LED SPOTLIGHT

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Abstract

This report details the development and construction of an LED spotlight useable in a theatrical setting. In depth background information, initial design concepts, lighting instrument specifications, assembly, testing, and conclusions from results are highlighted in this document. Project goals include efforts to support more energy efficient lighting in the arts and general lighting applications and a decrease in overall costs for energy used in all dramatic and architectural lighting applications. Completion demonstrates the knowledge and abilities capable of an Electrical Engineering undergraduate student at the California Polytechnic State University in San Luis Obispo, CA.

Prologue

My passion for theater began in 2006 during my senior year of high school and since 2008 I have pursued a minor in Theater, specifically Technical Theater at Cal Poly. When telling people I am an electrical engineering major and theater minor they react in two ways. Initially, they are stunned at the fact I am so deeply involved in two seemingly unrelated fields. Then, they assume I am an actor, which is untrue. Many people overlook the technical aspects even though all major theater productions today rely heavily on them. Hollywood, Broadway, and Las Vegas all survive by the entertainment industry and continue to dazzle audiences with new and creative technical masterpieces like *Cirque du Soleil, The Lion King* and *Wicked*. My coursework in the Theater Department is technology driven, including Stagecraft, Costume and Craft Creation, Stage and Scenery Design, and Lighting Design. I operated the light board for the Fall '09 production of *Blood Wedding* and was the Sound Designer for the Spring '10 production of *Marisol*. Though I will finish my college career one class short of fulfilling the minor my technical experiences within the Theater Department will be carried into my professional career, my life private life, and this senior project.

Acknowledgements

The entire project is produced by Eric Toussaint, an electrical engineering student at the California Polytechnic State University in San Luis Obispo, CA. This represents a culmination of the education received as an undergraduate student in the electrical engineering department at Cal Poly and demonstrates the ‘Learn By Doing’ philosophy Cal Poly has adopted. Because only one person completed this project, the wisdom of others was required along the project’s progression and is acknowledged here.

Thanks to David Braun for agreeing to advise the project’s completion. Since day one he expressed a positive attitude and was gracious with advice on moving the project forward. I greatly appreciate his fascination with theater lighting aspects and hope he will always value lighting design. He allowed a flexible project execution while still pushing complete fulfillment of all the requirements needed for a successful project.

Thanks to Tim Dugan, theater department chair, for his time and energy in his teaching of the old, current, and future lighting design technologies, their influence in theater and how to implement lighting design techniques. My technical theater education in lighting design and stage design is due to his teaching and I will not forget it.

Thanks to Howard Gee for taking time to thoroughly explain theater operation costs and power distribution. Without Howard I would not have been introduction to some of the nationally respected theater lighting inventors in San Luis Obispo. Questions were asked many times throughout the project and, with his office door wide open, all were answered with wisdom and a laugh.

Finally, a special thanks to Gary Dove of Dove Systems in San Luis Obispo. Without his donation of the spotlight housing the project would not have enough funding to finish such a magnificent lighting instrument. Whenever I needed a workbench to build or test the light he never denied me a spot in his shop. The meetings about different LEDs and drivers proved invaluable and ultimately shaped the project into what I only dreamed I could create. I wish him the best of luck in his LED lighting pursuits.

Introduction

Objective

This senior project aims to complete a stage light for operation in a little theater, black box theater, or architectural lighting setting. Using an LED light source in the lighting instrument demonstrates energy efficient and environmentally friendly practices. LED lighting uses significantly less power than modern stage lighting methods while achieving much longer light life than comparable stage bulbs. Currently, high power LEDs are seen as an exciting technology, possibly becoming the new standard for many consumer lighting applications. The key characteristics most consumers desire in a general lighting source are a high lumens/Watt ratio and a relatively small LED package. Therefore, this project investigates using a single LED or LED array as a light source for a stage instrument. Two goals the lighting instrument must achieve are as follows:

1. Save Electricity

   Americans today are determined to "Go Green" and think about how humans are abusing the Earth's natural resources and animal inhabitants. The 2010 publication "Key World Energy Statistics" produced by the International Energy Agency states coal produced 49.1% of the electricity consumed by the U.S. in 2008.[1] British Petroleum projects American coal reserves to run out in 245 years with no prospects for an alternative to coal in sight. [2] By consuming less electricity, less coal is consumed and this extends the time to find a replacement for coal. High Performance Lamps (HPLs) used in Source Four ellipsoidal reflector spotlights consume 575W of power while high power LED technology ranges from 2W LEDs to over 100W LED arrays. By using LED technology and consuming less than 20% of the current consumption of power, the United States could disperse energy elsewhere and perhaps begin to sell electricity to other countries, possibly decreasing the national debt.

2. Save money

   Looking at Hollywood, Las Vegas and Broadway one may think the theater and movie business is a goldmine of wealth. When analyzing a college theater department budget on the other hand, funds do not flow as easy. Currently, the Spanos Theater on Cal Poly's campus has roughly 35 weeks of performances throughout the year. Each day during a production week, around 200 spotlights using 575W bulbs are powered at full for 3 hours. At an electricity cost equal to 8¢ / kWh, this costs $27.60 each production day or $6,762 a year just to light the stage; This does not include house lights for classes during the day or any overnight lighting. If the Spanos Theater replaced the current spotlights with new LED lighting instruments using only 100W, costs could reduce to $4.80 a day or $1,176 a year, a

theoretical savings of $5,586 a year. This is enough money to build 90% of an entire stage production at Cal Poly. Also, some HPLs are only hate a 300 hour life rating meaning they are replaced about twice a year. If each bulb costs $20 the total cost to replace them is $8000 a year. LEDs are usually rated to last 50,000 hours equal to 5.7 years of continual use. If used in the Spanos Theater, the LED would need replacement after 68 years of use. However, after this time length new and better technology is most likely available, so the LED itself will not need replacing. The money saved could purchase new equipment for the theater like cycloramas, silk screens, moon boxes, or costume materials. The money could even pay for student scholarships for theater majors and minors. [3]

Background

The Light Emitting Diode (LED) is quickly becoming a replacement for many lighting applications throughout the world. Until recently consumers mostly used LEDs as indicator lights on electronic equipment or seven segment displays as these were the only applications practical for LEDs. Area lighting for an LED was impossible until 1993 when a decade worth of research by Shuji Nakamura produced the world's first high power LEDs. He invented the first blue and green high brightness LEDs and used them to produce 5mW blue semiconductor lasers in 1999. [4] He won the 2006 Millennium Technology Prize for his work.[5] Not only has his work made him the father of modern high brightness LED lighting but it has led to the creation of quicker semiconductor storage solutions such as Sony's Blu-Ray technology. Today, LEDs are common replacements for incandescent bulbs in flashlights, traffic signals and street lights. The theater industry has only recently benefitted from LED technology. Companies like Electronic Theater Controls and Chauvet are on a fast track to new stage lights and applications using high power LEDs.

Again, LEDs have never been used for general lighting purposes until very recently (and these applications are limited) but certain characteristics make LEDs a candidate to replace past lighting technologies. LEDs in modern consumer electronics consume very little power and fail rarely compared to an incandescent, fluorescent, or halogen light source of similar brightness (a comparison of these technologies is summarized in Table 1). The extremely long LED life, estimated at 60,000 hours and upwards, is much longer than comparable incandescent bulbs. For example, an in-home 40W incandescent light bulb by General Electric is rated at an average life of 1,000 hours and an HPL by Electronic Theater Controls (ETC) used in spotlights is rated at 1,500 hours. An LED can last 40 times longer than an HPL and 60 times longer than an incandescent light bulb. Also, LED life rating is not based on when the LED completely "burns out" like incandescent bulbs. Instead, the rating is based on the moment in time an LED outputs only 70% of the rated lumen output at full power. Used properly, LEDs have the potential to run for the entirety of their specified application to the point when the product becomes obsolete.

Two problems currently discourage consumers from transitioning to LED lighting: low lumen output per single LED and very high prices for LEDs compared to incandescent bulbs.

Until very recently a single LED could not emit enough light to illuminate a room effectively, even compared to a 40W incandescent bulb LEDs could not compete. Now, new high power LEDs achieve lumen outputs comparable to 300W bulbs eliminating lumen output as an issue for consumers in the months to come. The high LED price may continue to discourage consumers for a few years however. A 100W incandescent light bulb, a common product in any home, produces 1,750 lumens of light and costs around $5 for a 6-pack at Home Depot. A compact fluorescent light bulb producing the same lumen amount only consumes 23W and costs $8 for a 4-pack also at Home Depot. The brightest LED light bulb Home Depot sells outputs 850 lumens of light, consumes 18W (75W equivalent) and costs $45. Comparing total costs to replace burned out bulbs and electricity costs after 10,000 hours of use, LEDs cost less than incandescent bulbs but almost 3 times more than CFLs. Table 1 compares each technology. It will take a few years for LED prices to drop to levels affordable for consumers before high power LEDs are common in households.

Table 1: Lighting Technologies Comparison

Aspect	Incandescent Bulb	CFL bulb 100W equivalent	LED Bulb 75W equivalent	Luminous Devices CSM-360 90W equivalent	HPL 575W
Power Consumption (Watts)	100	23	18	90	575
Lumens	1260	1600	850	8,170	16,500
Lamp Cost (USD)	$0.83	$2.00	$45.00	$150	$13.00
Rated Life (Hours)	750	10,000	50,000	60,000	300
Efficacy (lumens/Watt)	12.6	69.5	47.22	90.77	28.6
Energy Cost (@$0.08/kwh for 10,000 hours)	$80	$18.40	$14.40	$72.00	$460
Cost to replace after 10,000 hours (USD)	$11.06	$2.00	$0.00	$0.00	$433.33
Total Cost (Lamp + Energy)	$91.89	$22.40	$59.40	$222.00	$906.33

Transitioning to the theater world, a 575W HPL by ETC (Figure 1) emits 16,500 lumens and costs about $13 through various online stores. If integrated into a stage light, the CSM-360 LED by Luminous Devices (Figure 1) operating at peak efficiency and correct color coefficient can produce 8,170 lumens using only 90W of power and cost $150 online. Though the lumen

output drastically differs between the two technologies (in favor of HPLs) the replacement costs after 10,000 hours of use also drastically differ (in favor of LEDs, see Table 1). After speaking with Howard Gee, using a lighting instrument for 10,000 hours is a completely feasible amount of time. As mentioned in the Objective Section, the Spanos Theater operates 35 weeks out of a full year. Each instrument runs at full brightness 7 days each week for around 3 hours each day. This means using the instrument for 10,000 hours equals about 13.6 years in a theater. If the LED is used for the rated 60,000 hours, an LED instrument theoretically will operate for 81.6 years until the LEDs do not produce adequate brightness.

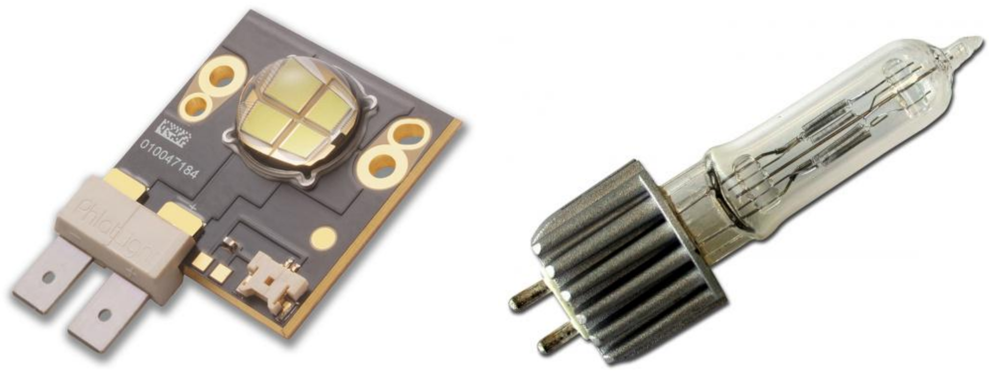

Figure 1: The CSM-360 LED by Luminous Devices [6] and the High Performance Lamp (HPL) by ETC [7]

Efficiently dissipating the high heat produced by a high power LED has become a large stumbling block to overcome for engineers. Small LED packages consuming large energy amounts release the energy in the form of light and heat, and this heat can sometime lead to LED overheating (For a more thorough explanation, refer to the thermal management section on pg. 17-18). The heat produced can achieve temperatures well over 150 degrees C and drastically reduce the LED life. In lighting designs with large cooling system sizes, heat dissipation is not a significant problem. When considering using a high power LED in a ceiling fan light where small size is crucial, cooling becomes a critical issue. Creative new heat sink designs have come forth to supercool high power LEDs but new and more powerful LEDs are invented faster than adequate heat sinks are to cool them. High power LED technology and innovative cooling solutions are still very new and more impressive designs are in the near future.

Specifications

Since the main purpose of this light is for use in theaters, similar functionality to already existing lighting fixtures is key to the design. The ability to hang on a fly line and instrument yolk rotation are features any theater technician prefers in a lighting fixture; a standard C-clamp design for the instrument fulfills the technicians needs. The lighting fixture will produce one color so proper dimming requires only one channel on a lighting board. At 100% working capacity an 800 lumen minimum will produce enough light useable on stage. As outlined in the Background section, a light life of at least 50,000 hours eliminates the need for replacement. A correlated color temperature (CCT) within ± 500°K of the traditional light color temperature 3,250 K is acceptable to match current HPLs CCT. Energy consumption less than 50W of power could possibly save hundreds of dollars in energy costs over the instrument life compared to current HPL lighting instruments. The following list summarizes the specifications for this LED lighting instrument project:

General

- Less than 50W of power consumed at full power (100% on a light board)

Physical

- Rotating yoke with C-clamp
- All metal housing
- Gel frame holder
- Thermally Insulated knobs

Electrical

- 100VAC to 240VAC 60 Hz power input
- Requires power from non-dimmable source

LED

- ±500°K of 3250°K traditional correlated color temperature (CCT)
- 50,000 hour lifetime minimum
- Output 800 lumens minimum at full power (100% on a light board)

Optical

- Tight beam angle, between 24° - 36°
- Spotlight capabilities; able to focus, soften and harden beam edges

Control

- DMX512 via XLR connector 3-pin or 5-pin
- Single channel control for light intensity

Thermal

- Ambient operating temperature 34°F - 104°F

This specification format is modeled after the specifications ETC creates for the Selador series LED lighting fixtures. [8]

Design Development

Fixture

Before beginning to design an LED lighting fixture, an investigation into the various LED stage light types and traditional stage lights is considered. 4 types of lighting instruments were considered for the project design: Par, Fresnel, ERS, and LED Color blending.

PAR – A PAR lamp (or Parabolic Aluminized Reflector lamp) produces a light distribution classified as floodlighting. Floodlights have soft edges and have the ability to illuminate large areas. The light beam is oval in shape, producing an uneven light distribution. The lamp has the unique ability to rotate, therefore controlling the oval beam direction.

Fresnel – Named after its' inventor, a Fresnel instrument technically produces a spotlight distribution but is also used for floodlight applications. The beam produces soft edges but those edges can sharpen slightly by moving the instrument lamp closer to or further from the single lens. The spherical reflector produces a circular light pattern and an even light field.

ERS – Ellipsoidal Reflector Spotlights are the most versatile spotlights in modern theater. The beam angle can range from 90° down to 5° and by shifting its' 2 lenses can produce the sharpest beam edges or very soft edges. The light has a large throw distance, reaching over 100', and can produce circular even light distributions. [9]

Figure 2: PAR Can [10] , Fresnel [11], and ERS [12] Lighting Instruments

LED Color blending – By far the most widely used LED lighting instruments use color blending practices to create the color spectrum. In April of 2009 the Cal Poly Theater

Department sponsored a seminar on stage lighting future technologies. Of the many technologies introduced the instrument surpassing all the rest was the *Selador: Vivid* LED flood light by ETC. Quite an impressive fixture, the *Vivid* uses seven colored LED arrays to create broader color spectrum than what is available in standard RGB color blending stage lights. An RGB system uses 3 LED colors – Red, Green, and Blue – to create the visible color spectrum. The *Vivid* uses 7 LED colors – Red, Red-Orange, Amber, Green, Cyan, Blue, and Indigo – to widen the visible color spectum. By including colors between red, green, and blue more specific and visually intense colors are created. For most RGB indicator applications in the past, specific colors where not important outside the primary and secondary colors. For example, if a yellow light is desired at full brightness for any standard RGB setup, a 1:1 Green to Red mix would produce a very recognizable yellow. In theaters the light quality and the light intensity is crucial to successful mood portrayal. A very common occurrence in stage productions is the creation of a sunset using only lighting on a cyclorama (the curtain furthest upstage away from the audience). The sun may appear yellow during the day but as the sun sets it emits the colors amber, orange, red-orange, and red. This can become a challenge to recreate on stage. Blending these four colors using individual lights creates a sophisticated and lifelike sunset. A color balance heavy on red and red orange may indicate the sun is lower to the ground than if the light was amber. The *Vivid* can create a sunset illusion potentially using one fixture instead of four, making it a powerful tool for lighting designers.

The initial design ideas for this project stemmed from the *Vivid* LED lighting fixture (Figure 3). Color blending is a trend most LED fixtures today follow because it eliminates the need for gels (the colored sheets of paper placed in front of the light beam to create colored light in PAR, Fresnel, and ERS fixtures). Saturated color gels tend to "burn out" quickly, meaning the color on the plastic actually burns away with intense light, and the gels become a costly expense to replace. The first design idea used the same color blending concept as the *Vivid* but using an Ellipsoidal, a PAR, or a Fresnel instrument body for the housing instead of the square body used in Selador instruments. The lighting company Chauvet further inspired PAR style designs, the COLORado series LED lighting instruments serving as a main inspiration (Figure 2). Unfortunately, due to budget decisions all color blending designs were rejected for this project. The *Vivid* uses 40 Philips Lumileds Rebel LEDs per fixture and at a cost between $4 and $8 per LED, purchasing 40 LEDs could reach over $300. With a budget around $250 these designs were not feasible.

Figure 3: Selador Fire and Ice [14] and the Chauvet COLORado 1-Tri Tour [15] LED Lighting Instruments

Instead, the project focused on light intensity for a small quantity of LEDs. Because of its wide usage in many LED fixtures like the *Vivid*, Rebel LEDs by Philips were the first investigated. It is clear why many lighting companies choose Rebels for their instruments: Rebels are relatively inexpensive compared to similar products, achieve lumen outputs above 100 lumens each and come in a wide color variety including white color temperatures. Unfortunately the required lumen output for this particular project and size restrictions for the eventual instrument housing chosen also made Rebels not feasible. A full scale design required 35 tri-star rebel LEDs at the amount of $660. Both initial design ideas cost too much money to manufacture so it was decided to look for someone to financially support the project. In the case a sponsor could not be found, a third design was created, a small scale project, using only 3 tri-star rebel LEDs, costing a total of $56 and producing around 1000 lumens.

Through connections within the theater department a meeting was set up with Gary Dove, the owner of Dove Systems in San Luis Obispo. Dove Systems specializes in dimmer boxes, dimmer racks and other lighting control systems and recently moved into the custom LED lighting fixture production. Gary Dove believes LED lighting is the future of the lighting industry and has embraced the technology for his future designs. After a quick demonstration of some recent LED fixtures he created we discussed possible funding for this project. Under his recommendation the project would now pursue a small scale fixture within the $250 budget rather than an expensive full scale project funded by an outside company. He did however offer to donate a lighting fixture to the project. Of the numerous fixture housings available the decision was made to choose a one similar to Ellipsoidal Reflector spotlights.

Because of the generous spotlight housing donation, the project could now progress with a more definite design for the lighting instrument. A spotlight with multiple lenses has many applications for use. The two lenses allow a wide focus range for the beam, a technology not yet seen in any lighting application using an LED light source. Spotlights are also used for 'specials' or moments during a show when the audience's attention is focused on a single point on stage. With tall architectural settings spotlights perform brilliantly because their focus can add definition or blending to wall textures and show off the building height and magnificence.

The small size of this particular spotlight however presents some interesting challenges when attempting to integrate an LED source. An LED array of more than about 3 LEDs is too large to fit in the given space and correctly focus each LED into a tight beam with the resources available. The quantity of LEDs in such a small space also creates thermal problems and adding a fan to account for the extra heat will add unnecessary noise to the instrument in a silence cherishing theater environment. These factors point to one solution for the light source type: a single high power LED. Unlike an LED array, a single LED needs little physical calibration to assure alignment with the instrument lenses. Also, the heat from a single LED is easier to manage than the heat from multiple LEDs on the same heat sink; more than one LED may lead to uneven heat distribution in the heat sink. With this in mind, an LED emitting over 800 lumens is currently a rare technology but still available. The heat amount emitted though requires a very specific heat sink to cool it to useable temperatures.

LED

Choosing a single LED to fit the specifications is achievable but detailed attention to the LED characteristics is the key to the project's success. Some high power LEDs can potentially emit thousands of lumens but at certain costs to color temperature and thermal resistance values. If these specifications are not met for this project it can lead to problems so severe consumers would never buy the instrument and theaters would never want the lights used in their facilities.

Color Temperature

When choosing an LED an important specification given on the datasheets is the LED color temperature measured in Kelvin. Usually the temperature is between 2500K and 10,000K. The color temperature is a critical part of this project; the wrong color temperature will eliminate any practical use for this light in theater. Color temperature refers to the temperature a black body radiator emits particular hues of colored light. A black body radiator is a theoretical object able to absorb all electromagnetic radiation and while emitting and reflecting nothing at room temperature. Graphite is an example of a good but not ideal black body radiator. When heat is applied to the black body radiator it will begin to glow. The measured color is given a correlated color temperature or CCT; this is comparable to placing an iron rod into a fire until it begins to glow red, orange, or yellow. At temperatures under 3500K the black body radiator emits a reddish hue, between 3500K and 5000K a pure white hue, and over 5000K a bluish hue. [9] It is much easier to describe white light in temperature rather than color language because white light combines all hues with infinite hue variations. The lower color temperatures are described as warm white light while higher color temperatures are described as cool white light. Historically the color red is compared to fire, the sun, deserts and so on, all also associated with heat or warmth. Likewise the color blue is compared to the ocean, rain, and ice, all also associated with the cold or coolness.

For over one hundred years the incandescent light bulb has emitted a warm white light and in modern theater lighting equipment this has not changed. Studies show warm white light is more pleasing to the eye than cool white light. Theories to why mostly lean toward the sun as it appears to humans is a warm white and therefore warm white is a natural color temperature. Studies also show blue light is more likely to cause eye damage for short term and long term vision. Incandescent bulbs are usually around 2700K and HPLs are rated at 3200K for short life bulbs (500 hours) and 3050K for long life bulbs (2000 hours). Choosing an LED close enough to this 3200K color temperature will ensure a pleasing white light output. [9]

LEDs with a warmer color temperature are widely manufactured but using them comes at a price. Generally the higher the color temperature the brighter the light emitted is. For example, the Cree XLamp XP-G with a CCT rated at 2600K has a max lumen output of 305

lumens. The same LED rated at a CCT of 8300K has a max lumen output of 450 lumens. Both LEDs consume 6.8W of power at their respective lumen output. While the XP-G rated at 8,300K has a luminous efficacy of 66 lm/W the same LED rated at 2,600K has a luminous efficacy of only 44 lm/W. This will result in a higher operational cost for lighting instruments using warm white LEDs.

Thermal Management

Contrary to popular belief LEDs do emit heat, and at higher drive currents they can create substantial heat. The small drive currents (less than 50mA) in many indicator LEDs do not produce enough heat to really affect the LED characteristics in a negative way. Due to increasing drive currents in high power LEDs, sometimes reaching above 10A, overheating is now a concern. As the LED junction temperature increases, a decrease in performance occurs in lumen output, lumen efficacy, and rated life. The heat amount may even lead to catastrophic failure and destroy the LED's ability to emit light. Many datasheets for LEDs provide a graph describing the decrease in luminous flux as the junction temperature decreases. Typically around the maximum rated junction temperature the luminous flux output is only 70-80% of the maximum light output.

The U.S. Department of Energy compares incandescent, fluorescent, and LED thermal characteristics in Table 2. The total power consumed in each source is divided into the percentage of visible light, Infrared light (IR), and heat remaining of the source but lost through convection or conduction. Infrared thermal energy is known to most people as the feeling of heat from light, the same feeling when walking into a sunlit area on a hot day after standing in the shade. Conduction thermal energy can occur when a heat sink is attached to the light source, promoting heat transfer from the light source to the heat sink and finally into the air by convection. Of the 60W used in an incandescent light bulb, 19% is lost through conduction and convection while 73% is lost through IR thermal energy; this means only 8% of the power consumed by an incandescent bulb directly translates to area lighting. Fluorescent lighting loses more power through thermal energy (around 42% of the total power consumed) but much less through IR emission (only 37%). The light efficiency nearly triples from incandescent to fluorescent with 21% of the total power translating directly to useable light. In LEDs, 75-85% of the total power is lost through conduction and convection, much higher even than fluorescent lighting. LEDs become much hotter to the touch than incandescent and fluorescent bulbs but emit nearly no IR light, meaning LEDs do not waste light emission on wavelengths invisible to the human eye. This means up to 25% of the total power used by LEDs translates directly to area lighting. This does however pose a problem for rapidly cooling LEDs consuming large amounts of power. Very tiny LED packages with small surface areas cannot cool themselves properly and require the assistance of a heat transfer device.

Table 2: Power Conversion for "White" Light Sources [15]

	Incandescent† (60W)	Fluorescent† (Typical linear CW)	LED*
Visible Light	8%	21%	15-25%
IR	73%	37%	~0%
Total Radiant Energy	81%	58%	15-25%
Heat (Conduction + Convection)	19%	42%	75-85%
Total	100%	100%	100%

† IESNA Handbook

* Varies depending on LED efficacy. This range represents best currently available technology in color temperatures from warm to cool. DOE's SSL Multi-Year Program Plan (March 2006) calls for increasing extraction efficiency to more than 50% by 2012.

In order to sustain maximum LED performance proper cooling is a must and the most popular solution currently is heat sinks. With proper heat sink selection the heat can quickly transfer from the LED to the heat sink and disperse into the environment through the cooling fins. The most important specification given for any heat sink is the thermal resistance, measured in °C/W. Thermal resistance is a measurement of how much an object resists heat transfer; the higher the material's thermal resistance is the more the material is able to block heat transfer. Heat sinks with lower thermal resistance usually have more surface area to release the heat and therefore are larger and more bulky in size. To increase the cooling speed and decrease the thermal resistance, fans are sometimes attached to the heat sink, allowing the heat to transfer to the air through convection. LEDs also have a thermal resistance measurement. Again the lower the thermal resistance the better heat can freely transfer from one material to the next.

To determine if a heat sink will properly cool a high power LED, Cree offers the following formula in their Luminaire Design Guide. [16]

$$T_j = T_a + (R_{th\ b\text{-}a} \times P_{total}) + (R_{th\ j\text{-}sp} \times P_{LED})$$

where

T_j = LED junction temperature
T_a = Ambient temperature
$R_{th\ b\text{-}a}$ = Heat sink thermal resistance
P_{LED} = Single LED power consumption
= (Operating current) x (Typical Vf @ Operating current)
P_{total} = Total power consumption = (# LEDs) x PLED
$R_{th\ j\text{-}sp}$ = LED package thermal resistance

When using a single LED instead of an LED array, the equation simplifies to the following:

$$T_j = T_a + (R_{th\ b\text{-}a} + R_{th\ j\text{-}sp}) \times P_{LED\ total}$$

LED Driver/Control

Dimming Control

The theater is unique in terms of how electricity is dispersed throughout the stage and how lighting instruments are dimmed. In a typical theatrical show at Cal Poly's Spanos Theater around 150 different lighting instruments are used during performance. For typical dance shows the figure is anywhere between 250 to 300 lighting instruments. Each lighting instrument is dimmed either in a group of lights or individually. 360 SCR dimmer modules are located throughout the building each with a separate outlet (called a dimmer-per-circuit system) somewhere within the audience or stage area: 44 outlets the stage floor, 89 in balconies above the audience, 75 hanging high above the stage on the fly rails and the remaining 152 above the fly gallery grid. At 2.4kW available per dimmer the Spanos Theater could potentially use 864kW of power at one time. Each dimmer is stored in a dimmer rack and the lighting board digitally controls each rack. The lighting board can access every dimmer and assign each to a lighting channel. These channels take the form of sliders on the light board creating user friendly control by increasing or decreasing the rms voltage delivered to each light, thereby controlling the light intensity of each fixture. [3]

Though Incandescent light bulbs have no problem using SCR dimming systems, LEDs do run into problems. First, high power LEDs will only emit light when a sufficient positive voltage difference is between the anode and cathode; sufficient negative voltage between the anode and cathode will actually destroy a high power LED. Only rectified signals can be used to power an LED. Since SCR dimming can have a peak negative voltage of -120V the signal must first be rectified. Also, at low light dimming LEDs sometimes have problems overcoming the threshold voltage. In an LED array where the threshold voltage could easily be 10-15V, light would not be produced until the rising sine wave surpassed that. This leads to a problem with very low lighting where the threshold voltage is never surpassed. Finally, SCR systems are set at a frequency of 60Hz and because of the ability to change polarity in an incandescent light bulb setup the light is actually emitted at about 120 Hz. When instantly powered on incandescent light bulbs will actually take some time to warm up before emitting full brightness; when instantly turning off an incandescent light bulb again it will take some time to cool off before completely going dark. LEDs on the other hand do not require nearly as much time to heat up or cool off. This means switching at 60Hz can sometimes become noticeable compared to incandescent light bulbs.

PWM Control and the Lighting Board

To insure the threshold voltage is always supplied to the LED, a dimming method called pulse width modulation control provides a proper solution. Instead of an AC sinewave input with constantly changing polarity a positive voltage pulse is used. The pulse reaches the maximum input voltage and holds. The duty cycle is variable, making the average voltage

delivered to the load variable. The average voltage of different pulse widths is seen in Figure 4. The pulse will always reach the same peak voltage which is set to a value higher than the LED threshold voltage. Average dimmer circuits in a theater do not support PWM so LED dimming currently is mostly done digitally using DMX512 technology.

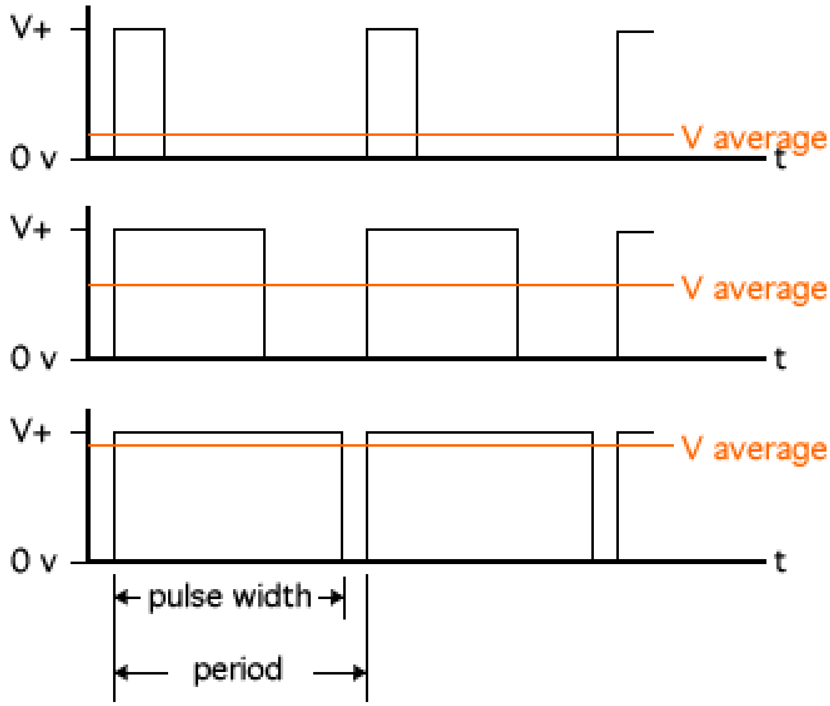

Figure 4: Varying Pulse Width and the Change in Average Voltage Delivered to LED [17]

The lighting board and dimmer rack communicate through DMX (Digital Multiplex) cables and all intelligent lighting is controlled with DMX. DMX512 uses an 11 bit binary number to digitally transmit the slider location on a lighting board to the dimmer rack. The lighting board will assign the slider position to a number between 0 and 255 and then covert the number into an 8 bit binary number. The signal is then transmitted using RS485 serial protocol through the DMX cable to the dimmer rack where the binary number is translated into a voltage. DMX transmits the 11 bit number as 1 start bit, 8 information bits, and two stop bits at 250,000 bits per second allowing refreshing of 512 channels around 44 times a second. Setting the slider at 50% total light output will allow the light board to send a digital signal to the lighting instrument with instructions to set the pulse width at 50%. The resulting voltage will look similar to the middle graph in Figure 4 and the light fixture should output 50% of the max brightness.

Final Design

With all the lighting instrument pieces thoroughly investigated an electrical block diagram of all the necessary parts is constructed. Beginning at the light board a DMX512 signal is sent out with two key binary numbers: the preprogrammed DMX address of a specific light and the new intensity the light should set to. As the signal enters the first DMX decoder in a lighting instrument the decoder checks the signal address for a match. If the address does not match the signal will move through the decoder's DMX Output path to the next lighting fixture decoder. If the address matches the decoder sets the new light fixture intensity. The DMX decoder programs a new output pulse signal width delivered to the LED circuit; again, this signal type is called a Pulse Width Modulated signal or PWM signal. The pulse width changes the average voltage delivered to the LED circuit and therefore the average power and LED brightness. A DC power supply powers the decoder with an output voltage set at the PWM signal's peak voltage. A resistor in series with the LED dissipates the excess energy not consumed by the LED and provides easy calculation for maximum current through the LED.

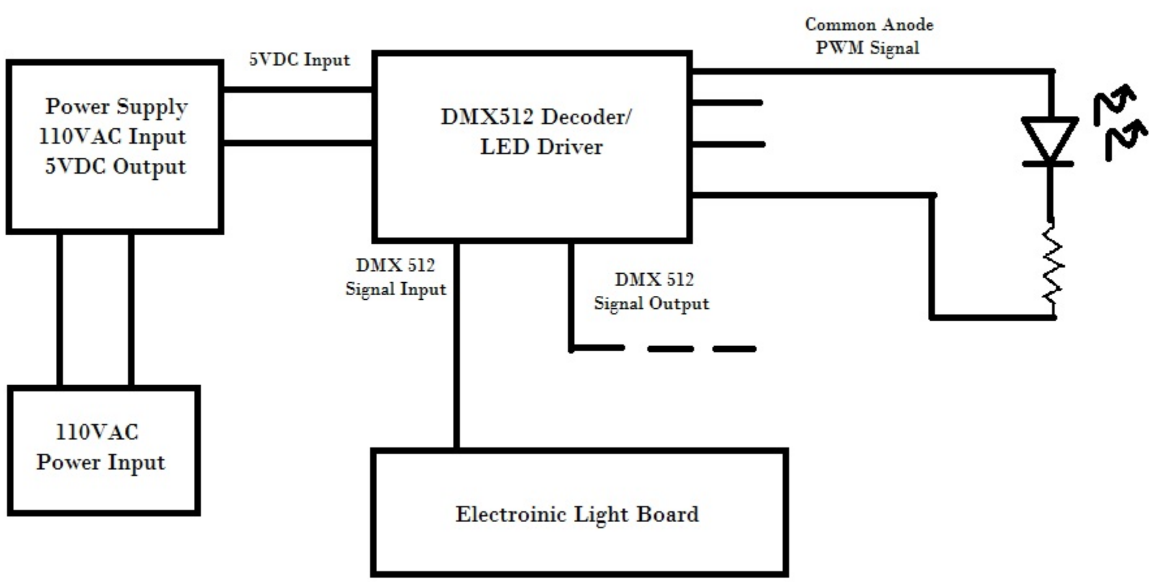

Figure 5: Electrical Block Diagram

Instrument Housing

The housing chosen is a spotlight design donated by Gary Dove. This spotlight has two adjustable lenses within the housing enabling beam focus control. The lighting instrument's compact design fits with the small budget design for this project. The rotating yolk and C-clamp attachment enables the light to hang on any fly line. The front also has a special attachment for gel frames to create color.

Figure 6: Lighting Instrument Housing

LED

The LED chosen for the light source is the Phlatlight CST-90. The CST-90 was chosen over the Luxeon Rebel and the numerous Cree LEDs available for numerous reasons highlighted in Appendix D. The first reason is the lumen output for the CST-90 was the highest I could find in a single LED package within the given price range. A Cree XLamp MC-E rated at a color temperature of 2,600K outputs 544 lumens at max current while the Luxeon Rebel at a color temperature of 3,100K outputs 330 lumens. The CST-90 has a color temperature of 3000 K and can emit 1750 lumens at max current. The near 3250K color temperature and higher lumen output make the CST-90 a great choice. What sets the CST-90 above the rest is the thermal resistance coefficient value. The Rebel has a thermal resistivity of 10 and the MC-E has an even better thermal resistivity of 3. The CST-90 however has a thermal resistance of 0.9 which means it can be used at higher power levels and still not reach temperature levels dangerous to the LED. At driving current of 6A, the CST-90 should output a minimum of 875 lumens and consume 21.6W of power.

Figure 7: CST-90 LED by Luminous Devices [18]

Heat Sink

Using the heat transfer equation given by Cree and assuming an ambient temperature of 50 C, the heat sink with no added fan must have a thermal resistivity of 4.9 at most. A heat sink able to nicely fit onto or into the back of the lighting instrument would be a plus. The HS122 Panel Mount heat sink by CST Crydom provides both the necessary thermal resistivity and correct size to fit onto the instrument (see Appendix E). The HS122 has a thermal resistance of 1.2 C/W without the assistance of a fan, well below the threshold needed to drive the LED at 6A. The HS122 measurements also come very close to the housing's outside parameter dimensions, enabling a very sleek design.

Figure 8: HS122 Heatsink by CST Crydom [19]

LED Driver/DMX Controller

The LED Driver chosen is the DMX 512 Decoder by EcoLight (see Appendix F). The decoder specifications state it can drive LEDs using up to 6A of current between the peak voltages of 5V - 24V. The spec sheet does not however state if the output signal is pulse width modulated or not. I contacted the manufacturer before purchase and confirmed it is indeed apulse width modulated signal. XLR-3 DMX signal input and output allow multiple DMX controlled systems to connect serially in a DMX array. DIP switches allow decoder DMX addressing and requires 3 addresses in a DMX universe. This decoder is made for RGB systems but will also work for single address systems.

Figure 9: DMX512 Decoder/ LED Driver by EcoLight [20]

Power Supply

The decoder requires power from a 5VDC – 24VDC source able to handle at least 35W of power. The LS50-5 5VDC power supply by TDK Lambda fits this description perfectly and was bought for this project (see Appendix G). The power supply accepts 115VAC input from any wall outlet, is able to deliver up to 10A of current and is rated at 50W. The output voltage can also be adjusted between 4.75V and 5.5V so fine tuning is possible.

Figure 10: LS50-5 5VDC Power Supply by TDK Lambda [21]

Resistor

Using a resistor in series with an LED allows the circuit designer to accurately determine how much current is driving the LED. Resistors are simple to add or remove from a circuit and are relatively inexpensive components compared to the other design components. This method however is one of the least efficient methods for driving an LED because a sizeable percentage of the power is lost in the resistor and not delivered to the LED. Initially for this experiment, the design required a driving current of 6A. According to the CST-90 datasheet a current of 6A flowing through the LED requires a forward votage of around 3.6V. Knowing the power supply delivers 5VDC, the resistance needed is calculated as $\frac{5V-3.6V}{6A} = 0.233\Omega$.

Because the DMX Driver/Decoder has a 6A max current rating per channel the current for the LED spotlight circuit was changed and is designed around a drive current of 5.5A. This allows a generous safety margin and will most likely extend the product life. According to the CST-90 datasheet if the current is 5.5A through the LED the Forward Voltage is approximately 3.5V. Using Ohm's law in the following equation, the resistance needed in series is found: $\frac{Voltage\ across\ R}{Current\ through\ R} = \left(\frac{4.7V-3.5V}{5.5A}\right) = 0.218\Omega.$

Using the formula $P = I^2R$ the theoretical total power dissipated by the resistor is $P_R = (5.5A)^2(0.218\Omega) = 8.48W$. A common ¼ Watt resistor or ½ Watt resistor will not work for this application. The final resistor chosen is a 0.22Ω resistor by Ohmite, able to dissipate up to 35 Watts of power.

DMX Decoder/ Power Supply Housing

Due to the small lighting instrument size and the necessity for easy access to the DMX Decoder, the purchase or production of a second enclosure might be necessary to house the DMX Decoder and the 5V Power Supply. There are a few design options to consider at this point:

1) Attaching both the DMX512 Decoder and the 5VDC power supply to the lighting instrument. Pros – This design is the most compact. All theater lights have enclosures large enough to house all the necessary parts so this design fits well with the criteria. Cons – The instrument's movement is hindered because attaching anything close to the instrument's yolk disables certain up/down and side to side movements.
2) Enclose both the DMX 512 Decoder and 5VDC power supply in a separate housing away from the lighting instrument but also hung on the fly line. Pros – This design allows full lighting instrument movement and isolates the potentially hot power supply from adding additional heat to the LED. This also presents a nice and easy way to demonstrate visually how the electrical circuits work. Cons – Requires another yolk to support the extra housing. The lighting instrument and the housing are only hung close to each other on the pipe which may impede maneuverability.
3) Enclose both the DMX512 Decoder and 5VDC power supply in a separate housing located on the ground away from the lighting instrument. Pros – Again, this allows full Lighting instrument movement and isolates the potentially hot power supply from adding additional heat to the LED. Cons – Requires a potentially very long extension cord from the ground unit to the instrument hung on the fly line.

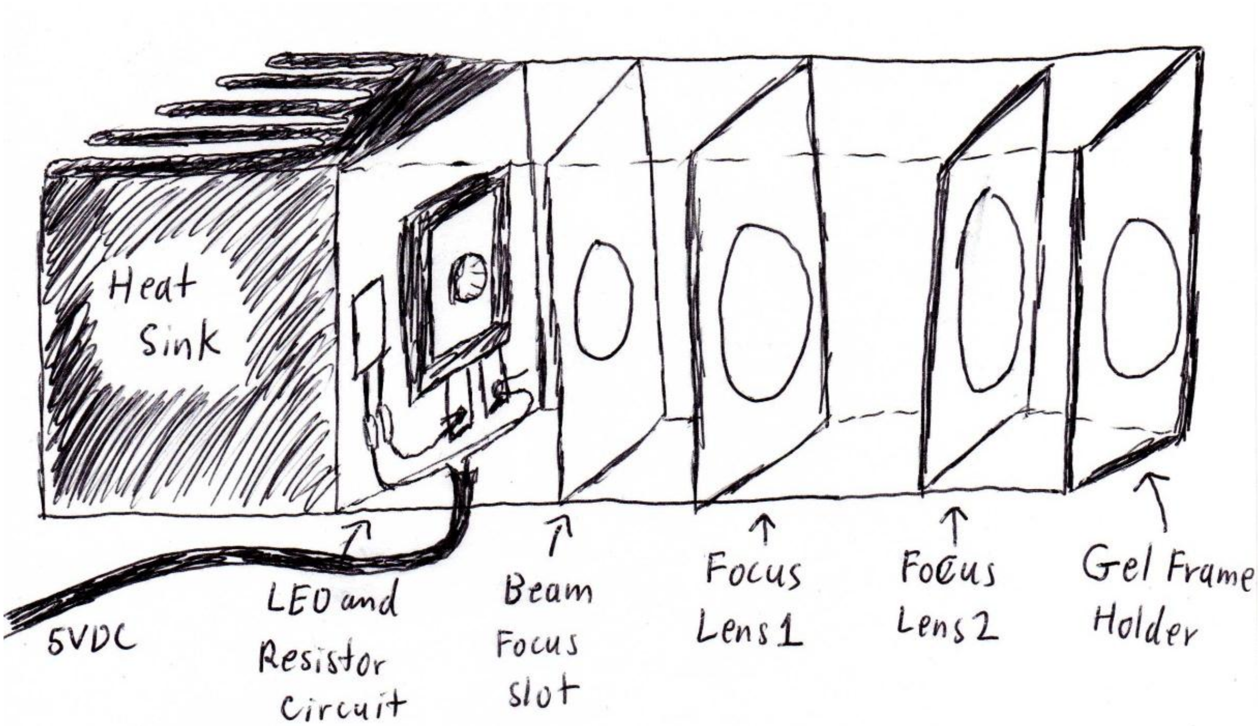

Figure 11: Final LED Spotlight Design Sketch

After carefully considering all three of the previous options, option #1 is the most desirable. Instrument maneuverability is a key instrument specification; without complete maneuverability, it is not a light many theaters would want in their inventory. Very long extension cords from the ground to the air can be a recipe for disaster on stage. Unless there is a designated area to place potentially dozens of power supplies, hanging them in the air would be the best place to put them. Hanging 2 separate housing for each light may become a difficult task for productions requiring many lights in a small area. The separate power supply housing may take other lighting instrument's places, meaning less lights are used. Option #1 compacts all the components and if built with maneuverability in mind will work. With the desired instrument layout chosen, final layout sketches were drawn. Figure 11 and Figure 12 are sketches of how the LED lighting instrument was imagined to look before the final product was built. The final product looks very much what is shown in Figure 12.

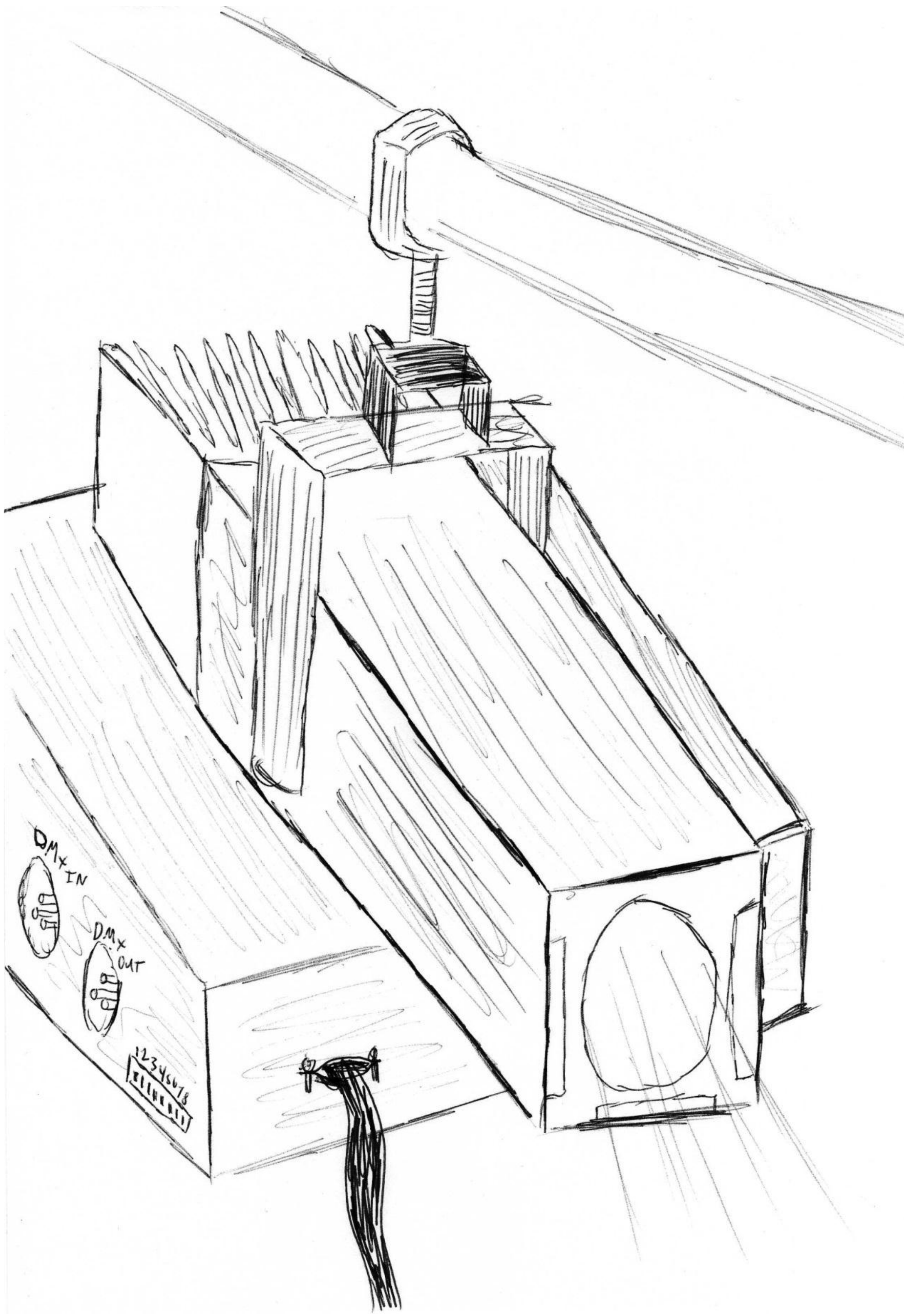

Figure 12: Final LED Instrument with DMX Decoder/Power Supply Housing Design Sketch

Testing

The testing phase is multi-staged and requires a few weeks to complete. First, individual component tests of the power supply, DMX Driver/Decoder, and are completed. Second, the LED and heat sink temperature measurements are taken. Third, the light quality characteristics are measured to ensure correct functionality. The final step is a full scale stage demonstration of the instrument's capabilities and a Q&A session with some project supporters.

Resistor

In the final design, the chosen theoretical resistance in series with the LED is 0.22Ω. Since this resistance is so small, the lead resistance used to measure the resistor is also accounted for. The measured resistor resistance with the leads is 0.287Ω and the measured lead resistance is 0.072Ω. This means the actual resistance of the resistor is $(0.278\Omega - 0.072\Omega) = 0.215\Omega$ which is well within the resistor's ±5% tolerance. This measurement is required to calculate the circuit's drive current.

Power Supply and LED Driver

As mentioned previously, the LS50-5 power supply is rated at 5VDC output but by tuning will also output 4.75VDC to 5.5VDC. Ideally with the power supply set to 5VDC unloaded, the LED driver should also output 5VDC with an LED load; this assumption is false when considering the voltage loss through the LED driver. With the LED and series resistor acting as a load to the LED driver and the driver connected to the power supply tuned to 5VDC, the LED driver average output voltage with a duty cycle of 100% is 4.7VDC; this means a loss of 0.3VDC in the driver. The datasheet for the driver does not specify any losses within the device but further inspection provides two explanations accounting for the loss. First, using 5VDC is near the rated input voltage minimum for the driver and efficiency losses are generally expected when close to the minimum and maximum rated voltages. Second, the driver is also a DMX decoder meaning the decoder circuits may extract some voltage expected in the output, lowering the total output. Calculating the total power not delivered to the LED load requires the knowledge of how much voltage is lost in the driver.

Power Calculations

Using the power equations $P = I^2R$ and P = VA, the total available instrument power consumed (excluding the DC Power Supply) when at full brightness is shown in Table 3:

Table 3: Power Consumption from Available Power at Full Brightness

Component	Voltage (V)	Current (A)	Power (W)	% Total Power
LED	3.52V	5.50A	19.36W	70.40%
0.22Ω Resistor	1.18V	5.50A	6.49W	23.60%
DMX Driver/Decoder	0.30V	5.50A	1.65W	6.00%
All Components	5.00V	5.50A	27.50W	100.00%

Because this design requires a DC power supply from an AC source there is some power loss in conversion from AC voltage to DC voltage. Table 3 accounts for the available power from the power supply. Looking at the datasheet for the LS50-5 AC to DC converter, the typical efficiency is 80%. Therefore the actual total power consumed by all design components is 34.375W and new values for total power are calculated in Table 4.

Table 4: Actual Power Consumption at Full Brightness

Component	Power (W)	%Total Power
LED	19.360W	56.32%
0.22Ω Resistor	6.490W	18.88%
DMX Driver/Decoder	1.650W	4.80%
Power Supply	6.875W	20.00%
All Components	34.375W	100.00%

LED and Heat Sink Temperature

The LED temperature is the most critical measurement in the project. Heat sink measurements with the LED at maximum brightness were taken in a controlled setting. The air temperature in the room was measured at 76°F or 24.44°C which was also the starting heat sink temperature. The test was conducted over 30 minutes and heat sink temperature measurements were taken at 1 minute intervals up to the 5 minute mark and then at 5 minute intervals up to the 30 minute mark. The results are seen in Figure 13 as Test 1 - Heating. The

power to the LED was then shut off and the same test was performed to the heat sink. These results are also seen in Figure 13 but as Test 2 – Cooling.

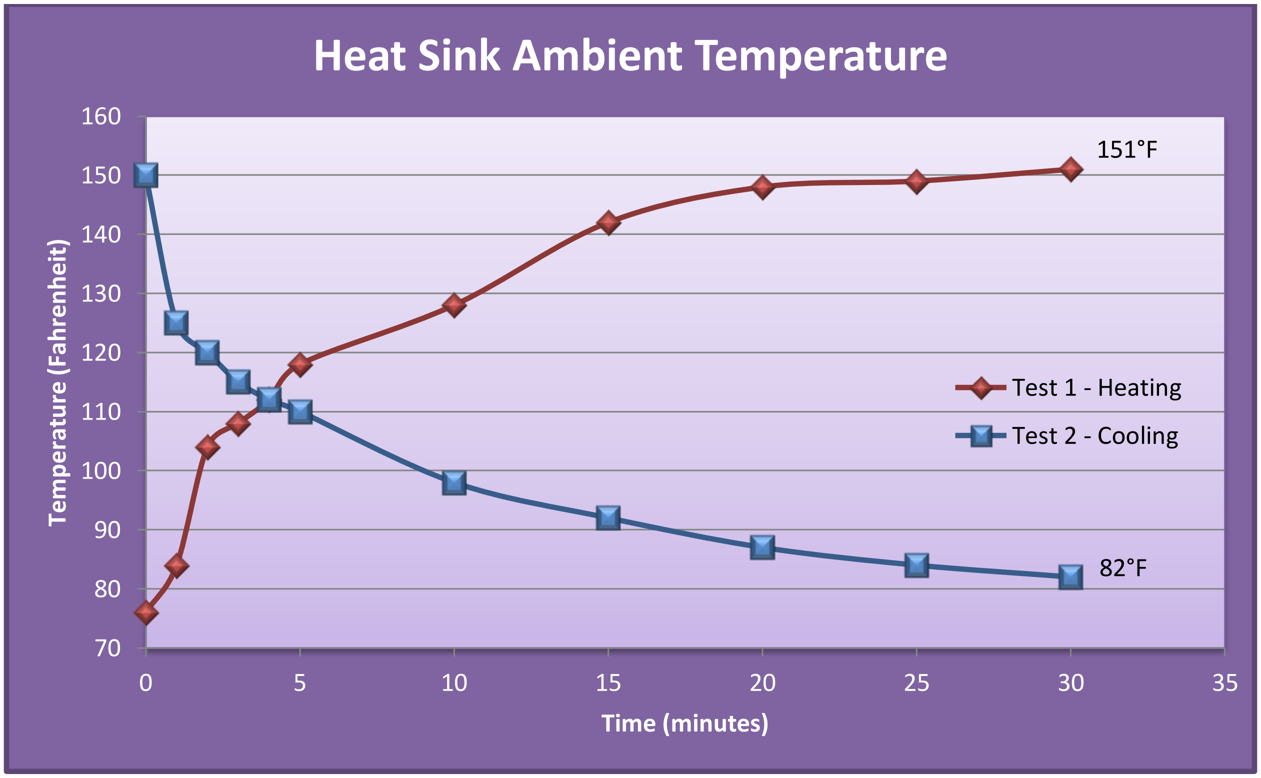

Figure 13: Heat Sink Temperature With LED at Full Brightness

Using the data available in Figure 11 and the equations given in the Cree Luminaire Design Guide, the LED junction temperature while the LED is at full brightness is calculated as follows:

$$T_j = T_a + (R_{th\ b\text{-}a} \times P_{total}) + (R_{th\ j\text{-}sp} \times P_{LED}) + (R_{th\ res} \times P_{res})$$

where

T_j	= LED junction temperature	= ?
T_a	= Ambient room temperature	= 24.44°C
$R_{th\ b\text{-}a}$	= Heat sink thermal resistance	= 1.2°C/W
P_{total}	= Total power consumption = (LED + Resistor)	= 25.85W
$R_{th\ j\text{-}sp}$	= LED package thermal resistance	= 0.92°C/W
P_{LED}	= LED power consumption	= 19.36W
$R_{th\ res}$	= Resistor package thermal resistance	= 4.28°C/W
P_{res}	= Resistor power consumption	= 6.49W

$$T_j = 24.44°C + (1.2°C/W \times 25.85W) + (0.92°C/W \times 19.36W) + (4.28°C/W \times 6.49W)$$

$$T_j = 24.44°C + (31.02°C) + (17.81°C) + (27.77°C) = 101.04°C$$

LED junction temperature affects the LED lifetime and also the overall LED brightness. The CST-90 has a maximum junction temperature of 150°C; If surpassed the LED lifetime dramatically decreases. Since the maximum temperature for this device is around 101°C the 50,000 hour lifetime is not affected and if anything it may increase. The CST-90 brightness when the junction temperature is around 100°C, the lumen output is only 90% of the rated output.

LED Measurements

To measure other LED optical characteristics, measurements were taken in the labs of USL, Inc. (Ultra*Stereo Labs) in San Luis Obispo. USL is engaged in the manufacture, research and development, and sale of motion picture sound, audio equipment, sound process controls and visual test equipment. The Projection Color Analyzer-100 is one of the many products they make and the PCA-100 was used to measure the stage light's spectral intensity, chromaticity and color temperature. Figure 14 displays the intensity of different wavelengths emitted from the stage light.

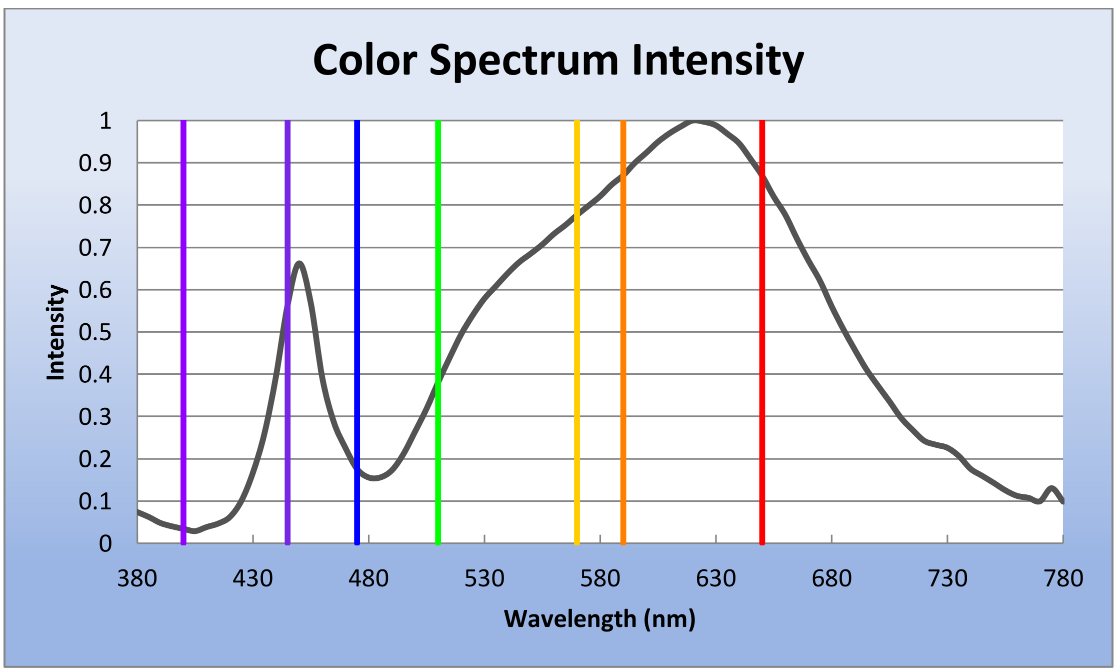

Figure 14: LED Stage Light Color Spectrum

Expectedly, the 580nm to 660nm range is elevated indicating a strong warm color presence including red (650nm), orange (590nm) and yellow (570 nm). There is also a large spike in the graph at 450 nm very close to the color indigo (475nm). This most likely means the LED is a Phosphor-based white LED. In phosphor-based LED production, a blue LED is coated with phosphor of different colors to form a white light emission. Portions of the blue light undergo a shift and emit a photon with less energy and a longer wavelength than originally absorbed photon. The difference in energy between the absorbed photon and the emitted photon is called the Stokes Shift. Many high power LED manufacturers use this technology.

Figure 15 is a screenshot of the measurements collected by the PCA-100. A perfect black body radiator of color temperature 3000K has a chromaticity of Eix = 0.4362, Eiy = 0.4061. The LED light fixture has a correlated color temperature of 2994K and a chromaticity of Eix = 0.4286, Eiy = 0.388, making it just below the perfect black body radiator line shifting toward the violet colors. This makes sense after discussing the Stokes Shift effects.

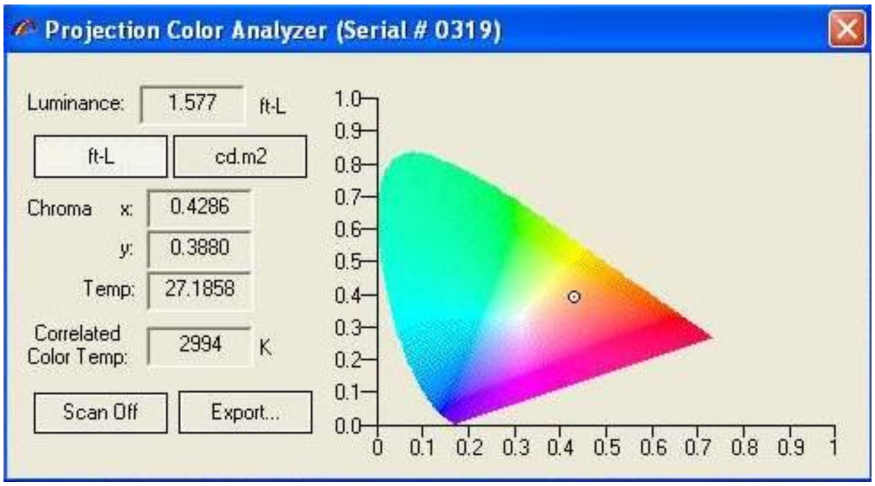

Figure 15: Chromaticity and Correlated Color Temperature

Unfortunately the equipment at USL, Inc. cannot measure the LED lumen output but rather the LED luminance. The luminance is the amount of light reflected off a surface. At a distance of 20 feet, the light emitted from the stage light and bouncing off an object is 1.577 foot-Lamberts. Foot-Lamberts is a common measurement in the motion picture industry while candelas per square meter is common in lighting situations. To convert, use the equation as follows:

$$1 \text{ ft-L} = 3.462 \text{ cd/m}^2$$

Therefore, at a distance of 20 feet from the stage light, the amount of light reflecting off the surface of an object is 5.459 cd/m^2. Luminance is an interesting measurement but not a useful one when describing light sources. Illuminance is the light flux measurement per unit area falling onto a surface. Illuminance is measured in footcandles, or lumens per square foot, in English units and in lux, or lumens per square meter, in metric units. The conversion equations are as follows:

$$1 \text{ fc} = 10.76 \text{ lux} \qquad 1 \text{ cd/m}^2 = 3.14 \text{ lux}$$

Therefore, at a distance of 20 feet from the stage light, the amount of light falling on an object is 1.59 fc or 17.14 lux. This is rather small compared to other stage lights on the market. The Selador *Vivid* measures 92 fc or 991 lux at 20 feet.

The LED lumen output is estimated using the data collected from the datasheet and previous experiments. The CST-90 from flux bin WJ at a drive current of 3.15A is rated at a lumen output of 500 lm. Driving the LED at 5.5A increases the output to around 175% of the output capacity, making the estimated lumen output at 875 lm. As time passes the LED will

heat up and cause the overall lumen output to drop to 90% of the estimated lumen output. This results in a total lumen output of 787.5 lm. The lumen output from the CST-90 LED is different however from the stage light's lumen output because of light lost due to the two convex lenses. The final lumens output cannot be estimated with precision but the lumen output will be less than 787.5 lumens.

Beam Angle

To calculate the beam angle, three measurements are taken at three distances. At each distance the beam circle diameter created on the wall is measured. Table 5 displays each measurement and the calculated beam angle for each. To find the beam angle, use the equation $2tan^{-1}(\frac{Beam\ Distance}{2\ x\ Throw\ Distance})$

Table 5: Beam Angle Measurements

Throw Distance (inches)	Beam Width (inches)	Beam Angle (degrees)
12	5	23.54
34	14.5	24.07
113	48	23.98

The beam angle is around 24° which is within the 36° beam angle requirement.

Demonstration

On 2/11/11, a demonstration of the final project was held in Rm 212 of the Music building on Cal Poly's campus. Those in attendance included Dr. David Braun of the Cal Poly Electrical Engineering Department, Tim Dugan, Department Chair of the Theater Department, Howard Gee, Technical Director of the Theater Department, and Lowell Olcott, Cal Poly graduate and On Site Administrator of Electronic Theater Controls. This demonstration was the final test for the design. The light was hung in the fly gallery and light intensity was controlled via DMX connection. The light intensity was compared to a Source Four Jr. Zoom spotlight and by consensus of those in attendance the LED light intensity at 100% was the same as the Source Four Jr. Zoom spotlight at 50%. During the demonstration a problem was discovered: the light would suddenly loose power when hanging on the fly gallery bar and only when on the bar. The first assumption was there may be a grounding issue with the instrument. After opening the instrument a disconnection in a solder joint between the DMX Driver/ Decoder ground and the series resistor was discovered. After a quick fix of the solder joint the lighting instrument was rehung on the bar and the problem could not be replicated.

Conclusions

The final design surpasses all expectations initially conceived at the project's start. This design meets every specification desired at the project's onset and exceeds all expectations I had in a final product. High power LED technology is rapidly accelerating into a replacement for general lighting purposes and soon may become a viable and affordable option for theater lighting.

If this project were redesigned and improved upon using a larger budget and more resources, the light could possibly reach light outputs of over 400% the current light output. The changes would begin at the LED level, where this project initially began, by replacing the CST-90 with a CSM-360 high power LED. This immediately boosts the light output from 500 lumens to 2,500 lumens of 3,000K light at a drive current of 3.15A. Replacing the 3,000K CSM-360 with a 6,500K CSM-360 then increases the lumen output to 4,300 lumens at 3.15A. (After a conversation with Tim Dugan it was determined a high color temperature in this application would not matter as much as initially thought. Color correction gels are widely available for the specific purpose of lowering or raising a stage light's output color temperature; this process is mostly used in the film and movie industry but has also been performed in a theatrical setting.) Using a larger fixture may allow room for two or three CSM-360 LEDs potentially increasing the lumen output to near 13,000 lumens of output light, an extremely bright output about 60% of the average HPL lumen rating.

The drastic increase in lumen output will also drastically increase both the power consumed and heat emitted in the LED. At 3.15A of drive current each CSM-360 LED uses about 40W of power meaning this new light may consume up to 120W of power. This most likely means a larger heat sink with very low thermal resistance (less than 0.5 °C/W) and a fan to help air flow through the heat sink fins. The LS50-5 power supply will not work in this new configuration, but the LS150-15 will. The LS150-15 supplies a constant 15VDC output and can handle up to 150W of power. Unfortunately the EcoLight DMX Driver/Decoder used in this experiment has been discontinued but an upgrade, the EcoLight DMX XLR3 & RJ45 Driver/Decoder, will accomplish the same task of controlling the light output.

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[29] Ohmite, “TCH Series 35 Watt TO220 Package Thick Film Power,” Resistor .22 OHM 35W TO220 datasheet, Available: http://www.ohmite.com/catalog/pdf/tch.pdf. Accessed 11 February 2011

Appendix A - Senior Project Analysis Report

Design Requirements

The final design is a lighting instrument capability of use in a little theater or blackbox theater setting. An LED source outputs a light pattern similar to an ellipsoidal spotlight instrument: a circular light beam with the ability to sharpen or soften the edges. Gel slides slip into the front to create color. This LED lighting instrument has a longer bulb life than Source Four HPLs used in ETC instruments and consumes much less energy. This saves the theater potentially thousands of dollars each year in energy costs and supports a 'greener,' more energy efficient lifestyle.

Primary Constraints

The most significant decision in the project was the choice of which lighting instrument body to use. Due to a limited budget, purchasing or building a custom housing quickly became an unrealistic scenario. Sheets of various metal materials cost upwards of $200 for such small amounts leaving little budget for the bulk of the project. A donation was the only feasible step to take towards a useable instrument body. Once Gary Dove stepped forward and offered to donate one of the many instrument housings he had in his shop, another challenge rose in which type of housing to choose. Narrowing the search to 2 very different housings subjected the pros and cons of each to full analysis and finally a decision was made.

The most difficult challenge faced was calculating heat sink to LED compatibility. Each design of high power LED and heat sink has a different thermal resistivity. Finding low values for each was a challenge taking 6 weeks to finally solve. The requirements of this process were tedious:

1) The LED must emit over 800 lumens at a drive current less than the maximum current the LED could handle.

2) The LED and heat sink must have low enough thermal resistivity values to continuously cool the junction temperature of the LED to less than the maximum rating.

3) The size of the heat sink must correspond with the size of the lighting instrument housing. A heat sink too large would hinder the directional capabilities of the light.

Economic

Initial Cost Estimate (Full Scale)

Warm White Rebel, Pre-Mounted on Tri-Star Base x 35		$660.45
Pre-Cut Thermal Adhesive Tape x 4		$29.96
Heat Sink x 4		$80.00
Instrument Metal Housing w/ twist-lock plug		$200.00
Miscellaneous Parts		$200.00
		$1,170.41
CA Sales Tax (≈ 9%)		x 1.09
	Total	$1,275.75

Development Time –

- LED Array – 30 hours
- Thermal Management – 10 hours
- Instrument Housing Attachment – 25 hours
- Testing – 10 hours
- Total Development Time – 75 hours

Initial Cost Estimate (Reduced Scale)

Warm White Rebel, Pre-Mounted on Tri-Star Base x 15		$283.05
Pre-Cut Thermal Adhesive Tape x 2		$14.98
Heat Sink x 2		$40.00
Instrument Metal Housing w/ twist-lock plug (Donated)		FREE
Miscellaneous Parts		$100.00
		$438.03
CA Sales Tax (≈ 9%)		x 1.09
	Total	$477.05

Actual Final Cost

For actual final costs refer to Appendix C.

Original Estimated Development Time

- LED Array – 20 hours
- Thermal Management – 10 hours
- Instrument Housing Attachment – 15 hours
- Testing – 10 hours
- Total Development Time – 55 hours

Actual Development Time

LED Research – 20 hours
Thermal Management Research – 15 hours
Instrument Housing Research– 3 hours
DMX Driver/Decoder Research – 25 hours
Power Supply Research – 5 hours
Resistor Research – 2 hours
Build Time – 7 hours
Testing and Measurements – 10 hours
Total Development Time – 87 hours

Manufacturability

Estimated devices sold per year

Las Vegas Theater (500 lights x 5) = 2,500 devices

The Largest Theaters in the world do not have new shows every week but rather one show ever 2-5 years so extremely large lighting collections are necessary

Large Theater (200 Lights) x 36 = 7,200 devices

Larger Theater houses will be able to purchase many lights at one time to replace an entire collection of older model lights. Example would include the Performing Arts Center in San Luis Obispo
(3 customers per month)

Small Theater (40 Lights) x 24 = 960 devices

Smaller Theater houses will not be able to purchase large amounts of equipment at once like new larger theaters. Example would include the Spanos Theater in San Luis Obispo
(2 customers per month)

Small Inventory Replacement (12 Lights) x 264 = 3,169 devices

Many Theater houses like to replace smaller quantities of lights to slowly phase out older technology. Examples would include the SLO Little Theater in San Luis Obispo
(22 customers per month)

Individual Purchases (1 Light) x 1200 = 1,200 devices

Purchases will be individuals buying 5 or less lights at a time to test and use on their own before making larger purchases.
(100 customers per month)

Total Purchases = 15,029 devices sold per year

Estimated Total Build Cost per device = $250
Total Manufacturing Cost per year = $3,757,250
Estimated Purchase Price = $500
Estimated Annual Revenue = $7,514,500
Estimated Annual Profit = $3,757,250
Lifetime of device = 50,000 hours

Operation Cost over lifetime (not including power usage) = 0.008¢ / hour
Operation Cost over lifetime(including power usage) = 0.008¢ + 8¢ = 8.008¢ / hour

Environmental Impact

Compared to incandescent light bulbs, light emitting diodes have a much longer life and are not disposed of nearly as often. The HPLs created by ETC are rated at only 300 hours lifespan. The Phlatlight CST-90 series LED is rated at 60,000 hours, meaning the lifespan of one LED is the same as around 200 light bulbs. 200 light bulbs are around 100 pounds of landfill waste whereas 200 of the CST-90 LEDs are only 15.66 pounds.

The warm white color of the CST-90 LED is created using an Indium Gallium Nitride (InGaN) combination. When burned, Gallium Nitride emits toxic fumes of ammonia, though in small levels not large enough to cause health problems other than irritation after inhalation. Indium in its metal form has not been found toxic to humans. This form of indium is widely used in the welding and semiconductor industries. Experiments on the toxicity of indium in humans have produced the widespread conclusion of low toxicity and minimal health hazards. However, indium compounds such as indium trichloride ($InCl_3$) show signs during animal testing to suggest probable toxicity in humans. [22]

Sustainability

The topics of Green Energy and Sustainability have in recent years become a goal many companies and industries strive to achieve. By living up to sustainable standards consumers and corporations can save money, live healthier lives, and promote the wellness of future generations. Sustainability describes a condition in which natural systems and social systems survive and thrive together indefinitely [23]. These systems, called the 4 E's, are the Environment, Economy, Energy, and Equity systems. When these four systems harmonize with each other they promote sustainable designs. High power LEDs may hold a future for the world's general purpose lighting needs and would benefit future generations more if manufactured with sustainability in mind.

Economy:

Consumers are most excited for the integration of high power LEDs into projectors, architectural lighting, and in general lighting for the home. The initial transition from incandescent lighting to LED lighting is costly but over time becomes a cost effective decision. Online, LED bulbs cost between $10 and $40; this means replacing 20 incandescent bulbs in a home with 20 LED bulbs currently costs anywhere from $200 to $800. If LED lighting continues to grow in popularity the price per LED bulb will dramatically decrease to levels affordable to the general consumer. As highlighted in Table 1 on pg. 9, costs for electricity considerably decrease when using LED bulbs instead of incandescent bulbs. After about 2 – 3 years, the initial LED bulb cost is spread over a large time frame and costs less than using and replacing

incandescent bulbs. After 20 years the LED bulb may still not need replacement and will continue to save money for the consumer.

Environment:

If high power LED technology becomes common in general lighting applications, world indium supplies will continue to decrease and may soon run completely out, at least according to some reports. Many white high power LEDs are made using Indium Gallium Nitride (InGaN) blue LEDs encapsulated in a phosphor coated epoxy. In 2004 a report by the U.S. Geological Survey estimated indium reserves would not run out anytime in the foreseeable future, even considering the large boost in indium mining due to LCD display production [24]. 3 years later in 2007 an article written in the New Scientist Magazine suggested indium reserves would run out by the year 2020 [25]. Later that year, the Indium Corporation, the world's largest supplier of indium, announced new methods of indium extraction from the earth's crust, claiming these new mining techniques make the supply of indium sustainable, reliable, and sufficient to meet the current and future needs for indium [26]. Some scientists do believe indium reserves will run out in the near future but no further evidence has come forward to support their claims. Recently scientists have also struggled to determine Gallium reserves. The price of Gallium skyrocketed in 2000 due to inventory overstocking by cell phone manufacturing companies fearing a shortage in Gallium. Since then Gallium prices plummeted after suppliers confirmed plenty of reserves still in existence. Like indium mining companies, gallium miners promise faster and improved processes to extract the metal from the earth's crust [26].

Energy:

As LED technology continues to improve in brightness and lumens per watt efficiency, most incandescent light sources may very well become obsolete in the coming years. LED technology recently has taken ahold of a portion of the flat screen television, car headlight, and general lighting markets. Because of LEDs each market benefits from lower energy consumption and lower costs for electricity. The high power LED development process does however consume large amounts of energy year round. Production requires nitrogen enriched cleanrooms to prevent the InGaN die from oxidizing. The cleanrooms also prevent water molecules and dust particles from contaminating the LED wafers [27]. The fans within cleanrooms run 24 hours a day every day of the year meaning they constantly consume energy. The amount of energy consumed in one year for a 1,000,000 m3/h Class 5 cleanroom can surpass 4.85 billion kWh and costs well over $300,000 [28]. Though the final LED products consume less power than current lighting techniques the process to manufacture them consumes very large amounts of power.

Equity:

Potentially, high power LED lighting could influence the entire world in the years to come. China, Japan, the United States of America and Europe consume by far most of the world's electricity. By setting the example to other countries these four regions could benefit the most first in energy savings and then by economic profit in the development of more LED technology. Third-world countries have not acquired reliable electricity distribution like the U.S. has so electricity easily becomes a precious commodity. Saving energy on lighting costs using LED technology may increase the benefit to humanity and hopefully lead to a better planet.

Ethical

This project involves a device handled everyday by theater technicians, students, volunteers, and anyone lending a helping hand in a theater. Because this instrument uses high enough voltages and currents to cause injury or death, becomes hot enough when in use to cause severe burns, and emits a light bright enough to cause vision loss it is imperative to create the necessary training and educational material to properly train those using the instrument.

Health and Safety

As with any theater light there are many hazards along with the use of the LED lighting instrument. Highly saturated gel colors will burn out when used for long periods of time. The light fixture will get to temperatures beyond 130° F, the temperature at which skin begins to burn when in contact for an extended time. Accidental eye exposure to the brightness of the LEDs can lead to vision loss, so precaution must be taken when pointing the light towards the face. Electrical safety is a must due to voltages of up to 120V and high amperage. When hanging the light you must use a proper safety cable. These instruments are very heavy and when falling from an elevated height could cause severe injury.

Social and Political Concerns

If LED lighting fixtures become bright enough to light a stage as a spotlight rather than just a floodlight, incandescent light bulbs will become relics. There is already small shifting in the market from high performance lights to LEDs. LED fixtures have already proven themselves as very viable sources of stage flood lighting. Currently LED fixtures are in the thousands of dollars rather than the hundreds and many production companies are hesitant to spend so much money upfront for this newer technology. If prices were reduced to 50% LEDs would quickly become the first choice when replacing broken or old fixtures. Theater houses not in position or ownership of LED fixtures may not receive as many shows coming through due to their old technology.

Appendix B – Vendor Details

Digikey Corporation
www.digikey.com
701 Brooks Avenue South
Thief River Falls, MN 56701 USA
1-800-344-4539

Mouser Electronics
www.mouser.com
1000 North Main Street
Mansfield, TX 76063
1-800-346-6873

Avnet Electronics Marketing
2211 S. 47th St.
Phoenix, Arizona 85034
1-800-332-8638

EcoLight LED Lighting Solutions
www.ecolightled.com
255 Distribution Drive, Unit 104
Sparks, Nevada 89441
1-866-348-3492

Dove Systems
3563 Sueldo St. Unit E
San Luis Obispo, CA 93401
1-805-541-829

RadioShack
481 Madonna Road, Suite A
San Luis Obispo, CA 93405
1-805-544-5400

Appendix C – Total Costs

Table 6: Total Costs

Description	Manufacturer	Place of Purchase	Part #	Cost
CST-90 LED	Luminous Devices	Avnet Electronics	W30M-C12-GK701	$47.93
1.2 C/W Heatsink	Crydom Heatsinks	Mouser Electronics	558-HS122	$30.00
DMX512 Decoder/Driver RGB LED	EcoLight LED Lighting Solutions	EcoLight LED Lighting Solutions	LC-LT-3DMX	$74.99
Power Supply 5V 10A	TDK Lambda	Digikey Corporation	LS50-5	$25.26
Resistor .22 OHM 35W	Ohmite	Digikey Corporation	TCH35PR220JE	$9.23
Thermal Tape Double Sided .005"	Bergquist	Digikey Corporation	BP100-0.005-00-1112	$18.39
8" x 6" x 3" Project Enclosure Box	Radioshack	Radioshack	270-1809	$6.99
			Total Tax	$12.15
			Total Shipping	$37.40
			Total Expenses	$262.34

The total expenditures for this project were $262.34 and the initial budget was $250.00. This project went $12.34 over budget or 4.93% of the total estimated cost. This is not a concern for the project and is considered successful.

Appendix D – LED Decision Matrix

Table 7: LED Decision Matrix

LED	Phlatlight CST-90	Cree X-Lamp XP-G	Luxeon Rebel	Weight
Rated Lumen Output	+	+-	-	10%
Thermal Resistance	++	-	--	30%
Rated Power	-	+	++	10%
Lumens/Watt	-	+	+-	5%
Color Temperature	+	-	+	15%
Maximum Lumens	++	+	--	30%
Totals	330	0	-235	100%

Key
++ = 5
+ = 3
+- = 0
- = -3
-- = -5

The above decision matrix compares three LED options considered for the design at the beginning of this project. The weights stated represent the importance of each specification. By far the maximum lumen output and thermal resistance weigh the most. Thermal resistance determines how well heat transfers from the LED to the heat sink. If the heat of the LED grows above 150°C the lifetime ratings and maximum lumen output dramatically decrease. This project hinges on lumen output above 800 lumens and the Luxeon Rebel comes nowhere near this amount. Where the XP-G performs well in lumen output it loses in thermal resistance. The CST-90 performs very well in both lumen output and thermal resistance, therefore the CST-90 was chosen for this project.

Appendix E – Heat Sink Decision Matrix

Choosing a heat sink to cool the CST-90 LED requred calculations from the Luminare Design guide to determine the necesarry thermal resistance of the heat sink:

$$T_j = T_a + (R_{th\ b\text{-}a} \times P_{total}) + (R_{th\ j\text{-}sp} \times P_{LED})$$

where

T_j = 150°C maximum (from CST-90 datasheet)
T_a = 23°C (room temperature)
P_{LED} = 6A x 3.6V = 21.6 W
(With 6A of drive current, the CST-90 will theoretically emit 875 lumens.
With 6A of drive current, the CST-90 Forward voltage ≈ 3.6V)
P_{total} = 21.6 W
$R_{th\ j\text{-}sp}$ = 0.9°C/W (from CST-90 datasheet)

Solving for $R_{th\ b\text{-}a}$,

$$R_{th\ b\text{-}a} = \frac{\mathrm{Tj-Ta-(Rth\ j-sp\ x\ PLED)}}{Ptotal} = \frac{150°C-24°C-(0.9°C/W\ x\ 21.6W)}{21.6W} = 4.93°C/W$$

Table 8: Heat Sink Decision Matrix

Heat Sink	Aavid TO-220	Ohmite SA-176E	Crydom HS122	Weight
Rated Thermal Resistance	+-	+	++	40%
Ease of Mounting to LED	+	++	++	15%
Ease of Mounting to Instrument	--	--	++	35%
Price	++	+	-	10%
Totals	-80	50	420	100%

Key
++ = 5
+ = 3
+- = 0
- = -3
-- = -5

The above decision matrix clearly highlights the desired qualities of the Crydom HS122 compared to two other technologies considered for the project. The Aavid TO-220 and Ohmite SA-176E are custom made heat sinks for high power LED cooling applications but are very awkwardly shaped and would not easily mount to the instrument body. All three heat sinks have lower thermal resistivities than required but the HS122 has the lowest, making it the most likely to transfer heat efficiently.

Appendix F – DMX Driver/Decoder Decision Matrix

Table 9: DMX Driver/Decoder Decision Matrix

Driver/Decoder	Elation ELAR Driver 1	EcoLight DMX	Creative Lighting DMX	Weight
DMX ready	+-	+	+-	20%
High current output	+	+	+-	40%
Low Output Voltage	--	+	++	20%
Price	+-	+-	+-	15%
Size	+	+	+-	5%
Totals	35	255	100	100%

Key
++ = 5
+ = 3
+- = 0
- = -3
-- = -5

To emit 800 lumens in the CST-90, the LED driver must deliver 6A to the LED circuit. A resistance in series with the LED allows easy setting of the current but can possibly consume more power than the LED if the voltage and resistance is set too high. Smaller voltage supplies and smaller resistance values can drive the same current as larger values without consuming nearly as much power. It is also important for the driver to have an easy to connect DMX plug for ease of use for stage technicians. Though the Elation ELAR Driver 1 and Creative Lighting DMX drivers both have DMX capabilities the necesarry DMX plug is seperately purchased. The EcoLight DMX Driver/Decoder makes connecting the lighting instrument to a DMX universe simple.

Appendix G – Power Supply Decision Matrix

Table 10: Power Supply Decision Matrix

Power Supply	CUI VSBU-125	CUI VOF-45-5	TDK LS50-5	Weight
Output Voltage	++	++	++	30%
Power	++	++	++	35%
Ease of Mounting	+	-	+	25%
Price	--	+	+-	10%
Totals	350	280	400	100%

Key
++ = 5
+ = 3
+- = 0
- = -3
-- = -5

Power supplies converting AC voltage to DC voltage come in seemingly infinite different variations and many are so similar it becomes a matter of personal preferance in deciding which to buy. The TDK Lambda LS50-5 fit the power supply description needed for the DMX driver/decoder and came at an inexpensive price. Power supplies manufactured by CUI come in very similar styles to the TDK Lambda products but at a much higher price.

Appendix H – LED Datasheet [18]

Datasheet Available at Referenced Website

Appendix I – Heat Sink Datasheet [19]

Datasheet Available at Referenced Website

Appendix J – DMX512 Driver/Decoder Datasheet [20]

Datasheet Available at Referenced Website

Appendix K – Power Supply Datasheet [21]

Datasheet Available at Referenced Website

Appendix L – Resistor Datasheet [29]

Datasheet Available at Referenced Website

Appendix M – Initial Gantt Chart

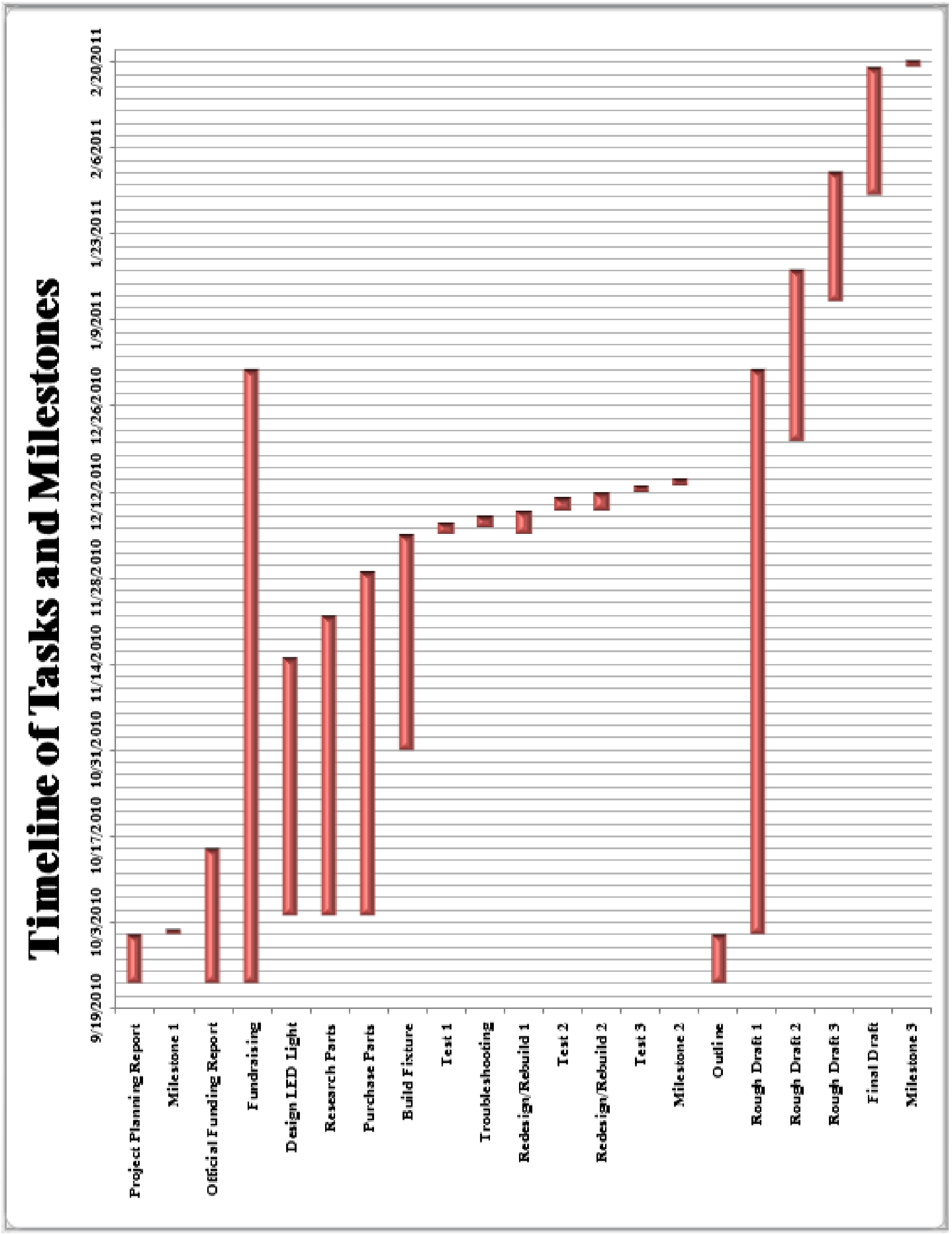
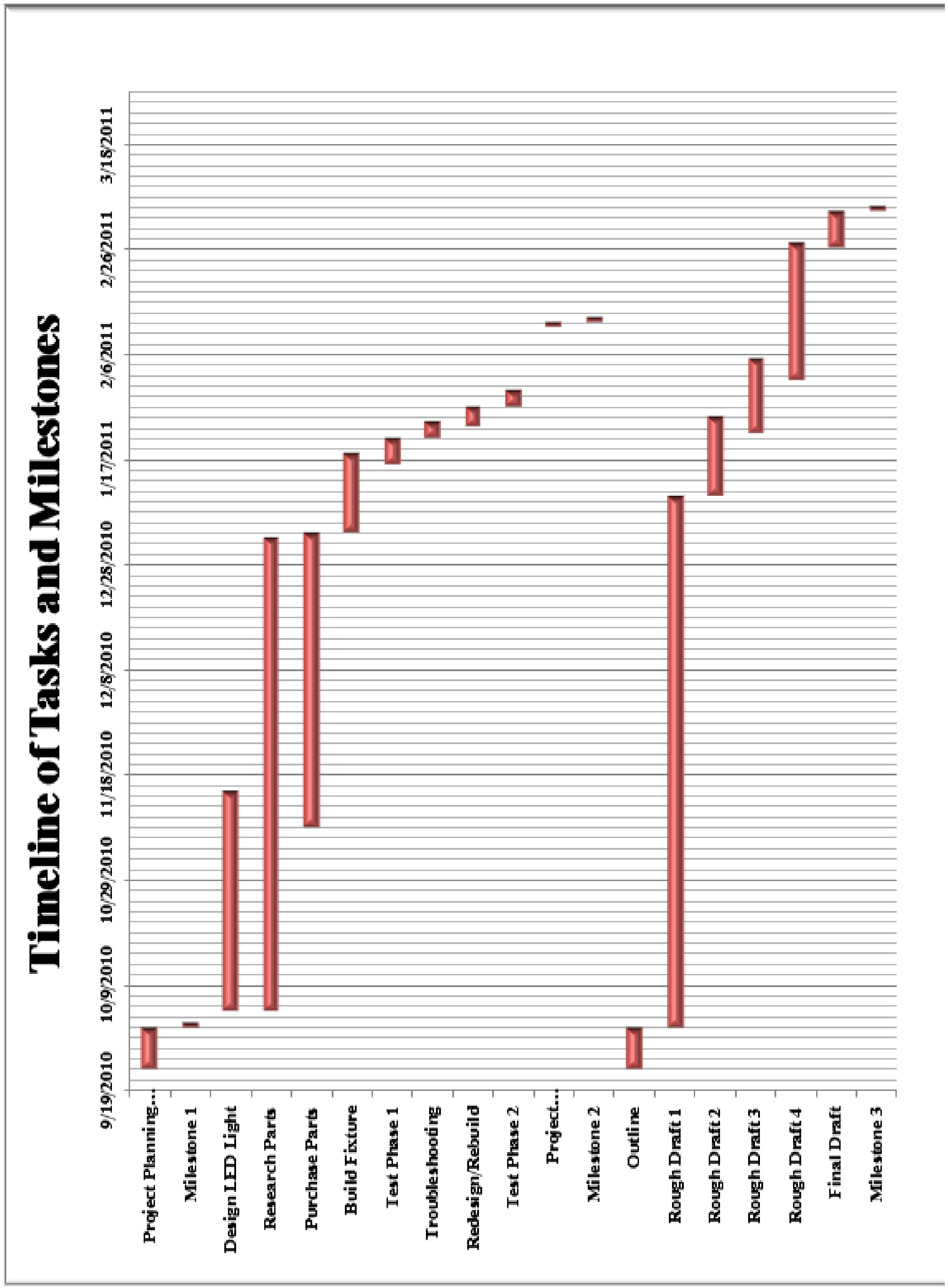


Figure 16: Initial Gantt Chart

Appendix M displays the intended timeline for the project. Created in October 2010, this Gantt chart provided a timeline for project completion. Appendix N displays the actual timeline followed for the project. Fundraising the project never blossomed into any significant portion so it was completely cut out. The research and design tasks required much more time than initially anticipated. This pushed the time to write project report drafts to mid-January instead of December. This also resulted in replacement of the testing phase to January instead of December.

Appendix N – Final Gantt Chart



Figue 17: Final Gantt Chart