The Kinkajou Project:
Power System Optimization for a Low Cost Microfilm Projector

by

Martin Tolliver

Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the
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Abstract

The Kinkajou projector, an educational tool for the developing world, uses an LED to project microfilm images. An alpha prototype of the Kinkajou was built in Fall 2002. For this paper, basic product development processes were applied to the design of the Kinkajou system, and the design of a beta prototype is proposed. As a result, the effectiveness, efficiency, portability, and robustness of the projector will be improved while reducing cost.

The power storage system is the first of many proposed changes in the design of the Kinkajou projector for the beta prototype. Three lead-acid D cells will provide six hours of service life, twice that of the alpha prototype, at half the cost. Improvement in the thermal design considerations will increase the brightness of the LED by more than 50%, making the Kinkajou a more effective learning tool. The proposed microfilm interface will increase the robustness and flexibility of the Kinkajou. The proposed system architecture improvements allow the projector to be 70% smaller than the alpha prototype and sealed from dust, increasing the portability and robustness of the Kinkajou. A new, more reliable indexing system is proposed. A new project documentation process allows for easy future improvement to the Kinkajou.

The Kinkajou project won the Spring 2003 MIT IDEAS Competition first prize of $5000. This funding will be used toward the manufacture of the new Kinkajou beta prototype designed in this paper. It will also allow students to take the Kinkajou to Mali in Summer 2003 for proof of concept as an effective learning tool. With the design improvements detailed in this paper, the Kinkajou will be ready for Mali.

Thesis Supervisor: Professor Yang Shao-Horn
Title: Assistant Professor

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Nomenclature

AC: Alternating Current. Electricity is distributed over a grid in this form.
Battery: a product consisting of at least one cell.
Capacity: amount of electrical energy retrievable from the active materials of a cell (Amp-hour).
Cell: the basic unit that converts chemical energy to electrical energy.
Chemistry: the chemical makeup of the anode/cathode/electrolyte of a cell.
Configuration: the size, construction, or design of a particular cell.
C-rate: a measure of the load drain on a cell relative to its capacity (C). For example, a 0.1C or C/10 discharge rate for a battery rated at 5 Ah is 0.5 A.
Cutoff voltage: the voltage to which a cell is discharged (Volts).
Discharge profile: the plot of voltage versus time over the discharge of a cell.
DPDT: Double-Pole, Double-Throw.
Energy density: volumetric energy density (Watt-hour/Liter).
LED: Light Emitting Diode.
PCB: Printed Circuit Board.
Primary cell or battery: a cell or cells not able to be electrically recharged.
Secondary cell or battery: a cell or cells able to be electrically recharged to their original condition before discharge.
VCR: Video Cassette Recorder.
VHS: Video Home System, video cassette format (patented by JVC).

1. Introduction

1.1 Background on the Kinkajou Project

During 2.009, MIT Mechanical Engineering's undergraduate Product Design Process course, student teams were tasked with designing and delivering a product to a real customer. The course had a problem statement which required the product serve underprivileged users, such as people living in the developing world.

Today, a large fraction of the world's population cannot read. The high cost and scarcity of both books and electricity are two main obstacles in the struggle towards literacy. In Spring 2002, David LoBosco, Saul Griffith, and Timothy Prestero proposed the "portable library," a device which uses an LED to project microfilm images. In Fall 2002, my 2.009 team developed this idea in to the "Kinkajou" projector system.

With this system, readily available educational material is transferred onto microfilm at a low cost and spooled onto modified VHS cassettes. These cassettes, which can hold upwards of 7000 pages, can then be put into the Kinkajou projector and be displayed. The projected image can be a personal size or a larger size suitable to be read by a small classroom, such as those used by our target customer, World Education, at adult literacy classes Mali.

A representative of World Education, a non-governmental organization dedicated to increasing worldwide literacy, was in attendance at the 2.009 presentation on 4 December 2002 and expressed great interest in our product. However, the prototype required further development before we would be able to take it to Mali.

1.2 Improvement-Essential Realms of the Kinkajou

During 2.009 in Fall 2002, each team of sixteen students began with literally hundreds of ideas and had to narrow them down to six idea posters, then four sketch models, then two mock-ups, then one working prototype. In short, the entire product design process was compressed in to one semester. This meant that probably some of the materials-selection and design decisions made were not as informed as possible. The purpose of this project is to look deeper in to the background knowledge needed to make good design decisions and make recommendations for the beta prototype.

While there are many good things about the alpha prototype of the Kinkajou projector, a major part of the design process is iteration and improvement. The design changes this project recommends build upon the previous design. Some challenges of this design project are cost limitations, size requirements, and considerations concerning the environment in which it will be used.

The purpose of the following sections is to describe some weaknesses associated with the alpha prototype.

1.2.1 Power Storage System

I consider the power storage system to be an area of the alpha prototype which can undergo much improvement, and optimization of power usage is vital to the battery-powered Kinkajou system.

The battery of alpha prototype consists of six rechargeable Nickel-Metal Hydride C cells. The battery lasts about 3 hours. It accounts for 20% of the total system cost based on a liberal calculation of production at over 1,000,000 units. Reduction in the cost of the power storage system would be a significant improvement for making the Kinkajou inexpensive.

Besides cost, another concern with the alpha prototype's battery system is ease of replacement. Since the battery will fail in a matter of a few years, a much shorter timeframe than the rest of the system's parts, the battery should be inexpensive and easy to replace. As a result, the functionality of the system will not be so impinging on the expensive battery.

1.2.2 Power Circuit

When someone would first look at the Kinkajou projector, they would often be confused by the purpose and number of controls. After speaking with World Education, it was determined they did not want the dimming feature as it would only lead to confusion or misperception that the projector was broken. They would only require using the LED at the brightest setting.

1.2.3 Thermal Design Considerations

When most people first see the Kinkajou, they often ask, "What is the heat sink for?" or "Why is the heat sink so big?" People do not generally think of LEDs as dissipating a significant amount of heat, but on the 5 Watt scale, thermal considerations become a serious concern. Because not every electron passed through the LED translates to one photon, energy must dissipate through heat irradiation. This answers the question why a heat sink, but what about the question of size? The heat sink should have to radiate no more that 5 Watts (the input electrical power). Most applications that require dissipation of 5 Watts of heat employ small natural convection heat sinks. However, the Kinkajou projector requires a heat sink with a much lower thermal resistance than heat sinks used in these typical applications because of the rather large thermal resistance between the LED junction and the heat sink.

Figure 1: Heat Sink of Kinkajou Alpha Prototype.

The purpose of using of a large heat sink for the Kinkajou alpha prototype (as seen in (Figure 1) was to keep the heat sink's thermal resistance low by increasing surface area, but since the heat source is not dissipated evenly over the entire base of the heat sink, there is added thermal resistance. Also, the fin-spacing is too small for natural convection. Due to the viscosity of air, the spacing between fins in natural convection must be a given distance to avoid "choking" of the resulting boundary layers. This fin spacing results in heat sink volumes three to four times larger than equivalent forced convection heat sinks. Typical spacing for many natural convection heat sinks is a half inch; the heat sink used in the alpha prototype has spacing of only an eighth of an inch.

1.2.4 Microfilm Interface

For the alpha prototype, Modified VHS cassettes were used to hold microfilm. The 16mm microfilm had to be trimmed using the piece of equipment shown in Figure 2 to fit on the VHS spools. The film then had to be wound onto VHS spools and put in the cassette which was modified to allow the optics unit to project the image on the film. The modified cassette is shown in Figure 3.

Figure 2: Microfilm Trimmer. Using mat-cutters, 16mm microfilm is cut down 1/8" so it fits on standard VHS spools.

Figure 3: Modified VHS Cassette. The cassette has a hole cut in it so the microfilm can interface with the optics unit.

The justification for using VHS cassettes was to make manufacturing simpler and cheaper by using an existing product that definitely works. Also, parts from existing indexing systems (VHS rewinders or VCRs) could be borrowed. However, the idea turned out to put many limitations on the design. The optics unit could not fit inside the cassette because of the size of the condenser lens set, so a mirror was required to bend the light. The mirror could not be placed anywhere in the optical arrangement because of the required closeness of condenser lens, image (film), and projection lens. Therefore, the mirror had to be placed after the projection lens. Because of the described optical arrangement (Figure 4), the cassette had to be arranged vertically. If it were to be arranged parallel to the table surface, then the image would have to be projected either towards the ceiling or towards the floor. A second mirror to bend the light another 90º was not practical because of the size of mirror necessary at this distance away form the projection lens. The required vertical arrangement of the cassette greatly increased the size of the system.

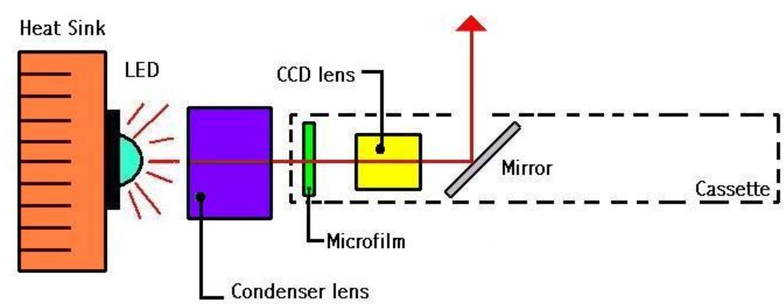

Figure 4: Optics Schematic for the Kinkajou Alpha Prototype. This figure is reproduced from work by an original 2.009 team member.

Use of a VHS cassette exposed the microfilm to dust. Also, the required interface between the cassette and the system made the internal components of the projector susceptible to dust. This exposure to dust compromises the robustness of the system. A few places where dust can easily invade the system interior are shown in Figure 5.

Figure 5: The Alpha Prototype is not Sealed From Dust. The cassette interface is shown on the left. In the center and at the right are images of the consequent gaps in the outer housing of the Kinkajou.

1.2.5 Optics Unit

In the Fall of 2002, when the alpha prototype was made, 5-Watt LEDs were not available in white. Images projected by the cyan LED are not as readable as possible with a white LED. Also, in the alpha prototype, nothing prevents the projection lens from being accidentally removed while adjusting the focus.

1.2.6 Indexing System

For the alpha prototype, using parts from an existing VHS indexing system (a VHS rewinder) seemed to be a good solution. However, retrofitting a VHS-rewinder system into the alpha prototype compromised the functionality. It also involved the necessity of making several small parts like pulleys for the belt-and-pulley system. Using an o-ring for a belt was not a reliable solution. The belt failed after several weeks. For installing a new o-ring, about 45 minutes of disassembly/assembly was required.

1.2.7 System Architecture

The alpha prototype leaves much room for improvement in terms of compactness and robustness. It is more than 600 cubic inches in volume. As mentioned earlier, the internal components are not sealed from dust.

1.3 Scope of this Project

In this project, I will explore the design of the power storage system, power circuit, cooling system, microfilm interface, optics unit, indexing system, and overall system architecture. I will employ basic product development processes to improve the system design to better fit the user needs.

2. Background

This section is intended to provide the necessary background to make informed design decisions about the power system of the Kinkajou. It gives justification for use of an LED as a light source for the projector and explores what must be used to suitably power and cool the LED for reliable function.

2.1 LED Advantage

When people say things like “LEDs are 90% more efficient than incandescent bulbs,” they probably are referring to *efficacy*, not *efficiency*. When considering input power, luminous efficacy is the important value. Luminous efficacy is a measure of the amount of luminous flux produced per unit of input electrical energy. The measure of lumens accounts for the variable sensitivity of the human to wavelength. For example, one watt of radiation at 555 nm (yellow-green) produces a strong sensation of light. The sensation decreases progressively as wavelength moves toward the edges of the visible spectrum, namely 380 and 780 nm, where one watt (or any amount) of radiation produces almost no sensation of light in the human eye. Thus, how “bright” a light-source seems depends on its spectral power distribution. Because incandescent light bulbs radiate energy over a broad range of wavelengths (much of which is >700nm), they have low luminous efficiency (luminous flux per unit of radiant energy). LEDs, on the other hand, radiate energy over a very narrow range of wavelengths, making their spectral power distribution “spiky” as shown in Figure 6.

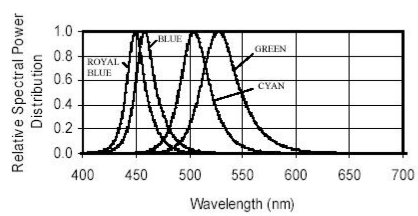

Figure 6: Wavelength Characteristics (T_j = 25ºC). This figure is reproduced from Luxeon™ 5W Star Data Sheet.

If a LED is manufactured to have this spike of radiation near 550 nm, it will have a very high luminous efficiency, i.e., all of the radiant energy will translate well in to response of the human eye. If the LED is manufactured to radiate near 400 nm, it will not have high luminous efficiency since energy at 400 nm does not as efficiently invoke sensation of the human eye.

As mentioned before, luminous efficacy is most important when input electrical power is a concern. The Luxeon™ 5 Watt Star Cyan LED data sheet specified an output of 120 lumens. This means a luminous efficacy of 120lm ÷ 5W = 24lm/W. Efficacy values for incandescent bulbs range from 10-20 lm/W. So, while it is true LEDs can in some cases be use input power 90% more “efficiently,” one should note that efficacy values for tubular fluorescent lighting can reach 70 lm/W and are upwards of 100 lm/W for high pressure sodium lighting (street lamps). LEDs, as well as incandescent bulbs, more easily can provide the intensity needed for projection. For a given image brightness desired, an LED can project it with much less input power and will generate a far less amount of heat when compared to an incandescent bulb designed to do the same task. Also, the efficacy of LEDs has been rapidly improving over the past decade and should reach 100lm/W in the next ten years.

2.2 Background on Various Battery Chemistries

This section gives background information needed to make a decision about what power storage system can best power the LED. The fact that so many different power storage systems exists shows the inherent complexity involved in choosing an appropriate system. Each chemistry and configuration has advantages and disadvantages associated with it. The selection process resides in matching those particular benefits and drawbacks with the requirements of the product served. The following equation defines the relation among important parameters pertinent to power considerations:

$$P = I \times \Delta V \tag{Eq. 1}$$

Where P is power, I is current, and ΔV is potential difference.

2.2.1 Battery System Selection

Many factors must be kept in mind when matching system requirements with an appropriate battery chemistry and configuration: type of battery, system requirements, cell voltage, load current and profile, duty cycle, temperature requirements, service life, shelf life, physical restraints, charge-discharge cycle (if secondary), environmental conditions, safety and reliability, maintenance and re-supply, and cost. Each of these areas is explained more deeply in Section 1 of Appendix A.

2.2.2 Factors Affecting Battery Performance

The following is a list of factors that affect the performance of most cells, regardless of chemistry or configuration: drain rate, mode of discharge, temperature, duty cycle, voltage regulation, charging, and cell design. Section 2 of Appendix A explains how these factors affect the performance of cells.

2.2.3 Primary Cells

Conventional primary batteries are used in many consumer applications because of their low cost, availability, an adequate performance. Recent advances in primary battery technology like lithium anodes significantly increase performance characteristics. The specific performance of a primary cell is very dependent upon the cell's design and the load's discharge profile. The main advantages and shortcomings associated with primary zinc-carbon, alkaline/manganese dioxide, and metal-air cells are made clear in Section 3 of Appendix A.

2.2.3 Secondary Cells

In comparison to primary batteries, secondary batteries are usually better when it comes to high discharge rates and low temperature performance, but primary batteries are generally superior in terms of capacity and shelf life. Perhaps the most significant difference is cost. Secondary batteries incur twenty to ninety times the initial cost per Watt-hour to the user. However, secondary batteries can pay off in the long term depending on the drain rate and how often the device is used.

The use of secondary cells is generally cost effective when power is regularly needed, charging facilities are readily available, and drain rate is high. If the calculated break-even point for a secondary system over a primary one is near the calendar life of the secondary cells, it is generally not advantageous to use them. If usage is low and drain rate is moderate, then primary cells are usually best. In addition, the inconvenience of recharging is not necessary.

The main advantages and shortcomings associated with secondary lead-acid, nickel-cadmium, nickel-metal hydride, lithium-ion, and alkaline/manganese dioxide cells are made clear in Section 4 of Appendix A.

Sometimes a combination of primary and secondary cells is employed to exploit the capabilities of both.

2.3 Background on Heat Sink Selection

Once the LED is properly powered, it must be cooled effectively because the reliability and life of electronic components are inversely proportional to the temperature at which the component operates. It is necessary to sufficiently dissipate heat from the component in order to keep operating temperature below manufacturer specifications.

Heat sinks are devices which enhance heat dissipation from a heat source to an ambient fluid, air in most cases. A heat sink achieves improvement of heat dissipation by increasing the area of interface between solid and air. Simply increasing surface area, however, is not always advantageous because this means adding material. At some point, solid material can be cooled better by convection and radiation than by conduction (through more heat sink material). This balance is optimized for different applications through various heat sink designs.

2.3.1 Thermal Considerations

Table 1: Definitions of Variables Needed for Thermal Calculations		
value	units	Description
Q	W	total power, rate of heat dissipation
T_j	ºC	junction temperature of electronic component
T_c	ºC	temperature of the electronic component casing
T_s	ºC	temperature of the heat sink
T_a	ºC	temperature of ambient air
ΔT_{xy}	ºC	temperature difference between two locations specified by subscript
R_{xy}	ºC/W	thermal resistance between two locations specified by subscript

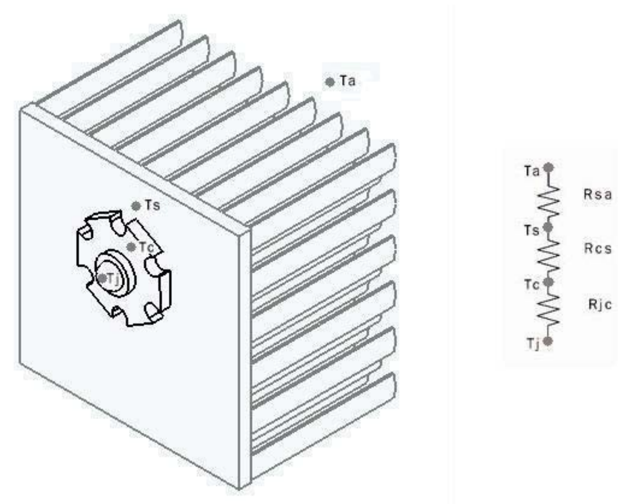

Figure 7: Thermal Circuit Schematic. The left side shows an example of an LED fixed on an aluminum-core PCB, mounted on a heat sink. The right side shows the equivalent thermal circuit.

Knowing the characteristics of the LED, an appropriate heat sink can be specified for the simple case shown in Figure 7. Using the concept of thermal resistance, the process is shown step by step below. Thermal resistance (R), temperature gradient (ΔT), and rate of heat dissipation (Q) are related by Equation 2. It will be useful for the calculation.

$$R = \frac{\Delta T}{Q} \qquad \text{(Eq. 2)}$$

The values represented by the variables in this equation are described in Table 1. This equation is analogous to Ohm's Law,

$$R = \frac{\Delta V}{I} \qquad \text{(Eq. 3)}$$

where R is electrical resistance, ΔV is potential difference, and I is electrical current.

The maximum junction temperature, T_j, is specified by the manufacturer of the LED. The thermal resistance between the junction and the casing of the electronic device, R_{jc}, also specified by the manufacturer, is defined as

$$R_{jc} = \frac{\Delta T_{jc}}{Q} \quad \text{(Eq. 4)}$$

where Q is total power. By the same reasoning, the thermal resistances between the device casing and the heat sink, R_{cs}, and between the heat sink and ambient air, R_{sa}, are respectively,

$$R_{cs} = \frac{\Delta T_{cs}}{Q} \quad \text{(Eq. 5)}$$

$$R_{sa} = \frac{\Delta T_{sa}}{Q} \quad \text{(Eq. 6)}$$

Clearly, the total thermal resistance between the junction and ambience, R_{ja}, is:

$$R_{ja} = R_{jc} + R_{cs} + R_{sa} = \left(\frac{\Delta T_{ja}}{Q} \right) \quad \text{(Eq. 7)}$$

2.3.2 Heat Sink Thermal Resistance

Once the relationship among each part of the thermal circuit is specified, the required thermal resistance for the heat sink can be found. Rearranging and re-writing Equation 7, the thermal resistance for the heat sink, R_{sa}, can be isolated:

$$R_{sa} = \frac{(T_j - T_a)}{Q} - R_{jc} - R_{cs} \quad \text{(Eq. 8)}$$

In this equation, T_j and Q are specified by the LED manufacturer or otherwise known. R_{jc} is also specified, and there is little one can do to reduce this value because it is dependant on the construction of the LED. R_{cs} can be a negligible value if thermal compound is properly applied to the device during assembly. Finally, T_a depends on the situation of use. Thus, R_{sa} determines the maximum resistance allowable when selecting a heat sink to maintain a particular T_j.

Once the required thermal resistance for the heat sink is determined, various and complicated methods can be employed to determine the needed material, volume, fin length, and airflow for the required heat sink. However, often, the easiest method of finding an adequate heat sink is perusing manufacturer product specification information and finding a heat sink of satisfactory thermal resistance.

One major factor affecting the thermal resistance of a heat sink is the airflow condition. A given heat sink can have a wide range of values for thermal resistance when used in different airflow conditions. This information can usually be found in manufacturer specifications.

Airflow in the context of heat sink performance is usually specified in linear feet per minute (LFM). However, the airflow produced by a fan is usually measured in cubic feet per minute (CFM). The convert from CFM to LFM, simply divide by the cross-sectional area (in square feet) of airflow.

In summary, when using an electronic component, dissipation of heat is necessary for reliability and long life. Knowing the characteristics of the electronic component and its conditions of use, a few calculations can determine what heat sink is needed to sufficiently cool the device.

3. Analysis and Results

This section puts the background knowledge explained in Section 2 in context with the Kinkajou projector. A new design for the beta prototype will be proposed.

3.1 Analysis Procedure

The procedure for analysis of each improvement-essential realm discussed in Section 1.2 is to relate the attributes of the system to the user needs. The proposed results build upon the alpha prototype of the Kinkajou.

3.1.1 Assess User Needs

The purpose of iterating in the design process is to bring the product closer to fulfillment of the needs of the user. A design that meets these needs is more likely to be successful as a product. Listed below are the basic user needs obtained from interviews with representatives of foundations that promote literacy in the developing world.

Effectual – In order to have an impact on literacy in the third world, the Kinkajou projector must be a practical and effective learning tool.

Portable – The Kinkajou projector should be portable to widen its area of impact.

Robust – Due to the generally hot, harsh, humid, wet, and dusty nature of the environments in which the Kinkajou projector is most likely to be employed, the device must be able to withstand these conditions and function reliably.

Inexpensive – For successful deployment of this educational tool in the third world, cost is a major concern. Customers and users must be able to see the economic benefit of using the Kinkajou projector over existing technology for the system to be accepted.

3.1.2 Establish Design Specifications

For the Kinkajou to strive to fulfill the user needs, each requisite should be considered carefully and broken down to actual product specifications that can be measured. This allows the designer to establish physical parameters for the product.

Effectual – The projected image should be bright enough to read in a dark room. The projector should be efficient and easy to use.

Portable – The device should be light and compact enough to be carried easily by one person.

Robust – Sensitive components of the Kinkajou system need to be sealed from dust. Sufficient convection for the thermal dissipation must still be allowed.

Inexpensive – The system should be cheap and easy to manufacture and assemble. This includes minimizing the number of parts.

3.1.3 Determine Improvement-Essential Realms

Because an alpha prototype has been made, we do not need start from scratch in the pursuit of fulfillment of the user needs for the Kinkajou. The basic idea and platform of the alpha prototype is the starting point for the next iteration. Section 1.2 discusses the weakness of parts of the Kinkajou alpha prototype. The following section includes detailed analysis of the improvement-essential realms.

3.2 Power Storage System

Because the power storage accounts for 20% of the system cost in the alpha prototype, its performance should be analyzed carefully. The battery should be cheap and easy to replace as it will likely fail before any other component.

3.2.1 Analysis of Power Storage System

Information about characteristics of various battery chemistries was found in *McGraw-Hill*'s <u>Handbook of Batteries</u>. Specific values for cells considered were taken from data sheets on the respective manufacturer's website. To perform necessary calculations, data was entered in to a Microsoft Excel spreadsheet on a PC running the Windows operating system.

Keeping in mind the user needs (effectual, portable, robust, and inexpensive), functional requirements for Kinkajou battery can be specified:

- **Type**: primary or secondary
- **Operating voltage**: 6-8V
- **Load current profile**: constant current discharge
- **Duty cycle**: continuous discharge
- **Operating temperature**: 40-45ºC
- **Service life**: 3-4 hours
- **Physical restraints**: less than 2.5 kg and 250 cc
- **Charge-discharge cycle**: cycling service, float charging possible
- **Maintenance and re-supply**: should be available
- **Cost**: less than $10 in bulk

When first considering a power system for the Kinkajou, it is useful to consider existing products with similar power constraints. As it turns out, camcorders have similar discharge load and service life requirements as the Kinkajou projector: 700-1000mA and 3-4 hours, respectively. In addition, portability is a concern for both devices. Most camcorder batteries on the market use Ni-MH or Li-ion cells. Perhaps the careful regulation of charging and discharging these expensive cells is not feasible in the third world. For the Kinkajou, maybe portability is not as major a concern as it is for camcorder. In any case, more in depth analysis follows.

To begin narrowing down the choices, data about the characteristics of the various battery chemistries were entered in to a spreadsheet for ease of comparison. A simple comparison of battery chemistries is shown in Table 2. Metal-air and alkaline MnO_2 cells were not considered for the product because these primary cells are not available in the locations where the Kinkajou projector is likely to be used.

Table 2: Comparison of General Characteristics of Battery Chemistries. The values for specific energy and energy density are based on drain rates optimized for highest capacity.

cell chemistry	Units	Zn-C	Alkaline MnO_2	Zinc-air	Pb-acid	Ni-Cd	Ni-MH	Li-ion
anode		Zn	Zn	Zn	Pb	Cd	MH	Li_xC_6
cathode		MnO_2	MnO_2	ambient air (O_2)	PbO_2	Ni oxide	Ni oxide	$Li_{(l-x)}CoO_2$
primary / secondary		primary	primary	primary	secondary	secondary	secondary	secondary
specific energy	Wh/kg	85	145	370	35	35	75	150
energy density	Wh/L	165	400	1300	70	100	240	400
calendar life	years		4.5		5.5	5	5	>5
cycle life	cycles		n/a	400 hr	225	450	450	1000
min operating temperature	ºC	-5	-20	5	-40	-20	-20	-20
max operating temperature	ºC	45	55	35	60	45	45	60
relative cost per Watt-hour (initial cost to user)		1	2		20	30	50	90

In the same spreadsheet, the Kinkajou system requirements were entered as shown in Table 3.

Table 3: System Requirements

$V_{forward}$	V	5.43
damage threshold	V	8.31
duration	h	3.00
current req	A	0.70
$V_{typical}$	V	6.84
LED power req	W	4.79
circuit power req	W	5.99

The LED forward voltage ($V_{forward}$), the damage-threshold voltage, the current requirement, and the typical LED operating voltage ($V_{typical}$) were all taken from the Luxeon™ 5W Star LED data sheet. A typical use cycle is three hours, as found from interviews with World Education, so the battery needs to last at least that long. The LED power requirement is calculated from $V_{typical}$ and the current requirement. The circuit power requirement accounts for an 80% efficient current regulation circuit.

Next, the battery characteristics were taken in to account. For each chemistry, the number of required cells was determined by dividing $V_{forward}$ by the cutoff voltage of a cell. This number was then rounded down to the next whole number. Rounding down ensures that during discharge the forward voltage of the LED will be reached before the cutoff voltage of the battery. Thus, the LED will stop emitting light before the cells are over-discharged. (The current regulator has a dropout voltage of only 0.2V.)

Knowing the number of cells arranged in series, one can then calculate the midpoint operating voltage of the battery (by multiplying the number of cells by the midpoint operating voltage of a single cell). Next, the current requirement of each cell is found by dividing the circuit power requirement by the battery midpoint operating voltage (to get the total current) and then dividing by the number of cells. Once the cell current requirement is determined, the current capacity needed of each cell can be found by multiplying the duration and the cell current requirement. Typically, cell capacities are rated for very low drain rates on commercial packaging. To ensure the cell can provide sufficient energy, the cell capacity for the actual drain rate should be taken in to account. Once a required capacity is determined, a specific cell size can by chosen. Figure 8 shows various cell chemistries and sizes considered. The results of the comparison are shown in Table 4.

Zn-C C cells	Pb-acid D cells	Ni-MH AA cells
		

Figure 8: Pictures of Various Cell Chemistries and Sizes.

Table 4: Battery Specifications for Various Chemistries. The "nominal cell capacity" is based on a C/10 drain rate and is used for the cost comparison. The "actual cell capacity" is based on the drain rate applied to each cell based on the system requirements listed in Table 3. This value is used for the battery life comparison.

cell chemistry		Zn-C	Pb-acid	Ni-Cd	Ni-MH	Li-ion
cell		C	D	AA	AA	IMP 30/103/103
number of cells		6	2	5	5	2
nominal cell capacity	Ah	1	2.5	1.3	1.2	2.29
cell volume	cc	33.10	62.15	8.06	8.06	31.80
actual cell capacity	Ah	0.60	2.00	0.65	0.60	2.29
cell weight	kg	0.04	0.18	0.02	0.02	0.06
battery life	hr	4.33	6.02	3.26	3.01	5.82
battery volume	cc	198.60	186.46	40.30	40.30	63.60
battery weight	kg	0.25	0.54	0.12	0.08	0.13
battery weight	lb	0.59	1.30	0.28	0.18	0.30
nominal battery capacity	Wh	43.20	45.00	39.00	36.00	34.81
relative initial cost		1.00	20.83	27.08	41.67	72.52

With the number of cells and cell type specified for each battery chemistry, the various batteries' size, weight, service life and relative initial cost can be easily calculated and compared. Results are shown below in Figures 9-12. The data in these figures are calculated for the proposed multi-cell battery determined in Table 4. The relative initial cost is based on data comparing all the chemistries' cost per Watt-hour from the Handbook of Batteries. The rated capacity at a C/10 discharge rate was used for this cost calculation.

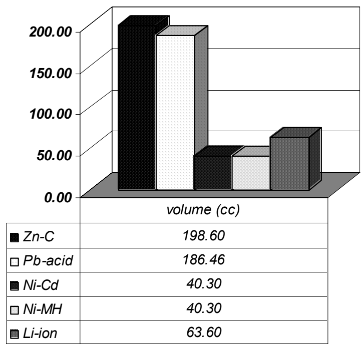

Figure 9: Battery Volume Comparison.

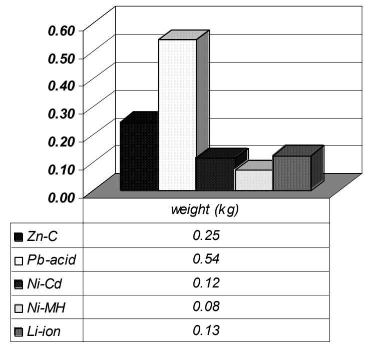

Figure 10: Battery Weight Comparison.

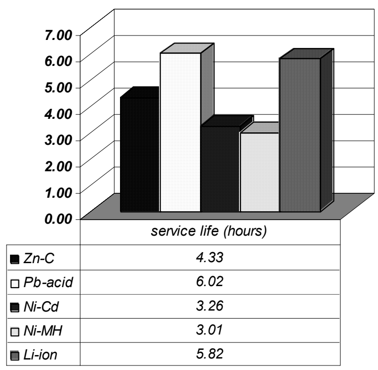

Figure 11: Service Life Comparison.

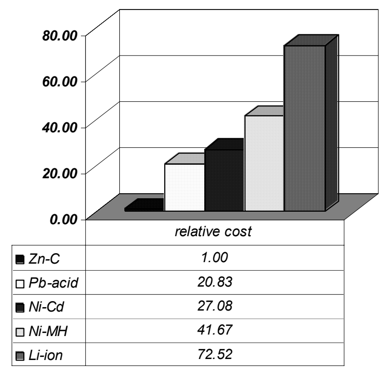

Figure 12: Relative Cost Comparison.

Cost is a complicated issue. While the primary zinc-carbon battery has the lowest initial cost, it is not the cheapest chemistry in the long run as shown in the Table 5 and Figure 12 below. Again, these data are calculated for the multi-cell battery specified in Table 4 for each chemistry. Table 5 takes in to account the cost and cycle life of the batteries and assumes readily available recharging methods.

Table 5: Advantage of Rechargeable Cells. This table shows how often the battery must be recharged (changed in the case of the primary Zn-C battery) as a function of duration. It also considers the higher initial cost of secondary batteries and calculates how long it takes to become economically beneficial ("break-even") using secondary cells taking cycle life and replacement cost in to account.

	Zn-C	Pb-acid		Ni-Cd		Ni-MH		Li-ion	
usage (h/day)	change after (days)	recharge after (days)	break-even (days)	recharge after (days)	break-even (days)	recharge after (days)	break-even (days)	recharge after (days)	break-even (days)
0.5	8.66	12.03	180	6.52	235	6.02	361	11.63	628
1	4.33	6.02	90	3.26	117	3.01	180	5.82	314
2	2.17	3.01	45	1.63	59	1.50	90	2.91	157
3	1.44	2.01	30	1.09	39	1.00	60	1.94	105
4	1.08	1.50	23	0.81	29	0.75	45	1.45	79

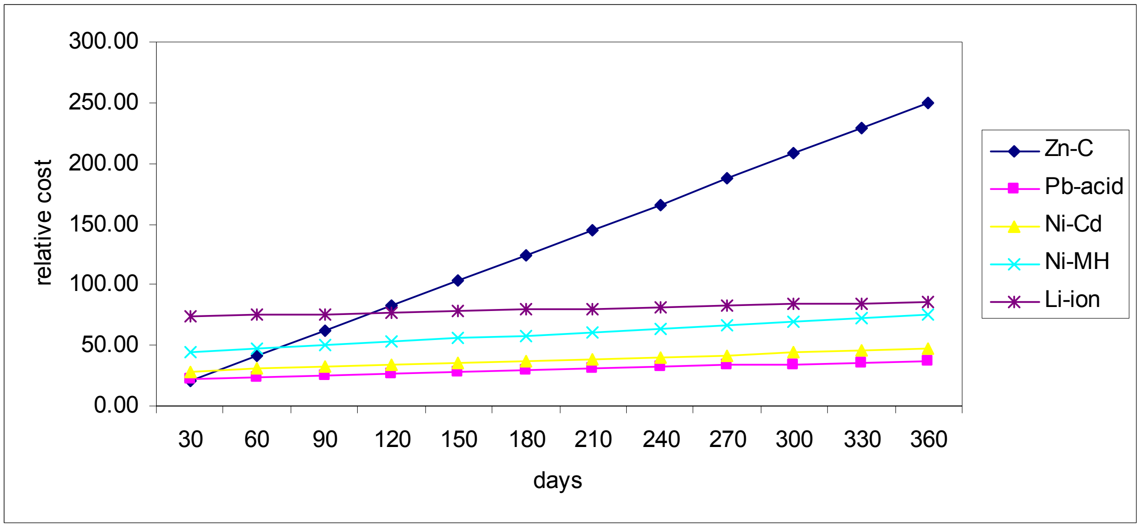

Figure 13: One-year Cost Comparison. This chart compares the cost of using each battery system over one year assuming three hours of use in the Kinkajou per day.

Bearing in mind the results in Figure 13, it can be seen that there is very considerable advantage to using secondary batteries for the Kinkajou application. With Pb-acid and Ni-Cd cells, the cost advantage begins in less than a month. For Ni-MH it takes about two months, and using Li-ion cells pays off after about 4 months. Since these break-even time frames are far less than the lifetime of the secondary cells, there is a distinct advantage for secondary technology. As can be seen in Figure 13, the one-year operating cost of using Pb-acid cells is an order of magnitude less than the cost of using primary Zn-C cells. The entire spreadsheet used for the above calculations is included in Appendix B.

3.2.2 Results: Power System Recommendation for Beta Prototype

The results of the battery chemistry comparison conducted above show that using lead-acid cells is the most economic way to fulfill the system requirements. It may be the heaviest system explored, but one pound is definitely in the realm of portable. When considering this small amount of mass, maybe a little inertia is not a bad thing at all: it will add stability and help prevent the projector form getting accidentally knocked off a table. The performance-cost ratio results work out nicely because lead-acid cells also have many other attractive characteristics for the Kinkajou system. Besides being inexpensive and portable, lead-acid cells are highly robust and efficient in terms of charging and general use. Lead-acid cells are also able to accommodate float service so the projector can be partially human-powered if the battery is running low.

Figure 14 pictures the Ni-MH battery of the alpha prototype and the proposed lead-acid battery which results in better performance at a lower cost.

Figure 14: Old and New Battery Packs. The new three-cell Lead-acid pack (foreground) costs less than a third as much and will provide more than twice the life of the six Ni-MH C cells (back) used in the Kinkajou alpha prototype.

A Molex connector (Figure 15) is used to connector the LED driver circuit to the power source on the outside of the projector. This flexibility allows the projector to be run off a AC adapter, a variety of batteries, or a generator.

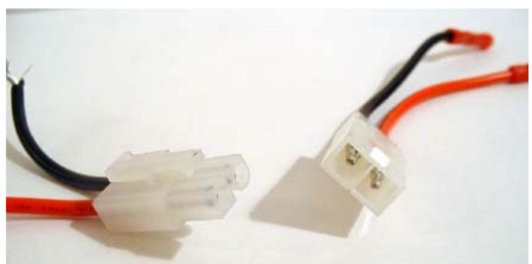

Figure 15: Molex Connector for the Input Power. This connection will allow multiple power sources to be tested with the beta prototype.

3.3 Power Circuit

After the power storage system is determined, the driver circuit which translates that power to the LED must be analyzed.

3.3.1 Analysis of Power Circuit

The LED driver circuit used for the alpha prototype of the Kinkajou projector is a linear circuit that provides a continuously variable regulated current. The circuit requires only 0.2V of headroom above $V_{forward}$ of the LED.

To better fit the user need, the circuit was modified to have the LED driven always at the maximum current, 700mA. The modified circuit is shown in Figure 16. This was done by replacing the 10kΩ potentiometer with a 10kΩ resistor and connecting two other leads, effectively fixing the 10kΩ pot at its maximum resistance in the circuit schematic (shown in Figure 17). The components were also more tightly packed on the board to facilitate a more compact design.

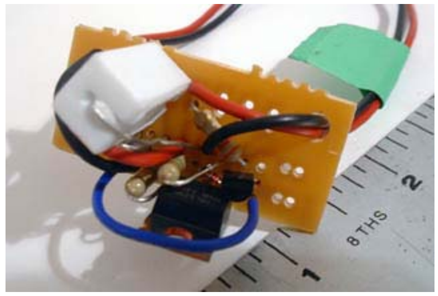

Figure 16: Modified Driver Circuit. Provides a regulated current of 700mA to the LED.

Investigation was done in to a simpler driver circuit for the Kinkajou, and the LM317 can be used as a current regulator. Dropout voltage is 2.5V. The circuit schematic is shown in Figure 18. This circuit has much fewer components. They sum to less than a third of the cost of the circuit used for the alpha prototype. The output load current is easily regulated. It is held at (1.5V ÷ R1). That means a 2W 1.7Ω resistor for 700mA.

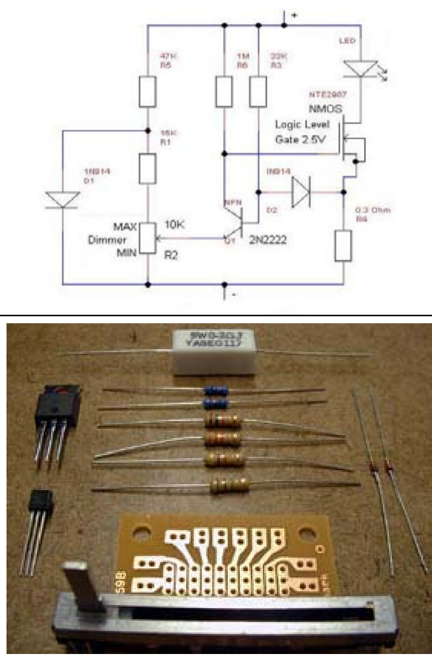

Figure 17: Alpha Prototype LED Driver Circuit Schematic and Parts.

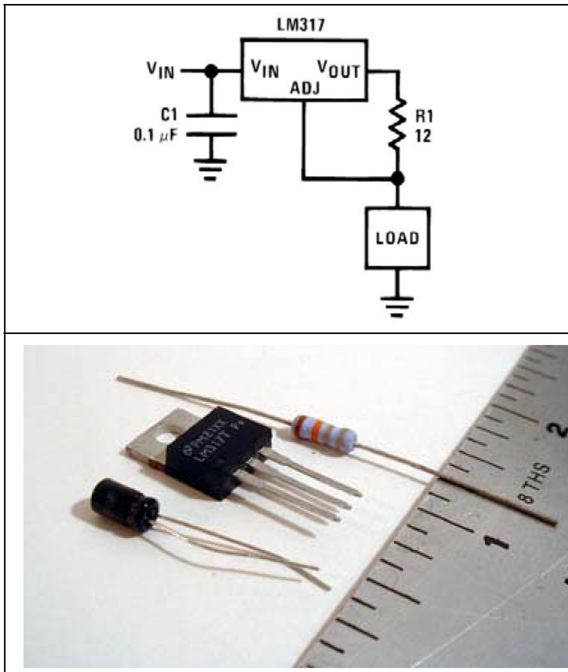

Figure 18: LM317 Current Regulator Circuit and Parts. Pictured resistor is 1.2Ω (1W). The schematic is reproduced from national.com.

Although the LM317 circuit is much simpler, it would require at least one more cell in the battery because of the 2.5V overhead. Using a voltage step-up DC-DC controller chip, such as the MAX1771, is another possibility, but this adds inefficiency and complexity and requires further analysis and testing.

3.3.2 Results: Improved Driver Circuit for Alpha Prototype

The modified LED driver circuit shown in Figure 9 was installed in the alpha prototype. It will be used in the beta prototype as well.

3.4 Thermal Design Considerations

Once the power usage of the LED is known, we have to figure out have to adequately cool the LED so that it works efficiently.

3.4.1 Analysis of Thermal Design

The data sheet for Luxeon™ 5 Watts Star LEDs specifies a thermal resistance of 11 ºC/W between the LED junction and the aluminum-core PCB. The PCB is mounted on the heat sink with thermal compound to eliminate air gaps and keep the thermal resistance of this interface negligible. Since the junction temperature must be kept below 135ºC to prevent damage to the LED, the aluminum-core PCB correspondingly must be kept below 80ºC when driving the LED at 5W, as shown in Equation 9.

$$135^{\circ}C - (5W \times 11^{\circ}C/W) = 80^{\circ}C \qquad \text{(Eq. 9)}$$

Equation 10 determines that 40ºC is the remaining temperature gradient to ambient air at 40ºC.

$$80^{\circ}C - 40^{\circ}C = 40^{\circ}C \qquad \text{(Eq. 10)}$$

Heat across this gradient must be dissipated by the heat sink. Equation 11 derives the required thermal resistance.

$$40^{\circ}C \div 5W = 8\ ^{\circ}C/W \qquad \text{(Eq. 11)}$$

This is a practical thermal resistance for a natural convection heat sink, so everything seems fine, but one must observe the performance of the LED at the absolute maximum rated junction temperature of 135ºC. Also, this accounts for no safety factor.

For comparison sake, a moderately sized forced convection heat sink is considered (Figure 19).

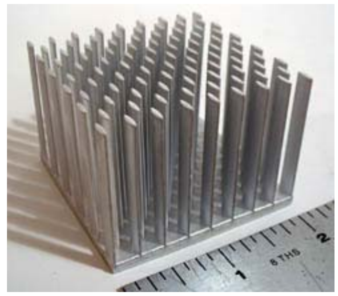

Figure 19: Proposed Heat Sink for Improved Performance of the Kinkajou. Model #HS4115 from Radian Heat Sinks.

With airflow of 200 LFM, its thermal resistance is 1ºC/W. The mounting plate temperature is calculated in Equation 12.

$$40^{\circ}C + (5W \times 1^{\circ}C/W) = 45^{\circ}C \qquad \text{(Eq. 12)}$$

The LED junction temperature can then be found with Equation 13.

$$45^{\circ}C + (5W \times 11^{\circ}C/W) = 100^{\circ}C. \qquad \text{(Eq. 13)}$$

The Light Output Characteristics figure found on page six of the Luxeon™ data sheet (Figure 20) shows the dependence of light output on junction temperature. At 100ºC the cyan LED is only operating at 80% of its efficiency when junction temperature is 25ºC. Extrapolating from the same graph, the LED only performs at 52% efficiency when junction temperature is 135ºC.

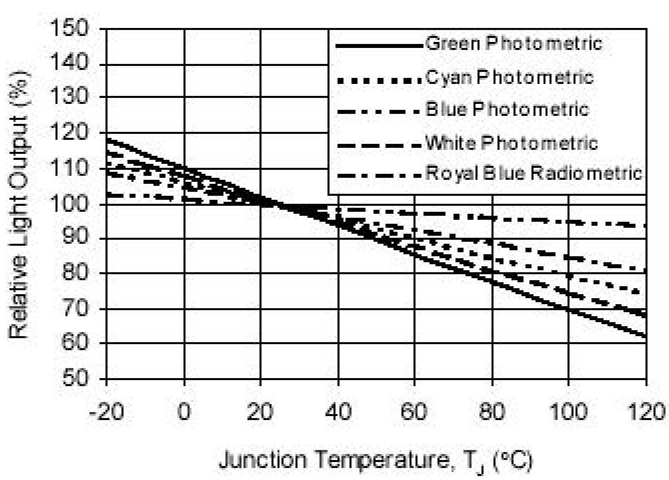

Figure 20: Light Output Characteristics. This figure is reproduced from Luxeon™ 5W Star Data Sheet.

Compared to running the LED with a junction temperature of 100ºC, running it at 135ºC "wastes" 1 – (52% ÷ 80%) = 35% of the input power because that much less light is output. With input power of 5W, wasted power is 35% × 5W = 1.75W. If a fan can provide 200 LFM of airflow with less than 1.75W, then the forced convection heat sink will be more effectual than the natural convection heat sink. Not only will it save power for the Kinkajou, but the LED will project the images brighter.

The 200 LFM airflow is needed over the cross-sectional area of the heat sink, which is 2.1" × 1.5" = 3.15 in^2 or 0.022 ft^2. This means airflow of about 200 LFM × 0.022 ft^2 = 4.38 CFM. A small 40mm fan (shown in Figure 21) used for some computer cooling applications can produce about 9 CFM at 12V and 110mA. Required power is therefore 1.32W. If the fan is run directly connected to the battery at 6V, the power will reduce to about 0.65W, sufficiently blowing 4.5 CFM of air.

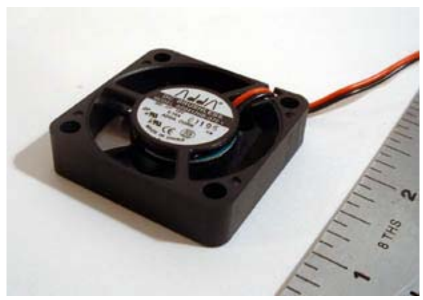

Figure 21: 40mm 12VDC 110mA Fan. This fan can blow up to 9 CFM at about 1 Watt

Besides a heat sink, a two-phase material was considered to keep the aluminum-core PCB a constant temperature until all the material melted. Elvax grade 150 wax has a melting point of 63ºC. Maintaining a PCB temperature of 63ºC running the LED at 5W translates to a junction temperature of 118ºC as shown in Equation 12.

$$63^{\circ}\text{C} + (5\text{W} \times 11^{\circ}\text{C/W}) = 118^{\circ}\text{C} \qquad \text{(Eq. 14)}$$

At this temperature, the LED outputs 75% of the light produced by a by running the junction temperature at 25ºC. The required amount of Elvax to maintain this constant temperature throughout a three-hour runtime at 5W is approximately 1.3 Liters, weighing almost three pounds. Also, the freezing point of Elvax grade 150 is 41ºC which may not be high enough to solidify the mass after use on a hot day. Considering size and reliability, the heat sink seems to be a better option than a two-phase material for heat dissipation for the Kinkajou.

3.4.2 Results: Thermal Design Recommendations for Beta Prototype

Use of a the proposed forced convection heat sink will increase the brightness of the LED by more than 50%, making the Kinkajou a more effective learning tool.

3.5 Microfilm Interface

Aside from aspects of the LED power and cooling systems, the Kinkajou projector has many subunits. The next of these systems to be analyzed is the microfilm interface.

3.5.1 Analysis of Microfilm Interface

The most significant change to the alpha prototype in the proposed design of the new Kinkajou projector is the microfilm interface system. The new design proposes use of standard 16mm microfilm spools (Figure 22) that can be found in any library. This means that the Kinkajou will be easily adaptable to a myriad of existing data. It also means there will be far fewer parts for the microfilm interface. VHS tapes have more than 100 parts, most of which are not needed for the Kinkajou projector.

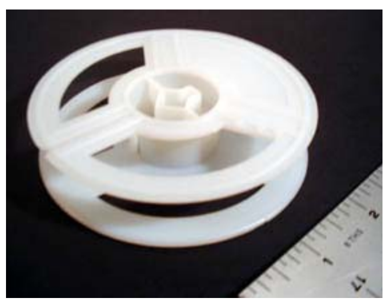

Figure 22: Standard 16mm Microfilm Spool.

The only disadvantage to using microfilm spools instead of cassettes is that a new system for quickly changing the material in the projector will be required. This drawback is far outweighed by the advantages of sealing the system and the microfilm from dust, especially since the customer, World Education, will only need to change the material every few years.

3.5.2 Results: Design Recommendations for Microfilm Interface of Beta Prototype

To create solid models of components for the new design, the CAD software, SolidWorks2000 installed on a PC running the Windows operating system, was used. The specifications of available parts such as belts, pulleys, and heat sink were found from the websites of McMaster-Carr, W.M. Berg, MSC Industrial Supply, and Radian Heat Sinks.

As seen in Figure 23, the microfilm spools will sit on the main base-plate of the system and, once the outer housing is fixed similar to the housing of the alpha prototype, the film will be sealed from environmental elements. It also will be sealed from the internal corridor which allows for convection of the heat sink.

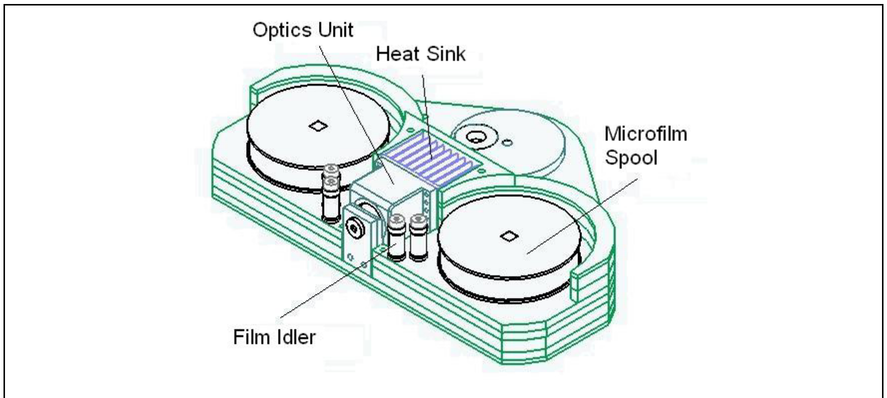

Figure 23: New Microfilm Interface. Microfilm on standard 16mm microfilm spools is placed in the system to be projected.

This compact arrangement of components is made possible by the elimination of the restraint of the cassette. Figure 24 shows the size compassion of the two designs.

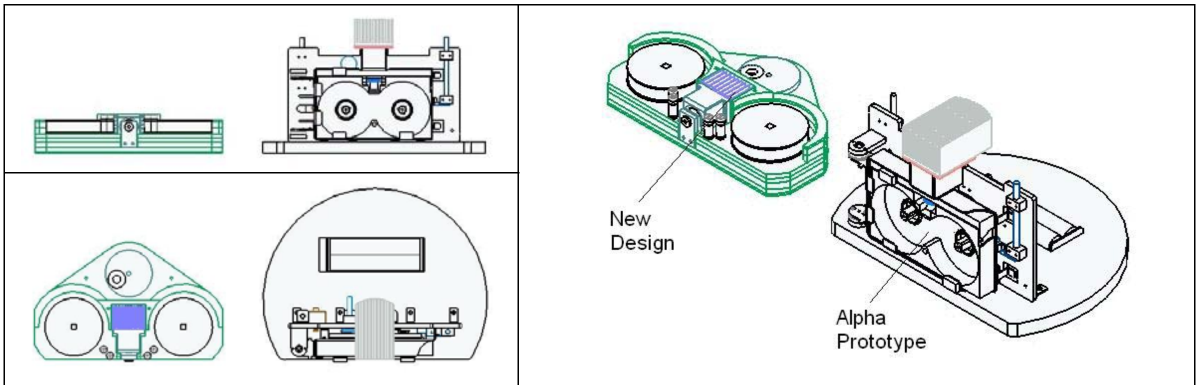

Figure 24: Size Comparison of Alpha Prototype and New Design. This figure shows top, front, and isometric views of the solid models of the new design and alpha prototype side by side.

3.6 Optics Unit

With the improvements of the proposed microfilm interface, an improved optics unit can be designed.

3.6.1 Analysis of Optics Unit

White LEDs have become available since the alpha prototype was made. Using a white LED for projection of microfilm increases the readability of the image and therefore increases the effectiveness of the Kinkajou as learning tool. Instructions for installation of an LED in the alpha prototype are given in Appendix C. Once installed, the white LED projects a much more readable image than the previous cyan LED.

Of course, a white LED will be used for the new prototype. Besides utilizing a white LED for a light source, there are other changes to the optics unit. To make the unit more efficient in terms of LED performance, a new heat sink was selected as detailed in section 3.4. Also, redesign of the optics unit parts eliminated the need for a mounting plate, reducing the thermal resistance between the LED and ambient air.

3.6.2 Results: Design Recommendations for Optics Unit of Beta Prototype

As well as making the Kinkajou more efficient, the elimination of the mounting plate makes manufacture and assembly much simpler, and therefore cheaper. Figure 25 shows an exploded view of the new optics unit design. Because of the linear arrangement, no mirror is needed, and one can see that assembly is much easier as there is no mounting plate. This reduces the complexity of assembly and eliminates the need for application of thermal compound in multiple places.

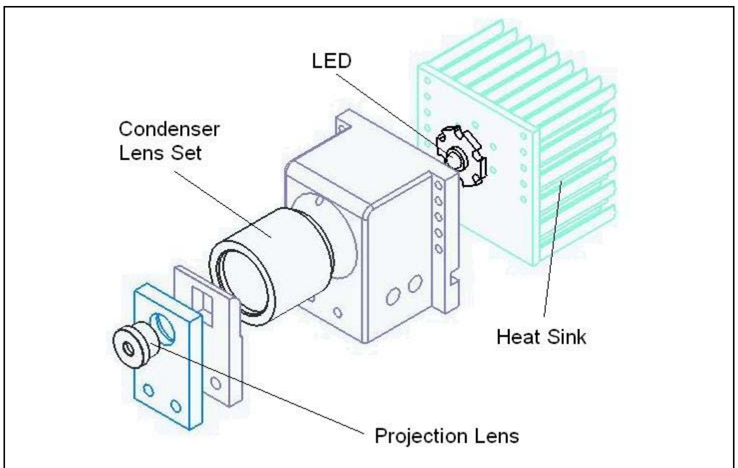

Figure 25: Exploded View of Proposed Optics Unit.

The piece in which the projection lens is held will be two pieces, and a retaining ring will constrain the projection lens from coming out. Appendix D details the assembly and arrangement.

3.7 Indexing System

Once the proposed design of the optics unit is determined, the indexing system can also be optimized.

3.7.1 Analysis of Indexing System

With the new microfilm interface, there is a possibility of a simpler, more reliable indexing system than the one used in the alpha prototype. The basic idea for the first iteration in redesigning the indexing system was to use a gear train. The design is explained in depth in Appendix E.

Even though the gear-train concept is more reliable than the o-ring and pulleys from the alpha prototype, it has drawbacks. These include the delay that occurs when reversing direction of indexing. Also, the system requires many parts, and it impinges upon force of a spring to provide friction. There may be little room for error for this quantity.

3.7.2 Results: Design Recommendations for Indexing System of Beta Prototype

To overcome the uncertainties associated with the above proposed solution, another concept was considered for indexing. The use of two roller-locking clutches, three pulleys, and a belt was proposed by Professor Woodie Flowers during a design review. In roller-locking clutches, shown in Figure 26, the inner race freely rolls with respect to the outer casing when turned one way, and it transmits torque to the outer casing when turned the other direction. The feature is used to provide bidirectional indexing capability. A timing belt was chosen for increased reliability and robustness. Figure 27 shows the belt with appropriate timing belt pulleys.

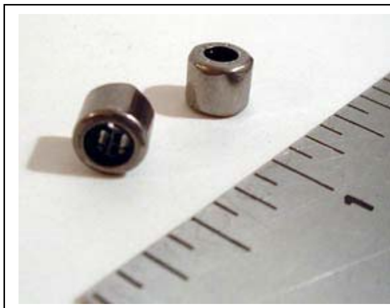

Figure 26: Roller-Locking Clutches. For 1/8" diameter shafts.

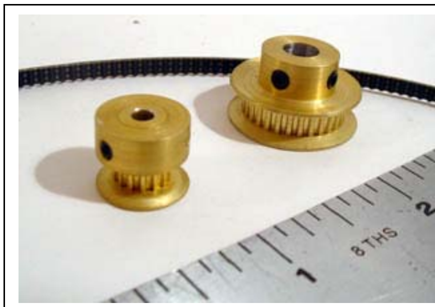

Figure 27: Timing Belt and Timing-Belt Pulleys.

Figure 29 shows how the indexing system is integrated into the Kinkajou. The clutches are oriented such that as the belt advances clockwise, the right-hand clutch transmits torques to the right-hand spool and the left-hand clutch turns freely.

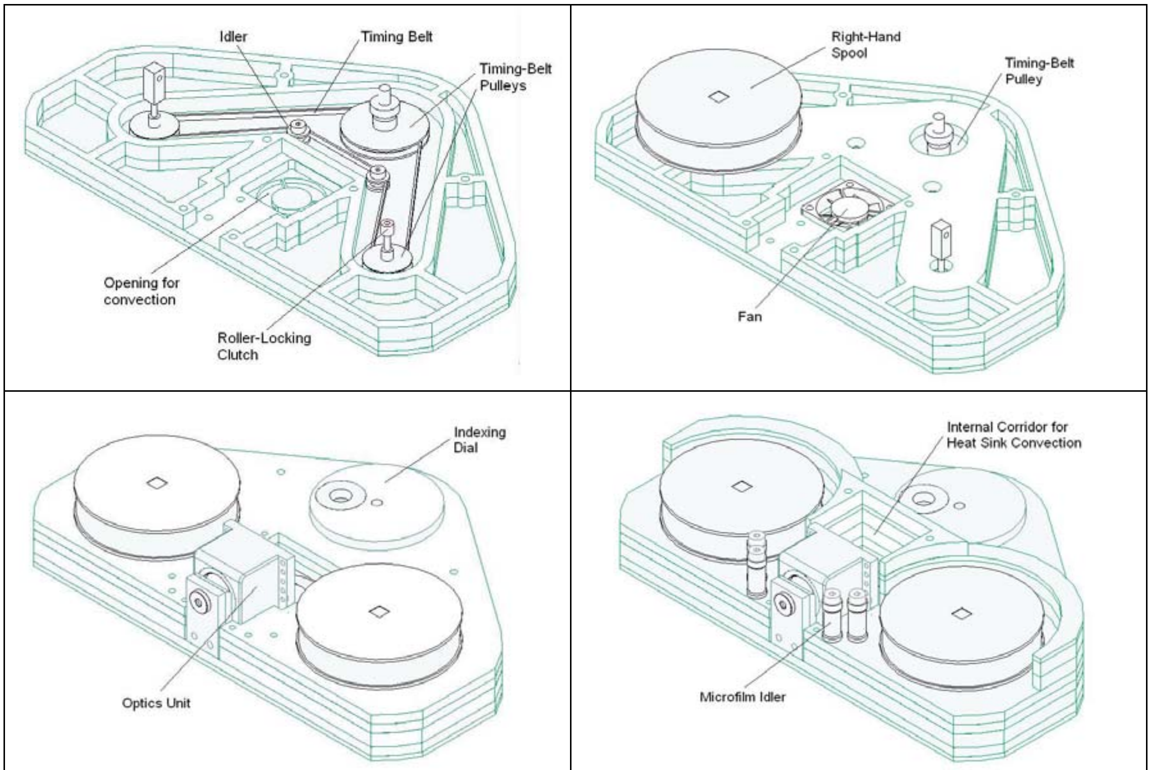

Figure 29: Proposed Indexing System.

Figure 36 in Appendix E shows the exploded view of the indexing axles. Telfon bearings, shown in Figure 30, are used for the shafts on which the pulleys are mounted. These bearings provide rotational resistance necessary for maintaining tension on the microfilm. This tension keeps the microfilm film image flat, assuring the entire projected image will be in focus.

Figure 30: Telfon Bearings for 1/8" Shafts.

3.8 System Architecture

To put all of the Kinkajou subsystems together in a way which better fulfills the user needs, a new system architecture design is proposed.

3.8.1 Analysis of System Architecture

The internal components are closely packed in the proposed design, as seen above in Figure 29. The alpha prototype of the Kinkajou wastes a lot of space, but the new design is much more compact. For the new design, the internal components will fit inside a stack of plates. The plates can be made using a water-jet cutter, and the prototype can be assembled layer by layer. Cavities formed by stacking the plates will seal the internal components from dust. The top-right picture of Figure 29 shows the indexing system completely isolated. Also, airflow through the internal corridor for the heat sink does not affect any other parts of the Kinkajou. The indexing dial will be fixed to its shaft after the outer housing is attached to the stack of plate. The housing will rest above the heat sink corridor, sealing the microfilm compartment from the airflow. Of course, holes in the housing above the heat sink will allow airflow.

3.8.2 Results: Design Recommendations for System Architecture of Beta Prototype

With the new design improvements to the Kinkajou projector, 53 parts will be needed. This is roughly the same as the alpha prototype disregarding the more than 100 parts in the VHS cassette. The parts for the beta prototype will be easier to manufacture. 25 fasteners will be used, as opposed to more than 70 in the alpha prototype. These results translate to less time required for the fabrication and assembly process.

3.9 Documentation

As the success of the Kinkajou project depends of the hard work of social (rather than capital) entrepreneurs, all calculation, experimental, and design work should be carefully documented so that all necessary information can be easily passed on to students who want to help improve the projector. The online collaboration tools provided by thinkcycle.org are very useful for this effort. Previous manufacture and assembly should be repeatable. Future design changes are made much easier with an easily interpretable and adjustable solid model and documented design process.

3.9.1 Apparatus for Implementing new Documentation Practice

The tools and webspace provided by thinkcycle.org were used to implement an improved documentation practice for the Kinkajou. Figure 33 shows a screenshot of the Kinkajou "thinkspace."

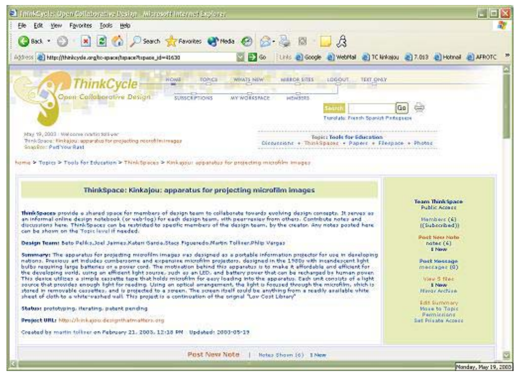

Figure 31: Kinkajou Thinkspace on ThinkCycle.org.

The first step in re-designing the Kinkajou was evaluating the original design. Important information about the specifications for the alpha prototype was often scattered or missing.

For the new design, the basis for each design decision was documented. The final result was recorded in a clear and usable way to facilitate future improvements.

3.9.2 Results: Improved Documentation Practice for Kinkajou Project

The Kinkajou thinkspace on thinkcycle.org includes all necessary information needed to build an alpha or beta prototype. All part drawings are on the site. The .dxf files needed for the parts made on the water-jet are included.

Also, background for the design of the Kinkajou is archived on the site. This includes prior art in the field of microfilm/fiche projectors for the developing world.; information about the alpha prototype made in 2.009; and finally information to be used used for making the new design.

4. Discussion

There are many proposed changes in the design of the Kinkajou projector for the beta prototype.

The specified power system, three lead-acid D cells, is a thrid the expense of the six Nickel-Metal Hydride C cells used in the alpha prototype. It provides six hours of service life -- twice that of the alpha prototype.

The elimination of the dimming feature with the driver-circuit modification makes the Kinkajou more user-friendly.

Selection of a new heat sink and use of forced convection increases the brightness of the LED by more than 50%, making the Kinkajou a more effective learning tool.

Eliminating need for a VHS cassette, the proposed microfilm interface uses standard 16mm microfilm spools. This system will allow the projector to be sealed from dust. Fewer parts are required, making manufacture and assembly easier. Information contained in readily available format will be able to be displayed using the Kinkajou. These changes will increase the robustness and flexibility of the system.

The proposed microfilm interface allows for a linear optics setup. The new optics unit therefore will not include a mirror. Other design changes to the unit include the reduction in thermal resistance between the LED and heat sink and improved ease of assembly. A retaining ring will be added to the projection lens, fixing it in the unit, preventing loss or damage of the lens, while still allowing focus adjustment. These changes will increase the efficiency and robustness of the system, while reducing cost.

The linear optics arrangement allows the overall system to be much smaller and compact. The proposed beta prototype will be about 200 cubic inches, less than 30% the size of the alpha prototype. This will increase the portability of the Kinkajou.

A new indexing system was designed. As opposed to the alpha prototype, no motor will be used. Roller-locking clutches will replace a swinging-gear arrangement for bi-directional capability. A timing belt and timing-belt pulleys will replace an o-ring and pulleys. These changes will increase the reliability and robustness of the indexing system. Also, time to machine the parts of the beta prototype will be 25% shorter, reducing cost.

The internal components will be sealed from dust by the proposed design. Fewer parts and less material will be used, and assembly of the projector will be easier.

With the new project documentation process on thinkcycle.org, it is possible for anyone with internet access to obtain detailed background and design information about the Kinkajou. They can contribute to the project by posting comments or reviews on the webpage.

5. Conclusions and Recommendations

The Kinkajou beta prototype specified by the proposed design described in this paper is effectual, portable, robust, and inexpensive. The resulting product will be an improvement over the starting point of the alpha prototype. The new Kinkajou will be taken to Mali in Summer 2003. There, proof of concept as a learning tool can be conducted for the projector. The reactions of teachers and students to the Kinkajou can then be translated in to more design improvements.

5.1 Power System Recommendations

Battery

The battery specified for the beta prototype by this paper is a good choice; however, a better solution may be available. While working on the comparison of various battery chemistries, I had the opportunity to hear Dr. David Irvine-Halliday, founder and president of Light Up the World (LUTW), speak. LUTW is an organization dedicated to the goal of world literacy. They work towards this goal by designing affordable solid-state lighting to people in the developing world. Obviously, there are many parallels between the Kinkajou and the work of LUTW. LUTW has "lit" hundreds of villages. The villages which have lamps powered by pedal generators or solar chargers use readily available 7 Ah 12V lead-acid batteries (Figure 32) for power storage. These batteries are very robust and can be found almost anywhere in the world.

Figure 32: 12V 7Ah Lead-acid Battery. These batteries can be found almost everywhere in the world and are relatively inexpensive when compared to other rechargeable batteries. The six Ni-MH C cells used for the alpha prototype are show on the right.

Making the Kinkajou able to tolerate the use of a 12V power source is a wise choice. This would allow for easier distribution of the product as its power requirement could be filled by batteries that are readily available to the users. If a user did not already have a power source or if a battery failed, then another could be found easily. The cost of the 7Ah battery is slightly less than 3 D cells, so the cost benefit of the lead-acid chemistry shown in section 3.2 still holds true. The capacity is about the same.

Driver Circuit

The LED driver circuit should include a feature to protect the battery against over-discharge once the cutoff voltage is reached. The user may not realize that battery has to be disconnected or turned off once the LED goes off.

Thermal Considerations

If the fan turns out to be unreliable in the field because of dust, perhaps a peltier cooling device placed between the aluminum-core PCB of the LED and the heat sink would provide for sufficient heat dissipation with natural convection.

5.2 System Architecture Recommendations

The aim of this work was to make the projector cheaply manufacturable while in the prototyping stage of the product design process. Cheap manufacture of the proposed beta prototype relies heavily on use of complex manufacturing processes like water-jetting with an OMAX machine. The goal of making the projector very cheap and able to be made from materials local to where the Kinkajou will be used is an area that was not explored. This should be the next step after the proof of concept of the Kinkajou.

Acknowledgments

Thanks are due to the other members of the Kinkajou team for 2.009 Fall 2002. Without all their hard work, I would not have had a starting point for my thesis. They are Teresa Baker, Sarah Daigh, Alex DeFeo, Katheen Dobson, Kateri Garcia, Leonardo Hochberg, Joel Jaimes, Cat Kelly, Tulika Khemani, Monica Krishnan, Joshua Ornstein, Beto Peliks, Ray Speth, Eric Varady, and Philip Vargas.

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I want to thank the Public Service Center Staff and MIT IDEAS Competition staff for allowing us to work on the Kinkajou.

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Finally, this paper could not have happened without the help and support of my advisor, Professor Shao-Horn. Other mentors include Dr. Jim Bales, Prof. Woodie Flowers and Prof. Dave Wallace.

Without all these people, the Kinkajou would not be the award-winning reality it is.

Appendix A: Background on Batteries

This appendix explains the basic characteristics of the various battery chemistries considered for use in the Kinkajou, and how to compare them.

1. Battery System Selection

The following are factors to keep in mind when matching system requirements with an appropriate battery chemistry and configuration:

- **Type of battery**: primary, secondary
- **System requirements**: minimum and maximum permissible voltage
- **Battery**: nominal voltage, operating voltage, discharge curve, voltage regulation
- **Load current and profile**: constant current, constant resistance, constant power, variable, pulsed
- **Duty cycle**: continuous or intermittent, if intermittent, schedule
- **Temperature requirements**: minimum and maximum operating temperatures
- **Service life**: the amount of time a battery can provide power
- **Shelf life**: the amount of time charge can be retained in an unused battery
- **Physical restraints**: size, form, weight, interface
- **Charge-discharge cycle** (if secondary): float or cycling life, availability and characteristics of charging source, charging efficiency
- **Environmental conditions**: vibration, acceleration, pressure, humidity
- **Safety and reliability**: high temperature operation, environmental friendliness
- **Maintenance and re-supply**: ease of battery distribution acquisition, replacement, disposal
- **Cost**: initial cost, life cycle cost

2. Factors Affecting Battery Performance

The following is a list of factors that affect the performance of every cell, regardless of chemistry or configuration:

- **Drain rate**: Cells are made to provide a certain current for a certain length of time. This is a cell's capacity specification. Draining the cell at a higher current than rated will lead to a reduction in service life, or capacity of that cell. At higher drain rates, a cell discharges at a lower voltage and the discharge curve is more pronounced. These effects are due to internal resistance losses and polarization effects.
- **Mode of discharge**: A constant-resistance discharge leads to shortest service life because initial current and voltage is high. Discharging with constant power gives longest life because current is lowest throughout discharge. Constant current discharge provides intermediate service life.

- **Temperature**: Discharging at lower temperatures generally reduces the capacity of a cell. The best operating range for most cells is 20-40ºC. At higher temperatures, internal resistance decreases; therefore, discharge voltage and cell capacity increase. However, chemical activity, and therefore self-discharge, is increased, so higher temperatures may lead to a net loss in capacity. It should be noted that draining a cell at a high rate can increase the temperature of the cell, making it susceptible it to these high-temperature effects.
- **Duty cycle**: Intermittent discharge of a cell can lead to greater capacity than continuous discharge of the same cell. This results from some voltage recovery during idle periods. However, a load profile that includes sharp pulses can reduce capacity when compared to continuous discharge.
- **Voltage regulation**: If a system is limited to a 15% voltage spread, then a flat discharge curve will lead to longer life. If a cell's discharge profile is not flat, voltage regulation (through circuitry) can allow cells to be discharged to lower cutoff voltages, and service life increases. It should be noted that discharging multi-cell series to low cutoff voltages can be dangerous as one poor cell may be driven in to voltage reversal and rupture. If voltage regulation is used, the cells pay, in energy, the price of the inefficiency of the circuit. Careful consideration should be done as to whether regulation will increase the service life of a battery.
- **Charging**: If a battery is to be used in conjunction with another power source, the battery and equipment must be able to tolerate the charging voltage. If primary cells are used, diodes must be placed in the circuit to prevent unsafely charging the cells. In all cases of designing and selecting a battery system for a requirement, the proper orientation of the cells should be clearly marked.
- **Design**: Cells can be configured to optimize various characteristics. For example, spirally wound cells are optimized for high-rate capability, as this configuration allows for large electrode (reaction) area, and internal resistance is minimized. These properties enhance the current density of the cell at the expense of capacity. Generally, secondary and high-rate primary cells are spirally wound. Cells can also be optimized for long service life. For example, bobbin-type cells contain maximum quantities of active material and perform best at relatively low discharge rates.

The following sections explain the main advantages and shortcomings associated with various battery chemistries.

3. Primary Cells

3.1 Zinc-Carbon (Leclanche) Cells

This cell chemistry has been in use for over a century. While use of Zinc-carbon cells in the United States is declining due to the superiority of other available battery chemistries, the global market for the cells is growing as low-drain applications, such as flashlights, become prevalent in the developing world.

Advantages

- Low cost
- Large variety of configurations available
- Wide distribution and availability

Drawbacks

- Low energy density
- Poor high drain performance
- Steep discharge profile
- Poor shelf life

Comments

- Capacity is greatly affected by drain rate.

3.2 Alkaline Manganese Dioxide Cells

This battery chemistry dominates the portable battery market in the US. For a slightly higher cost, it outperforms its competitor, the zinc-carbon cell, in every category.

Advantages

- Higher energy density than Zn-C
- Better high-rate performance
- Longer shelf life

Drawbacks

- Higher initial cost

Comments

- The new high-rate optimized cells have impressive performance. For example, AA cells have 33% more capacity than AA-size rechargeable Ni-MH cells.

3.3 Metal-air Cells

These cells use ambient air for the cathode, and therefore have very high energy density. There is a tradeoff between environmental tolerance and power capability: higher power capability requires more exposure of the anode to the air, and therefore the environment.

Advantages

- Very high energy density
- Very flat discharge profile
- Long shelf life if sealed
- Low cost

Drawbacks

- Susceptible to harmful environmental conditions such as humidity

Comments

- Zinc-air button cells are the only widely available metal-air cells at this time. This tends to weigh heavily in perception of zinc-air cell performance, but it is the button configuration that limits the power capacity of the cell. Cells can be optimized for high drain rates by sufficiently exposing the anode to air, allowing high power capability. For example, a high-rate primary zinc-air battery of a similar volume to a Li-ion camcorder battery can have up to 6 times the capacity.

Also, other metal-air batteries can be comparable in life to lead-acid batteries at one quarter the weight and volume.
- Zinc-air cells can be designed to be electrically or mechanically (by anode replacement) rechargeable.

4 Secondary Cells

When multi-cell secondary batteries are used, each cell must have the same capacity. If this is not the case, the cell with maximum capacity will determine the charge duration, and the cell with the minimum capacity will determine the discharge duration. Also, appropriate guards should be in place to prevent abuse during charging for certain types of secondary batteries. For example, voltage and current control and temperature sensing are necessary to charge Ni-Cd or Ni-MH cells faster than the C/20 rate. Also, some batteries, like Li-ion require strict discharge control to protect the cells. In all cases, precaution must be taken to avoid over-charging or over-discharging.

4.1 Lead-acid Cells

Pb-acid batteries account for 40% of all (primary and secondary) battery sales due to the chemistry's vast array of applications. Their most common use is engine starting, vehicle lighting, and engine ignition (SLI). The batteries provide good performance and life characteristics at a low cost.

Advantages
- Low cost secondary battery
- Available globally in many configurations
- Good high-rate performance
- Good charging turnaround efficiency (70%)
- High cell voltage (2.0V)
- Good float service
- Easy state-of-charge indication
- Good charge retention for intermittent charge

Drawbacks
- Relatively low cycle life
- Limited energy density
- Small sizes (<500mAhr) not available

Comments
- Precaution must be taken to prevent over-discharge.

4.2 Nickel-Cadmium Cells

Ni-Cd cells are used in a wide variety of applications from lightweight portable power to high-capacity and standby power.

Advantages
- Long cycle life
- Long shelf life

Drawbacks
- Memory effect (voltage depression)
- Higher cost than Pb-acid
- Low capacity

4.3 Nickel-Metal Hydride Cells

In Ni-MH cells, hydrogen replaces the Cadmium used in a corresponding Ni-Cd cells.

Advantages
- Higher capacity than Ni-Cd
- Long cycle life
- Long shelf life

Drawbacks
- High-rate performance worse than Ni-Cd
- Moderate memory effect
- Requires protective circuitry
- Higher cost (negative electrodes)

4.4 Lithium-ion Cells

Li-ion cells are used widely in consumer electronics and military applications.

Advantages
- Long cycle life
- Long shelf life
- High-rate/power capability
- High specific energy and energy density
- No memory effect

Drawbacks
- Moderate initial cost
- Degrades at high temperatures
- Requires protective circuitry

4.5 Rechargeable Zinc / Alkaline-Manganese Dioxide Batteries

These cells are corollaries to the primary alkaline MnO_2 cells.

Advantages
- Low cost rechargeable
- Long shelf life
- No memory effect
- Higher capacity

Drawbacks
- Limited cycle life
- Limited drain-rate capability

Appendix B: Assessment of Various Battery Chemistries for the Kinkajou

The following table contains the Microsoft Excel spreadsheet used to compare various battery chemistries for the Kinkajou. Parameters for each chemistry were entered. Then the system requirements were input. Finally, the best arrangement of cells was determined for each chemistry, and the resulting choices were assessed.

Table 6: Spreadsheet Comparing Various Battery Chemistries.

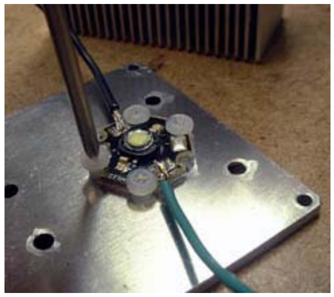
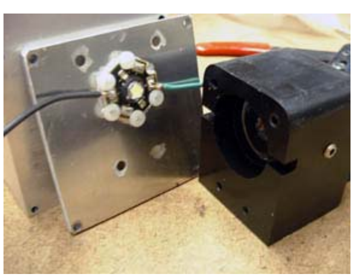
cell chemistry		Zn-C	Lead-acid	Ni-Cd	Ni-MH	Li-ion
	units					
anode		Zn	Pb	Cd	MH	Li_XC_6
cathode		MnO_2	PbO_2	Ni oxide	Ni oxide	$Li_{(1-x)}CoO_2$
primary / secondary		primary	secondary	secondary	secondary	secondary
specific energy	Wh/kg	85	35	35	75	150
energy density	Wh/L	165	70	100	240	400
avg shelf life (charge retention at 20 ºC) (years)	years	4.5	0.625	0.625	0.375	.875
avg calendar life (years)	years	n/a	5.5	5	5	>5
avg cycle life (cycles)	cycles		225	450	450	1000
min operating temperature	ºC	-5	-40	-20	-20	-20
max operating temperature	ºC	45	60	45	45	60
relative cost per Watt-hour (initial cost to user)		1	20	30	50	90
open circuit voltage	V	1.5	2.1	1.3	1.3	4.2
cutoff voltage	V	0.9	1.75	1	1	2.5
midpoint voltage	V	1.2	2	1.2	1.2	3.8
system requirements						
$V_{forward}$	V	5.43				
damage threshold	V	8.31				
duration	h	3.00				
current req	A	0.70				
$V_{typical}$	V	6.84				
LED power req	W	4.79				
circuit power req	W	5.99				
battery properties						
number of cells		6.03	3.10	5.43	5.43	2.17
number of cells		6	3	5	5	2

maximum voltage of battery	V	9.00	6.30	6.50	6.50	8.40
midpoint voltage of battery	V	7.20	6.00	6.00	6.00	7.60
cutoff voltage of battery	V	5.40	5.25	5.00	5.00	5.00
current drain per cell	A	0.14	0.33	0.20	0.20	0.39
current capacity needed per cell	Ah	0.42	1.00	0.60	0.60	1.18
best cell to fulfill above needs						
cell chemistry		Zn-C	Pb-acid	Ni-Cd	Ni-MH	Li-ion
cell		C	D	AA	AA	IMP 30/103/103
nominal capacity per cell	Ah	1	2.5	1.3	1.2	2.29
cell volume	cc	33.10	62.15	8.06	8.06	31.80
actual capacity per cell	Ah	0.60	2.00	0.65	0.60	2.29
cell weight	kg	0.04	0.18	0.02	0.02	0.06
battery life	hr	4.33	6.02	3.26	3.01	5.82
battery volume	cc	198.60	186.46	40.30	40.30	63.60
battery weight	kg	0.25	0.54	0.12	0.08	0.13
battery weight	lb	0.59	1.30	0.28	0.18	0.30
nominal battery capacity	Wh	43.20	45.00	39.00	36.00	34.81
relative initial cost		43.20	900.00	1170.00	1800.00	3132.72
usage (h/day)		change after (days)	charge after (days)			
0.5		8.66	12.03	6.52	6.02	11.63
1		4.33	6.02	3.26	3.01	5.82
2		2.17	3.01	1.63	1.50	2.91
3		1.44	2.01	1.09	1.00	1.94
4		1.08	1.50	0.81	0.75	1.45
days used		relative cost	relative cost			
30		897.75	959.85	1241.82	1919.70	3181.20
60		1795.50	1019.70	1313.64	2039.40	3229.68
90		2693.25	1079.55	1385.46	2159.10	3278.16
120		3591.00	1139.40	1457.28	2278.80	3326.63
150		4488.75	1199.25	1529.10	2398.50	3375.11
180		5386.50	1259.10	1600.92	2518.20	3423.59
210		6284.25	1318.95	1672.74	2637.90	3472.07
240		7182.00	1378.80	1744.56	2757.60	3520.55
270		8079.75	1438.65	1816.38	2877.30	3569.03
300		8977.50	1498.50	1888.20	2997.00	3617.51
330		9875.25	1558.35	1960.02	3116.70	3665.98
360		10773.00	1618.20	2031.84	3236.40	3714.46
1825		54613.13	4540.88	5539.05	9081.75	6081.83

Appendix C: Installation of LED in Alpha Prototype

The LED of the alpha prototype was changed to a white LED in order to increase the readability of the projected image and the effectiveness of the Kinkajou as a learning tool.

Table 7: Installing LED. This table shows the necessary steps for installing an LED in the alpha prototype of the Kinkajou projector.	
	Detach Aluminum door from cassette holder by unscrewing 3 hex screws with 5/64" hex wrench.
 	Take off housing by removing 17 flat head screws with 5/64"hex wrench. Remove optics unit from base plate.
	Dismount heat sink from 1/8" aluminum mounting plate by removing 4 machine screws with flat head screwdriver.
	Unfasten 1/8" aluminum mounting plate from black Delrin optics unit by removing 4 flat head screws using 3/32" hex wrench.

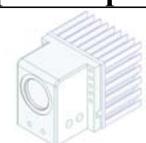
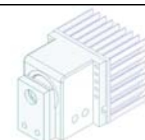
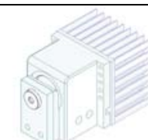
<table>
<tr><td colspan="2"></td><td>Unfix LED form mounting plate by removing 6 plastic machine screws using #2 philips head screwdriver.</td></tr>
<tr><td colspan="2"></td><td>Solder leads onto PCB of new (white LED).</td></tr>
<tr><td colspan="2"></td><td>Clean surfaces contact surface of LED PCB, aluminum mounting plate, and heat sink with isopropyl alcohol.</td></tr>
<tr><td></td><td></td><td>Apply thermal compound to contact surface of LED PCB. Spread compound evenly over surface.</td></tr>
<tr><td></td><td></td><td>Fix LED to mounting plate. Reattach mounting plate to black Delrin optics units.</td></tr>
</table>

<table>
<tr><td colspan="2"></td><td>Apply thermal compound and, using a credit card, spread evenly on cleaned contact surfaces of mounting plate and heat sink.</td></tr>
<tr><td></td><td></td><td>Reattach heat sink to mounting plate and fix optics unit to base plate. Refasten housing and aluminum cassette door to system.</td></tr>
</table>

Appendix D: Details of Proposed Design of Optics Unit for Beta Prototype

This appendix shows details of the proposed design for the optics unit for the beta prototype. Table 8 details the assembly process.

Table 8: Assembly Steps for Proposed Optics Unit.

				
Mount the LED to the heat sink with six plastic 4-40 thread machine screws.	Fix condenser lens set in the Delrin condenser-lens holder using with an 8-32 thread set screw.	Attach heat sink to Delrin condenser-lens holder using six to eight 4-40 thread machine screws.	Attach the two pieces of the projection-lens holder to the condenser-lens holder with two 8-32 thread machine screws.	Finally, screw in the projection lens into its holder.

The projection lens casing is threaded to facilitate focus adjustment. The lens is simply turned to adjust its axial position relative to the microfilm. The piece in which the lens is held will be two pieces, and a retaining ring will be fixed to the projection lens casing. Figure 33 shows the arrangement.

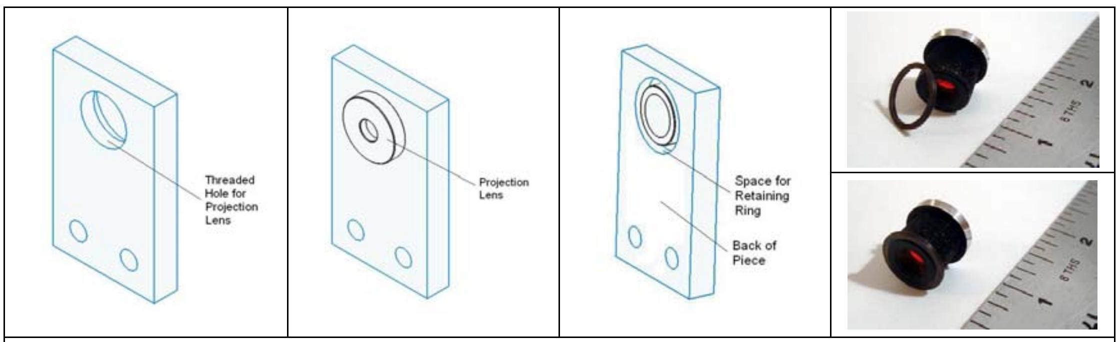


Figure 33: Retaining Ring Setup for the Projection Lens.

Appendix E: Details of Indexing System Design Iteration

This appendix describes the details of the gear-train indexing system proposed as an improvement over the indexing system of the alpha prototype. This design will not be used for the beta prototype because the indexing system was further improved as described in Section 3.7.

The design uses plastic gears (Figure 34).

Figure 34: Plastic Gears. These gears can be used as part of an indexing system.

A mechanism modeled from the idea of that VHS rewinders employ for bi-directional indexing would be used. Figure 35 illustrates the gear mechanism. When the handle is turned counter-clockwise, the left hand spool turns counter-clockwise. When the handle is turned clockwise, the right-hand spool turns clockwise. This is accomplished through a gear couple: gear A is attached to the handle's shaft. Gear B's axle is attached by a thin plate (AB) to the shaft of gear A. Thus, it is only confined radially to gear A, and depending on which way gear A is turned, gear B will swing to the left or right and contact the next gear in the chain (CL or CR) to turn it. The force to swing gear B to the left or right is from the friction between of plate AB and gear A. This friction can be controlled by a spring. The gear ratio and handle moment arm match those of microfilm readers commonly found in libraries.

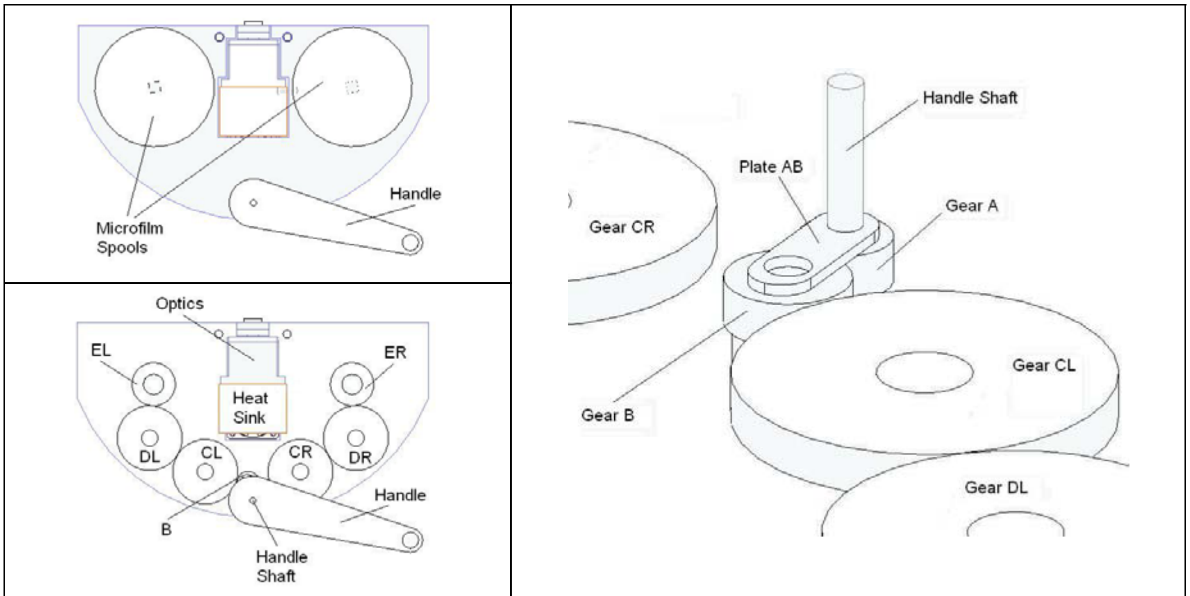


Figure 35: Gear Indexing. This figure shows how an indexing system could work using gears.

Figure 36 shows an exploded view of the axle used in the proposed design explained in Section 3.7.

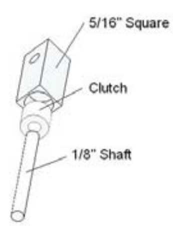


Figure 36: Exploded View of Indexing Axle. The clutch is inserted in the left and right axles in opposite orientation to allow for bi-directional indexing.

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