rise in space relative humidity, the humidifier steam valve modulates to the closed position, followed by the opening of the chilled water coil valve to provide dehumidification. During the dehumidification cycle, the space temperature sensor modulates the heating coil valve to maintain space temperature conditions.

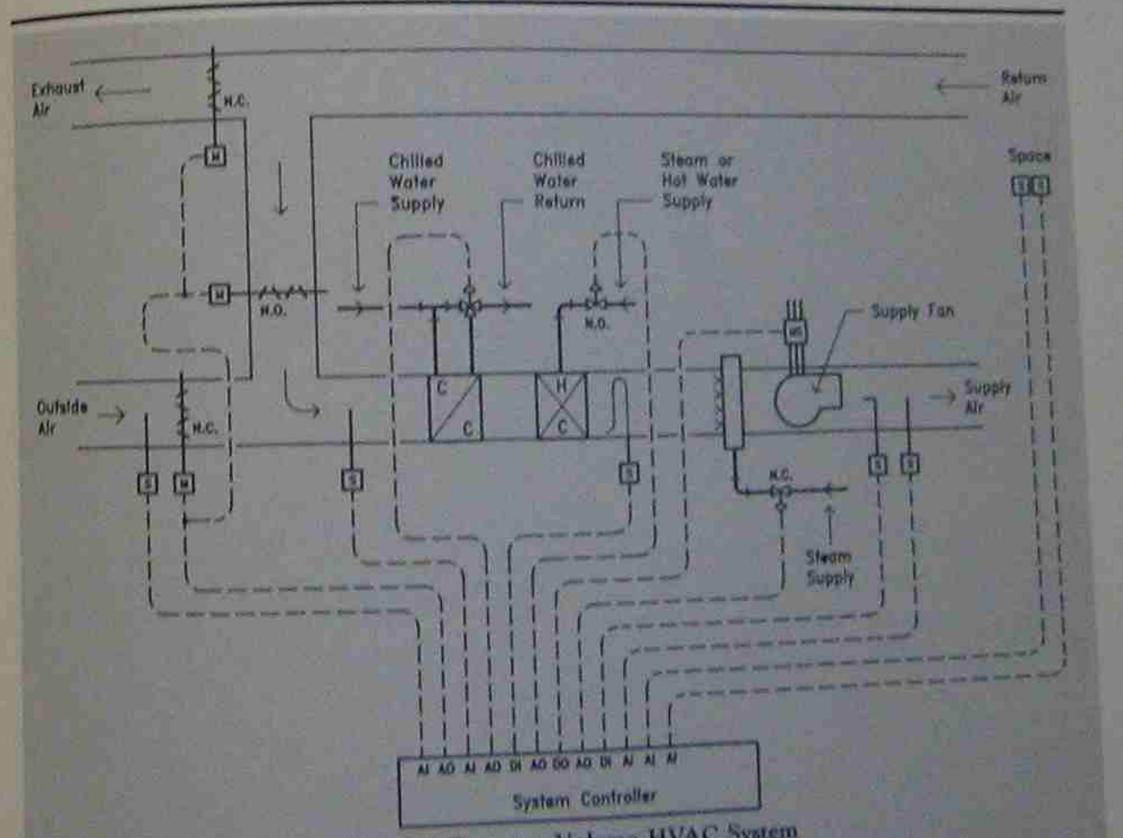
A low-temperature controller, with its capillary located on the discharge side of the heating coil, will, through the controller, de-energize the unit fan, close the outdoor and exhaust dampers, and open the return damper if discharge air temperature drops below its setting (40°F). Whenever the unit fan is de-energized, as sensed by the supply duct static pressure sensor, the damper control system will be de-activated, closing the outdoor and exhaust dampers and the humidifier steam control valve.

Host Computer

All DDC controllers are capable of operating in either a stand-alone mode or as part of a distributed process system with other controllers. Controllers can share data with each other, or with a central host computer, over a common communications bus. To assist with stand-alone operation, or to simplify maintenance, most system manufacturers offer a portable, hand-held operator's terminal which allows direct access to system point data and operating information through any controller. This terminal can also be used to issue commands or alter programs.

The central host computer is a PC that acts as an operator-machine interface to the DDC controllers. The controllers provide local loop control and energy management functions over HVAC systems. The host computer hardware includes the personal computer, with hard disk and diskette drives, keyboards, CRTs, and printers. Figure 4.26 shows a typical BAS with DDC.

Most manufacturers' software provides menu-driven selections of system functions. They provide conversational guidance in data file programming; English language descriptors and messages; current status of controller inputs and outputs; historical log printouts; and alarm monitoring, override control and programming of controllers linked to the PC over the communications bus. Figure 4.27 shows a typical CRT screen format. The printer maintains hard copy documentation of alarms and logs. Some more common application programs are described in the following sections.



Typical Constant Volume HVAC System

Figure 4.25

Storage and Retrieval of Historical Data

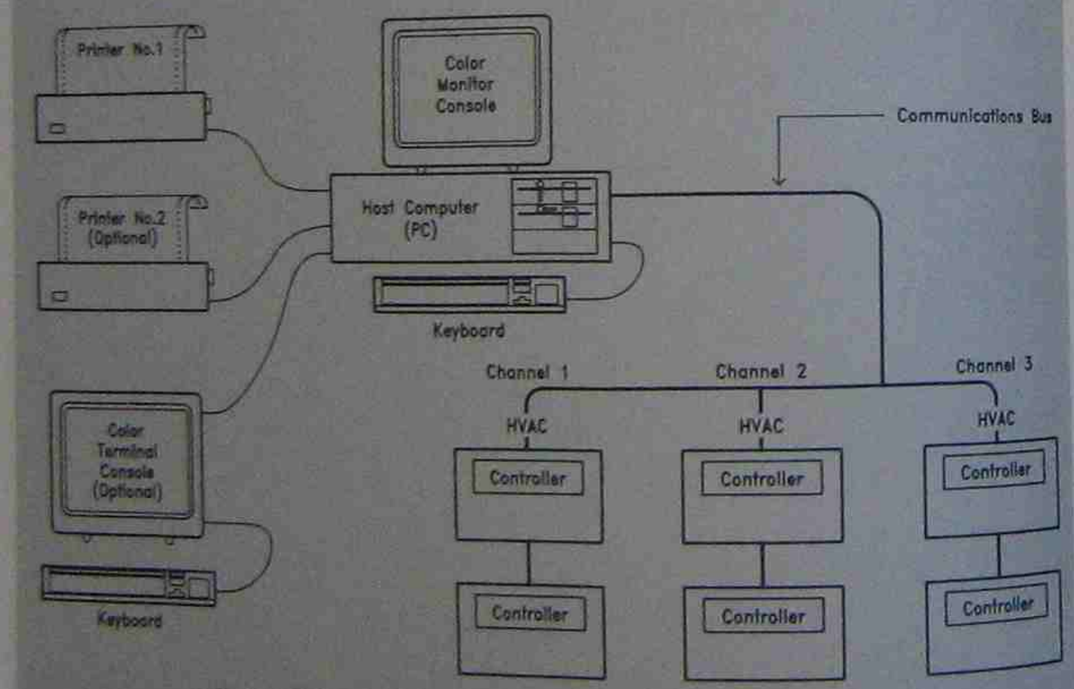
This capability can assist operating personnel in forecasting breakdowns by observing trends. Operators can initiate the storage of information on any point. They can also initiate reports manually, or program a weekly or calendar schedule for automatic initiation of reports containing the desired point data, including alarms, return-to-normal, or status of selected points.

Action Messages

Action messages can be programmed to display on the CRT and print whenever a specified point generates an alarm or trouble condition. This is extremely helpful to an operator monitoring critical points or systems. It is also helpful to a new operator who is unfamiliar with emergency procedures.

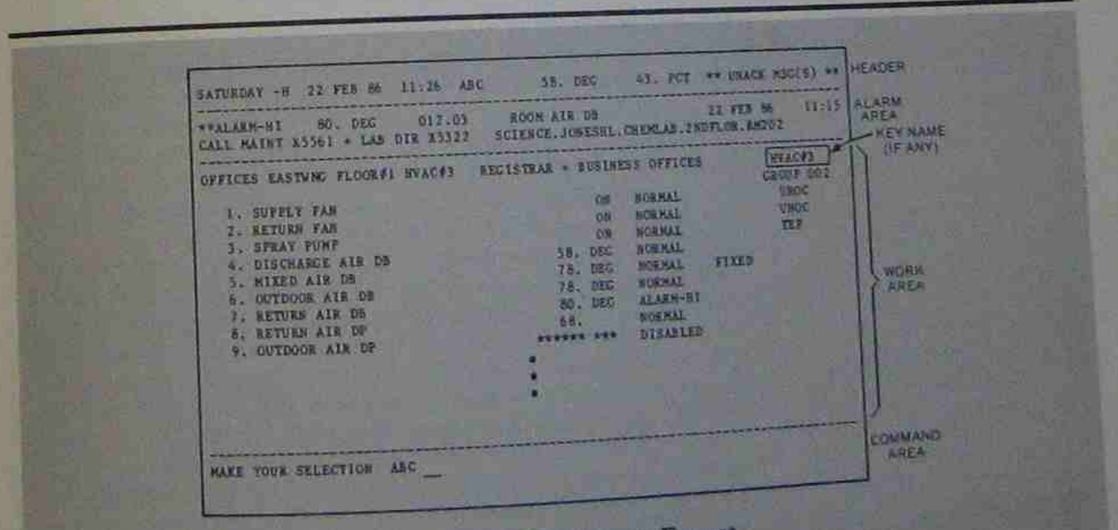
Energy Auditor Program

The energy auditor program allows the user to keep records of building energy consumption. This data assists operations personnel when reviewing and evaluating current and historical energy consumption trends. A spreadsheet format is utilized to convert measured data into meaningful statistics and historical comparisons. Output can be a listing of energy consumed per day (kilowatt hours, cubic feet of gas, gallons of oil), or the measured information can be converted to management reports (kilowatt hours or BTUs per square foot of building). The user can design the report format: everything from labels and descriptive messages, to content and display format. This program makes it possible for building management personnel to predict building energy trends, evaluate energy conservation strategies, anticipate problems, and budget energy costs more effectively.



A Typical Building Automation System with Direct Digital Control

Figure 4.26



Typical CRT Screen Format

Figure 4.27

Maintenance Management Program

This program allows the user to schedule preventive maintenance based on the run time of the equipment. Printouts document the preventive maintenance tasks, the materials and skills required to accomplish the task, and any special tools or instruments needed. The preventive maintenance activities may be scheduled based on calendar time (every 3 months, for example) or on the run time of the equipment (for example, every 400 hours). Filter changes can be scheduled upon the generation of a dirty filter alarm. This is an event occurrence method of scheduling filter changes. Work orders for preventive maintenance can be printed with the following information:

- Maintenance task instructions
- Equipment to be serviced within the building and location
- Type of tradesman required (electrician, pipefitter, etc.)
- Time required to accomplish the task
- Materials and/or special tools required.

Upon completion of the task, the actual time and materials used are entered into the data files. The program updates costs and tracks maintenance costs on an ongoing basis. This information can be retrieved and printed out for historical information on maintenance costs.

To assist in the supervision of maintenance personnel, a printout of incomplete work orders can be generated. Maintenance activity reports and work orders can be printed manually by the operator to cover unusual situations. If a historical cost summary is required on a piece of equipment, the program can print a complete maintenance activity report on that piece of equipment over any period of time.

Since the data stored in this program is sensitive, most systems have more than one level of operator access. A lower level operator may be cleared to access completed work orders and request management reports, while a higher level operator can perform the lower level functions as well as change database information.

Color Graphics

Most systems on the market today have a color graphics software option. A library of standard symbols and icon-based graphics makes on-line creation of graphics possible. Every input-output point in the DDC controllers can be displayed graphically at the host CRT. Floor layouts, zones, building elevations, HVAC systems, and piping layouts can be shown. Point data on the graphic display can include point status or value, color-coded to indicate normal or alarm condition. Representation of point status or value can be in animated form. For instance, fan status can be shown with the blades rotating when the fan is energized, and stationary when the fan is off. Damper blades can actually be shown changing from the open to the closed position. When a point goes into alarm, the associated graphics will be displayed, giving the operator a visual location of the point. The color graphics option provides a high-resolution display of building information, reports the status of all system points, and displays critical alarms for operator acknowledgment. All displays appear in multiple colors for clarification and distinction of information.

Group and Historical Logs

From the operator's terminal, an operator can request an *all-points summary*, an *alarm summary*, or a *group point summary*. An all-points summary generates a printout of the status or value of every point in the system. The alarm summary generates a printout of all points currently in alarm. The group point summary produces a printout of the status or value of all points in a logical group.

Historical trend logs store the status and value of selected points on a hard disk. This can be done over designated periods of time. It is a valuable tool in the hands of maintenance personnel seeking to identify potential HVAC system problems.

Line Graphs, Bar Charts and Pie Charts

This program takes historical database information and transfers it to a spreadsheet program. The operator can construct bar or pie charts or line graphs using the spreadsheet information. These charts and curves display data and trends in more understandable form than a simple column of figures. Figure 4.28 shows some sample charts and graphs.

Voice Communications Option

Most BAS's on the market today offer a voice communications option. This program allows the user to receive notification of alarms or other specified information at a preprogrammed telephone number during predefined periods of time. When an alarm or critical condition occurs at one of the predefined points, the software automatically dials an assigned telephone number or its backup. A synthesized voice message is issued to the person who answers. This feature ensures notification of critical alarms to authorized personnel during periods when a building is unoccupied. Authorized personnel can call the host computer from an off-site touchtone telephone and request the status of predefined points. Predefined points can also be issued commands if deemed necessary. Figure 4.29 illustrates the voice communications option.

With direct digital control, control systems can be designed with state-of-the-art accuracy, dependability, and flexibility. Building owners and their operating staff can take advantage of a multitude of computerized programs to assist them in running a more efficient, comfortable and safe building.

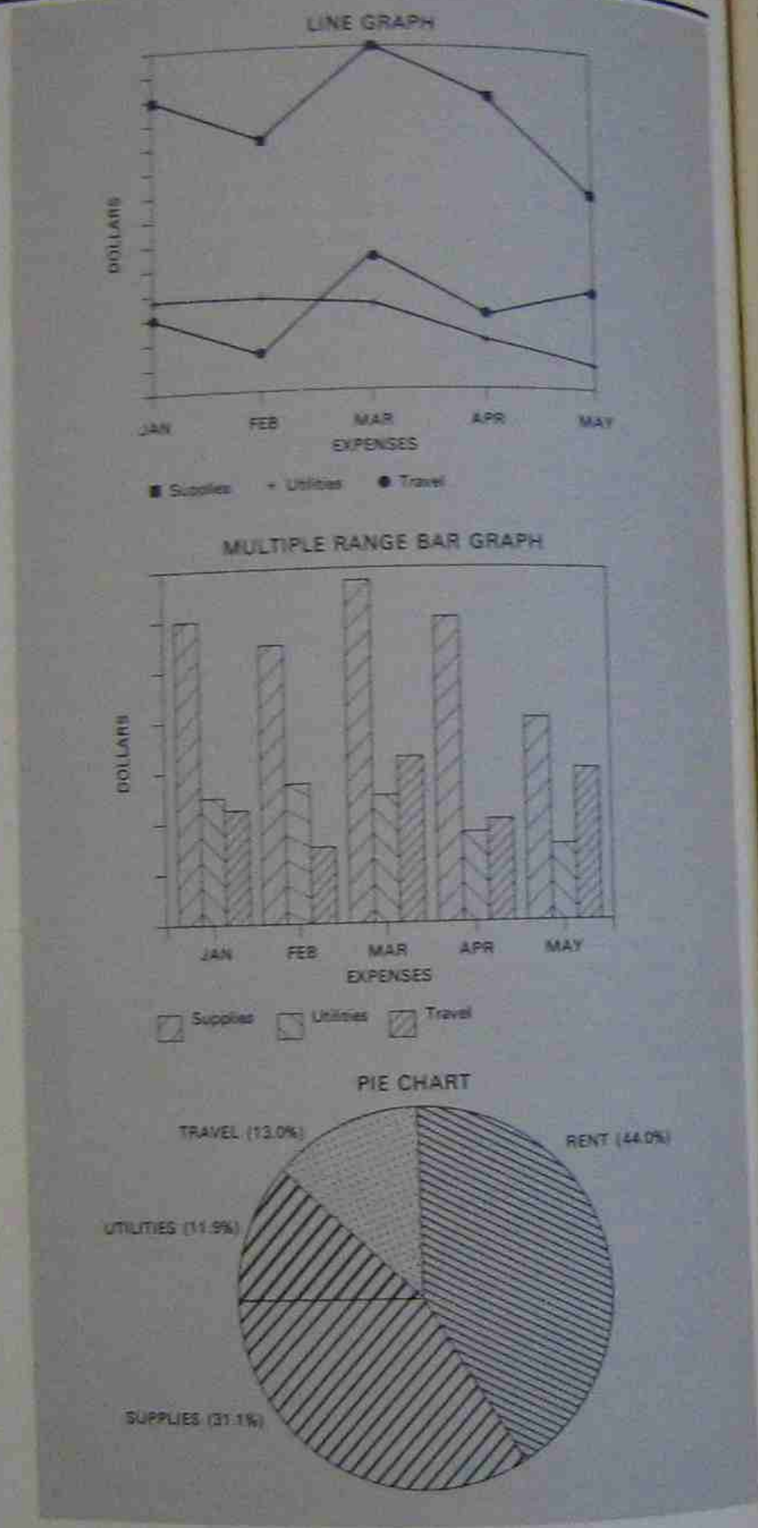


Figure 4.28

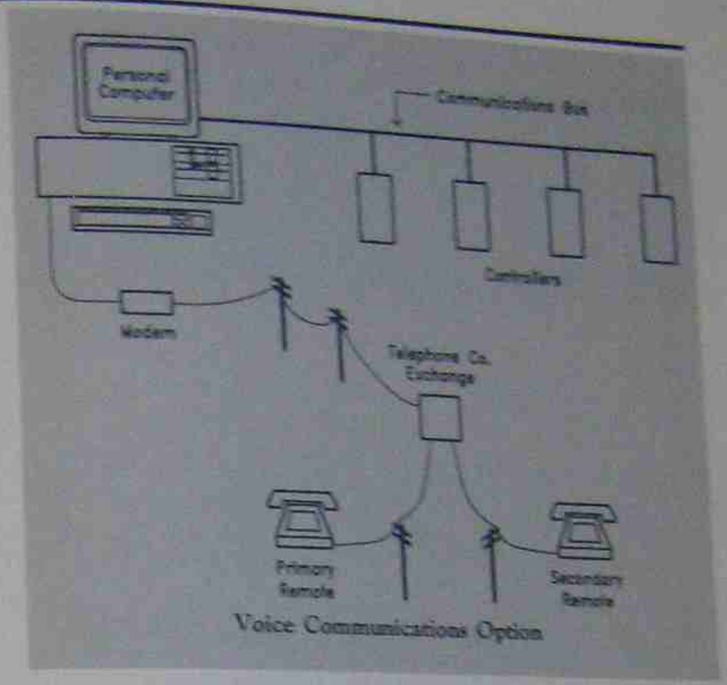


Figure 4.29

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Chapter Five

Energy Management Programs

Before installing a Direct Digital Control system, whether the system is a new building installation or replacing an existing conventional control system, consideration should be given to the activation of energy management programs. These programs are incorporated in the controller, and can generate impressive financial paybacks that may partially offset the installation cost. Most major manufacturers of these systems will provide an estimate of energy savings and submit, with their proposal, a payback summary which may be achieved by instituting various energy management programs.

Approximately 67% of the energy consumed in an office building is electrical. Thirty-three percent is oil, gas, and purchased steam or hot water. A breakdown of the electrical energy consumed reveals that cooling systems use 40%, lighting systems use 33%, heating, 12%, and the remaining 15% is consumed by other means. The energy management strategies, resident in the DDC controllers, address all of these areas of energy consumption.

A major source of energy savings, in most buildings, is through reduced run time of HVAC systems. Electricity is saved by reducing fan and/or pump operations. Additional savings are achieved through reduced outdoor air intake, thereby relieving a burden on the heating and cooling equipment. Some energy management programs use outdoor air for cooling. This reduces the load on the mechanical cooling equipment, resulting in reduced energy consumption. Reset programs can maintain the temperature of air delivered to the spaces at optimum levels to satisfy comfort conditions. This eliminates the energy waste that results from overheating and subcooling.

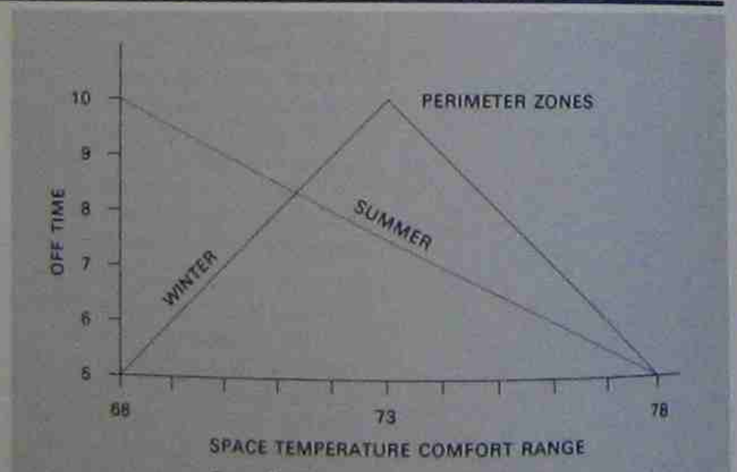
Electrical power companies are promoting programs to reduce the demand for electricity and relieve pressure on their limited generating capacity. Many companies offer rebate incentives to encourage customers to install energy management systems that will reduce building electrical demand. For example, the replacement of inefficient light fixtures and bulbs can result in savings on electrical costs. Additional savings can be realized by reducing lighting levels, and turning off lights during unoccupied periods.

All energy management programs should be approached with a degree of caution. If not properly applied, these programs could damage expensive equipment, compromise comfort conditions, and have a negative impact on air quality. What follows is a discussion of some of the energy management programs used today.

Duty Cycle Program

The *duty cycle program* reduces electrical energy consumed by the fan in an HVAC system by cycling the fan on and off. The off periods are a function of space temperature, as sensed by a space temperature sensor. When space temperature is at the midpoint of a preprogrammed comfort range, the fan can be turned off for an extended period of time without affecting comfort. As space temperature approaches the end of the comfort range, the off periods are decreased (Figure 5.1).

The operator programs the duty cycle period, the comfort range in degrees Fahrenheit (for example, 68°F-78°F), minimum on and off times, and the maximum off time. These times are set to avoid the equipment damage that can result from too rapid cycling. When the space temperature is at the midpoint of the comfort range, as sensed by a space temperature sensor, loads such as fans are turned off and outdoor air dampers are closed for the maximum off time in the period. When space temperature deviates from the midpoint, the off periods shorten proportionally. At the extreme ends of the comfort range, which usually occur at outdoor design conditions, the duty cycle program cancels and the load is energized continuously.



Sample Duty Cycle Schedule
Space Temperature Compensated

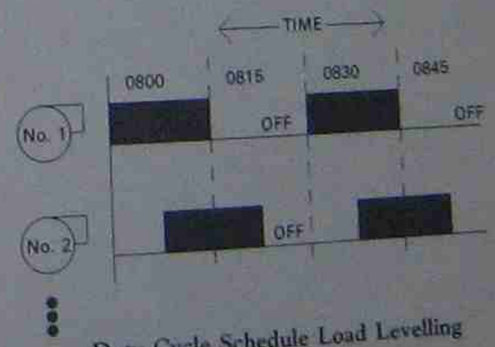
Figure 5.1

Multiple space sensors may be used for space temperature compensated duty cycling programs. In this case, the program selects the highest space temperature sensed for cooling and the lowest temperature sensed for heating. When multiple electrical loads are duty cycled, the program automatically adjusts the cycle periods so that they do not occur simultaneously, thereby causing a power surge. This is shown in Figure 5.2.

There are certain cautions that should be exercised in the application of the duty cycle program. First, the best candidates for this program are heating, ventilating, and air conditioning unit fans (under 100 horsepower only), exhaust fans, and hot water pumps. HVAC units and exhaust fans serving critical areas such as computer rooms, clean rooms, laboratories, operating rooms, and areas where toxic materials or plastics of any kind are stored, should not be duty cycled.

Second, many questions have been raised about the effect of duty cycling on electric motors. Research has shown that the only serious problem that may arise is overheating of the motor during startup. The two important factors to consider when duty cycling electric motors are the minimum time between starts (minimum interval) and the minimum off time. Figure 5.3 depicts guidelines for cycling induction motors.

The minimum off time is determined by the cooling requirements of the motor after running at its normal operating temperature. For small motors, three minutes is adequate cooling time before restarting. Notice in Figure 5.3 that the interval and the off time are extended as the motor size increases. As a general rule, motors larger than 100 horsepower should not be duty cycled. If HVAC fan motors of this size are installed, alternatives should be considered, such as cycling inlet vanes or mixing dampers, to achieve energy savings. However, belts and magnetic starters, if properly sized and installed, will be minimally affected by a properly applied duty cycle program.



Duty Cycle Schedule Load Levelling

Figure 5.2

Power Demand Limiting Program

Electrical utility companies charge for energy consumption over an established billing period (usually one month). These charges cover fuel costs, operating costs, and the utility's investment in generating equipment.

The charges are calculated based on readings taken from the building's electric meter. Every commercial building has a *kilowatt-hour meter*. This meter records, on a continuous basis, the kilowatt-hours of electricity consumed by the building. At the end of the billing period, the utility company reads the meter and bills the customer for the energy consumed. The charges are frequently based on a sliding scale, so that the more energy consumed, the lower the unit cost. Added to the cost per kilowatt-hour is a fuel adjustment charge to cover the fluctuating cost of fuel used to produce electricity during that billing period. This is a fixed charge per kilowatt-hour regardless of the number of kilowatt-hours consumed.

Since the demand for electricity by commercial customers is heavier at certain times of the day than at others, the utilities must have equipment and transmission lines capable of handling these peaks. Although these peak demand periods occur only occasionally and for relatively short periods of time, the generating capability must nonetheless be available. *Demand charges* were established to pay for the installation and maintenance of this excess generating capability. Figure 5.4 shows a typical building load profile.

Demand charges are based on the average kilowatts consumed during a demand interval. A *demand interval* is a specific period of time established by the utility company. This period of time varies depending on the utility company, but in most cases is 15 or 30 minutes. Demand charges are based on the maximum demand (*demand peak*) during any demand interval in the billing period. Many utility companies have a ratchet clause which states that the customer must pay for this maximum demand for eleven months. If, during the eleven-month period, a new, higher demand peak occurs, this will establish the basis for the demand charge over the next eleven months.

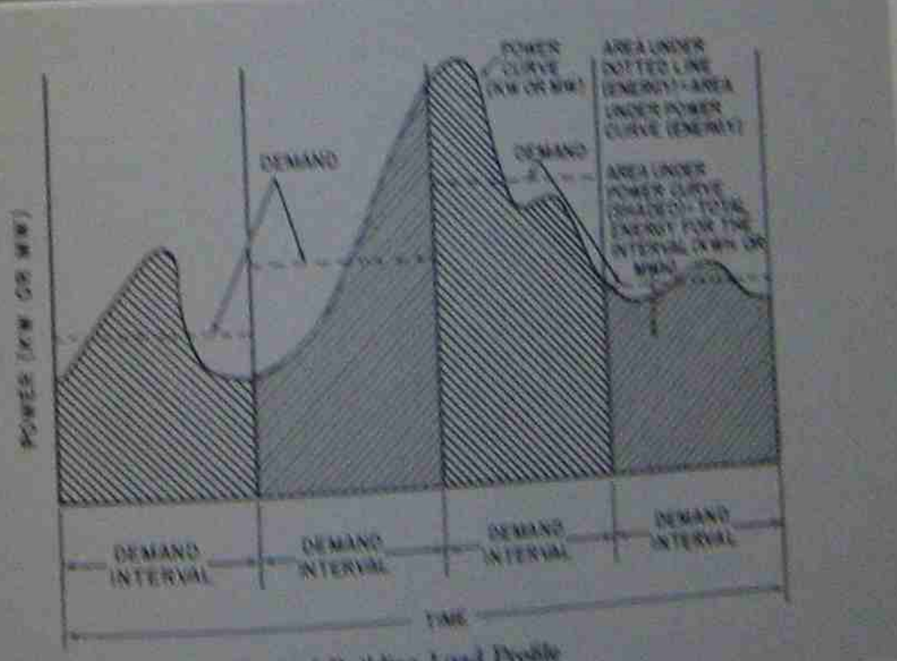
The power demand limiting program monitors electrical consumption during each and every demand interval, and sheds (turns off) assigned loads as required to reduce demand. Before such a program can be implemented, however, the building owner or engineer must determine which loads in the building are "sheddable" for brief periods of time without creating serious environmental problems. For instance, shedding air-conditioning for a computer room or an operating room would not be acceptable, nor would shutting down a ventilating unit for hospital patient areas or intensive care units. Air-conditioning units and exhaust fans supplying general office areas, on the other hand, can be shed for brief periods, as can units supplying conference rooms, lobbies, coffee shops, and cafeterias. Also, the set point of large, electrically driven chillers can be set up a few degrees as a temporary demand limiting strategy.

Loads are prioritized according to their importance to environment and comfort conditions in the building. Low-priority loads are shed first and restored last. High-priority are the last to be shed and the first to be restored. If multi-speed motors are assigned to the load shed program, they can be shed in multiple steps.

Motor Cycling Guidelines			Nema Design Types A–F	
HP	1/4–10	10–20	20–80	80–100*
Min Interval (Minutes)	10	20	30	40
Min Off Time (Minutes)	3	5	7	7
Suggested Max Off Time	5	7	10	10
Min % KW Savings	30%	24%	23%	17%

*With reduced voltage start only

Figure 5.3



Typical Building Load Profile

Figure 5.4

The power demand limiting program monitors power consumption from the data input of a pulse transmitter located on the building's electric meter. However, not all building meters are equipped with a pulse transmitter. The building owner should check with the power company before applying this program to determine whether or not the building has one. If the transmitter does not exist, there will be a charge by the power company for the installation.

The power demand limiting program during the 15- or 30-minute demand interval, computes the energy consumed and forecasts the power demand at the end of the interval. After completing the forecast, the program adds or sheds loads to maintain the demand level within programmed limits.

If all assigned loads have been shed and electrical consumption continues to increase, the program automatically shifts the demand limit upward. When seasonal variations in electrical demand occur, the program compensates rather than maintain the original limits. Figure 5.5 is a sketch showing how the basic demand limiting program works.

Unoccupied Period Program

With the exception of residential-type buildings, most buildings have occupied and unoccupied periods. Office buildings are typically occupied 40 to 44 hours per week, which means that they are unoccupied approximately 72% of the time. Hospitals have certain areas, such as administrative offices, gift shops, cafeterias, x-ray departments, and operating rooms which are not occupied full-time. If unoccupied buildings or building zones are heated, cooled, or ventilated to the same levels as when occupied, energy is being wasted.

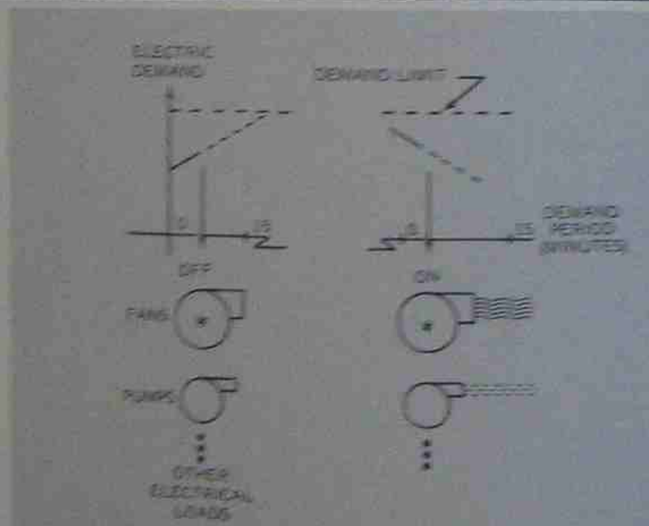


Figure 5.5 **Demand Limiting Program**

Considerable energy savings can be achieved by setting temperatures back during unoccupied periods in the heating season, and by during unoccupied periods in the cooling season. Savings in hot water radiation systems can be achieved by decreasing water temperatures during the unoccupied periods. Air-handling systems, which are cycled to maintain reduced temperatures during unoccupied periods, should have their fresh air dampers closed.

The unoccupied period program, or night cycle program, is primarily a heating season function. It can, however, maintain a high space temperature limit during the cooling season, if desired. A space temperature sensor maintains space temperature at preset levels during unoccupied periods by cycling the heating or cooling source. If multiple sensors are used, the program will control from the lowest temperature in the heating season and the highest temperature in the cooling season.

If humidity is of critical importance in a building or building zone, a relative humidity sensor can be installed to override the program and cycle the air-handling system to maintain a high or low space relative humidity level.

Optimum Start-Stop Program

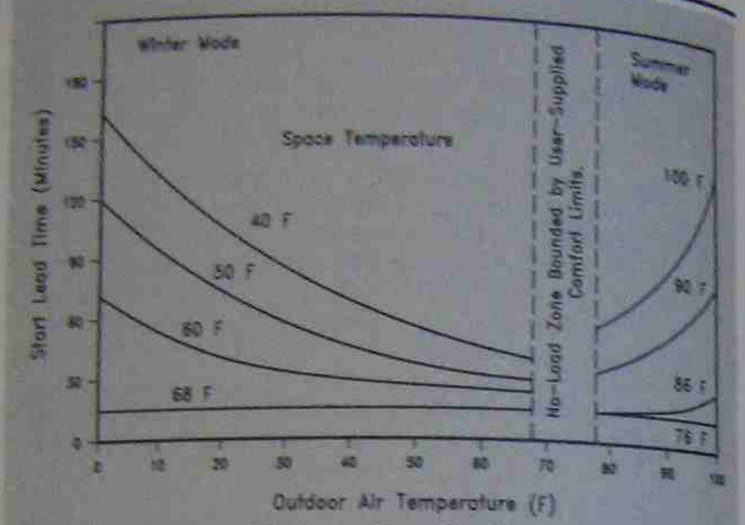
Program clocks have been used for many years to automatically determine the occupied/unoccupied periods for buildings or building zones. These devices have saved building owners millions of dollars in energy costs at a minimal installation cost. In order to achieve comfortable building temperatures at occupancy time, however, the clock must be set for outdoor design heating or cooling conditions. For instance, if it takes two hours to bring a building up to comfort levels at occupancy, under design heating conditions, the program clock must be set to turn the heating equipment on two hours prior to occupancy. At the end of the occupied period, the program clock is usually set to place the building in the unoccupied mode. However, such design conditions occur only a few days each winter.

During non-design days, heating equipment that starts two hours early results in wasted energy. The same principle applies to the cooling season.

The *optimum start-stop program* is an adaptive energy-saving program that uses intelligence and the flywheel effect (energy retention capacity) of a building to save a considerable amount of energy beyond that which can be saved with the program clock. The *optimum start program* monitors space and outdoor air temperatures several hours prior to the programmed occupancy time of the building or zone. If the space temperature is within comfort limits, the heating or cooling equipment will be started exactly at building or zone occupancy time. If space temperature is not within comfort limits, the program will calculate the correct start-up time necessary to achieve comfortable temperatures at occupancy time. After weekends or holiday periods, a building may require longer warm-up or cool-down periods. The optimum start program automatically compensates by extending the run time of the heating or cooling equipment prior to occupancy.

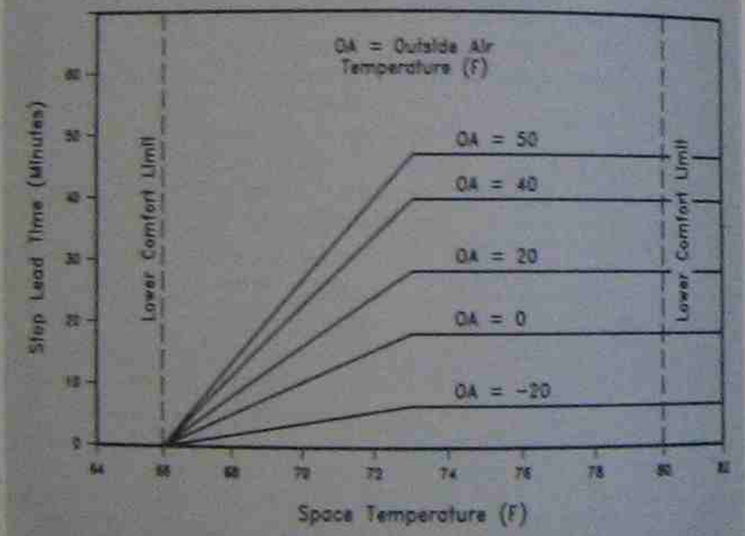
Figure 5.6 is a graphic representation of the optimum start program for both the summer and winter modes.

Figure 5.7 shows a typical optimum stop graphic representation for the heating mode.



Optimum Start Graph

Figure 5.6



Optimum Stop Graph

Figure 5.7

The optimum stop program occurs at the end of the building or zone occupancy time. It calculates the earliest time during the occupancy period, that the heating or cooling equipment can be shut down, allowing the flywheel effect of the building to stabilize temperature levels until the end of the period.

Both optimum start and optimum stop programs can function with multiple space sensors. The program will be sensitive to the area or zone sensor which is exposed to the most extreme temperatures.

Unoccupied Night Purge Program

During the summer cooling season it is not unusual for the outdoor air temperature to drop considerably at night. Frequently, during the early morning hours prior to building occupancy time, the outdoor air temperature is below building space temperatures. This cool outdoor air can be utilized to cool the building, thereby eliminating the need for mechanical cooling during early morning occupancy hours. This free cooling will generate energy savings and also save wear on the mechanical cooling equipment.

At a preprogrammed time in the early morning hours, the program begins to monitor space and outdoor temperature and humidity. If space conditions indicate a need for cooling, and if outdoor air conditions are suitable, the *Night Purge Program* is initiated. The program starts the HVAC supply fan and associated exhaust fan, and opens the outdoor air damper 100%. Warm air from the building continues to be purged until the space temperature and relative humidity indoors reach the same levels as the outdoor air conditions, or until the morning start-up program begins. The outdoor air temperature must be above a preselected minimum to ensure that the program is operable only during the cooling season. Figure 5.8 shows a flow chart of the night purge program operation.

The *night purge program* can be applied to most HVAC systems that are capable of using 100% outdoor air. Some package-type HVAC units and rooftop units are limited mechanically to admit 10 or 20% outdoor air, and therefore do not qualify.

Enthalpy Program

The traditional mixed air economizer control system saves energy by using outdoor air for cooling rather than mechanical cooling equipment. This control loop functions by sensing dry bulb temperatures. When the outdoor air dry bulb temperature reaches a level at which it is no longer suitable for cooling, the fresh air damper closes to the minimum position and the mechanical refrigeration equipment becomes operable. It is at this point that the *enthalpy control system* becomes important.

The economizer system, since it measures dry bulb temperature only, keeps the system on return air throughout the cooling season. The enthalpy control system, however, selects the air source (return air or outdoor air) which has the lowest total heat (*enthalpy*), and therefore requires the least amount of heat removed by the cooling coil.

The enthalpy program monitors the temperature and relative humidity or dewpoint of the outdoor and return air. During occupied periods when cooling equipment is in operation, the program calculates the total heat, or enthalpy, of the outdoor air and return air. It then positions the outdoor air and return air dampers to use the air source with the lowest total heat or least enthalpy.

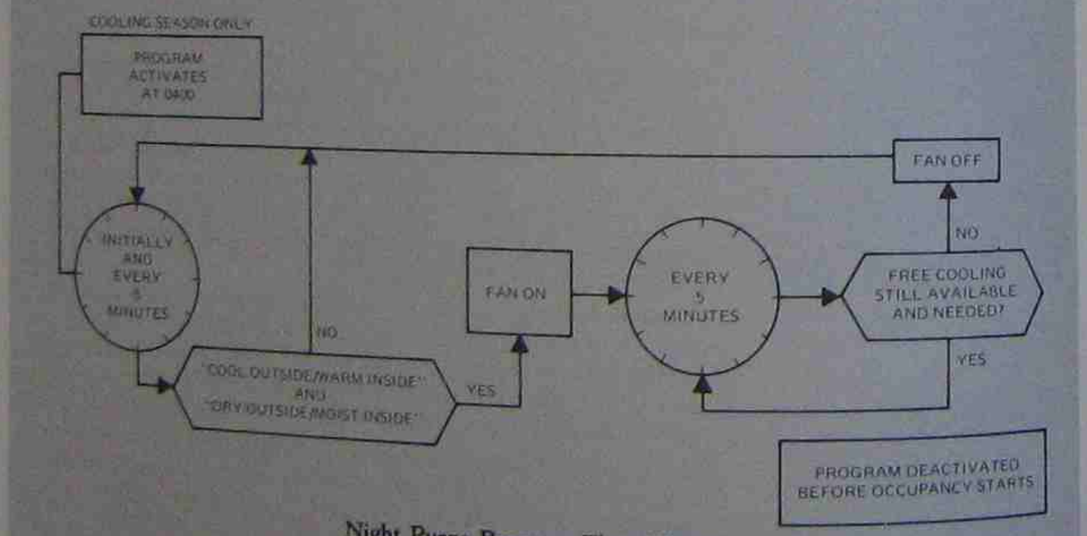
This program will work with HVAC systems that have sprayed or unsprayed cooling coils. The system must have the capability of operating on 100% outdoor air, or 100% return air.

Load Reset Program

HVAC systems are sized for design conditions, or the peak load during the heating and cooling seasons. These peak load periods are of short duration and occur infrequently, which means that most systems operate under partial load conditions most of the year. This results in inefficient performance. If the systems are not properly controlled, energy is wasted.

The *load reset program* controls heating and/or cooling to maintain comfort conditions in the building while consuming a minimum amount of energy. This is accomplished by resetting the heating and cooling discharge air temperatures to satisfy the zone with the greatest heating or cooling load. When no heating or cooling is required, the program de-energizes both sources.

If an HVAC system supplies multiple zones with different exposures such as North, South, or locations (interior, exterior), the heating and cooling requirements could vary widely. The load reset program will accept and evaluate inputs from multiple zone sensors and issue signals, if necessary, to actuate the heating, cooling, or heating *and* cooling systems. If the lowest zone temperature is below the preprogrammed comfort level, the heating source will be enabled and the discharge air temperature will be reset in proportion to the amount of deviation from the comfort level. If the lowest zone temperature is above the preprogrammed comfort level, the heating source will be shut off.



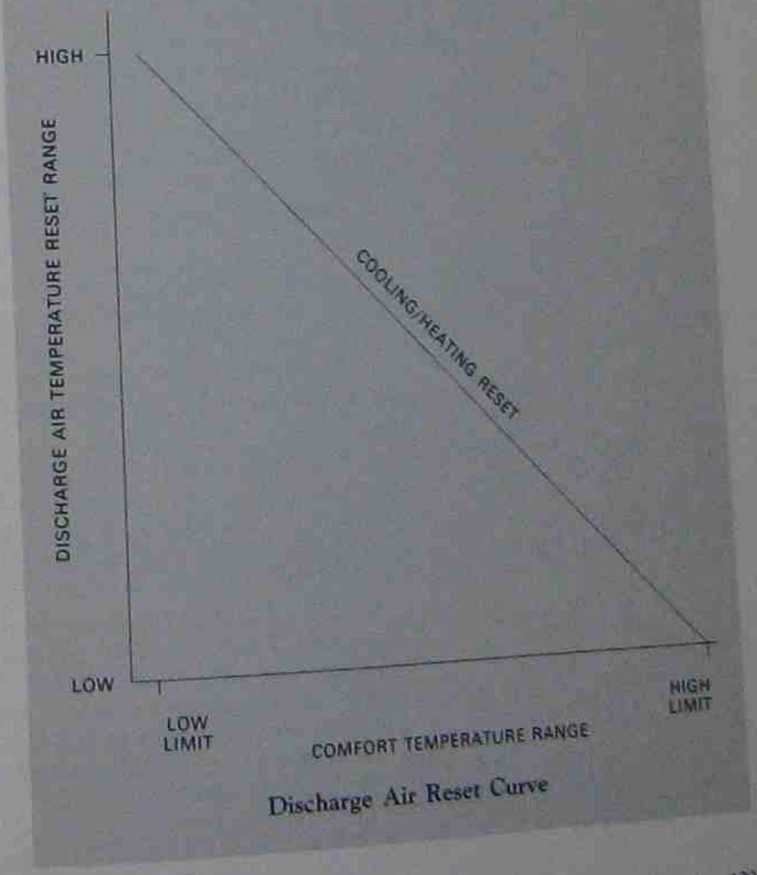
Night Purge Program Flow Chart

Figure 5.8

If the highest zone temperature is above the preprogrammed comfort level, the cooling source will be enabled and the discharge air temperature will be reset in proportion to the amount of deviation from the comfort level. If the highest zone temperature is below the preprogrammed comfort level, the cooling source will be shut off.

The load reset program also has a high-limit humidity or dewpoint option. If space relative humidity is critical, space relative humidity or dewpoint sensors can be installed. Any one of these sensors can lower the cooling reset schedule to compensate for increasing space relative humidity levels.

In a terminal reheat system, the HVAC unit discharge air temperature will be reset to the point at which the zone sensor with the greatest demand for cooling is satisfied. In dual duct and multi-zone units, the cold deck is reset according to the zone sensor with the greatest demand for cooling, and the hot deck is reset according to the sensor with the greatest demand for heating. When all space sensors are satisfied at the preprogrammed comfort levels, both the heating and cooling sources will be shut off.



Discharge Air Reset Curve

Figure 5.9

Figure 5.9 shows how discharge air temperature in a hot and cold deck system is reset as a function of the sensor with the greatest demand for heating or cooling.

Zero-Energy Band Program

This program finds its application in HVAC systems that have heating and cooling capability. The program saves energy by avoiding simultaneous heating and cooling of air delivered to spaces. The space comfort range is divided into three sections: heating, cooling, and zero-energy band. In the zero-energy band portion of the comfort range, both heating and cooling sources are disabled. When space temperatures drop to the lower end of the comfort range, the heating source is energized and the discharge air temperature is reset upward. When space temperature enters the upper end of the comfort range, the cooling source is energized and the discharge air temperature is reset downward. The reset action that takes place in the heating and cooling sections of the comfort range is a preprogrammed function of the temperature range of the heating or cooling section. In other words, a load reset program operates in both the heating and cooling sections of the comfort range (See Figure 5.10).

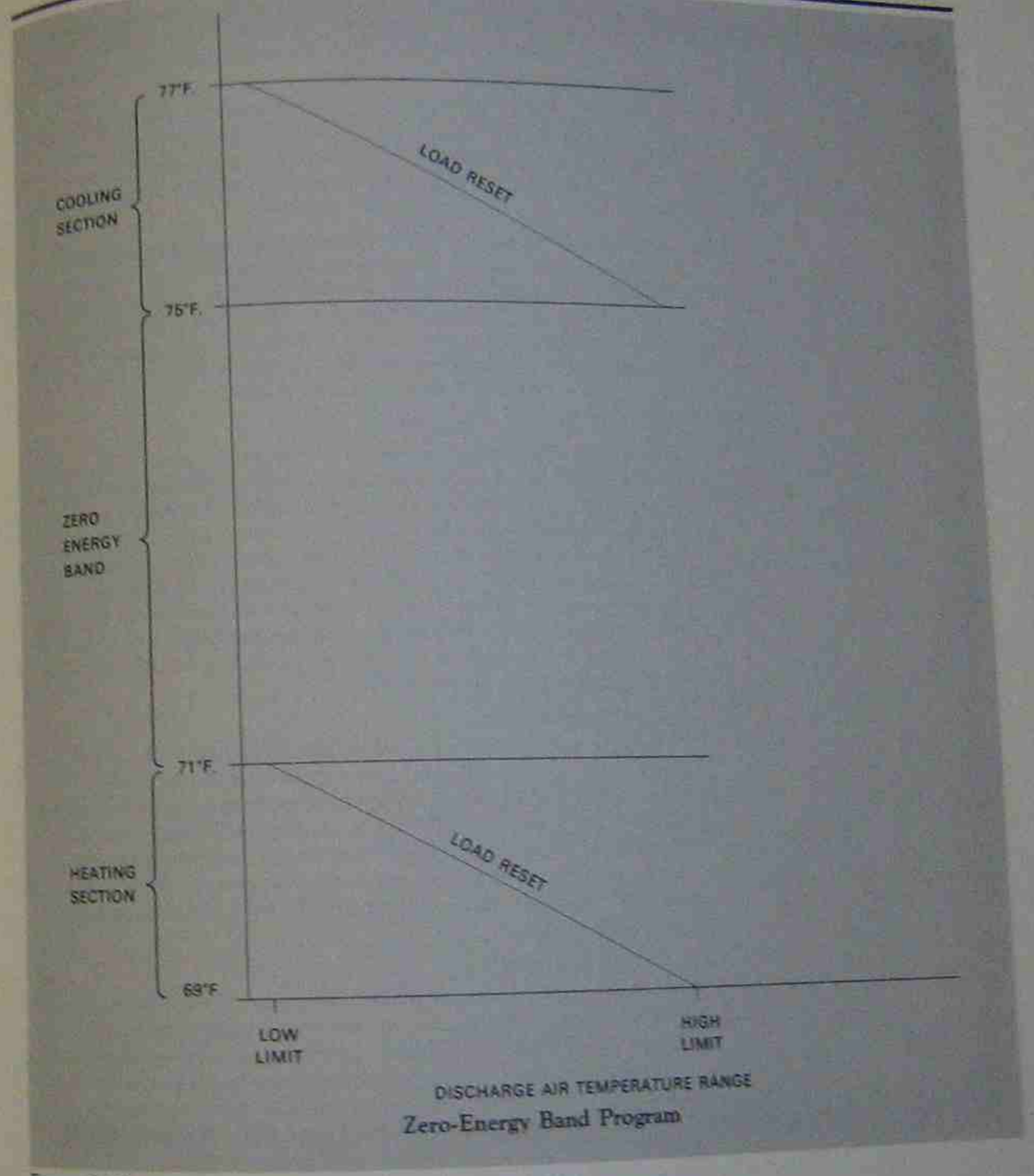
When an HVAC system serves different zones, or rooms, the heating and cooling requirements will vary widely. Therefore, when the temperature in the coldest room or zone falls into the low end of the comfort range (the heating section), heat will be delivered. The temperature of the air, however, will be reset according to the degree of penetration into the heating section. Cooling follows a similar process. When the temperature in the warmest room or zone rises into the high end of the comfort range (the cooling section), cool air will be delivered. The temperature of the air will be reset according to the cooling load in the room or zone. When all room or zone temperatures are within the zero-energy band, both heating and cooling sources will be disabled. Within the zero-energy band, the program can reset discharge air temperature by modulating the mixing dampers (outdoor air and return air) to maintain space comfort conditions.

Host Computer

In a distributed process system, the remote DDC controllers perform their energy management and control loop tasks on a stand-alone basis. The central host computer, however, acts as the operator-machine interface to the controllers and remote sensors. This is accomplished over a communications bus, which links the controllers to the host.

The host computer is an intelligent operator-machine interface which consists of hard diskette drives, keyboard, CRT, and printer. The hard disk holds all operating programs as well as data files for the PC host and controllers. The diskette drive provides the capability for storage of historical data and logs.

The keyboard and CRT provide the primary operator interface with the system. The PC keyboard is similar to a typewriter keyboard and includes a numeric keypad. The CRT displays conversational menus which guide the operator to available functions. When a programming task is to be performed, the operator receives guidance on what data to enter, through conversational prompting and fill-in-the-blanks requests.



Zero-Energy Band Program

Figure 5.10

The printer operates in a receive-only mode and provides hard copy records of alarms and logs. All logs, such as all points, alarms, trends, and groups can be requested from a log menu and printed for record purposes. Multiple printers may be installed so that alarms and logs may be segregated.

The host software provides menu-guided or system selection functions. It also provides conversational directions in data file programming, English language descriptors and action messages, current status and historical logs, alarm monitoring, programming, and program override of all controllers on the communications bus.

The central host computer develops and prints management reports based on energy consumption information supplied to it by remote sensors. The programs discussed in the following sections assist facilities management personnel in evaluating the effectiveness of the energy management programs used in their buildings. If the programs are not accomplishing the anticipated results, changes in parameters and strategies can be made through the central host.

Energy Auditor Program

The energy auditor program can convert measured data, such as electric demand meter input information, into valuable statistics and trend data. A printout can be generated listing peak demand for each day of the month. Inputs from electric and gas meters can supply data to develop energy consumption trends in spreadsheet format. The output can be a simple listing of data, or a calculation can convert the data to management-level reports such as KWH per square foot, or cubic feet of gas per square foot. This program can be a valuable tool to building owners and managers for tracking costs, predicting trends, budgeting, and managing energy consumption.

Graphs and Charts

Line graphs and bar or pie charts can be displayed on the CRT to depict trends in any of the variables supplied for the spreadsheet program. Through the trend log spreadsheet programs, bars or graphs can be constructed to display data in a more easily understood form. Trends in daily peak demand, or kilowatt-hour consumption, are easier to read and comprehend when represented as bars of various heights, as opposed to multiple columns of figures. Figure 5.11 shows sample charts and graphs.

Action Messages

Action messages can be programmed to appear on the CRT and to be printed whenever a specified point generates an alar or trouble condition. This feature is extremely helpful to an operator monitoring critical points or systems. Action messages can be programmed to interact with the power demand program. The operator can be notified if all available loads have been shed and a new demand peak is imminent. The CRT and printer can display corrective action instructions.

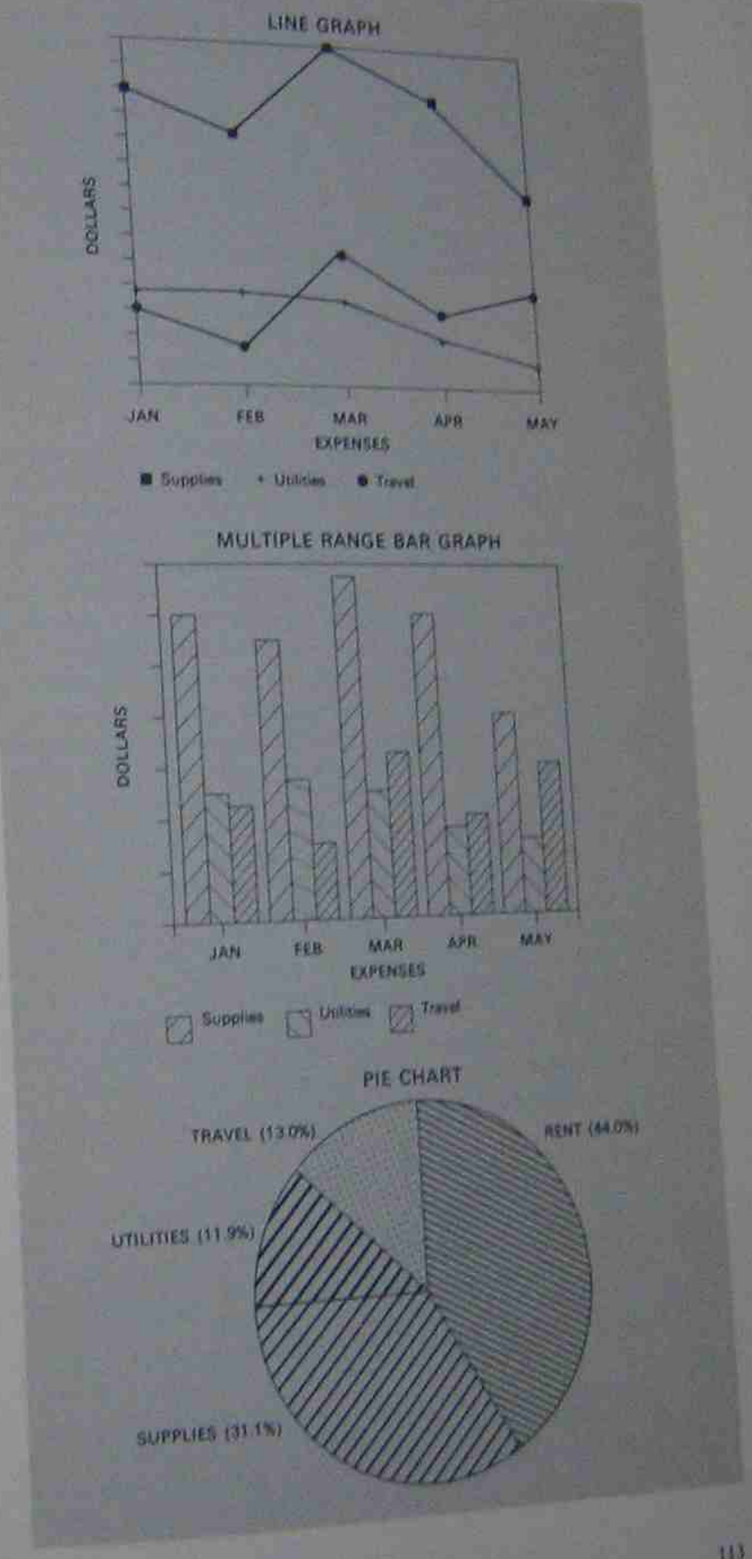


Figure 5.11

All of the energy management programs outlined in this chapter are included in the DDC controller software. As energy costs escalate and energy shortages occur, these programs offer an answer to the control and management of building operating costs.

Assigned personnel can receive alarms at authorized telephone numbers during predefined periods of the day or night. When an off-normal condition occurs on one or more specified points, the software automatically dials the preprogrammed telephone number or its alternate and issues the appropriate voice message. The program then issues a request for commands.

An authorized operator can dial into the host computer from an off-site location and request the status of a point or issue commands. Specific status points and command points can be assigned and programmed for access through the dial-in program. This program enables building operations personnel to remain in contact with their building after regular business hours.

Chapter Six

Lighting Control

Lighting accounts for 30-40% of the electrical operating costs in commercial buildings. Yet the average commercial building is unoccupied approximately 75% of the time. In many of these buildings the lights remain on during the unoccupied periods. During occupied periods, the lighting levels in these buildings are often considerably higher than required by the occupants for the work they perform. Furthermore, the heat produced by lights in a building, although beneficial during the heating season, places a burden on the air-conditioning systems during the cooling season.

There are steps that can be taken to reduce lighting costs while maintaining optimum lighting levels during occupancy periods in large buildings. Building owners can institute lighting control programs which effectively operate the lighting system in their building by means of manual and automatic control. Because lighting requirements vary according to the tasks being performed and the occupancy schedule of a particular zone, lighting control programs provide the flexibility of controlling illumination levels according to occupant needs and occupancy schedules. For example, lights can be turned on in the cafeteria zone in the morning and maintained at required levels for the breakfast period. At the end of this period, the levels can be reduced slightly until lunch, when they will be restored. Following lunch the light levels will decrease. At the end of the working day the lights can be turned off or maintained at reduced levels for security purposes. Lighting can be preprogrammed for the entire work week, weekends, and holidays.

In order to apply lighting control successfully, however, the building's lighting system must meet certain requirements. Distribution panels must contain lighting circuits only—no outlets, or motors. If a mixture of lighting, outlets, motors, and other electrical equipment exists on a panel, the lighting must be transferred to a separate circuit breaker panel. There is no need for local switching of lights under a centralized lighting control system. Wall-mounted light switches in individual offices or classrooms are not necessary.

Lighting control generally works best on open area lighting design such as in cafeterias and open landscape office areas. The availability of natural light is also important, to supplement artificial lighting, thereby reducing electrical energy costs.

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Building Automation Systems can provide two major strategies for lighting control. One strategy is a simple on-off program for occupied-unoccupied control. The second strategy monitors total lighting levels in the perimeter zones of the building and supplements the natural light with artificial light to maintain the required lighting levels.

Occupied-Unoccupied Lighting Control

The first strategy to reduce light operating costs is called *occupied-unoccupied lighting control*. This lighting control system is a time-based program that schedules the on/off time of lights, for a building or zone to coincide with occupancy schedules. Multiple programs are available, which makes it possible to arrange for lighting to match occupancy schedules of different zones in a building. Although this is a very basic method of lighting control, it can generate impressive savings in electrical costs if no lighting control program is presently in operation.

Lighting Level Control

Another way to reduce the costs associated with lighting is to control the level of lighting in a building or building zone. Lighting level control is accomplished by two different methods: *multi-level lighting* and *modulated lighting*. Before applying either of these programs, however, a study should be conducted of building lighting requirements. Zones with similar lighting requirements should be listed. All activities in a zone should have approximately the same occupancy schedules. Window and wall configurations should be similar throughout a zone. Exposure to daylight should be uniform throughout the zone. Zones should be small enough so that one or two people working overtime will not require excessive lighting.

Multi-Level Lighting Control

Multiple levels of illumination are made possible by dividing three- and four-lamp fixtures into three and four circuits respectively. By switching the ballasts, three-lamp fluorescent fixtures can provide four levels of control: off, one-third, two-thirds, or full-on lighting. Figure 6.1 shows four levels of lighting control. Two- or four-lamp fixtures can provide three levels of control: off, one-half, or full-on lighting.

Multi-level lighting is applied primarily to perimeter zones where daylight is available to supplement the artificial light. Light sensors are installed in these zones to energize fixture lamps in an on-off manner. The sensors measure levels of natural light in the zone and, through the lighting program, energize the appropriate number of fixture lamps to maintain preset lighting levels.

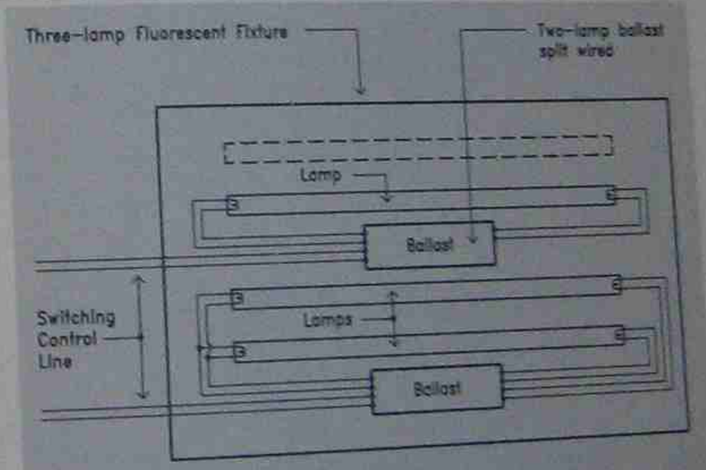
Cleaning crews and security and maintenance personnel frequently work after normal building occupancy hours. A program can be developed to provide the required light levels to accommodate cleaning schedules for each zone. Another option is to install occupancy sensors to energize lights when employees enter a zone after normal occupancy hours. The program will turn off the lights after a preprogrammed amount of time has elapsed. The central host computer can also be used to manually override lighting programs. If there is a 24-hour security guard station in the building, specific zones can be illuminated from the terminal at the guard station for unscheduled activities.

Modulated Lighting Control

Modulated lighting control differs from multi-level control in that it is not limited to two or three levels of lighting, but can modulate to any level over the complete range from off to full-on.

Modulated lighting is specifically designed to control the standard four foot, rapid-start fluorescent lamps found in most large buildings today. Standard fluorescent lamps, when first installed, provide more light output than required, so that rated output is provided over the life of the lamp. This type of lamp consumes 100% of its power requirement over its entire life. The modulated lighting program provides even light levels throughout the lamp life by adjusting output to the needs of the zone occupants. Figure 6.2 shows the comparison of standard lighting levels and power consumption to that of modulated lighting control.

Modulated lighting control systems employ the same basic closed-loop process used to control temperature and humidity through DDC systems. Light level sensors containing photocells are mounted on acoustic ceiling panels or on standard electrical boxes. The sensors send input signals to a zone control unit in direct proportion to the ambient



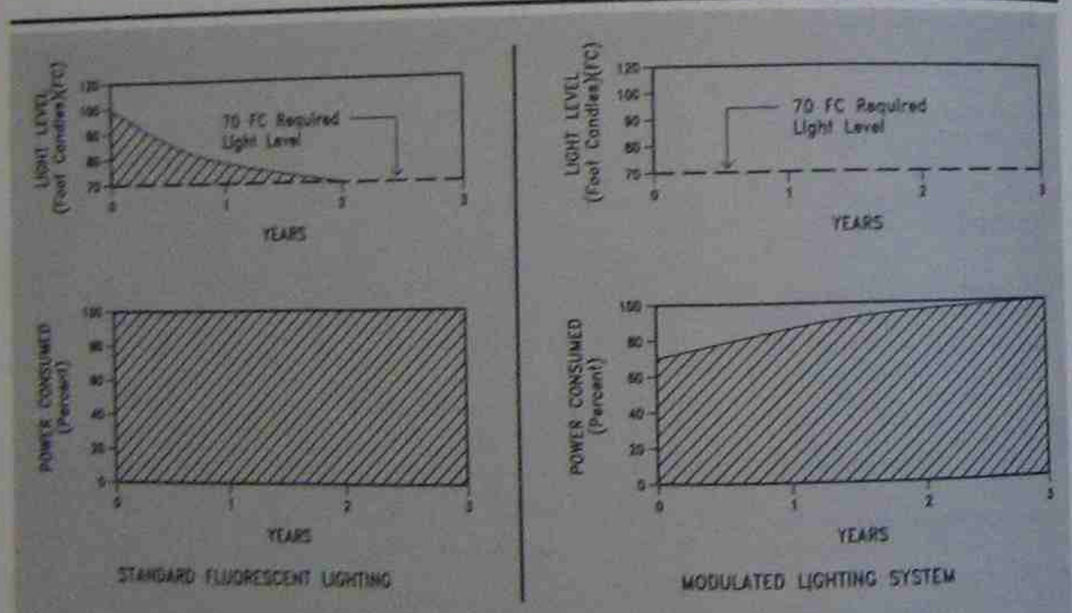
Four Levels of Lighting Control

Figure 6.1

light levels. The zone control unit has an illumination level set point. The unit compares this set point to the input signals from the illumination sensors. If ambient light levels deviate from this set point, the zone controller sends an output signal to the power controller. The power controller, in turn, adjusts the power output level delivered to the lighting control ballasts. (Keep in mind that because the power controller is installed ahead of the circuit breaker panel, it is imperative that the breaker panel contain only lighting circuits and no wall outlets or appliances.) The control ballast then adjusts the output of the rapid-start fluorescent lamps to compensate for the change in illumination.

Control ballasts are specifically designed for lighting control systems. A full-power control ballast is used where 100% lighting capacity is required. Reduced power control ballasts may be used for applications in which lighting is overdesigned, or for lighting circuits near windows, where 100% light output is not required.

Figure 6.3 shows a closed loop, modulated lighting block diagram.

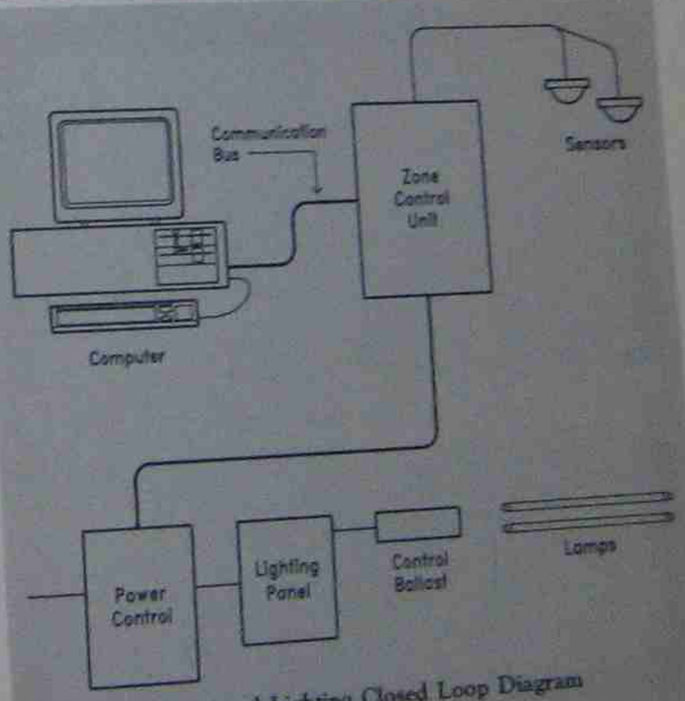


Modulated Lighting vs. Standard Lighting Levels and Power Consumption

Figure 6.2

Host Computer

In lighting control systems, the host computer acts as the operator-machine interface to the control and energy management programs. Through the color graphic software package, color-coded floor layouts can be constructed. The light status (on-off) of a room, a zone, or an entire floor can be displayed graphically on the CRT. If lighting levels in a zone drop below or exceed preset levels, an alarm will be activated at the host computer and the appropriate floor will appear on the screen to show the operator which zone is in alarm. From the operator's terminal, the operator can override lighting programs to accommodate unusual occupancy schedules. This can be done weeks in advance and can be programmed to occur on specific nights and for specific time periods. The printer will provide hard copy documentation of the program override date, zone, and length of time. The computer can be programmed to calculate the total kilowatt-hours consumed during the override period for tenant billing purposes. It is also possible to combine lighting with HVAC systems for occupied-unoccupied scheduling.

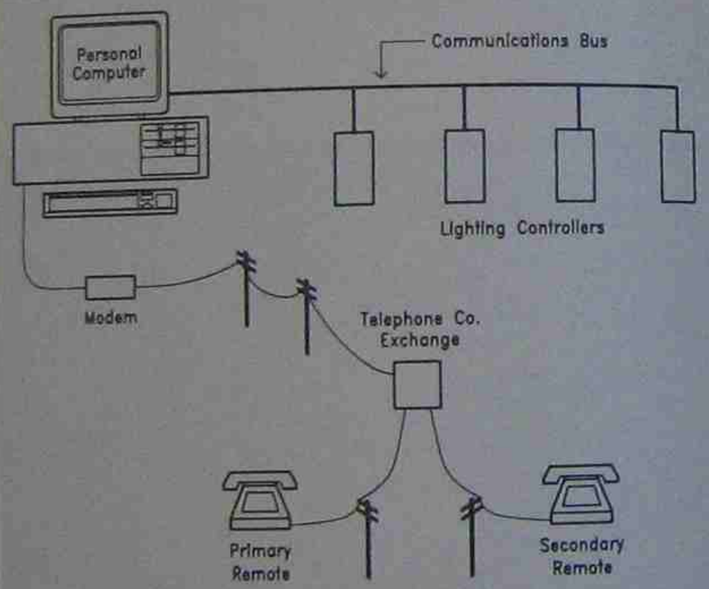


Modulated Lighting Closed Loop Diagram

Figure 6.3

Voice Communications Option

Most Building Automation Systems on the market today offer a voice communications option. Authorized personnel and/or tenants are issued system access password codes. During off hours, they can call the host computer from an off-site touchtone telephone and command the turning on of lights and, in some cases, the appropriate HVAC systems for a specific area over a specific time period. When occupants arrive, the appropriate area lighting will be on and/or the associated HVAC systems will have pre-conditioned the area to comfort levels. Figure 6.4 illustrates the voice communications option.



Voice Communications Option

Figure 6.4

Chapter Seven

Fire Safety Integration

Fires occur in buildings of all types and sizes. As a result, life and property protection have become a top priority for insurance companies, government agencies, and numerous private fire protection organizations. Most states, cities, and towns in the United States have strict building codes which specify minimum standards for design and construction. These codes were written specifically to minimize the risk of fire in public buildings as well as protect the lives of the building occupants. One system that has become a standard fixture in most buildings today is a fire alarm system.

Fire alarm systems fall into two general categories: *life safety* and *property protection*. Life safety systems are installed in buildings that are "occupant-intensive," such as schools, health care facilities (hospitals, nursing homes, mental institutions), prisons, and multiple-story office buildings. The primary goal of a life safety system is early detection and prompt notification, to allow for an orderly and safe evacuation of the building occupants.

Property protection systems are installed in buildings that contain valuable merchandise or confidential or irreplaceable records and documents. Computer rooms, warehouses, museums, art galleries, and libraries fall into this category. The primary goal of a property protection system is detection of fire in the early stages of combustion. Prompt notification of fire fighting personnel and strict guidelines regarding fire extinguishing methods are of major importance in such buildings. See Figure 7.1.

Basic Fire Alarm Systems

First and foremost, the fire alarm system must have the ability to detect a fire and announce its existence and location to the proper authorities at a continuously occupied, central site. There are a number of functions, either directly or indirectly related to fire management, that a fire alarm system can perform. For example, fire alarm systems may also contain and/or evacuate smoke, and release secured doors to allow people to vacate the building.

All fire detection and alarm systems contain basic components. Every fire alarm system must have:

- an initiating circuit
- an indicating circuit
- a control unit

The *initiating circuit*, sometimes called a *sensing circuit* or *sensing loop*, is a circuit designed to detect a fire condition. The *indicating circuit*, sometimes called the *bell loop*, provides notification of the fire condition. The fire alarm control is described in detail later in this chapter. Each of these components is shown in Figure 7.2 and is discussed in the sections that follow.

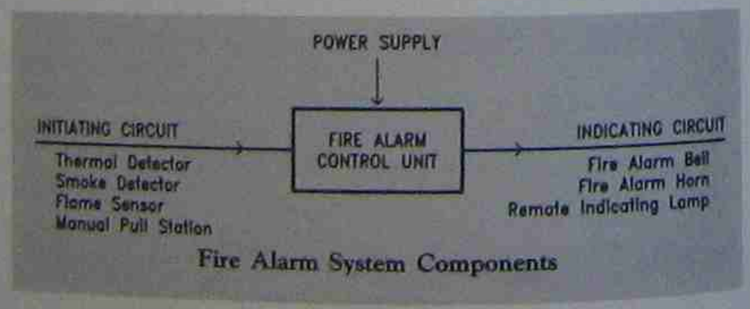
Initiating Circuit

The detection of a fire condition originates with a sensor or sensors in the fire alarm system initiating circuit. Each type of sensor has unique characteristics that make it better suited for certain applications. (The National Fire Protection Association pamphlet titled "NFPA 72E Sensors" contains standards for the installation of fire alarm system sensors.) Some types of sensors commonly found in initiating circuits are:

- thermal detectors
- smoke detectors
- sprinkler heads (waterflow)
- manual pull stations

General Categories of Fire Alarm Systems

Figure 7.1



Fire Alarm System Components

Figure 7.2

Thermal Detectors

Thermal detectors, as the name implies, are actuated by temperature. These detectors are usually mounted on the ceiling in the area to be protected. The time required for a thermal detector to respond to a fire is directly related to its proximity to the fire.

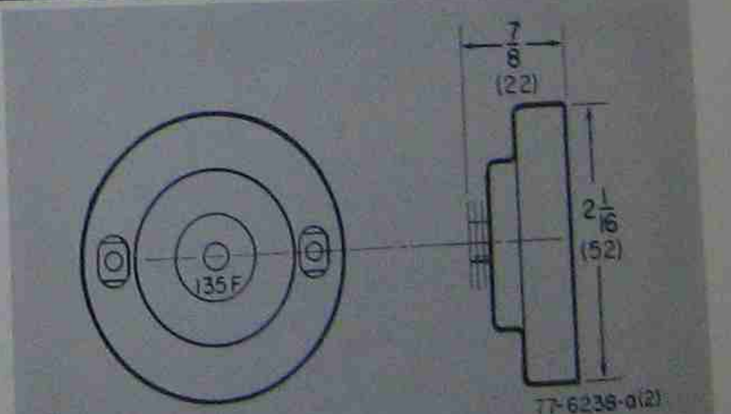
There are basically two types of thermal detectors: *fixed temperature* and combination *rate-of-rise/fixed temperature*. Fixed temperature detectors are available with different, fixed actuation temperatures. The most common is 135°F. They are also available for high-temperature actuation (190°, 200°F). See Figure 7.3.

Combination rate-of-rise/fixed temperature detectors have two different methods of actuation. They will operate at a specific temperature, in the same manner and with the same actuation temperatures as the fixed temperature detector. This type of fire detector will also operate on an abnormally rapid temperature rise over a short period of time. Frequently in the event of a fire the rate-of-rise actuation occurs before the fixed temperature is reached. Figure 7.4 shows a combination rate-of-rise/fixed temperature detector.

Smoke Detectors

Smoke detectors are another type of initiating device. They are actuated by products of combustion released in the very early stages of a fire. These products may be in the form of very tiny particles, invisible to the human eye, or they may be in the form of visible smoke.

There are two types of smoke detectors. *Ionization detectors* contain a small amount of radioactive material that ionizes the air passing through the detector. Products of combustion slow the ionization process, which causes the detector to go into alarm. There are very strict rules governing the installation (location, spacing, and area of coverage) of these detectors. Figure 7.5 shows an ionization smoke detector.



Fixed Temperature Detector

Figure 7.3

Photoelectric detectors, while similar in appearance to ionization sensors, operate only when visible smoke has been generated. A small beam of light is directed through a small, dark-colored cylinder. A photoelectric sensor is located in a branch off the cylinder. Smoke entering the cylinder will deflect the light to the photoelectric sensor, thereby causing the detector to go into alarm. See Figure 7.6.

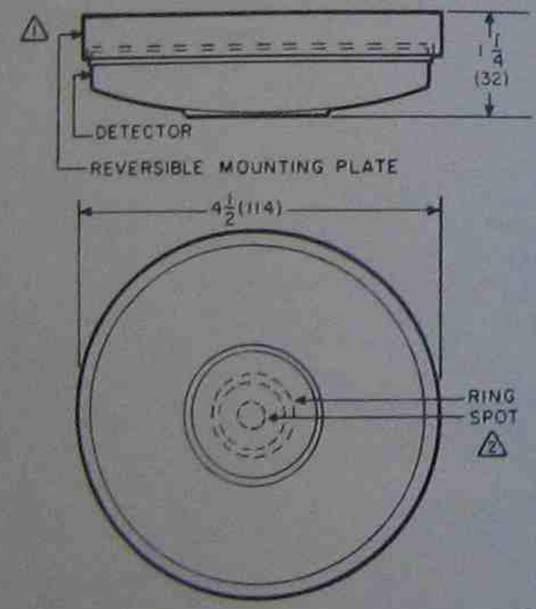
Figures 7.5 and 7.6 depict ceiling-mounted smoke detectors. These detectors are primarily for open-area protection. Duct-mounted smoke detectors of both types are also available to sample air passing through air handling systems. These detectors can be used to close smoke dampers, shut down fans, and send an alarm signal to a central location. Figure 7.7 shows a duct-mounted smoke detector.

Water Flow Sensors

Sprinkler heads are similar to thermal detectors in that they actuate when they reach a fixed temperature setting. When a sprinkler head is actuated, water begins to flow in the piping system. A water flow switch, located in the sprinkler piping, is then actuated to cause an alarm at a central location. Sprinkler heads, however, are not as sensitive as thermal detectors and therefore do not respond as rapidly as thermal detectors. This is because of the mass of the sprinkler heads and their associated piping. The advantage of this slightly slower reaction is that they do not activate so quickly, and thereby may avoid unnecessary water damage. Figure 7.8 shows two types of sprinkler heads.

Manual Pull Stations

Manual pull stations are not automatic fire alarm devices – they require a person to actuate them manually. These devices are normally



Combination Rate-of-Rise/Fixed Temperature Detector

Figure 7.4

Ionization Smoke Dectecor

Figure 7.5

Photoelectric Smoke Detector

Figure 7.6

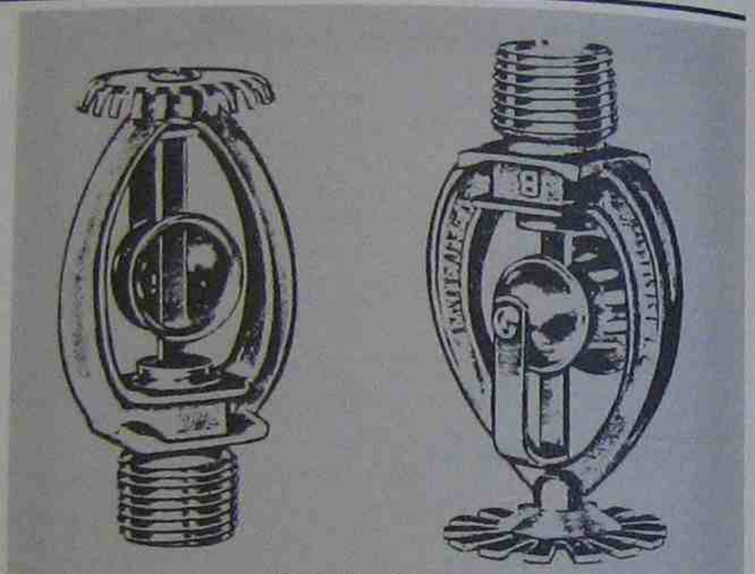
Duct-Mounted Smoke Detector

Figure 7.7

mounted in hallways and lobbies near exit doors. Figure 7.9 shows a manual pull station.

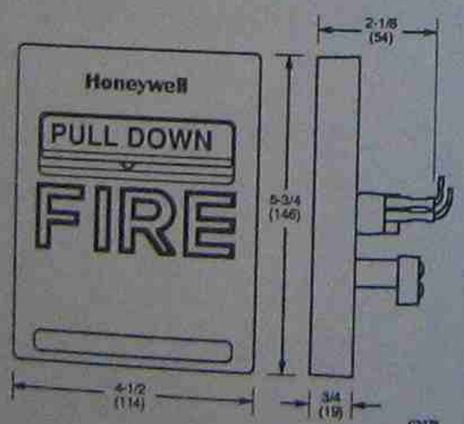
Indicating Circuit Devices

The indicating circuit in a fire alarm system contains devices that notify building occupants of the presence of fire. Bells and horns are commonly used to signal an alarm condition to building occupants. When bells are utilized for other purposes in a building, however, horns must be used for fire alarm notification. See Figures 7.10 and 7.11.



Sprinkler Heads

Figure 7.8



Manual Fire Alarm Station

Figure 7.9

There are other types of signals used for alarm notification. In buildings where coded alarms are necessary, such as hospitals, chimes are used as indicating devices. Chimes also have a softer, less irritating sound than bells or horns. For outdoor applications, or indoor areas with loud background noise, sirens are commonly used. For the benefit of building occupants who have hearing difficulties, bells and horns are available with accompanying high-intensity strobe lights to provide visual indication of an alarm condition (See Figure 7.12). High-efficiency loudspeakers are also used as indicating devices in fire management systems. These speakers are capable of transmitting audible fire alarm signals and voice communication messages. They are suitable for indoor and outdoor installation.

Fire Alarm Control Units

Since a fire alarm system is in a standby or passive state for extensive periods of time, there should be constant indication that the system is operationally sound. Consequently, most of the control panel external circuits are electrically supervised on a continuous basis, to assure that they are in working order. If a circuit malfunction occurs, an audible trouble alarm will be energized, and a visual trouble alarm light will illuminate at the control panel. A fire alarm system that cannot operate due to a faulty circuit or device could result in destruction of property and/or loss of life. Therefore, the supervision of circuits is required to provide circuit continuity on a constant basis. Fire detection and alarm

Fire Alarm Horn

Figure 7.10

Fire Alarm Bell

Figure 7.11

panels are classified as *fire alarm control units* when their initiating circuits and indicating circuits are supervised. Fire alarm control units contain contacts for remote alarm and trouble indication. These contacts can be used for additional functions such as releasing fire doors, or remote station operation. Operation from stand-by rechargeable batteries with an automatic battery charger is also an option.

There are two types of fire alarm control units: *single-zone units* and *multiple-zone units*. A single-zone fire alarm control unit has one initiating circuit that is wired to multiple initiating devices, and one indicating circuit that is wired to multiple indicating devices. See Figure 7.13.

A *multiple-zone fire alarm control unit* consists of multiple, single-zone modules, as required, to meet the building's fire alarm zoning needs. Each module of the multiple-zone fire alarm control unit is autonomous and operates independently of the other zone modules. See Figure 7.14.

Fire management panels (Figure 7.15) consist of initiating circuits using the same single-zone modules as a multi-zone fire alarm control unit. In place of bells, horns, or chimes in the indicating circuits, fire management panels use speakers powered by amplifiers. An interface module provides command functions to the speaker zones. A telephone module with remote telephones allows firefighters to communicate between the control panel and remote locations. There is also an HVAC module that can control fans or dampers, as required, to contain smoke or fire in any zone.

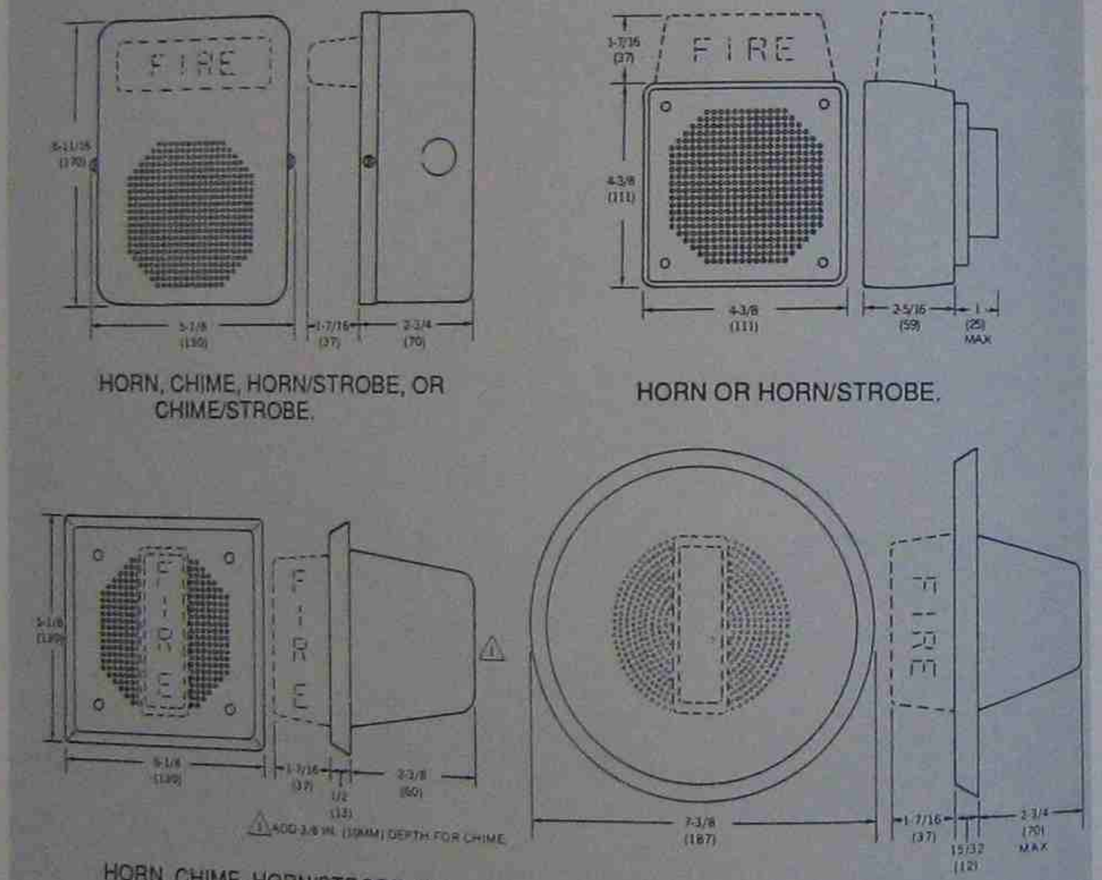


Figure 7.12

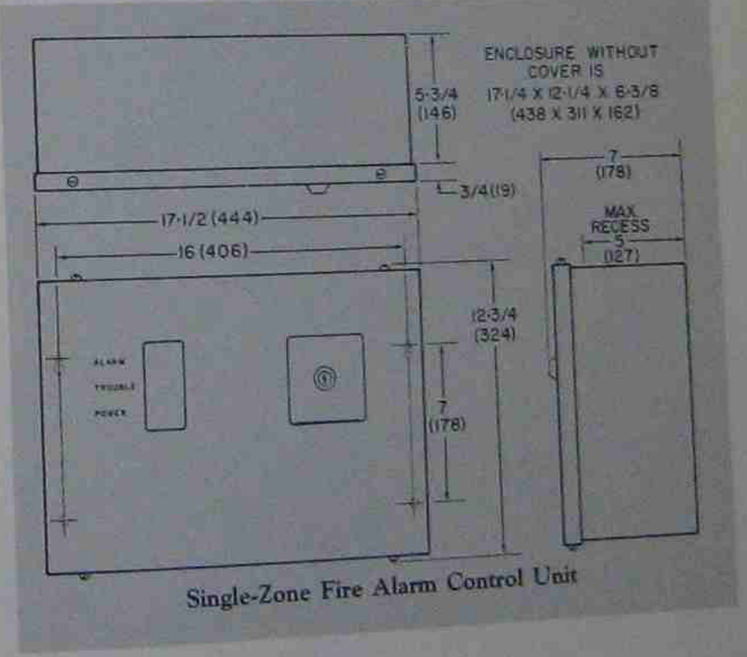


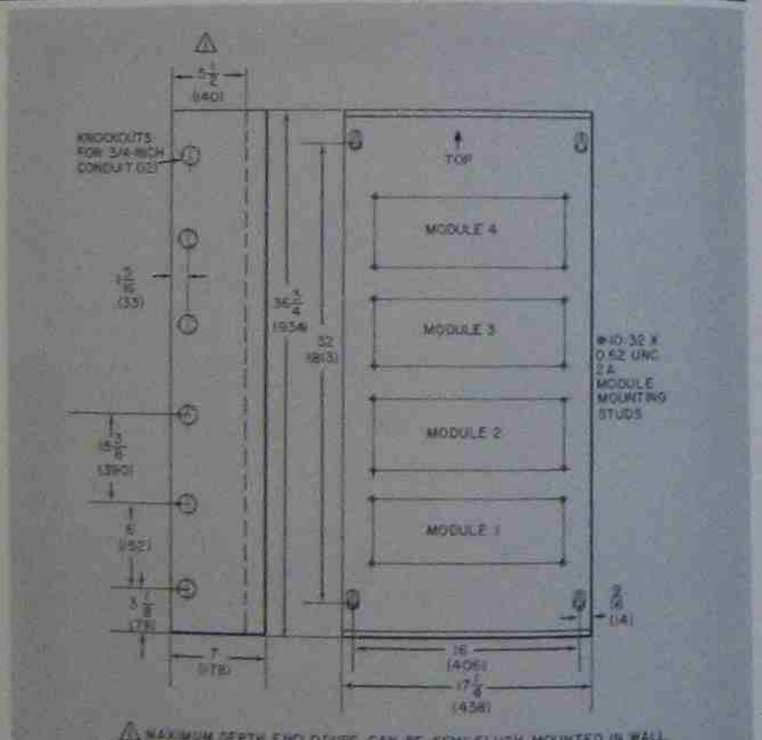
Figure 7.13

Microprocessor-Based Fire Alarm System

The use of microprocessor-based distributed process system technology has led to the development of more sophisticated fire alarm systems. This technology has added intelligence to the fire alarm control unit to improve reliability and flexibility.

Stand-Alone Fire Alarm Control Unit

A basic stand-alone fire alarm control unit is a multiple-zone fire alarm control unit with its function modules mounted on plug-in circuit boards. The control unit monitors conventional fire sensors that are arranged by zones. All the variables of a multiple-zone fire alarm control unit are addressed by software programmed into the control board. The addition of an interface board, in most systems, allows a basic stand-alone fire alarm control unit to communicate, via a communication bus, to a higher level central host personal computer. However, if communication with the central host is lost, the stand-alone control unit will continue to perform its fire alarm initiating and indicating functions.



Multiple-Zone Fire Alarm Control Unit

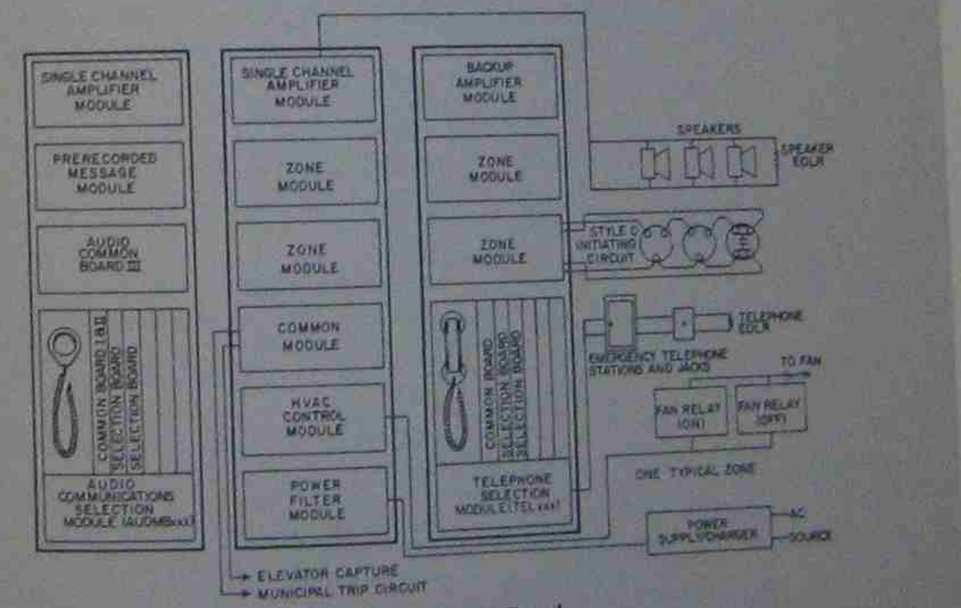
Figure 7.14

Stand-Alone Fire Management System

This system consists of a basic stand-alone fire control unit, a fire command station, and a remote audio cabinet. The system's indicating circuits notify the building's occupants of a fire by broadcasting special fire tones or a voice message over speakers. Like the basic stand-alone fire alarm control unit, the fire management system can also communicate with a higher level central personal computer.

Stand-Alone Intelligent Fire Alarm System

This system uses intelligent initiating circuit sensors, such as thermal sensors or photoelectric and ionization smoke sensors. Intelligent indicating circuit devices are also used to provide software-driven fire alarm notification. Each intelligent initiating circuit sensor and indicating circuit device contains a custom integrated circuit, enabling two-way communication to a stand-alone intelligent fire alarm system control unit. Also, each sensor can communicate its individual point address (based on sensor type) and an analog value to the fire alarm control unit. In general, most systems can analyze the analog signal to measure each sensor's sensitivity and to determine its status, such as pre-alarm (signaling the need for maintenance), normal, trouble, or alarm state. Like the basic stand-alone fire alarm control unit, the intelligent fire alarm system can communicate with a higher level central host personal computer.



Fire Management Panel

Figure 7.15

Fire Alarm System Integration

A fire alarm system can be integrated with other building systems, such as heating, ventilating, and air-conditioning (HVAC), lighting, security, and access control, through a Building Automation System (BAS). The BAS can receive and process information from these various building systems. In the event of a fire, interactive software programs can activate sequences which will notify building occupants of a fire, control HVAC systems to contain smoke or provide smoke-free areas for occupants, take control of the elevators, and notify authorized personnel of the fire's location and what action to take.

There are two ways to incorporate a fire alarm system into a Building Automation System: 1) an existing, stand-alone, functioning fire alarm system can be connected to a BAS, or 2) a new state-of-the-art BAS-compatible fire alarm system can be installed.

Partial Integration

An existing fire alarm system is basically a stand-alone system that has an initiating circuit, an indicating circuit, and a control unit. It may also have a central operator interface, or monitor, to indicate fire location and monitor system status.

The control unit has auxiliary alarm contacts for each zone, and auxiliary contacts for system trouble indication. These auxiliary contacts are considered to be digital output points from the control unit. When hard-wired to a BAS system controller, they become digital input points. Each set of alarm or trouble contacts connected to a system controller is a digital input point. In the event of a fire, the control unit will actuate the indicating circuit, announce the fire's location and other pertinent information at its central monitor, and actuate the appropriate zone auxiliary switch. The BAS host computer will display and print preprogrammed information, such as time, date, fire location, and operator action messages. Through software programs, the BAS system controller can also activate HVAC control sequences such as smoke containment or smoke evacuation.

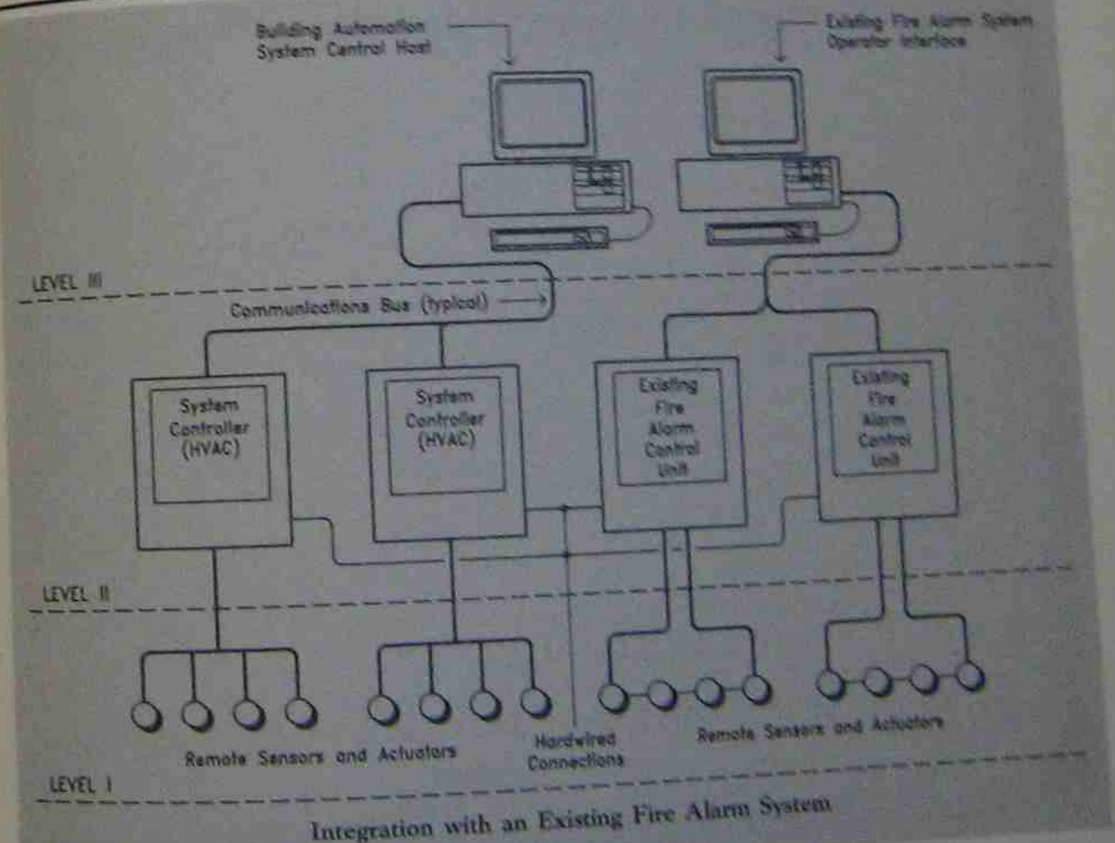
There are some advantages to integrating a fire alarm system through a BAS with other building systems. First, an existing fire alarm system, if functional, can be connected to the BAS at a considerable cost savings. Second, the interaction of software programs can add some life safety and property protection features to the existing fire alarm system. Third, it allows central monitoring of the fire alarm system and other building systems by one operator.

One disadvantage of partial integration is that the interconnecting wiring between the existing fire alarm control unit and the BAS controller is not supervised. As a result, there could be a failure of this wiring without notification. Figure 7.16 shows the connection of an existing fire alarm system to a Building Automation System.

Total Integration

In new building construction, or in renovation of existing buildings, serious consideration should be given to the total integration of as many building systems as possible. At that time it is possible to combine HVAC, lighting, fire, security, and access control under one central Building Automation System. Total integration of the fire alarm system means that a single central host computer serves the fire alarm system as well as the other building systems. The fire alarm control panels and the system controllers (HVAC and lighting) communicate with the central host computer over separate communications buses. The fire alarm control panels, like the HVAC system controllers, are designed to operate as stand-alone systems if the communications link with the central host computer is lost. The central host computer can monitor both the HVAC systems and the fire alarm systems. An optional fire alarm monitor can also be located remote from the central host to monitor only the fire alarm points. Figure 7.17 shows how a fire alarm system is integrated with HVAC systems.

One of the major benefits of total building systems integration is systems interaction. Assume, for example, that the fire alarm control units and HVAC system controllers are integrated through software. If a fire occurs on one floor of a multi-story building, the ventilating units can be used to prevent the smoke from spreading. Exhaust dampers can be opened and outdoor air intake dampers closed on the fire floor. On the floors above and below the fire floor, the exhaust dampers can be closed



Integration with an Existing Fire Alarm System

Figure 7.16

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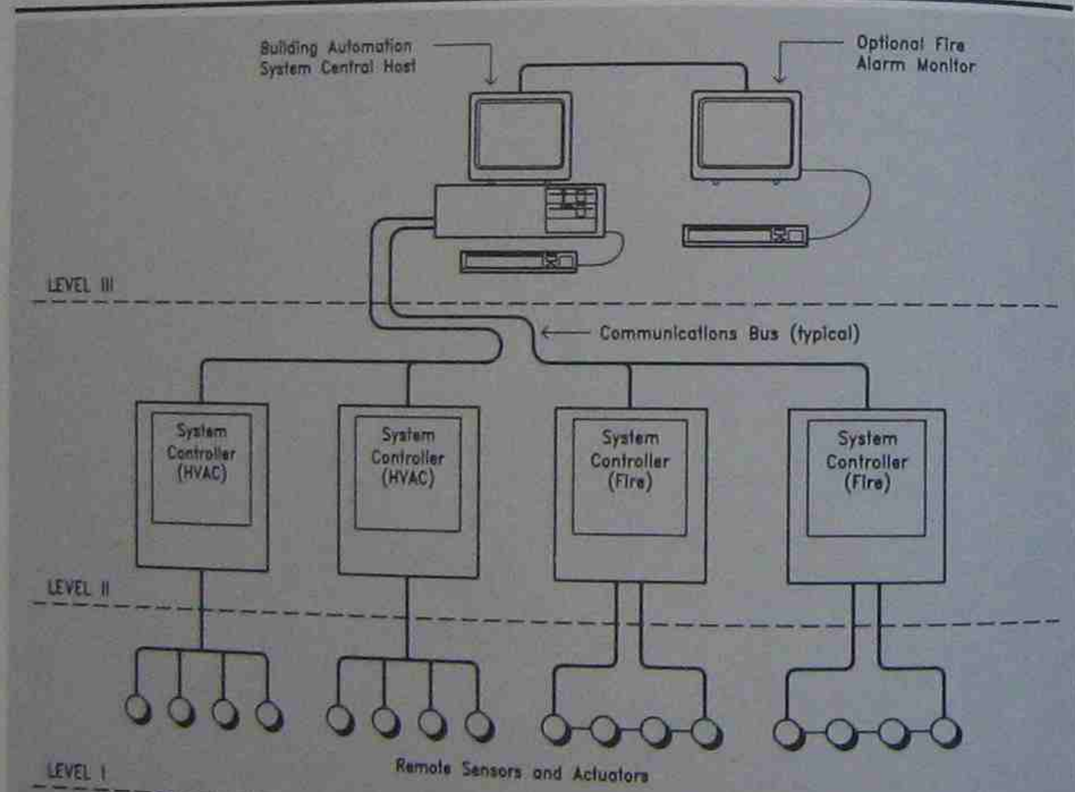
and the outdoor intake dampers opened. This will pressurize the area surrounding the fire floor, thereby containing the smoke (See Figure 7.18). This is only one of many possible Fire/HVAC software strategies which can be employed through building systems integration.

Central Host Computer

The central host PC, when connected to intelligent fire alarm control panels, can monitor individual fire initiating devices, such as smoke detectors and thermal detectors. Consequently, alarm response and evaluation can be based on the initiating device location rather than multi-device zone location.

Color graphic software provides a library of standard symbols and graphics packages to simplify the on-line construction of graphics. Floor layouts can be created graphically that depict fire initiating devices in their actual locations. In the event an initiating device goes into alarm,



Fire Alarm System Total Integration

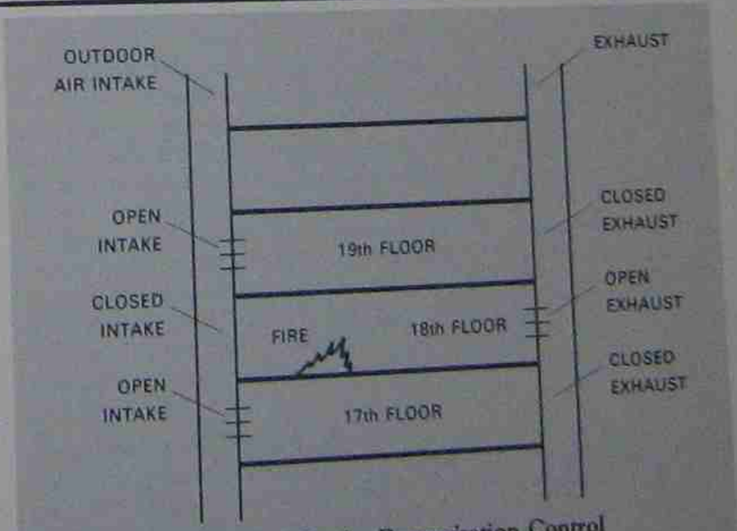
Figure 7.17

the appropriate floor layout can be displayed on the monitor (CRT), showing the operator the alarm location. The monitor can display emergency action instructions for the operator to follow, while the printer generates a hard copy of these instructions. The printers associated with the central system provide documentation of all pertinent system activity. In the event of a fire alarm, the printers record the type of alarm, the zone or individual sensor location, the time of the alarm, an operator acknowledgment code, and the time of acknowledgment.

Event-initiated programs can activate interactive software programs among integrated building systems. A fire alarm system can interact with HVAC systems to prevent the migration of smoke to other zones or floors. A fire alarm can also interact with the access control system to unlock secured doors and allow building occupants a means of egress.

Alarms can be prioritized, enabling more critical alarms to supersede less critical alarms. For example, if an HVAC fan failure alarm occurs simultaneously with a fire alarm, the fire alarm will appear first. When the fire alarm has been acknowledged, the fan failure alarm will display. Fire alarms from critical areas can be programmed to override fire alarms from areas or zones not considered to be as critical.

Most BAS's have multiple levels of operator access to the system through the central host terminal. These authorization levels are assigned by the system owner. Operators sign on with an ID and



Example of Smoke Pressurization Control

Figure 7.18

password, which define that operator's level of access. For example, an operator may only be authorized to receive and acknowledge alarms, not to make program changes. This feature prevents operators from intentionally or inadvertently deleting or changing fire alarm programs.

Integrating a building fire alarm system with other building systems can offer many benefits. Interactive software programs can increase the quality of life safety programs, and consolidating building monitors and alarm activities at a central location offers some economic and operational benefits as well. There may also be some advantages in the installation phase from fire alarm system integration.

Chapter Eight

Security-Access Control Integration

The theft, vandalism, and violence which permeate our society today have increased the demand for security systems and services. There was a time when simply locking the door at the end of the day was sufficient protection. Today, the worldwide security market is a multi-billion-dollar industry that continues to grow annually at a tremendous rate.

Businesses have special security needs. Inventory in warehouses and stockrooms must be protected against theft from both internal and external sources. Confidential records and documents must be protected from unauthorized access. Computer rooms, which are critical to the operation of most companies today, make tight security and personnel access control extremely important. The threat of vandalism alone makes security around the perimeter of any building almost mandatory. Some businesses have building zones that must be secure on a 24-hour basis, while in other buildings, the entire system can be deactivated during occupied periods and activated during unoccupied periods.

Building Security Systems

Major advances in microelectronics have resulted in the development of more sophisticated building security systems. Not long ago, magnetic switches on perimeter doors and windows comprised a building's entire security system. Today, this basic form of intrusion protection represents only a portion of a comprehensive building security system. Extremely sensitive motion detectors located in interior zones of a building can detect even the slightest movement of a person or object in the protected area. Pulsed, infrared, and photoelectric beam sensors have been developed to replace the old lamp-type sensors that were easy to compromise. Many other types of security sensors, such as pressure mats, glass break detectors, vibration detectors, taut wire detectors, and audio detectors, are now available to effectively render a building secure.

Categories of Protection

Building security systems provide three categories of protection, which may be thought of as lines of defense. These lines of defense are: 1) perimeter protection, 2) area protection, and 3) object protection.

Perimeter protection is protection against unauthorized intrusion into a building through exterior walls, windows, doors, transoms, skylights, or ventilating ducts. Detection of this type of entry can be sensed by vibration detectors, magnetic door and window switches, and glass door and window tape.

If perimeter penetration is achieved, a second line of defense is *area protection*. The primary goal of this type of protection is to detect movement in the protected area. Motion detectors, infrared detectors, and photoelectric beams can be used for movement detection.

A third line of defense is *object protection*. This method of protection is used where a specific item or object is to be protected. Filing cabinets, safes, or art objects fall into this category. Proximity sensors, infrared detectors, and vibration detectors are commonly used as sensors for this type of protection.

Basic Security System Components

All security systems must be capable of sensing unauthorized intrusion and providing notification to some responsible person or persons. There are also a number of functions, directly or indirectly related to security, that the security system can perform, such as elevator alarm, panic alarm, or hold-up alarm, releasing doors to allow people to leave the building or securing them in a protected area.

All building security systems contain basic components. A basic security system consists of a control unit, initiating devices (a circuit to sense unauthorized intrusion), and indicating devices (a circuit to provide an indication of the alarm). See Figure 8.1. The relay shown in Figure 8.2 is located in the control unit, the door and window switches in the initiating circuit, and the horn in the indicating circuit. The batteries are the power source. If a door or window is opened, the respective door or window switch will open, interrupting power to the relay in the control unit. The relay contacts will go to their normally closed position, connecting the alarm battery to the horn, thereby causing an alarm.

Security Initiating Circuit Devices

Initiating circuits operate with switching contacts that either close or open under alarm conditions. This may be as simple as a magnetic switch that opens or closes when a door is operated, or as complex as an electronic alarm panel connected to numerous sensing devices. Regardless of how it is accomplished, the initiating circuit is either opened or short-circuited in the event of an alarm condition.

Initiating circuit devices fall into several categories.

Contact Devices
- Magnetic door and window switches
- Mechanical switches (roller, butt, etc.)
- Window tape
- Duress switches
- Pressure mats
- Glass break detectors
- Vibration detectors
- Thermal switches
- Taut wire detectors
- Traps

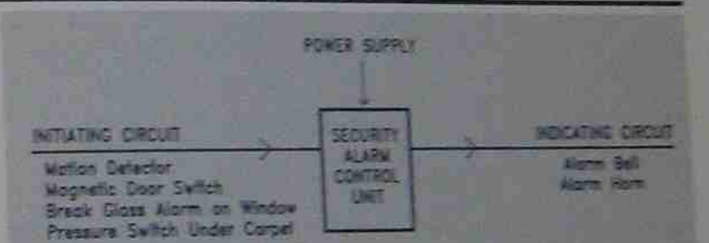
Audio Detectors
- Ultrasonic sensors
- Audible sound devices
- Electronic vibration detectors

Microwave Detectors

Infrared Detectors
- Passive infrared
- Photoelectric beam

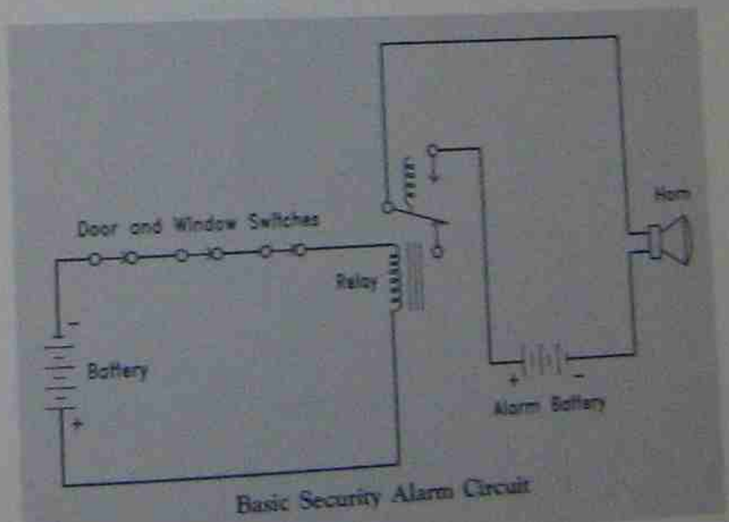
Security Indicating Circuit Devices

Security systems in large buildings do not use the same type of local indicating devices or alarms as those used in residential security systems. In some commercial buildings, a monitor or annunciator at a central guard station is considered to be the indicating device and control unit.



Security Alarm System Components

Figure 8.1



Basic Security Alarm Circuit

Figure 8.2

Security Control Unit

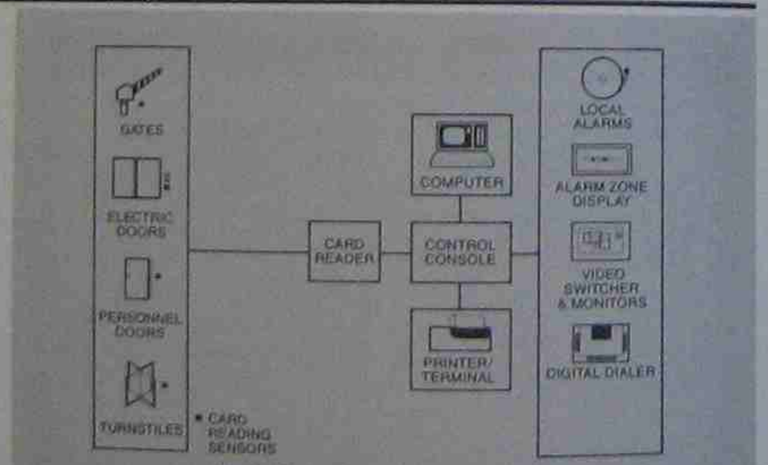
In buildings with stand-alone security systems, the initiating circuit devices communicate directly to a central monitoring station (security control unit). The central monitoring station acts as the security control unit and indicating device.

Access Control Systems

In the past, access to a building or area was controlled by security guards, locked doors, and fences. The advent of closed circuit television (CCTV) made it possible for one centrally located person to guard a number of doors or gates through electrically controlled locks.

Card reader access control systems are an effective means of controlling personnel movement in a building. The cards are issued to select individuals and read by a card reader which, in turn, unlocks doors assigned to the card holder. These systems limit access to restricted areas to authorized personnel only. After-hours access to a building can be restricted to specific cardholders and specific doors. The card reader access control system can also be used for time and attendance record keeping. The concept of using coded cards has been available since the late 1950s. Newer systems have been developed to provide a much higher security level. For example, recent technology has made possible the use of a person's physical features, such as a handprint, voice, or eye characteristics, to identify the person and allow access.

Figure 8.3 illustrates a typical access control system.



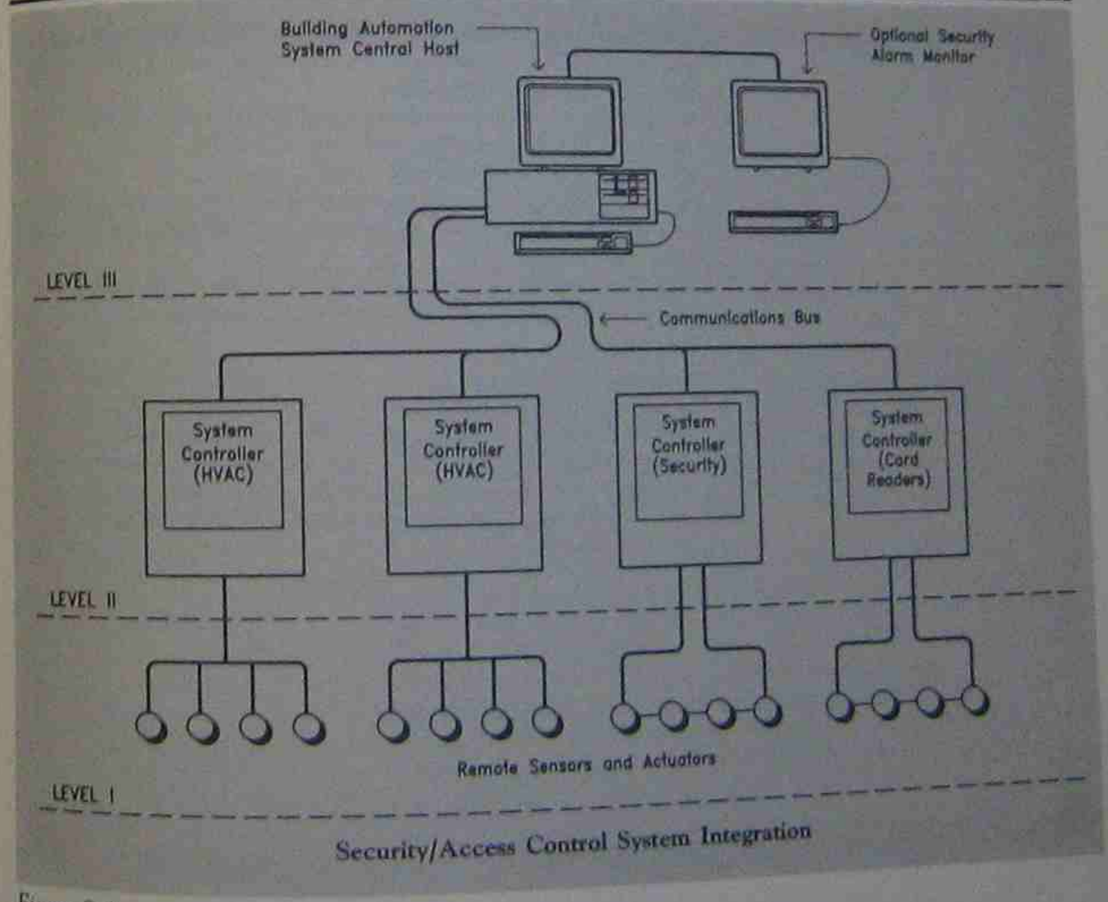
Typical Access Control System
(courtesy Schlage Electronics)

Figure 8.3

Building Automation System (BAS) Integration

Most of the security and access control systems on the market today can operate in a stand-alone manner. However, the trend in new buildings is toward the total integration of building systems. To some degree this integration exists today. Through total system integration, a BAS can receive information from a security access control system. This is shown in Figure 8.4.

The integration of security and access control, and other building systems (such as HVAC, lighting, fire) into a Building Automation System can provide both economic and operational benefits. First, initial installation work, such as electric wiring, can be consolidated, resulting in cost savings. Substantial paybacks can be generated through HVAC energy management and lighting programs, thereby offsetting some of the costs involved in the integration process. Second, the cost



Security/Access Control System Integration

Figure 8.4

of on-site guard services can be greatly reduced. After-hours monitoring of all alarms (HVAC, fire, security), can be accomplished by one operator from a single, central location. Third, interactive software programs between security-access and fire alarm systems can, in case of fire, unlock perimeter doors, providing a means of emergency egress from the building. Finally, independent terminals and printers, serving each system, can be provided at different locations.

Central Host Computer

A single central host personal computer serves the security-access system, fire, and HVAC system controllers. The Level II security-access control units, fire, and HVAC system controllers communicate over separate communication buses. The Level II controllers are designed to operate as stand-alone systems if the communication link with the central host PC is lost. The Level II security-access control units can also provide annunciation locally, or to a remote or central station system. The central host terminal and printers can be located at a security office and, if desired, limited to security-access information. However, the security-access control system, fire, and the HVAC system controllers are interactive through software. Upon activation of a security-access initiating sensor, the central host can provide the following:

1. A description of the zone or initiating sensor detecting an unauthorized intrusion appears on the CRT and printer. The CRT may also show an area, building, or floor layout indicating the location of the intrusion alarm. Emergency action instructions are also displayed on the CRT.
2. A hard copy is printed out documenting the location of the unauthorized intrusion, time and date, and alarm acknowledgment by whom and when.
3. Operator can override exit doors, locked by the security-access system, to permit entrance or egress during emergency or unusual situations.
4. CRT displays (with a hard copy printout) a list of cardholders entering and leaving a secured area by card number, time, date, and location.

The integration of security and access control systems with other building systems offers an opportunity for cost savings on the initial installation and ongoing operating costs. The consolidation and monitoring of all building systems at a central operating center provides some obvious economic benefits. The interactive software program potential of total integration creates an enhanced quality of life safety and property protection.

Chapter Nine

Facility Management Programs

A Building Automation System (BAS) is a tool that can be used to assist facility management and operating personnel in four important ways. First, Building Automation Systems maintain comfort conditions in a building. BAS are designed to control HVAC systems in the most efficient manner, while providing adequate ventilation and comfortable temperature and relative humidity levels. Microelectronic sensors feed signals to microprocessor-based controllers, which control environmental conditions to within very close tolerance levels. As a result, building occupants are exposed to only the highest level of indoor air quality.

Second, Building Automation Systems control operating costs. For example, BAS energy management software programs control energy-consuming systems (HVAC and lighting) in the most cost-effective manner. These energy management programs are included in the standard software offered by most manufacturers today. Significant energy dollars can be saved without sacrificing comfort conditions by activating these energy-saving strategies.

Third, Building Automation Systems monitor other building systems. BAS is designed for total integration of HVAC systems, lighting, fire safety, and security and access control. The advantages of integrating these building systems are: lower initial cost, lower operating cost, improved life safety, reduced control system maintenance requirements, and the ability to monitor and manage all building systems from a central location.

Finally, a building automation system has the ability to generate management reports from information supplied to it from remote sensors and input devices. These management reports are a useful tool for extending equipment life expectancy, controlling operating costs, scheduling preventive maintenance tasks, controlling inventory, monitoring efficiency of energy-consuming systems, and recording energy consumption for an individual zone or for the entire building. This feature is discussed in more detail in the next sections.

Computerized Maintenance Management Programs

In general, many third-party computerized maintenance management software programs now available schedule maintenance activity on a real-time basis. The monitoring and reporting features provide facility management personnel with the tools needed to protect equipment, control costs, schedule workloads, review historical trends, manage materials, and plan budgets. The program issues work orders either automatically or by operator request, based on calendar time, equipment run time, or event occurrence. CRT display and hard copy printouts depict detailed work status, delinquent maintenance, inventory, and financial statistics reports. Supervisors can assign system access levels so that maintenance personnel will have access to information that pertains to their job classification only.

Maintenance Scheduling

The operators can set up *tasks* based on user-defined material, skill, and tool data bases. Multiple tasks are linked together for a *maintenance activity* on a specific piece of equipment. Maintenance schedules for a maintenance activity, or *job* depict detailed work orders for each associated task. Figure 9.1 shows the maintenance activity/job process.

Figure 9.2 is a work order that can be scheduled on a calendar basis *(every six months)*, equipment run time basis *(every 2,000 hours of run time)*, or event-occurrence basis *(dirty filter alarm)*. An operator can also request a work order manually.

Work Order Printout

Maintenance schedules are printed out automatically at a user-defined interval: daily, weekly, monthly, or yearly. The work orders can be sent to a remote printer or located in the department responsible for the work.

In general, maintenance requests consist of *task control* and *work order pages* (Figure 9.3). The task control and work order pages contain all pertinent information relating to the work to be performed. Overview information includes a work order reference number, issue date, supervisor, requesting person, due date, last work order reference number, and other descriptions. When all work is completed, the maintenance person fills out the "Comments" area of the work order, noting the materials expended and time required to complete the work.

Next, the completed work order is processed by the system operator. If the maintenance is delayed, the operator can list it in backlog or, if the work is not required, cancel the work order. Figure 9.4 illustrates the work order mechanism (from issue to completion of the work order).

Maintenance History

Most maintenance management software programs can archive all work order data. The operator can then retrieve historical information about equipment, skills, materials, and tasks.

Material Inventory

A maintenance management software program may include a record keeping system for maintenance materials. Figure 9.5 depicts an inventory control printout which is used to track material quantity, costs, usage, and stock location. When material inventories drop below a predetermined level, the program issues a reorder request, as shown in Figure 9.6. This ensures that the parts and materials are available to maintenance personnel on an as-needed basis.

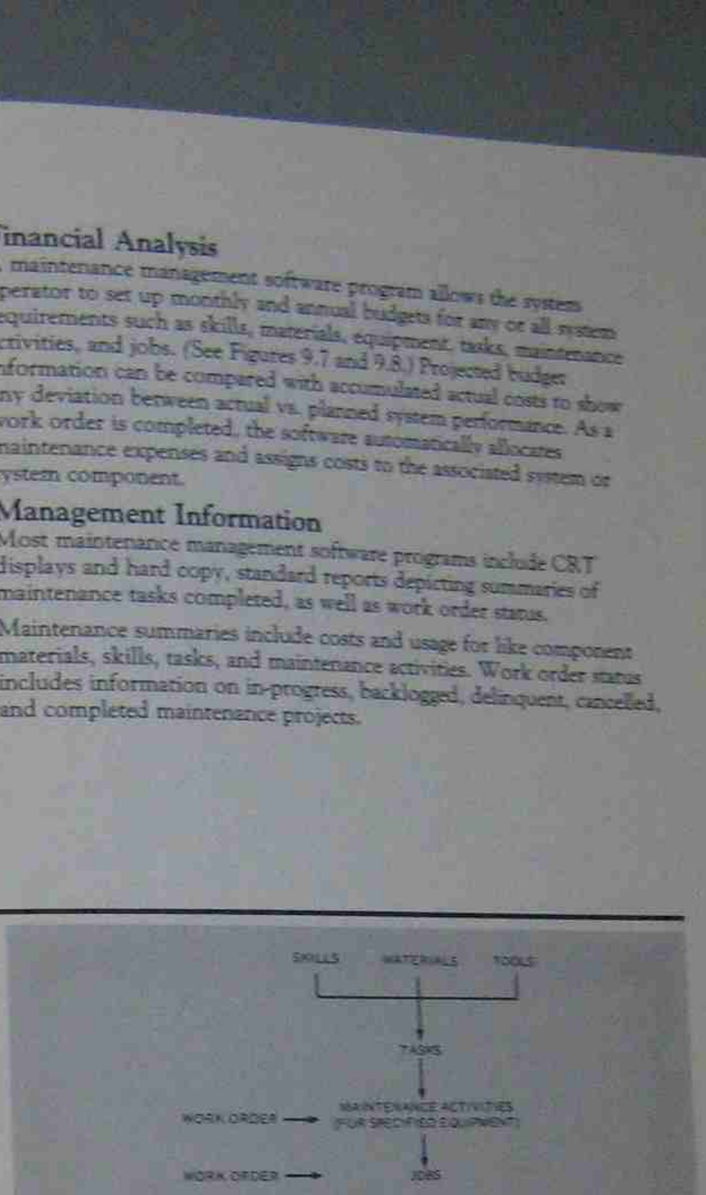
Financial Analysis

A maintenance management software program allows the system operator to set up monthly and annual budgets for any or all system requirements such as skills, materials, equipment, tasks, maintenance activities, and jobs. (See Figures 9.7 and 9.8.) Projected budget information can be compared with accumulated actual costs to show any deviation between actual vs. planned system performance. As a work order is completed, the software automatically allocates maintenance expenses and assigns costs to the associated system or system component.

Management Information

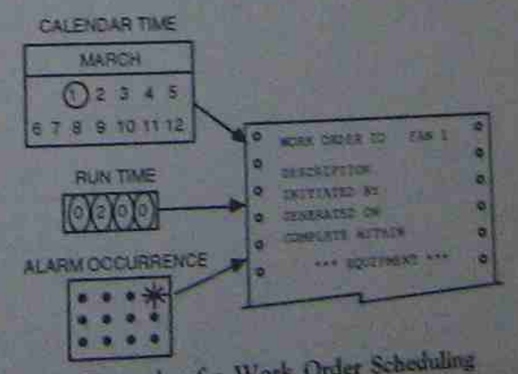
Most maintenance management software programs include CRT displays and hard copy, standard reports depicting summaries of maintenance tasks completed, as well as work order status.

Maintenance summaries include costs and usage for like component materials, skills, tasks, and maintenance activities. Work order status includes information on in-progress, backlogged, delinquent, cancelled, and completed maintenance projects.



Maintenance Activity/Job Process

Figure 9.1



Example of a Work Order Scheduling

Figure 9.2

TASK CONTROL

DATE: 1985/01/07

EQUIPMENT: ABSRIT-N WORK ACTIVITY: ABD-N

DUE DATE: 1985/01/09

PREVIOUS W.O.:

REASON FOR ISSUE: EVENT OCCURRENCE REF. POINT:

REQUESTED BY: R. RADFORD TEL #: 793-8111 EXT: 2745

NOTIFY USER? YES

EQUIPMENT: ABSRIT-N
NORTH AIR HANDLING UNIT

WORK ACTIVITY: ABD-N
PREVENTIVE MAINTENANCE FOR NORTH AIR HANDLING UNIT

TASK NO.	TASK ID	RELATIVE PRIORITY
1	AIRFTR	1
2	CLNFAN	2

ITEM	QUANTITY	UNIT	COST

COMMENTS:

WORK ORDER

AB-0000078-1 DATE: 1985/01/07

JOB: EQUIPMENT: ABSRIT-N WORK ACTIVITY: ABD-N

DUE DATE: 1985/01/09

PREVIOUS W.O.:

REASON FOR ISSUE: EVENT OCCURRENCE REF. POINT:

REQUESTED BY: R. RADFORD TEL #: 793-8111 EXT: 2745

NOTIFY USER? YES

EQUIPMENT: ABSRIT-N
NORTH AIR HANDLING UNIT

TASK: AIRFTR
REPLACE FILTER AND CHECK AIR PRESSURE.
1. REPLACE FILTER.
2. VERIFY PROPER AIR FLOW USING MANOMETER.

TOOL: M-MTR
MANOMETER

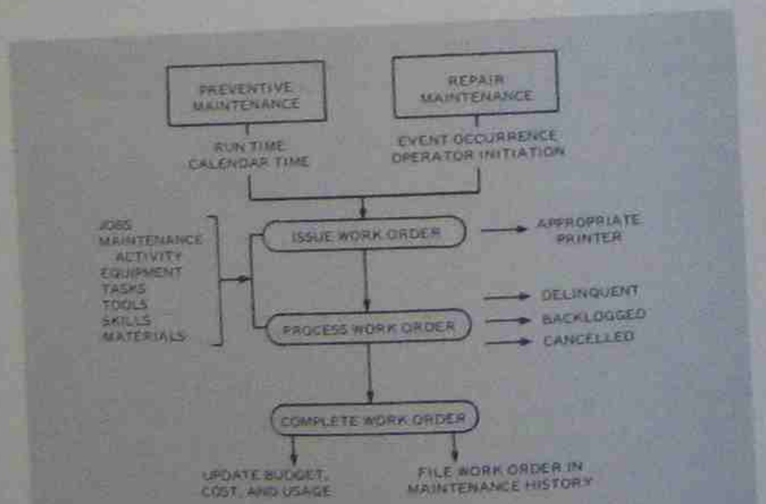
SKL: MECH3
LEVEL 3 MECHANIC

MAT: AAF328
FILTER FOR AIR HANDLING UNITS

COMMENTS:

Example of a Maintenance Request Document

Figure 9.3



Work Order Mechanism

Figure 9.4

Utilities Metering Program

It is frequently the responsibility of the building manager, director of facilities, or a member of the building owner's staff to periodically review and keep ongoing records of energy consumed by the facility. These records include the amount of electricity or fuel (natural gas or oil), purchased steam, or any other heating and/or cooling medium purchased from an outside source. In many cases, the building owner or his operating staff must rely on the accuracy of the vendor's meter for their energy consumption records. However, many times a single meter records energy consumption for an entire facility with multiple tenants. The question then is how to fairly allocate costs to each tenant. Energy costs are sometimes allocated on a square foot basis or on the basis of occupancy hours. Unfortunately, there is no accurate way of distributing the costs equitably unless individual meters are installed for each tenant.

MATERIAL DEFINITION

1) MATERIAL DATA
2) REORDER DETAILS
3) INVENTORIES PER LOCATION

PLEASE ENTER SELECTION:

MATERIAL-ID: AAF328
BUDGET-ID: AHUFTR UNIT COST: $35.00
QUANTITY ON HAND: 10.00 UNIT: FTR COST ON HAND: $350.00

DESCRIPTION: AIR FILTER FOR AHU'S

MATERIAL-ID: AAF328
REORDER POINT: 10.00 REORDER QUANTITY: 15.00 UNIT: FTR
ESTIMATED PRICE: $525.00 LEAD TIME (DAYS): 21
REORDER STATUS: W
DESCRIPTION: ORDER FROM:
ADDRESS—
AMERICAN AIR FILTER
10277 NATIONAL AVENUE
NEW YORK, NY 10109
PHONE—
(512) 376-4201
PART NUMBER:
AAF328

MATERIAL-ID: AAF328 UNASSIGNED INVENTORY: _____
LOCATION CODE: N-STC UNIT: FTR
QUANTITY IN LOCATION: 10.00

N-STG

Example of Inventory Control Printouts

Figure 9.5

1991/05/20

MATERIALS TO REORDER

Material ID	Unit	Quantity On Hand	Cost On Hand	Quantity To Reorder	Estimated Price
MAT01	EA	100	$ 200	200	$ 2
MAT04	EA	2	$ 250	10	$ 150
MAT05	EA	100	$ 200	200	$ 2
MAT06	EA	5	$ 170	30	$ 34
MAT08	DOZ	12	$ 4200	20	$ 350

*** END OF REPORT ***

1985/05/20

MATERIALS ON ORDER

Material ID	Unit	Quantity On Hand	Cost On Hand	Quantity Ordered	Estimated Price
MAT02	EA	100.00	$ 200.00	200.00	$ 2.00
MAT07	EA	5000.00	$ 50000.00	50.00	$ 10.00
MAT10	GAL	13.50	$ 1188.00	25.00	$ 88.50

*** END OF REPORT ***

Example of Material Reordering Reports

Figure 9.6

Budget ID: AHUFTR

Budget Year: 1991
Unit: FTR

	Costs		Maint. Schedules		Quantities	
	Plan	Actual	Plan	Actual	Plan	Actual
Jan	$ 35.00	$ 70.00	01	02	01.00	02.00
Feb	$ 00.00	$ 00.00	00	00	00.00	00.00
Mar	$ 35.00	$ 35.00	01	01	01.00	01.00
Apr	$ 00.00	$_____	00	—	00.00	_____
Jun	$ 35.00	$_____	01	—	01.00	_____
Jul	$ 00.00	$_____	00	—	00.00	_____
Aug	$ 35.00	$_____	01	—	01.00	_____
Sep	$ 00.00	$_____	00	—	00.00	_____
Oct	$ 35.00	$_____	01	—	01.00	_____
Nov	$ 00.00	$_____	00	—	00.00	_____
Dec	$ 35.00	$_____	01	—	01.00	_____

Example of a Monthly Budget Data Report

Figure 9.7

A Building Automation System provides the means to dynamically monitor and record a facility's energy consumption on a real-time basis. The strategic installation of utility meters by individual tenant, department, floor, zone, or mechanical system provides a method of fairly assessing a tenant's energy consumption. In addition, the BAS can monitor the outdoor air as well as space temperature and relative humidity. This information, combined with the building energy consumption data, can be used in historical trend graphs to determine the impact on energy consumption by these measured variables. The wealth of building operating cost information that can be provided by a BAS can help a building owner or operating staff to accurately define energy consumption areas, and make more informed decisions on how to control the energy consumption of HVAC and lighting systems.

Tenant Energy Monitoring Program

Air-conditioning in most commercial buildings today is provided by constant volume single zone air handling systems, heat pumps, or variable air volume systems. Most of the automatic temperature control companies manufacture direct digital control (DDC) controllers which regulate zone level terminal units supplied by these systems. These terminal units may be reheat coils, variable air volume boxes, or zone heat pumps. The DDC zone controllers, linked by a communications bus, can send air flow and temperature information to a central host personal computer. The computer, through energy algorithms, can calculate heating or cooling energy supplied to a tenant zone or floor. This provides an excellent means of determining how much energy a tenant consumed during overtime occupancy periods. The BAS can then automatically invoice tenants on a monthly basis for energy consumed in their areas. The invoice will document the invoice date, time period, and energy consumption.

Figure 9.9 shows how a variable air volume box can be monitored for energy consumption. The temperature of the air entering the box (called *primary air*), space temperature, and air flow through the box are monitored by the DDC zone controller over a specified period of time. The central host computer, using these variables, computes the energy consumed per hour and applies the number of hours of operation to determine the total amount of energy consumed during that time period. The computer then applies to this figure the cost per energy unit to determine total cost of energy used in that time period.

Budget ID: AHUFTR Year: 1991 Division: 870 Dept: 394 Acct: 799

	—Planned—	—Actual—
Costs	$ 210.00	$ 105.00
Maint. Schedules	6	3
Quantities	1	1.5

Description: Filter for Air Handling Units

Example of a Yearly Budget Data Report

Figure 9.8

Heating/Cooling Plant Efficiency Program

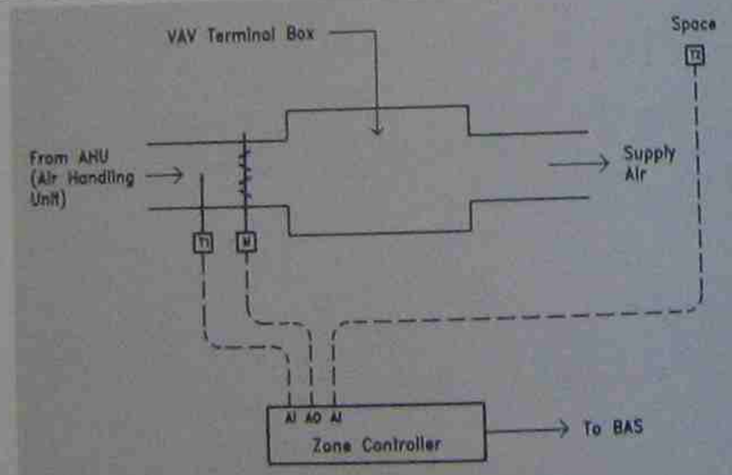
One of the primary goals of a building or facilities manager is to provide a comfortable, clean, and safe environment in the buildings he or she manages, and to do so in the most cost-effective manner. The rising cost of energy, and the changes to ventilation codes to improve indoor air quality, make this task extremely difficult. As previously stated, a sound preventive maintenance program on all heating and cooling equipment is the first step toward achieving this goal.

The next logical step is to continuously monitor the efficiency of the central heating and cooling plants (boilers and chillers). These primary heating and cooling sources frequently represent the largest portion of the energy bills for the physical plant. A small decrease in operating efficiency of these large central systems can result in a significant increase in energy consumption and its associated costs. Therefore, it is important that plant operating personnel be aware of any downward trend in plant operating efficiency so that corrective action can be taken immediately.

The same sensors used to monitor and control energy consumption can be used to monitor the efficiency of the heating or cooling plant. The simple equation for efficiency is:

$$\% \text{ Efficiency} = \frac{\text{output}}{\text{input}}$$

These sensors are strategically located in a central heating or cooling plant. Through a DDC controller, they constantly transmit critical



T1 = Duct Primary Air Temperature Sensor

T2 = Space Temperature Sensor

VAV Terminal Box Zone Controller Monitoring

Figure 9.9

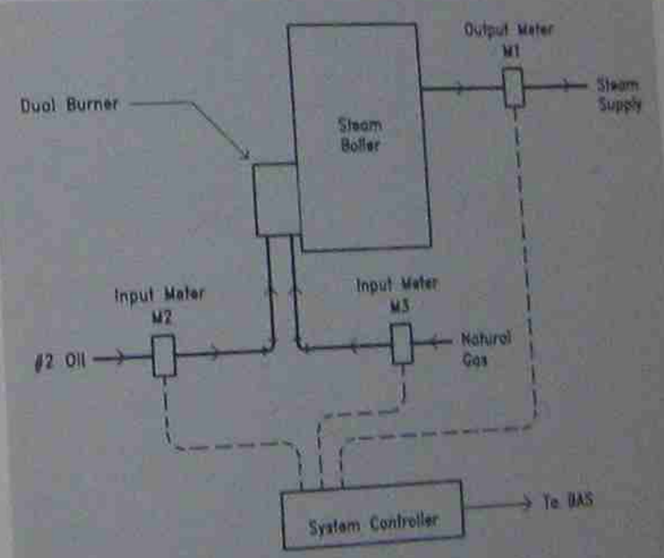
information to a central host computer. This information can be used by the computer to develop energy consumption spreadsheets, graphs, or charts. The building manager or owner can then use this valuable information to monitor energy consumption trends and plan budgets.

Fossil Fuel Steam Heating Plant

Figure 9.10 depicts a method of monitoring the efficiency of an oil/gas-fired steam heating plant. Oil or gas input to the dual burner is measured to complete the input side of the equation. A system flow meter measures output from the boiler. Figure 9.11 illustrates a method used by the BAS to calculate percent efficiency.

Fossil Fuel Hot Water Heating Plant

Monitoring the efficiency of a hot water boiler is similar to that shown for the fossil fuel steam heating plant. The flow of oil and natural gas is measured to provide the input side of the equation. The boiler output, however, is determined by measuring water flow through the boiler and the temperature pickup of the water as it passes through the boiler. Figure 9.12 shows a method of monitoring the efficiency of an oil/gas-fired hot water heating plant. Figure 9.13 illustrates a method used by the BAS to calculate percent efficiency.



M1 = Steam Flow Meter (lbs./Hour)

M2 = #2 Oil Fuel Meter (Gal./Hour)

M3 = Natural Gas Meter (CF/Hour or $Ft.^3$/Hour)

Fossil Fuel Steam Heating Plant Monitoring

Figure 9.10

Step 1: Determine Consumed Input Energy (BTU's)

#2 Oil:

$$\underbrace{\frac{(\text{Gal})}{(\text{Hour})}}_{\text{Meter M2}} \times \underbrace{\frac{139{,}600\ (\text{BTU})}{(\text{Gal})}}_{\text{Conversion Factor}} \times \underbrace{(\text{Hours})}_{\text{User-defined Time Period}} = \#2\ \text{Oil-BTU's}$$

Fig. 9.10

Natural Gas:

$$\underbrace{\frac{(\text{ft}^3)}{(\text{Hour})}}_{\text{Meter M3}} \times \underbrace{\frac{950 \text{ to } 1{,}150(\text{BTU})}{(\text{ft}^3)}}_{\text{Conversion Factor}} \times \underbrace{(\text{Hours})}_{\text{User-defined Time Period}} = \text{Nat. Gas-BTU's}$$

Fig. 9.10

Step 2: Determine Used Output Energy (BTU's)

Steam:

$$\underbrace{\frac{(\#)}{(\text{Hour})}}_{\text{Meter M1}} \times \underbrace{\frac{1{,}000\ (\text{BTU})}{(\#)}}_{\text{Conversion Factor}} \times \underbrace{(\text{Hours})}_{\text{User-defined Time Period}} = \text{Steam-BTU's}$$

Fig. 9.10

Step 3: Determine Percent Efficiency (% Eff.)

#2 Oil

or

$$\%\ \text{Eff.} = \frac{\text{Output}}{\text{Input}} \times 100\% = \frac{\text{Nat. Gas (BTU's)}}{\text{Steam (BTU's)}} \times 100\%$$

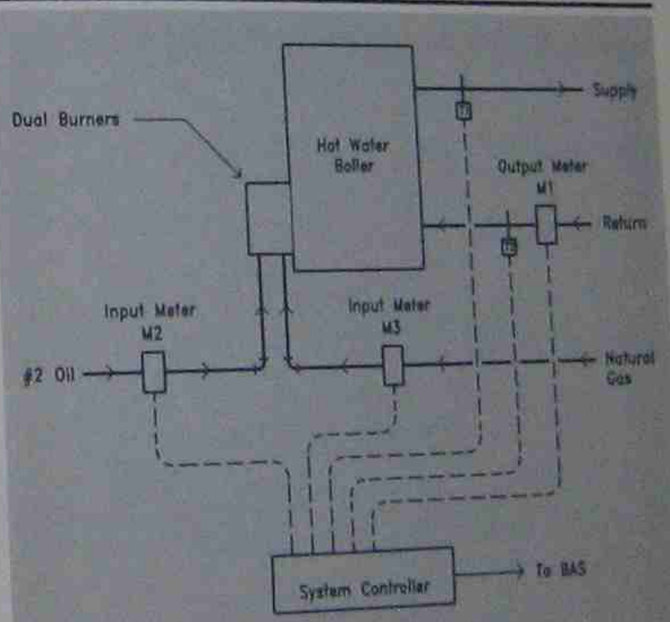
Fossil Fuel Steam Heating Plant Percent Efficiency Calculation

Figure 9.11

Electric Chiller Plant

Monitoring the efficiency of an electrically-driven chiller plant is similar to that shown for the fossil fuel hot water plant. Electrical power consumed by the chiller is measured for the input part of the equation. The output is determined by measuring water flow through the evaporator, and the temperature difference of the water as it passes through the evaporator. Figure 9.14 shows a method of monitoring the efficiency of an electrically driven chiller. Figure 9.15 shows a method used by the BAS to calculate percent efficiency.

The engineering units for the variables are clearly different. Steam flow is measured in pounds per hour, while fuel oil is measured in gallons per hour, water flow in gallons per minute, electrical consumption in kilowatt hours, and natural gas in cubic feet per hour. Conversion of these units so that they can be used in the efficiency equation takes place in the central host computer software program.



Fossil Fuel Water Heating Plant Monitoring

Figure 9.12

Step 1: Determine Consumed Input Energy (BTU's)

#2 Oil: $\underbrace{\frac{(Gal)}{(Hour)}}_{\text{Meter M2}} \times \underbrace{\frac{139{,}600\ (BTU)}{(Gal)}}_{\text{Conversion Factor}} \times \underbrace{(Hours)}_{\text{User-defined Time Period}} = \#2\ \text{Oil-BTU's}$

Fig. 9.12

Natural Gas: $\underbrace{\frac{(ft^3)}{(Hour)}}_{\text{Meter M3}} \times \underbrace{\frac{950 \text{ to } 1{,}150\ (BTU)}{(ft^3)}}_{\text{Fig. 9.15}} \times \underbrace{(Hours)}_{\text{Fig. 9.12}} = \text{Nat. Gas-BTU's}$

Step 2: Determine Used Output Energy (BTU's)

Hot Water: $\underbrace{500}_{\text{Constant}} \times \underbrace{\frac{(Gal)}{(Min)}}_{\text{Meter M1}} \times \underbrace{(T1 - T2)(^\circ F)}_{\text{Fig. 9.15}} = \frac{(BTU)}{(Hour)}$

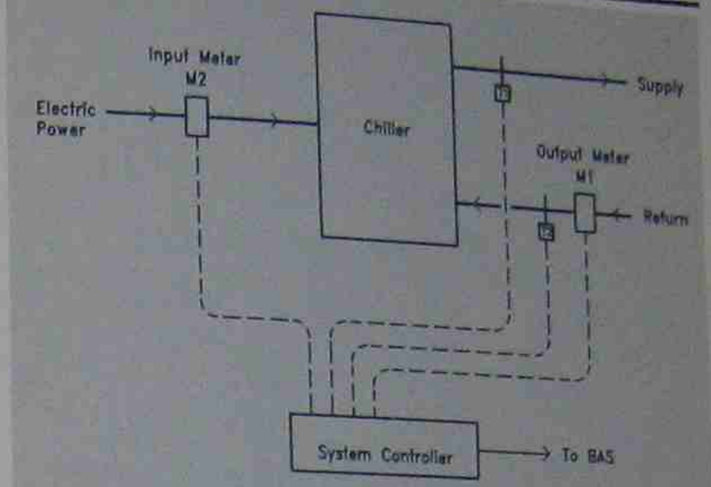
$$\frac{(BTU)}{(Hour)} \times \underbrace{(Hours)}_{\text{User-defined Time Period}} = \text{Hot Water BTU's}$$

Step 3: Determine Percent Efficiency (% Eff.)

$$\%\ \text{Eff.} = \frac{\text{Output}}{\text{Input}} \times 100\% = \frac{\text{\#2 Oil or Nat. Gas (BTU's)}}{\text{Hot Water (BTU's)}} \times 100\%$$

Fossil Fuel Hot Water Heating Plant Percent Efficiency Calculation

Figure 9.13



M1 = Liquid Flow Meter (Gal./Minute)

M2 = Electric Power Meter (KW-Hours)

T1 = Chilled Water Supply Temperature Sensor (°F)

T2 = Chilled Water Return Temperature Sensor (°F)

Electric Chiller Plant Monitoring

Figure 9.14

Step 1: Determine Consumed Input Energy (BTU's)

$$\text{Electric Power: } \underbrace{(\text{kw})}_{\text{Meter M2, Fig. 9.14}} \times \underbrace{\frac{(\text{Ton})}{.77 \text{ to } .93\ (\text{kw})} \times \frac{12{,}000\ (\text{BTU})}{(\text{Ton})\ (\text{Hour})}}_{\text{Conversion Factors}} \times \underbrace{(\text{Hour})}_{\text{User-defined Time Period}} = \text{Electric-BTU's}$$

Step 2: Determine Used Output Energy (BTU's)

$$\text{Chilled Water: } \underbrace{500}_{\text{Constant}} \times \underbrace{\frac{(\text{Gal})}{(\text{Min})}}_{\text{Meter M1, Fig. 9.14}} \times \underbrace{(T2 - T1)(^{\circ}F)}_{\text{Fig. 9.14}} = \frac{(\text{BTU})}{(\text{Hour})}$$

$$\frac{(\text{BTU})}{(\text{Hour})} \times \underbrace{(\text{Hours})}_{\text{User-defined Time Period}} = \text{Chilled Water-BTU's}$$

Step 3: Determine Percent Efficiency (% Eff.)

$$\%\ \text{Eff.} = \frac{\text{Output}}{\text{Input}} \times 100\% = \frac{\text{Electric-BTU's}}{\text{Chilled Water-BTU's}} \times 100\%$$

Electric Chiller Plant Percent Efficiency Calculation

Figure 9.15

Part Three

Planning and Estimating for BAS

The demand for improved environmental conditions in buildings has escalated over the past 15 years. This, combined with increased utility costs, competition in the office space rental market, the emphasis on indoor air quality, and the demands of building owners for better methods of control and management of building systems, has compelled the manufacturers of HVAC equipment to reevaluate their products. The automatic temperature control industry responded to these needs with some major innovations.

The development of microelectronics and advancements in digital technology revolutionized building environmental control systems. Miniaturization, reduced cost, flexibility, accuracy of control, and advanced software programs made this technology ideal for BAS.

To determine whether or not your building is receiving the maximum benefits from its current control system, take a closer look. The existing pneumatic control system may appear to be functioning properly. However, slow response, inadequate maintenance, calibration shifts, and mechanical wear, although not obvious, can result in wasted energy and poor comfort conditions.

The Direct Digital Control (DDC) systems on the market today offer accurate control, the ability to perform complex control sequences, low maintenance requirements, and flexibility — some impressive features unachievable with traditional pneumatic controls. DDC systems can also perform energy management strategies and, if connected to a central host personal computer, provide total integration of other building systems. For new buildings, DDC offers the latest in automatic control technology. DDC controllers are available for use with all types and sizes of systems, from simple heat pumps to large built-up systems. The standard software in these controllers can perform basic control loops as well as the most complex control sequences. They can also perform all the traditional energy management strategies.

DDC controllers can operate as stand-alone units, performing all local HVAC control functions, with the option of adding a central host personal computer at a future time. If management reporting, HVAC system monitoring, or integration of other building systems (lighting, fire, security, and access control) are required, a personal computer can be included in the initial installation.

DDC sensors are more sensitive than pneumatic sensors and therefore

respond faster and more accurately. DDC devices in general are not mechanical; they have no moving parts and therefore require minimum maintenance. Calibration of DDC sensors is usually not necessary.

The ideal time to convert to a DDC system in an existing building is when the HVAC system is being upgraded. When a control system is replaced, it is usually not necessary to replace all existing control devices. Valve and damper actuators, low temperature controllers, smoke and fire detectors, and many other devices, if functional, can be made compatible with the DDC controller. Chapter 10 examines the logical method of constructing a DDC system with a central host computer. It also reviews budget estimating using *Means Mechanical Cost Data*.

Chapter Ten

System Layout and Budget Estimate

This chapter presents an overall review of HVAC system layout, and the sequences of operation. The final section of this chapter shows how to prepare a budget estimate using a portion of the BAS system as an example.

System Layout

DDC controllers contain all of the software required to control HVAC systems and perform energy management strategies. A microprocessor replaces the pneumatic or electric analog controller, which connects the sensor with the actuator. The controller can receive input signals in one of two forms – digital or analog – and can take action through digital and analog output signals. These input and output signals are commonly referred to as *points*.

A digital input (DI) point is a switching action input (open-closed or on-off). An example would be a duct-mounted static pressure switch, with switching contacts that close when there is an increase in static pressure and open when static pressure drops below its setting. This device is commonly used to signal fan status (on-off) to a controller.

An analog input (AI) point is a variable input signal sent to a controller from a sensor that measures flow, temperature, pressure, or relative humidity. The input signal may be 500 ohms, 2 to 10 volts DC (VDC), or 4 to 20 milliamps (MA).

A digital output (DO) point is a two-position switching action by the controller. This switching action can be used to start and stop a fan or pump. It can also control a damper or valve actuator in a two-position (open-closed) manner.

An analog output (AO) point is a variable, or modulating output signal, from the controller that can modulate a damper or valve actuator. It can also be used to modulate a variable fan speed controller. Output signals can be 3 to 15 psi, 2 to 10 volts DC (VDC), or 4 to 20 milliamps (MA).

Software programs are routines that make the microprocessor in a DDC controller perform specific control functions. Input signals are converted to digital form and stored for future transmission. Or, the signals are converted from digital form to analog or digital output signals.

Standard software programs for HVAC applications are resident in DDC controllers. These programs can be configured and modified to fit a specific application. If a standard software program is not available, custom programs can be designed and combined with standard programs, as necessary, to accomplish the required control sequence.

DDC controllers also come with standard software for energy management programs. Among these programs are:

- Zero-energy band
- Load reset
- Optimum start
- Optimum stop
- Enthalpy control
- Duty cycle
- Night cycle
- Night purge
- Power demand limiting

These energy management programs can interact with the control loop programs, frequently using the same sensors and actuators. For instance, the control programs for a single zone HVAC unit can interact with the night cycle program. The unit can be cycled at night, at a reduced temperature, using the existing space sensor. During this cycling period, the existing outdoor air damper actuator can be maintained in the closed position. During summer operation, as determined by the existing outdoor air sensor, the fan can be cycled with cooling to maintain a maximum space temperature. Once again, the outdoor air damper actuator is maintained in the closed position to conserve energy. Many of the energy management programs listed in the previous paragraph would also apply to this HVAC unit using existing sensors and actuators. A layout of this system is shown in Figure 10.1.

Constructing a DDC System

Anyone who has designed a pneumatic or electric control system can construct a DDC system by following a few logical steps:

1. Make a schematic layout of the HVAC system to be controlled. Show all dampers, heating coils, cooling coils, fans, humidifiers, and any other pieces of mechanical equipment that are to be controlled. See Figure 10.2A.
2. Add actuators for the equipment to be controlled: damper actuators, control valves, relays, magnetic starters, contactors, and so forth. Next, add sensors, where required, to accomplish the anticipated control sequences. If additional sensors are required for energy management programs, add them at this time. See Figure 10.2B.
3. Enter the controller below the HVAC unit, and extend lines from all sensors and actuators to the controller. Label all input and output points at the controller according to their functions: digital input, analog input, digital output, analog output. See Figure 10.2C.
4. Compile a list of points connected to each controller, as shown in Figure 10.3. Note that DDC controllers will accept a limited number of input-output points. For this example (total 16 points), a 16 point controller can be used.

Sequence of Operation

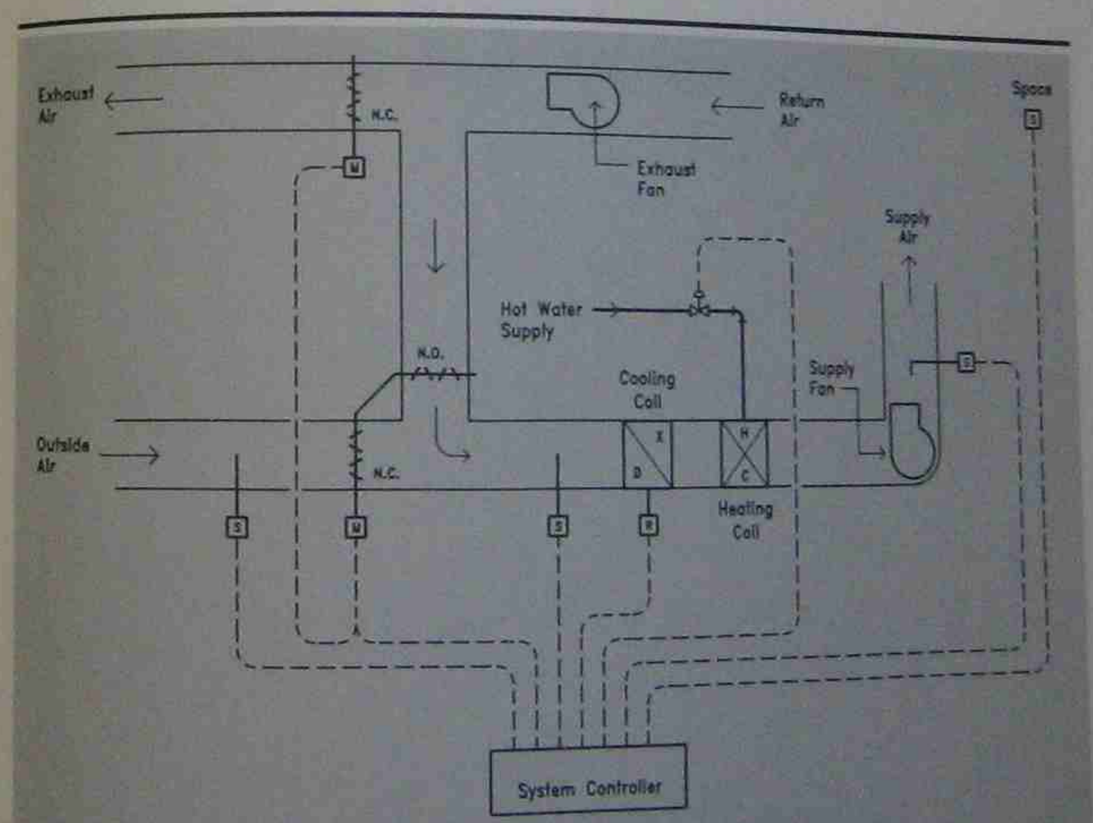
This section describes the basic sequence of operation of a central air handling unit and a VAV box with DDC.

Central Air Handling Unit

The sequence of operation for the central air handling unit, as programmed into the system controller is as follows:

When the unit fan is energized, as sensed by the discharge duct static pressure sensor, the outdoor, return, and exhaust damper control system will be activated. A duct-mounted, discharge air temperature sensor will, through the system controller, maintain 55°F air supply to the remote VAV terminal units.

When the outdoor air temperature is below 65°F, as sensed by the temperature outdoor air sensor, the cooling coil valve will be in the coil bypass position and the discharge air temperature sensor will maintain temperature by modulating the heating coil valve in sequence with the outdoor, return, and exhaust air dampers.



A Typical Direct Digital Control System

Figure 10.1

When the outdoor air temperature is above 65°F, the outdoor and exhaust air dampers will go to a preset minimum open position, and the return air damper will go to its corresponding open position. The discharge air sensor will now maintain air temperature by modulating the chilled water valve.

A low-temperature safety control, with its capillary located in the discharge side of the heating coil, will shut down the supply fan and return air fan and open the heating coil valve, if the heating coil discharge air temperature drops below its setting (35°F).

A static pressure sensor, located downstream from the supply fan, will maintain static pressure in the supply duct by modulating the supply air fan inlet vanes.

A ceiling-mounted static pressure sensor mounted in a representative location in the building will maintain a positive static pressure inside the building with reference to outdoors, by modulating the return air fan inlet vanes.

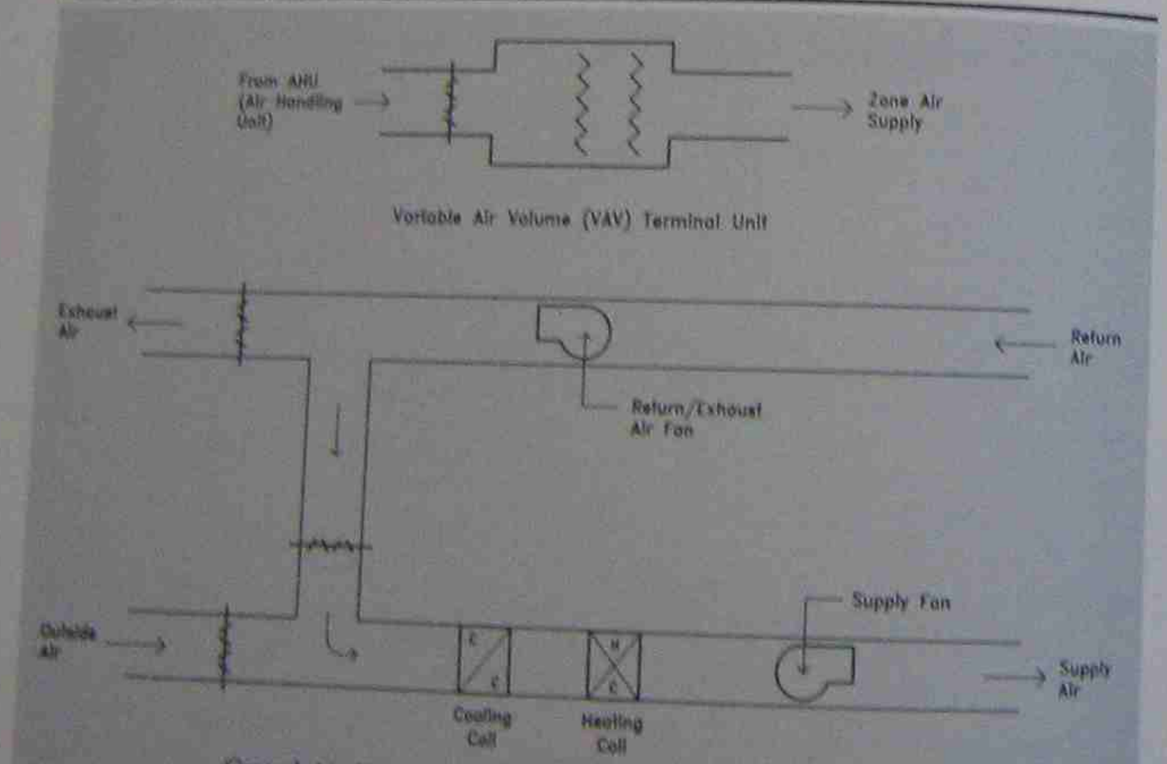


Figure 10.2a

Duct-mounted smoke detectors located in the supply and return air ducts will, upon sensing smoke, shut down the supply and return air fans, close the outdoor and exhaust dampers, and open the return air damper. (More complex smoke containment or evacuation sequences can be programmed if desired.)

During unoccupied periods in winter, the air handling unit fans will be de-energized, the outdoor and exhaust air dampers will close, and the return air damper will be in the full open position. If space temperature drops to the night setting (60°F) of a selected VAV terminal unit sensor (located in the coldest exposure), the unit fans will be cycled to maintain the reduced temperature. The outdoor and exhaust air dampers will remain closed; and the unit will operate on 100% return air. The heating coil valve will be open.

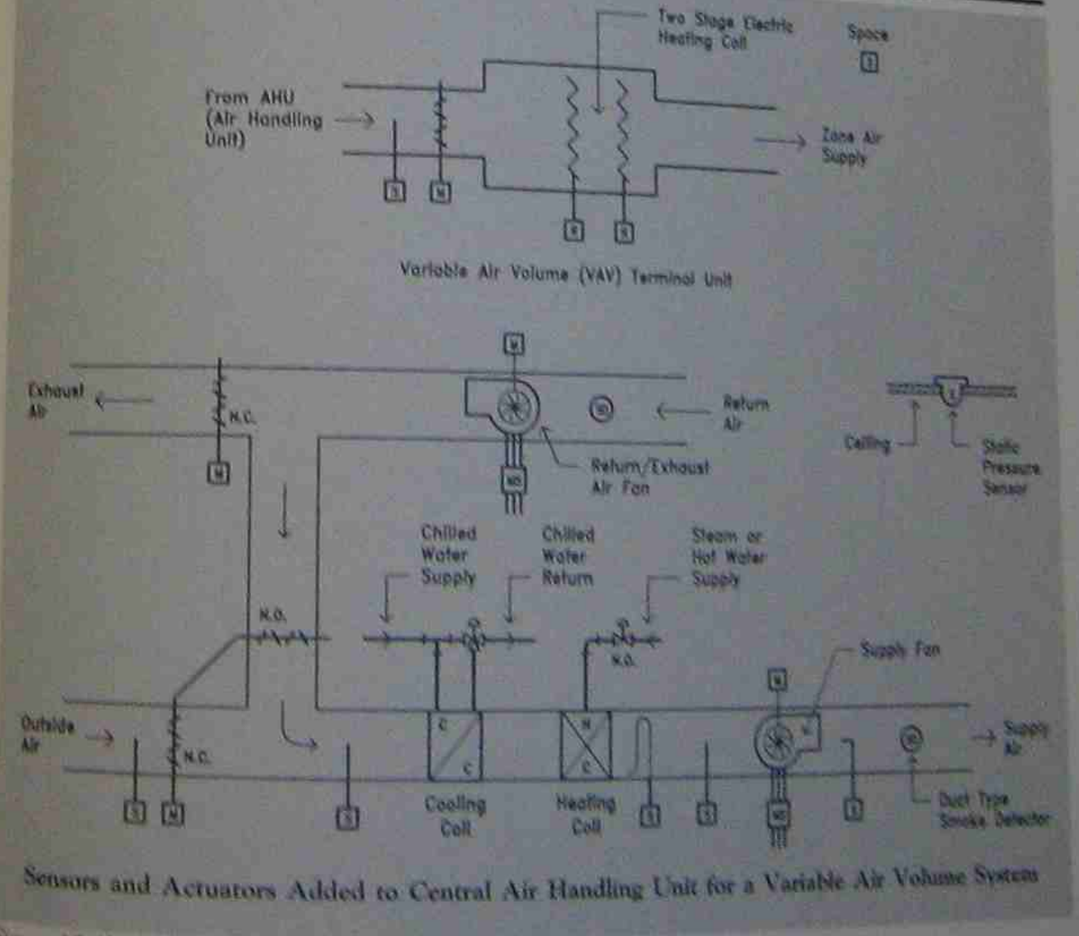
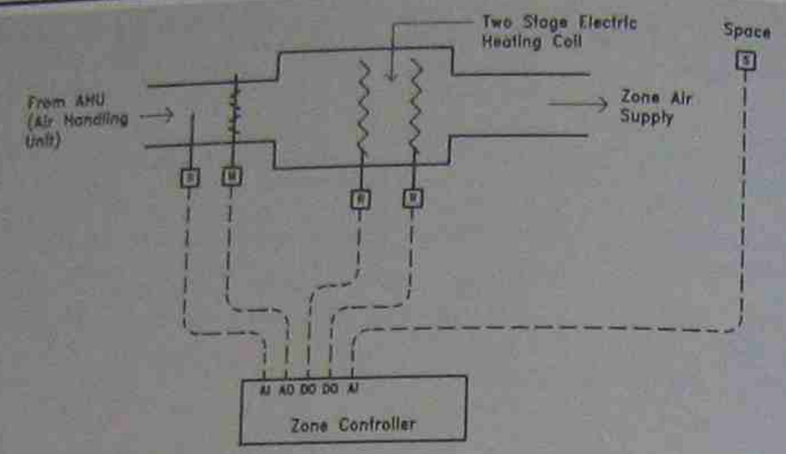
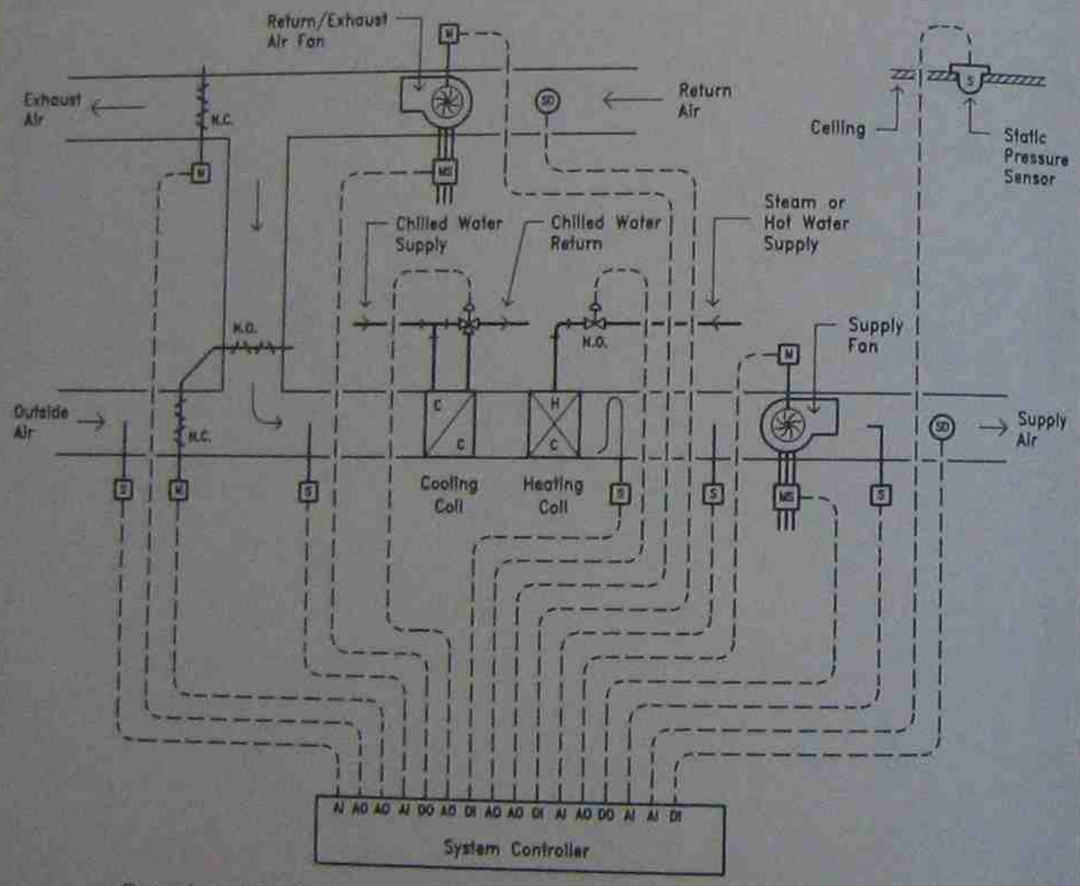


Figure 10.2b



Variable Air Volume (VAV) Terminal Unit with DDC



Central Air Handling Unit for a Variable Air Volume System with DDC

Figure 10.2c

During unoccupied periods in summer, the air handling unit fans will be de-energized, the outdoor and exhaust air dampers will close, and the return air damper will be in the full open position. If space temperature rises to the night setting (80°F) of a selected VAV terminal unit sensor (located in the warmest exposure), the unit fans will be cycled to maintain the maximum temperature. The outdoor and exhaust dampers will remain closed, and the unit will operate on 100% return air. This program assumes the availability of cooling during unoccupied periods.

Whenever the unit supply fan is de-energized, as sensed by the discharge duct static pressure sensor, the return air fan will be de-energized; the outdoor and exhaust air dampers will close; and the return air damper will open.

Energy management programs resident in the DDC controller which could be applied to this air handling unit are:

- Optimum start/stop
- Load reset
- Night purge

Variable Air Volume Terminal Units

The sequence of operation for the variable air volume terminal units, as programmed into the zone controllers, is as follows:

On a call for less cooling by the space sensor, the variable air volume unit damper will modulate to the minimum position. The damper will remain at the minimum position through an adjustable deadband. If space temperature, as sensed by the space sensor, continues to drop, the stages of electric heat will be energized in sequence. When the heat is energized, the controller adjusts the unit air supply to protect the electric heating elements. On a call for cooling, the sequence is reversed.

The optional central host computer provides the capability to monitor, alarm, and adjust the set point of all sensor points as follows:

1. Outdoor air temperature
2. Mixed air temperature
3. Discharge air temperature
4. Supply duct static pressure
5. Space static pressure
6. Supply fan status (on-off-alarm)
7. Low temperature safety control (normal-off)
8. Smoke detectors (normal-alarm)
9. Space temperatures (total of 20)

Central Air Handling Unit	
AI	5
AO	6
DI	3
DO	2
Total Points	16

Point Summary

Figure 10.3

The CRT will display, either on request by the operator or automatically at preprogrammed intervals, the status of the above points. If a point deviates from its preprogrammed alarm limits, the CRT will display the point, its status or value, time and date, and action message directing the operator as to what action is to be taken. The printer will generate hard copy printouts of the information displayed on the CRT.

The maintenance program will schedule preventive maintenance and issue work orders based on calendar or equipment run time, or on an event occurrence. The CRT and printer will also display delinquent maintenance, inventory, and financial statistics pertaining to the HVAC system.

Budget Estimating

Following the four steps identified under the section *Constructing a DDC System* will simplify any system layout and make the budget estimating process more accurate.

For budget estimating purposes, we will use the central air handling unit with 20 VAV terminal units, as shown in Figure 10.2C. We will include an optional central host computer with color graphics and basic maintenance manager software. Average wiring runs for points in mechanical rooms are estimated at 150 feet, and to space temperature sensors, 150 feet. Cost information is found in *Means Mechanical Cost Data* (HVAC/controls), Division 157-400 (420 and 422). See Figure 10.4. The 1991 edition was used for this exercise. See Figure 10.5 for the sample budget estimating procedures.

An accurate budget estimate requires discipline and a structured approach to system layout. Following the procedures discussed in this chapter will simplify the system layout and budget estimating process.

157 400 | Accessories

			CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL O&P
401	1570	Inlet or outlet transition, vertical									
	1880	Single pack to 5000 CFM, add					2%				
	1890	Single pack to 24,000 CFM, add					3%				
	1900	Double pack to 24,000 CFM, add					2%				
	2000	Electronic air cleaner, self-contained									
	2050	185 CFM	1 Shee	2.40	3.330	Ea.	211	67		278	360
	2100	200 CFM		2.30	3.480		410	67		477	565
	2150	500 CFM		2.30	3.480		585	67		652	775
	2200	1000 CFM		2.20	3.640		810	91		901	1,035
	2250	1200 CFM		2.10	3.810		1,190	95		1,285	1,450
	2300	2500 CFM									
	2400	In-line installation, duct or plenum		2	4		1,350	100		1,450	1,650
	2420	Power pack, one required for each									
	2430	Installation, one or two filter cells	1 Shee	2	4	Ea.	221	100		321	395
	2440	Filter cell, 2" thick, 1" perimeter offset		4	2		215	50		265	315
	2450	20" x 20"		4	2		170	50		220	265
	2460	20" x 16"		4	2		150	50		200	245
	2470	25" x 20"		3.50	2.290		193	57		250	305
	2480	25" x 16"		3	2.670		170	67		237	290
	2950	Mechanical media filtration units									
	3000	High efficiency type, with frame, non-supported				MCFM	28			28	31
	3100	Supported type					47			47	52
	4000	Medium efficiency, extended surface					5			5	5.50
	4500	Permanent washable					33			33	36
	5000	Renewable disposable roll					45			45	54
	5500	Throwaway glass or paper media type				Ea.	2.65			2.65	2.92
410	0010	ANTI-FREEZE Inhibited									
	0900	Ethylene glycol concentrated									
	1000	55 gallon drums, small quantities				Gal.	6.71			6.71	7.40
	1200	Large quantities					6.15			6.15	6.75
	2000	Propylene glycol, for solar heat, small quantities					7.35			7.35	8.15
	2100	Large quantities					6.74			6.74	7.40
420	0010	CONTROL COMPONENTS									
	0700	Controller, receiver									
	0730	Pneumatic, panel mount, single input	1 Plum	8	1	Ea.	183	25		208	240
	0740	With conversion mounting bracket		8	1		188	25		212	245
	0750	Dual input, with control point adjustment		7	1.140		206	29		235	270
	0850	Electric, single snap switch	1 Elec	4	2		229	30		259	295
	0860	Dual snap switches		3	2.670		317	67		384	450
	0870	Humidity controller		8	1		139	25		164	190
	0880	Load limiting controller		8	1		260	25		285	325
	0890	Temperature controller		8	1		125	25		150	175
	1000	Enthalpy control, boiler water temperature control									
	1010	governed by outdoor temperature, with timer	1 Elec	3	2.670	Ea.	125	67		192	235
	2000	Gauges, pressure or vacuum									
	2100	2" diameter dial	1 Stpl	32	.250	Ea.	9	5.40		14.40	18.50
	2200	2-½" diameter dial		32	.250		9.40	5.40		15.80	19.95
	2300	3-½" diameter dial		32	.250		12	5.40		18.40	23
	2400	4-½" diameter dial		32	.250		16.50	5.40		21.90	28
	2700	Flanged iron case, black ring									
	2800	3-½" diameter dial	1 Stpl	32	.250	Ea.	42.75	5.40		48.15	57
	2900	4-½" diameter dial		32	.250		51.75	5.40		58.15	66
	3000	6" diameter dial		32	.250		70.50	5.40		75.90	87
	3300	For compound pressure-vacuum, add					15%				
	3350	Humidistat									
	3360	Pneumatic operation									
	3361	Room humidistat, direct acting	1 Stpl	12	.667	Ea.	108	17		125	145
	3362	Room humidistat, reverse acting	"	12	.667	"	108	17		125	145

Figure 10.4

	157 400 | Accessories	CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL O&P	
420	3363 Room humidity transmitter	1 Spl	17	.471	Ea.	156	12		168	190	420
	3364 Duct mounted controller		12	.667		152	17		169	195	
	3365 Duct mounted transmitter		12	.667		152	17		169	195	
	3366 Humidity indicator, 3-½"		28	.286		57	7.30		64.30	74	
	3390 Electric operated	1 Shee	8	1		35.75	25		60.75	77	
	3400 Relays										
	3435 Pneumatic/electric	1 Plum	16	.500	Ea.	255	12.75		267.75	300	
	3440 Pneumatic proportioning		8	1		120	25		145	170	
	3450 Pneumatic switching		12	.667		61	16.95		77.95	92	
	3460 Selector, 3 point		6	1.330		42.80	34		76.80	98	
	3470 Time delay		8	1		120	25		145	170	
	3500 Sensor, air operated										
	3535 Humidity	1 Plum	16	.500	Ea.	164	12.75		176.75	200	
	3540 Pressure		16	.500		103	12.75		115.75	130	
	3560 Temperature		12	.667		118	16.95		134.95	155	
	3600 Electric operated										
	3635 Humidity	1 Elec	8	1	Ea.	40.40	25		65.40	82	
	3650 Pressure		8	1		485	25		510	570	
	3660 Temperature		10	.800		69.20	20		89.20	105	
	4000 Thermometers										
	4100 Dial type, 3-½" diameter, vapor type, union connection	1 Spl	32	.250	Ea.	95	6.40		101.40	115	
	4120 Liquid type, union connection		32	.250		133	6.40		139.40	155	
	4130 Remote reading, 15' capillary		32	.250		110	6.40		116.40	130	
	4500 Stem type, 6-½" case, 2" stem, ½" NPT		32	.250		24	6.40		30.40	36	
	4520 4" stem, ½" NPT		32	.250		33	6.40		39.40	46	
	4600 9" case, 3-½" stem, ¾" NPT		28	.286		40	7.30		47.30	55	
	4620 6" stem, ¾" NPT		28	.286		43	7.30		50.30	58	
	4640 8" stem, ¾" NPT		28	.286		49	7.30		56.30	65	
	4660 12" stem, 1" NPT		26	.308		55	7.85		62.85	72	
	5000 Thermostats										
	5020 1 set back, manual	1 Shee	8	1	Ea.	16.30	25		41.30	56	
	5040 1 set back, electric, timed		8	1		59.45	25		84.45	105	
	5050 2 set back, electric, timed		8	1		59.45	25		84.45	105	
	5100 Locking cover					13.90			13.90	15.30	
	5200 24 hour, automatic, clock	1 Shee	8	1		86.90	25		111.90	135	
	5220 Electric, 2 wire	1 Elec	13	.615		12.35	15.50		27.85	36	
	5230 3 wire	"	10	.800		14.95	20		34.95	46	
	5240 Pneumatic										
	5250 Single temp., single pressure	1 Spl	8	1	Ea.	115	26		141	165	
	5251 Dual pressure		8	1		159	26		185	215	
	5252 Dual temp., dual pressure		8	1		155	26		181	210	
	5253 Reverse acting w/averaging element		8	1		112	26		138	160	
	5254 Heating-cooling w/deadband		8	1		155	26		181	210	
	5255 Integral w/piston top valve actuator		8	1		144	26		170	195	
	5256 Dual temp., dual pressure		8	1		164	26		190	220	
	5257 Low limit, 6' averaging element		8	1		91	26		117	140	
	5258 Room single temp., proportional		8	1		58.30	26		84.30	100	
	5300 Transmitter, pneumatic										
	5320 Temperature averaging element	G-1	8	2	Ea.	79.80	46		125.80	159	
	5350 Pressure differential	1 Plum	7	1.140		438	29		467	525	
	5370 Humidity, duct		8	1		152	25		177	205	
	5380 Room		12	.667		156	16.95		172.95	195	
	5390 Temperature, with averaging element		6	1.330		104	34		138	165	
	5420 Electric operated, humidity	1 Elec	8	1		156	25		181	210	
	5430 DPST	"	8	1		35.50	25		60.50	76	
	6000 Valves, motorized zone										
	6100 Sweat connections, ½" C x C	1 Spl	20	.400	Ea.	34.10	10.20		44.30	53	
	6110 ¾" C x C	"	20	.400	"	34.10	10.20		44.30	53	

Figure 10.4 (continued)

	157 400 | Accessories	CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL O&P	
420	6120 1" C x C	1 Spl	19	.421	Ea.	38.15	10.75		48.90	58	420
	6140 ½" C x C, with end switch, 2 wire		20	.400		41.20	10.20		51.40	61	
	6150 ¾" C x C, with end switch, 2 wire		20	.400		43.10	10.20		53.30	63	
	6160 1" C x C, with end switch, 2 wire		19	.421		47.90	10.75		58.65	69	
	6180 1-¼" C x C, w/end switch, 2 wire		15	.533		52.90	13.60		66.50	78	
	7090 Valves, motor controlled, including actuator										
	7100 Electric motor actuated										
	7200 Brass, two way, screwed										
	7210 ½" pipe size	L-6	36	.333	Ea.	163	8.45		171.45	190	
	7220 ¾" pipe size		30	.400		162	10.15		172.15	195	
	7230 1" pipe size		28	.429		201	10.85		211.85	235	
	7240 1-¼" pipe size		19	.632		279	16		295	330	
	7250 2" pipe size		15	.750		425	19		444	490	
	7350 Brass, three way, screwed										
	7360 ½" pipe size	L-6	33	.364	Ea.	204	9.20		213.20	240	
	7370 ¾" pipe size		27	.444		230	11.25		241.25	270	
	7380 1" pipe size		25.50	.471		300	11.95		311.95	350	
	7390 1-½" pipe size		17	.706		308	17.90		325.90	365	
	7400 2" pipe size		14	.857		460	22		482	540	
	7550 Iron body, two way, flanged										
	7560 2-½" pipe size	L-6	4	3	Ea.	535	76		611	700	
	7570 3" pipe size		3	4		625	100		725	840	
	7580 4" pipe size		2	6		990	150		1,140	1,350	
	7590 6" pipe size		1.50	8		2,480	205		2,685	3,050	
	7850 Iron body, three way, flanged										
	7860 2-½" pipe size	L-6	3	4	Ea.	800	100		900	1,025	
	7870 3" pipe size		2.50	4.800		1,050	120		1,170	1,325	
	7880 4" pipe size		2	6		1,180	150		1,330	1,525	
	7890 6" pipe size		1.50	8		3,060	205		3,265	3,675	
	8000 Pneumatic, air operated										
	8050 Brass, two way, screwed										
	8060 ½" pipe size, class 250	1 Plum	24	.333	Ea.	112	8.50		120.50	135	
	8070 ¾" pipe size, class 250		20	.400		127	10.20		137.20	155	
	8080 1" pipe size, class 250		19	.421		153	10.70		163.70	185	
	8090 1-¼" pipe size, class 125		15	.533		215	13.55		228.55	258	
	8100 1-½" pipe size, class 125		13	.615		224	15.65		239.65	270	
	8110 2" pipe size, class 125		11	.727		330	18.50		348.50	390	
	8180 Brass, three way, screwed										
	8190 ½" pipe size, class 250	1 Plum	22	.364	Ea.	135	9.25		144.25	160	
	8200 ¾" pipe size, class 250		18	.444		140	11.30		151.30	170	
	8210 1" pipe size, class 250		17	.471		176	12		188	210	
	8220 1-¼" pipe size, class 125		11	.727		256	18.50		274.50	310	
	8230 2" pipe size, class 125		9	.889		345	23		368	415	
	8250 Iron body, two way, screwed										
	8260 ½" pipe size, class 300	1 Plum	24	.333	Ea.	486	8.50		506.50	560	
	8270 ¾" pipe size, class 300		20	.400		510	10.20		520.20	575	
	8280 1" pipe size, class 300		19	.421		690	10.70		700.70	780	
	8290 1-¼" pipe size, class 300		15	.533		990	13.55		1,003	1,100	
	8300 1-½" pipe size, class 300		13	.615		1,010	15.65		1,025	1,125	
	8310 2" pipe size, class 300		11	.727		1,010	18.50		1,028	1,150	
	8320 1-¼" pipe size, class 125		15	.533		385	13.55		398.55	445	
	8330 1-½" pipe size, class 125		13	.615		317	15.65		332.65	370	
	8340 2" pipe size, class 125		11	.727		395	18.50		413.50	460	
	8450 Iron body, two way, flanged										
	8460 2-½" pipe size, 250 lb. flanges	G-1	5	3.200	Ea.	2,060	78		2,138	2,375	
	8470 3" pipe size, 250 lb. flanges		4.50	3.556		2,200	81		2,281	2,550	
	8480 4" pipe size, 250 lb. flanges		3	5.330		2,330	120		2,450	2,675	
	8510 2-½" pipe size, class 125		5	3.200		805	73		878	770	

Figure 10.4 (continued)

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			CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL O&P
420	8520	3" pipe size, class 125	Q-1	4.50	3.560	Ea.	845	81		926	1,050
	8530	4" pipe size, class 125	"	3	5.330	"	1,060	120		1,170	1,325
	8540	5" pipe size, class 125	Q-2	3.40	7.060		1,720	170		1,890	2,150
	8550	6" pipe size, class 125	"	3	8		1,850	190		2,040	2,325
	8560	Ikea body, three way, flanged	Q-1	4.50	3.560	Ea.	760	81		841	960
	8570	2½" pipe size, class 125		4	4		915	92		1,007	1,150
	8580	3" pipe size, class 125		2.50	6.400		1,490	145		1,635	1,850
	8590	4" pipe size, class 125	Q-2	3	8		2,230	190		2,420	2,725
	8600	5" pipe size, class 125									
	8605	Pneumatic system misc. components	1 Stpl	20	.400	Ea.	42.25	10.20		52.45	62
	9010	Adding/subtracting repeater		16	.500		124	12.75		136.75	155
	9020	Adjustable ratio network		20	.400		126	10.20		136.20	155
	9030	Comparator									
	9040	Computator									
	9041	Air switching	1 Stpl	20	.400	Ea.	61	10.20		71.20	82
	9042	Averaging		20	.400		65	10.20		75.20	87
	9043	2:1 ratio		20	.400		56	10.20		66.20	77
	9044	Sequencing		20	.400		38	10.20		48.20	57
	9045	Two-position		16	.500		65	12.75		77.75	91
	9046	Two-position pilot		16	.500		61	12.75		73.75	86
	9050	Damper actuator	1 Stpl	8	1	Ea.	117	26		143	165
	9051	For smoke control	"	8	1	"	181	26		207	235
	9052	For ventilation									
	9053	Series duplex pedestal mounted									
	9054	For inlet vanes on fans, compressors	1 Stpl	6	1.330	Ea.	610	34		644	720
	9060	Enthalpy logic center		16	.500		128	12.75		140.75	160
	9070	High/low pressure selector		22	.364		27	9.25		36.25	44
	9080	Signal limiter		20	.400		38.25	10.20		48.45	57
	9081	Transmitter		28	.286		15	7.30		22.30	27
	9090	Optimal start									
	9091	Warmup or cooldown programmer	1 Stpl	10	.800	Ea.	448	20		468	525
	9092	Mixed temperature transmitter	"	18	.444	"	114	11.35		125.35	140
	9100	Step controller with positioner, time delay restrictor									
	9110	recycler air valve, switches and calm settings									
	9112	With cabinet									
	9113	6 points	1 Stpl	4	2	Ea.	330	51		381	440
	9114	6 points, 6 manual sequences		2	4		348	100		448	535
	9115	8 points		3	2.670		418	68		486	560
	9200	Pressure controller and switches									
	9210	High static pressure limit	1 Stpl	8	1	Ea.	97	26		123	145
	9220	Pressure transmitter		8	1		105	26		131	155
	9230	Differential pressure transmitter		8	1		438	26		464	520
	9240	Static pressure transmitter		8	1		268	26		294	335
	9250	Proportional-only control, single input		6	1.330		183	34		217	250
	9260	Proportional plus integral, single input		6	1.330		255	34		289	330
	9270	Proportional-only, dual input		6	1.330		206	34		240	275
	9280	Proportional plus integral, dual input		6	1.330		325	34		359	410
	9281	Time delay for slave proportional units		16	.500		72	12.75		84.75	98
	9290	Proportional/2 position controller units		6	1.330		214	34		248	285
	9300	Differential press. control dir./rev.		6	1.330		325	34		359	410
	9310	Air pressure reducing valve									
	9311	¼" size	1 Stpl	18	.444	Ea.	14.50	11.35		25.85	33
	9312	⅜" size		17	.471		27	12		39	48
	9313	½" size		16	.500		34	12.75		46.75	56
	9314	¾" size		14	.571		60	14.55		74.55	88
	9315	Pressure valve, ¼" size		17	.471		82.50	12		94.50	110
	9320	Air flow controller		12	.667		83	17		100	115
	9330	Booster relay volume amplifier		18	.444		45.75	11.35		57.10	67

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Figure 10.4 (continued)

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			CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL O&P
420	9031	Reverse acting	1 Stpl	18	.444	Ea.	95	11.35		106.35	122
	9040	Series restrictor, straight		60	.133		2.45	3.40		5.85	7.75
	9041	T-fitting		40	.200		3.80	5.10		8.90	11.95
	9342	In-line adjustable		48	.167		13.50	4.25		17.75	21
	9350	Diode tee		40	.200		8.25	5.10		13.35	16.75
	9351	Restrictor tee		40	.200		8.25	5.10		13.35	16.75
	9360	Pneumatic gradual switch		8	1		100	25		125	150
	9361	Selector switch		8	1		48.25	25		74.25	91
	9370	Electro-pneumatic motor driven servo		10	.800		406	20		426	480
	9380	Regulated power supply		10	.800		350	20		370	415
	9390	Fan control switch and mounting base		16	.500		42.25	12.75		55	66
	9400	Circulating pump sequencer		14	.571		455	14.50		469.50	525
	9410	Pneumatic tubing, fittings and accessories									
	9414	Tubing, urethane									
	9415	¼" OD x ⅛" ID	1 Stpl	120	.067	L.F.	.34	1.70		2.04	2.91
	9416	¼" OD x ⅛" ID		115	.070		.64	1.77		2.41	3.35
	9417	⅝" OD x ⅜" ID		110	.073		.36	1.85		2.21	3.15
	9420	Coupling, straight									
	9422	Barb x barb									
	9423	¼" x ⅝"	1 Stpl	160	.050	Ea.	.21	1.28		1.49	2.13
	9424	¼" x ¼"		156	.051		.29	1.29		1.58	2.25
	9425	⅜" x ⅜"		154	.052		.35	1.32		1.68	2.36
	9426	⅜" x ¼"		150	.053		.21	1.36		1.57	2.26
	9427	½" x ¼"		148	.054		.54	1.38		1.92	2.65
	9428	½" x ⅜"		144	.056		.45	1.42		1.87	2.61
	9429	½" x ½"		140	.057		.27	1.46		1.73	2.47
	9440	Tube x tube									
	9441	¼" x ¼"	1 Stpl	100	.080	Ea.	.92	2.04		2.96	4.06
	9442	⅜" x ¼"		96	.083		1.03	2.13		3.16	4.36
	9443	⅜" x ⅜"		92	.087		1.03	2.22		3.25	4.44
	9444	½" x ⅜"		88	.091		1.65	2.32		3.97	5.25
	9445	½" x ½"		84	.095		2.11	2.43		4.54	5.95
	9450	Elbow coupling									
	9452	Barb x barb									
	9454	¼" x ¼"	1 Stpl	158	.051	Ea.	.92	1.29		1.81	2.58
	9455	⅜" x ⅜"		154	.052		.50	1.32		1.82	2.57
	9456	½" x ½"		140	.057		.93	1.46		2.39	3.09
	9460	Tube x tube									
	9462	½" x ½"	1 Stpl	84	.095	Ea.	2.01	2.43		4.44	5.83
	9470	Tee coupling									
	9472	Barb x barb x barb									
	9474	¼" x ¼" x ⅝"	1 Stpl	108	.074	Ea.	.45	1.89		2.34	3.31
	9475	¼" x ¼" x ¼"		104	.077		.54	1.96		2.50	3.52
	9476	⅜" x ⅜" x ⅝"		102	.078		2.32	2		4.32	5.55
	9477	⅜" x ⅜" x ¼"		99	.081		.88	2.06		2.94	4.04
	9478	⅜" x ⅜" x ⅜"		98	.082		1.03	2.08		3.11	4.24
	9479	½" x ½" x ¼"		96	.083		.83	2.13		2.96	4.09
	9480	½" x ½" x ⅜"		95	.084		.83	2.15		2.98	4.12
	9481	½" x ½" x ½"		92	.087		.83	2.22		3.05	4.21
	9484	Tube x tube x tube									
	9485	¼" x ¼" x ¼"	1 Stpl	66	.121	Ea.	1.70	3.09		4.79	6.60
	9486	⅜" x ¼" x ¼"		64	.125		3.04	3.19		6.23	8.10
	9487	⅜" x ⅜" x ¼"		61	.131		2.63	3.34		5.97	7.90
	9488	⅜" x ⅜" x ⅜"		60	.133		2.37	3.40		5.77	7.70
	9489	½" x ½" x ⅜"		59	.136		4.07	3.52		7.59	9.70
	9490	½" x ½" x ½"		56	.143		4.07	3.64		7.71	9.90
	9492	Needle valve									
	9494	Tube x tube									

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Figure 10.4 (continued)

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		CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL. O&P
	0400	½" x ¾"	1 Stpi	80	.100	Ea.	2.38	2.07		4.45	5.40
	0410	¾" x ¾"	0.75	82		"	3.20			3.20	3.52
	0600										
	0610	Solenoid, valves max. components	1 Elec	.8	1	Ea.	193	35		227	270
	0612	Electric motor damper actuator		10	.800		42.50	25		67.50	100
	0620	Damper position indicator		12	.667		204	16.75		220.75	250
	0630	Pneumatic-electronic transducer		12	.667		71.50	16.75		88.25	105
	0640	Electro-pneumatic transducer		8	1.000		166	34		200	235
	0650	Aprtures, max. covers with motor drive		16	.500		80.70	12.60		43.30	55
	0660	Manual remote air point control	1	12	.667	1	140	16.75		156.75	180
	0670	Alarm unit with two adjustable points									
	0700	Solid state heater step controller	1 Elec	10	.800	Ea.	256	30		276	310
	0701	4 stage	"	8	1	"	320	25		345	390
	0702	6 stage									
	0710	Staging network	1 Elec	10	.800	Ea.	92.70	30		110.70	130
	0711	Heater one stage		6	.889		155	22		177	205
	0712	Two stage		8	1		164	35		199	235
	0720	Sequencing network	1	14	.500	1	105	12.60		147.60	169
	0730	Regulated 24 power supply									
	0740	Accessory unit regulator	1 Elec	8	.889	Ea.	83.50	22		105.50	125
	0741	Time function		8	1		101	25		126	150
	0742	Fan function		16	.444		25.80	11.20		38	46
	0750	Accessory power supply	1	16	.500	1	107	12.60		119.60	135
	0760	Step down transformer									
422	0010	CONTROL COMPONENTS / DDC SYSTEMS (Sub's quote incl. M & L)									422
	0100	Analog inputs									
	0110	Sensors (avg. 150' run in conduit)				Ea.					340
	0120	Duct temperature									610
	0130	Space temperature									640
	0140	Duct humidity, +/- 3%									980
	0150	Space humidity, +/- 2%									520
	0160	Duct static pressure									700
	0170	C.F.M./Transducer									900
	0172	Water temp. (see 156-210 for well top add)									2,200
	0174	Water flow (see 156-210 for circuit sensor add)									900
	0176	Water pressure differential (see 156-210 for tap add)									2,200
	0177	Steam flow (see 156-210 for circuit sensor add)									640
	0178	Steam pressure (see 156-210 for tap add)									1,250
	0180	K.W./Transducer									575
	0182	K.W.H. totalization (not incl. elec. meter pulse xmtr.)									1,000
	0190	Space static pressure									
	1000	Analog outputs (avg. 50' run in conduit)				Ea.					580
	1010	P/I Transducer									250
	1020	Analog output, card, in MUX									590
	1030	Pneumatic (not incl. control device)									350
	1040	Electric (not incl control device)									
	2000	Status (Alarms)									
	2100	Digital inputs				Ea.					400
	2110	Freeze									360
	2120	Fire									550
	2130	Differential pressure, (air)									780
	2140	Differential pressure, (water)									400
	2150	Current sensor									650
	2170	Duct smoke detector									
	2200	Digital output				Ea.					330
	2210	Start/stop									550
	2220	On/off (maintained contact)				"					
	9000	Controller w/I.V. panel, incl. function boards									

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Figure 10.4 (continued)

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		CREW	DAILY OUTPUT	MAN-HOURS	UNIT	BARE COSTS MAT.	LABOR	EQUIP.	TOTAL	TOTAL INCL. O&P
	2100	48 point			Ea.					
	2110	128 point			"					
	2000	D.D.C. controller (avg. 50' run in conduit)								
	2010	Mechanical room								
	2014	16 point controller (incl. 120v/1ph power supply)			Ea.					
	2016	32 point controller (incl. 120v/1ph power supply)			"					
	3200	Includes software programming and checkout								
	3250	Space								
	3298	V.A.V. terminal box (incl. space temp. sensor)			Ea.					
	3300	Host computer (avg. 50' run in conduit)								
	3301	Package complete with 386 PC, keyboard, printer, color CRT, modem, basic software			Ea.					
	4000	Front end costs								
	4100	Computer (P.C.) software program			Ea.					
	4200	Color graphics software								
	4230	Color graphics slides								
	4250	Additional dot matrix printer			Ea.					
	4400	Communications trunk cable			Ft.					
	4500	Engineering labor, (not incl. dftg.)			Hour					
	4505	Calibration labor								
	4700	Start-up, checkout labor			"					
	4800	Drafting labor, as req'd								
	5000	Communications bus (data transmission cable)								
	5010	#18 twisted shielded pair in conduit			C.L.F.					
	9000	Applications software								
	9050	Basic maintenance manager software (not incl. data base entry)			Ea.					
	9100	Time program			Point					
	9120	Duty cycle								
	9140	Optimum start/stop								
	9160	Demand limiting								
	9180	Enthalpy program			"					
	9200	Boiler optimization			Ea.					
	9220	Chiller optimization			"					
	9240	Custom applications								
	9260	Cost varies with complexity								
425	0010	CONTROL SYSTEMS, PNEUMATIC (Sub's quote incl. mat. & labor)								
	0100	Heating and Ventilating, split system								
	0200	Mixed air control, economizer cycle, panel readout, tubing			Ea.					
	0220	Up to 10 tons								
	0240	For 10 to 20 tons, add								
	0260	For over 20 tons, add								
	0270	Enthalpy cycle, up to 10 tons								
	0280	For 10 to 20 tons, add								
	0290	For over 20 tons, add								
	0300	Heating coil, hot water, 3 way valve,			Ea.					
	0320	freezestat, limit control on discharge readout								
	0500	Cooling coil, chilled water, room			Ea.					
	0520	thermostat, 3 way valve								
	0600	Cooling tower, fan cycle, damper control			Ea.					
	0670	condenser, water readout in/out at panel								
	1000	Unit ventilator, day/night operation,			Ea.					
	1100	freezestat, ASHRAE, cycle 2								
	2000	Compensated hot water from boiler, valve control,			Ea.					
	2100	readout and reset at panel, up to 80 GPM								
	2120	For 120 GPM, add								
	2140	For 240 GPM, add								
	3000	Boiler room combustion air, damper, controls								

Figure 10.4 (continued)

Figure 10.5

Means Forms
CONSOLIDATED ESTIMATE

SHEET NO 1 of 2
PROJECT BAS Budget Estimate
CLASSIFICATION HVAC/Controls
ESTIMATE NO 91-1
LOCATION Kingston, Ma.
ARCHITECT R. Carlson
DATE 1-4-91
TAKE OFF BY RD
QUANTITIES BY RD
PRICES BY RC
EXTENSIONS BY JC
CHECKED BY MG

Description	Quantities Budget	Unit	Installed Cost	Total Cost
Central Air Handling Unit				
Control Components (Electric)				
Damper Actuator (O.A.-R.A.)	1	Ea.	235	235
Damper Actuator (E.A.)	1	Ea.	235	235
Cooling Coil Control Valve - 2"	1	Ea.	540	540
Heating Coil Control Valve 1½"	1	Ea.	330	330
Damper Actuator (Supply Fan Vortex)	1	Ea.	720	720
Damper Actuator (Return Fan Vortex)	1	Ea.	720	720
				Total 2780
Control Components/DDC Systems				
Outdoor Air Temperature Sensor (A.I.)	1	Ea.	340	340
Damper Actuator O.A.-R.A. (A.O.)	1	Ea.	350	350
Damper Actuator E.A. (A.O.)	1	Ea.	350	350
Mixed Air Temperature Sensor (A.I.)	1	Ea.	340	340
Cooling Coil Control Valve (A.O.)	1	Ea.	350	350
Heating Coil Control Valve (A.O.)	1	Ea.	350	350
Low Temperature Detector (D.I.)	1	Ea.	400	400
Discharge Air Temperature Sensor (A.I.)	1	Ea.	340	340
Damper Actuator Supply Fan Vortex (A.O.)	1	Ea.	350	350
Damper Actuator Return Fan Vortex (A.O.)	1	Ea.	350	350
Supply Duct Static Pressure Sensor (A.I.)	1	Ea.	520	520
Space Static Pressure Sensor (A.I.)	1	Ea.	1000	1000

Figure 10.5 (continued)

Means Forms
CONSOLIDATED ESTIMATE

SHEET NO 2 of 2
PROJECT BAS Budget Estimate
CLASSIFICATION HVAC/ controls
ESTIMATE NO 91-1
LOCATION Kingston, Ma
ARCHITECT R. Carlson
DATE 1-4-91
TAKE OFF BY RD
QUANTITIES BY RD
PRICES BY RC
EXTENSIONS BY JC
CHECKED BY MG

Description	Quantities Budget	Unit	Installed Cost	Total Cost
Control Components/DDC Systems (cont'd)				
Duct Smoke Detector - Return Air (D.I.)	1	Ea.	650	650
Duct Smoke Detector - Supply Air (D.I.)	1	Ea.	650	650
Supply Fan Start/Stop	1	Ea.	320	320
Return Fan Start/Stop	1	Ea.	320	320
DDC System Controller (16 Point)	1	Ea.	3000	3000
				Total 9980
V.A.V. Terminal Units (Total of 20)				15500
V.A.V. Terminal Box (Includes space temperature sensor)	20	Ea.	775	Total 15500
Optional Central Host Computer				15000
386 PC, Keyboard, Printer, Color CRT, modem, Basic Software	1	Ea.	15000	3600
Colorgraphic Software	1	Ea.	3600	2700
Individual Colorgraphics	6	Ea.	450	1800
Maintenance Manager Software	1	Ea.	1800	Total 23100
				4250
Communications Bus				Total 4250
Communications Bus (#18 Twisted Shielded Pair in Enclosure)	500	Ft.	$.69/100 Ft.	
Grand Total				55610

Part Four

System Selection Criteria

When a decision is made to install a Building Automation System (BAS), certain steps should be taken and criteria established for the selection process. If a BAS is to be an effective tool for a building owner and his operating staff, a detailed review of available systems, their features, and capabilities is a must, prior to making a buying decision.

The review should be conducted by a team, comprised of the building owner or his/her representative, a financial advisor, a consulting engineer familiar with BAS, and a selected member of the building operating staff. The team should be assigned the responsibility of establishing the goals and objectives to be achieved by installing a BAS. Team members must follow a logical, structured approach in evaluating systems, with an emphasis on economy, compatibility with building systems, user-friendliness, and vendor support quality.

In the following chapter we will offer some suggestions on what criteria to use in evaluating Building Automation Systems.

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Chapter Eleven

System Selection Criteria

Why select a Building Automation System? A BAS is a powerful tool for building owners, managers, and operating personnel. It can provide accurate temperature control to ensure the optimum in comfort conditions and building air quality. Energy management programs are available to assist operating personnel in the most efficient utilization of energy-consuming systems. Continuous monitoring of building systems can assist the maintenance staff by providing early notification in the event of equipment failure. An operator can also predict equipment failure by observing ongoing trend reports. Preventive maintenance scheduling, energy audits, and many other building management reports are other important tools that a BAS provides for the day-to-day process of managing a building.

Building Automation Systems are designed to integrate building systems, such as HVAC, lighting, fire safety, and security access control. The integration of all of these systems can reduce initial and ongoing costs, and simplify building operation. In addition, interactive software programs can improve or enhance life safety and property protection. For example, fire safety software can interact with HVAC programs for smoke control. Fire safety software can also interact with door access programs to provide a means of egress for building occupants in the event of a fire. Both are advantages that improve the life safety conditions of a building.

The aforementioned, and many other features of BAS, provide major benefits to the building owner. They enhance comfort, energy management, life safety, and asset protection, which are the ultimate goals of every building owner or manager.

Although many manufacturers compete in the business of BAS, 80% of the market is virtually controlled by four or five of the vendors. There is, however, an opportunity to shop for the "best deal." It should be noted that the "best deal" is not necessarily the one with the lowest initial price, but rather that which provides the most cost-effective approach to achieving long term goals. Initial cost must, of course, be a buying consideration, but it should not dominate the decision-making process.

It is also important to remember that the hardware and software of different manufacturers are not compatible. For this reason, once a Building Automation System is installed, the owner may very well be committed to continue with the same manufacturer for future extensions to the system. Consequently, it is extremely important to closely evaluate not only the system and its capabilities, but also the manufacturer's past experience in the Building Automation System business and his commitment to the future of that business.

Considerations in Selecting a Building Automation System

Differences between the actual capabilities of a BAS and the owner's original expectations can cause great disillusion and costly problems. To avoid this, the decision-making team must first establish a list of goals and objectives to be achieved by installing a BAS. Next, they should acquire a thorough understanding of BAS capabilities and how these apply to the stated goals and objectives. This is an educational process and should include technical, financial, and operational considerations, as well as potential future requirements for system expansion.

Existing mechanical system deficiencies should be reviewed and corrected prior to the installation of a BAS. If there are design problems with the heating, ventilating, and air-conditioning system (HVAC), not only will they not be corrected by the installation of a Building Automation System, but they may even be aggravated. Indoor air quality problems, hot spots, cold spots, humidity problems or unusually high energy costs could be caused by inadequate maintenance, poor control, or mechanical systems which are not properly installed or applied.

Economics play an important role in the decision-making process. Accuracy of control by DDC technology can result in significant savings over an obsolete pneumatic or electric control system. Energy management programs can generate impressive energy savings with little or no change in building comfort conditions. Integration of other building systems can also lead to operational savings through consolidation of building operations at a central location. Furthermore, installing a Building Automation System can result in more effective utilization of manpower. Therefore, it is important to do a complete financial analysis to determine the return on investment that can be achieved by the BAS.

Planning for future expansion of the BAS is another consideration. If building expansion or additional buildings are a future possibility, the BAS must have the capacity to meet the requirements associated with that growth.

Planning Phase

An experienced building operations person and an engineer familiar with Building Automation Systems are indispensable members of a BAS evaluation team. Their technical expertise and understanding of building operations can be invaluable in verifying potential savings to be achieved through energy management programs, and in avoiding the pitfalls of misapplication of the Building Automation System. They can also survey and evaluate existing building systems (HVAC, lighting, fire, security, and access control), and make recommendations to upgrade, retrofit, or replace equipment or complete systems where necessary. In the case of a new building, these individuals can work with the HVAC and electrical engineers to ensure that the BAS is properly incorporated into the building system's design.

Installation Phase

During the installation phase of the BAS, the owner will want a technical representative available to oversee the installation and review any job site revisions. Here again, the building operations person and the engineer with knowledge of BAS are the ideal candidates.

Formal Acceptance

Upon completion of the installation, a formal acceptance test should be conducted to verify that the system is functioning as specified. Every point should be tested, with the engineer and operations representative present. All software programs, DDC control loops, energy management, lighting fire, security and access control should be completely tested subject to the approval of the engineer. It is extremely important that the entire BAS perform in a manner that satisfies the goals and objectives established by the original decision-making team, before it is accepted.

Training

Prior to final acceptance of the BAS, a formal on-site training session should be conducted by the BAS vendor for all operating personnel. Training should include details of BAS operations as they apply to the specific building and its systems. Trainers should also review the goals and objectives of the decision-making team and explain how the BAS meets those requirements. Finally, all operators should receive in-depth training in their individual duties regarding proper operation of the system. The vendor should offer advanced operational and programming courses so that operators can advance through progressive levels of responsibility. This system provides incentives for the operators and also assures the building owner that his operations staff is fully qualified.

Maintenance Requirements

The maintenance requirements of computerized Building Automation Systems are minimal in comparison to pneumatic and electric control systems. However, vendor support in some form is necessary to ensure the goals and objectives of the team are met on an ongoing basis. While some facility managers are fortunate enough to have in-house technical expertise to maintain a BAS, this is the exception rather than the rule.

Vendor support offerings vary. Some vendors offer comprehensive maintenance programs at a fixed annual cost. Most vendors will tailor a maintenance program to the customer's needs. Some minimum services that should be considered by BAS system owners are covered in the following sections.

Software Support

Revisions and updates to standard operating software constitute an important BAS feature, the purpose of which is to avoid system obsolescence and enhance overall system operation. Some vendors conduct a periodic review of data and application programs to verify correct operation. This is extremely important for systems with fire and security integration.

Some vendors have remote diagnostic capability. This allows the vendor to access the BAS software from a remote location for troubleshooting purposes. The remote operator can also change operating parameters, modify programs, or disable points.

Hardware Support

Since building automation and direct digital control systems are software-driven, hardware support is not as important as for traditional pneumatic and electric control systems. Software and applications support rank higher in importance than hardware support in BAS systems. From a budgetary standpoint, however, hardware support could be an important feature. Computer-related components and printed circuit boards can be expensive items. Under a service contract (which includes component replacement) an annual figure can be carried in the budget to cover unexpected replacement costs.

For systems with fire or life safety functions, hardware coverage could be critical. Most insurance companies require a fixed number of annual tests on initiating devices (fire detectors, smoke detectors, manual pull stations). Most vendors perform these required tests and furnish a written certification.

Emergency Service

Many vendors include emergency service on a seven-day, 24-hour basis as a feature of their service contracts. In fact, in many cases, a vendor will not respond to after-hours (overtime) emergency service calls unless the customer has a service contract specifically including this coverage. A system owner who has fire or life safety functions included in his system should include emergency service provisions. Some vendors will agree to a maximum response time for emergency calls if the building occupants or property will be adversely affected by a BAS malfunction. If the Building Automation System is critical to the health or safety of building occupants, or to the protection of property, a formal agreement should be made with the vendor for emergency service coverage.

Operator Training

Periodic operator training can be an important benefit to the BAS owner. Many vendors offer this feature to maintain a high level of operator proficiency. This type of training is usually conducted on-site, and the content determined jointly by the customer and the vendor. Some BAS manufacturers offer advanced formal training programs at their factories to upgrade operators in HVAC, fire, security and access control systems, building operations and BAS programming.

Vendor Selection Through Bidding Process

The decision-making team may decide that they wish to receive bids from multiple vendors for a Building Automation System. This complicates the decision-making process somewhat because of the different technology, experience levels, and conceptual approach offered by different vendors. For this reason, it is imperative that detailed specifications be produced to support the goals and objectives developed by the team. A vendor's representative may offer to provide off-the-shelf, non-proprietary specifications for the bid. This may be acceptable if the team reviews the documents carefully and customizes the wording where necessary. The consulting engineer and building operations person can provide invaluable assistance to the team in this task.

Evaluating Proposals

All proposals should be reviewed thoroughly and carefully by the decision-making team. The following list is presented as a guide to some of the key issues to consider in the areas of BAS functionality and vendor support.

- Central host computer malfunctions and breakdowns and their effect on the building systems.
- Costs and time required to alter the BAS data base and/or software.
- Costs of adding points after system is installed. User-friendliness to add and delete points and to change the software. Capability of performing changes without shutting down the system.
- Power failures and their effect on the BAS. System's capability to get back on-line after power is restored.
- Type and manufacturer of central host computer and whether it is a commonly used general purpose computer or specially configured for the BAS.
- Is the cost of software included with proposal or an added cost?
- How many password control levels of access?
- Access to future software revisions, enhancements, and programs.
- Central computer's capability to integrate DDC, energy management, lighting control, as well as fire and security access and facility management programs.
- Automatic dial-up or dial-out communications to an off-site BAS or PC in the event of an abnormal condition.
- Capability to expand in order to control additional systems, buildings, and modifications to the original BAS.
- Automatic dial-up capability versus dedicated telephone line requirements to operate separate buildings.
- BAS application requirements for U.L. listing, such as lighting control, integrated fire and security access systems.
- Experience and background levels of personnel who are to receive user training. Clarity and user-friendliness of the manufacturer's operator's manuals, and as-built documentation.
- Response time to repair a problem, stocking of repair parts, skill required.
- BAS maintenance requirements, availability, types, costs of manufacturer's maintenance agreements.
- Manufacturer and/or vendor experience in installing and servicing a BAS for the application.

The award should not be made based only on lowest price, but rather on value, as determined by evaluating the costs and benefits of each proposal. A common method used to evaluate proposals is value ranking. Each item of importance in the decision-making process is assigned a certain weight with an overall total, which may add up to 100 points. A value ranking system could be set up as shown in Figure 11.1.

Selecting a Vendor

After completing a proposal evaluation process, the selection should be narrowed down to two or three qualified vendors. In order to properly decide on the best suited vendor, the decision-making team should investigate and obtain as much information as possible about the vendor's past performance. At a minimum, some of the following actions should be taken:

- Site visit: View and inspect at least one, but preferably as many as possible, BAS's with similar applications.
- Discuss problems encountered by owners of similar BAS's.
- Interview the vendor's engineering, construction (if applicable), and maintenance staff who will be working on the project.
- Spend as much time as possible with the vendor in order to understand how the proposed BAS works, how user-friendly the software is, how to perform software programming, change start times, perform overrides, acknowledge alarms adding and deleting points, and any other item deemed important in the operation of the system.

The process of evaluating proposals and selecting a vendor requires some discipline and structure. The more extensive the review of the important factors, the more fundamentally sound the final vendor selection should be.

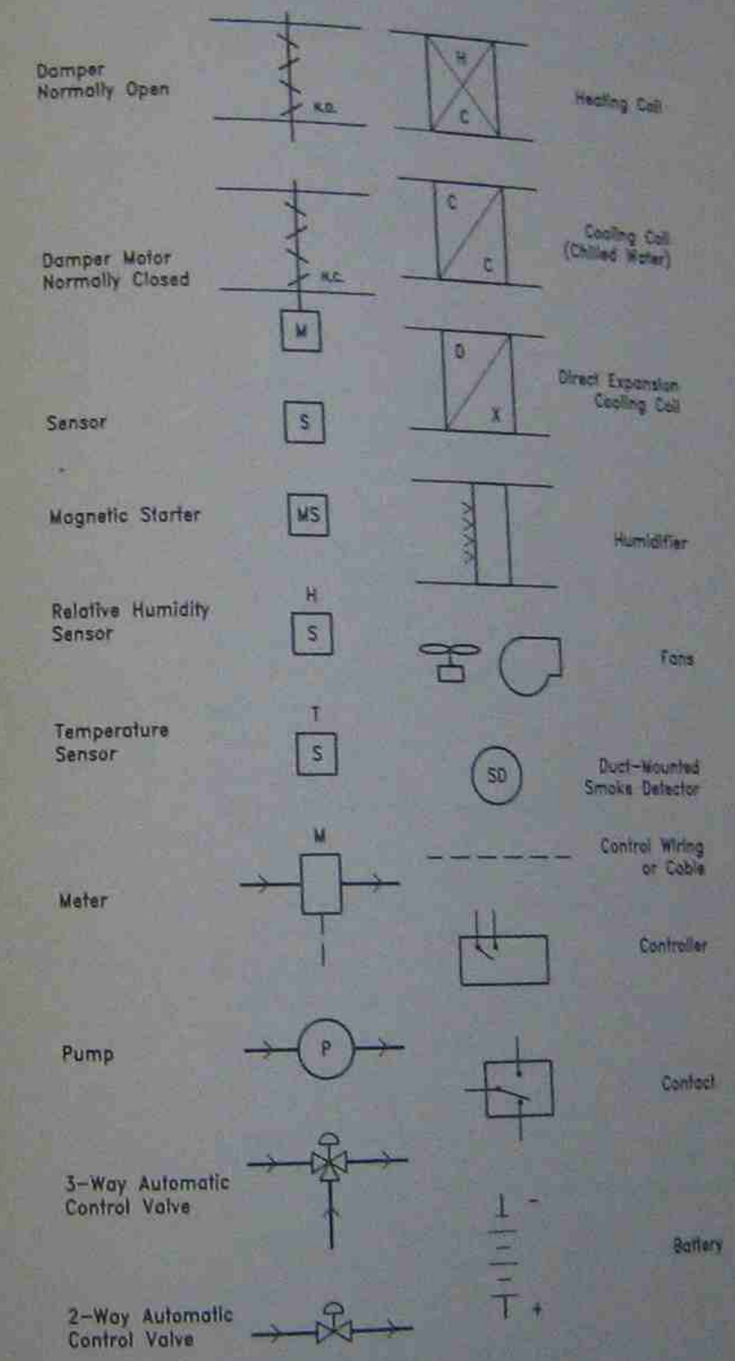
ITEMS	WEIGHTS
Proposal price	
Specification compliance	
Equipment quality based on proposal literature	
Hardware, software, and firmware quality based on proposal literature	
Expansion capability	
Fire system integration capability	
Security/access integration capability	
Lighting control integration capability	
System point capacity	
Number of installed systems and point size	
Options & features not specified	
Warranties	
Maintenance agreement costs	
Vendor experience	
Vendor financial stability	
Vendor reputation	
Engineering support & quality	
Field maintenance support & quality	
User training support & quality	
Installation quality	
Installation time schedule	
TOTAL	100

* Values to be determined by the decision-making team.

Example of a Value Ranking System

Figure 11.1

BAS Symbols



Glossary

Actuators
A device that converts an electric or pneumatic signal in order to position a control device such as a valve or damper.

AI
Analog inputs

Algorithms
A set of mathematical instructions, or a computer program, to produce a control output.

Analog
Continuously variable through a range. Not limited to discrete units.

AO
Analog outputs

Bell loop
The circuit that provides notification of a fire condition in a fire alarm system.

Bit
Abbreviation of "binary digit," the smallest unit of information in a binary system.

Built-up system
An HVAC system which is assembled on-site, usually a large system.

Central host computer
A personal computer (PC) that acts as an operator-machine interface to a Building Automation System.

Central Processing Unit (CPU)
The section of a computer where arithmetic and logical operations are performed, and instructions are interpreted and executed.

Centralized multiplexing system
A system of transmitting multiple signals simultaneously over a single circuit.

Cold deck (or duct)
Source of cold air, provides for cooling interior zones.

Communications bus
A communications medium which links controllers and a central host computer.

Control loop
A sensor-controller-actuator combination that processes an input signal and produces an output signal to position the actuator.

Direct expansion (DX)
Refrigeration systems that employ expansion valves or capillary tubes to meter liquid refrigerant into the evaporator.

Deadband program
See zero-energy band program

DDC
Direct Digital Controller

DI
Digital input

DO
Digital output

Digital transmission
The serial transmission of information, in bit form, over a single wire.

Direct Digital Controller (DDC)
A microprocessor-based device that controls and monitors HVAC equipment. Controllers typically have control loop programs and energy management programs.

Distributed process system
The consolidation of energy management and control loop programs into one intelligent microprocessor-based controller.

Dry bulb
The temperature as registered on a standard thermometer

Duct static pressure
The pressure acting on the walls of a duct; the total pressure less the velocity pressure; the pressure existing by virtue of the air density and its degree of compression.

Duty cycle
A program that turns electrical loads on and off while maintaining space comfort conditions, thereby conserving energy.

Economizer cycle
A system of dampers, temperature and humidity sensors, and actuators which maximizes the use of outdoor air for cooling.

Energy Management System (EMS)
A system which operates energy-consuming systems, in the most energy-efficient manner, through software programs.

Enthalpy program
A program which selects the source of air that contains the least total heat to be removed, thereby achieving savings on mechanical cooling.

Fan inlet vane damper
Adjustable blades or vanes at a fan inlet designed to give air a spinning motion in the direction of fan rotation.

Fire management panel
A fire alarm control unit consisting of multiple single zone fire alarm control modules, a telephone module, an HVAC module, and an audio communications module.

Firmware
Computer programs or instructions stored in the Read Only Memory (ROM). It performs the same function as software, but is in hardware form. Firmware is loaded into the equipment either at the time it is manufactured or later for preprogrammed controllers.

Flywheel effect
The tendency of a building to retain heat due to its mass-thermal-inertia.

Heat exchanger
A device designed to transfer heat between two physically separated fluids.

Hot deck (or duct)
Source of hot air, provides for heating interior zones.

Indicating circuit
See bell loop

Initiating circuit
A circuit containing sensors to detect a fire condition.

Integrated Building System
The consolidation of multiple building systems, such as HVAC, lighting, fire alarm, and security/access control into one central computer.

Intelligent (Buildings)
Building "intelligence" is defined by different levels of automation and integration of systems.

Kilobit
Thousand bits

Load reset program
A program that utilizes minimum levels of heating or cooling energy to satisfy the zone with the greatest heating/cooling requirement.

Load shedding
See power demand program.

Management host computer
A high level computer that acts as a management-machine interface to a BAS.

Microprocessor-based controllers
See Direct Digital Controller

Multi-conductor
An electrical cable containing multiple wires.

Night cycle program
A program that maintains a reduced temperature in the heating season or high limit temperature in the cooling season during unoccupied periods.

Night purge program
A program that replaces building air with cooler outdoor air during the early morning hours.

Off-normal alarms
An alarm generated by a deviation from preprogrammed limits.

Offset
A deviation between control point and set point on a modulating control loop.

Optimum start program
A program that delays HVAC system startup to the last possible moment, while still achieving comfort levels at occupancy time.

Optimum stop program
A program that takes advantage of the building flywheel effect to meet comfort requirements until the end of the occupancy period.

Pneumatic
A system of control that uses air pressure.

Point
A piece of equipment that is monitored or controlled by a controller or BAS.

Power demand program
The process of shedding electrical loads to avoid achieving a preprogrammed kilowatt demand limit.

Primary air
Conditioned air supplied to terminal units by a central HVAC system.

Protocol
A method by which microprocessors can communicate with each other in a common language.

Relay
An electromagnetic device activated by a variation in conditions in one electric circuit and controlling a larger current or actuating other devices in the same or another circuit.

Reset program
See load reset program

Sensing circuit
See initiating circuit

Set point
The setting of a controller (the desired level of control).

System controllers
A DDC controller used to control large central HVAC systems.

Time-based program
A program which starts and stops equipment as a function of preprogrammed time.

Variable Air Volume (VAV) system
An HVAC system which varies air flow to the conditioned space to maintain comfort conditions.

Variable speed drive
A method of controlling the fan speed in a central HVAC system.

VDC
Volts direct current

Wet bulb
The temperature read on a dry bulb thermometer enclosed in a wet wick.

Zero-Energy band program
A program that provides a control deadband between heating and cooling processes, during which no energy is consumed.

Zone controllers
A DDC controller used to control primarily terminal units or small package-type HVAC units.