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P08428 LED Lighting Technologies for a Sustainable Entrepreneurial Venture

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ABSTRACT

Light Emitting Diodes (LED) have gained much interest recently. LED's have a great potential to lead the lighting industry as efficient light sources. Implementation of LED's to walkway lighting systems will provide a launch pad for new technology to develop an energy efficient environment with a focus on sustainability. The greatest lighting conditions are achieved when LED's are used in conjunction with reflectors positioned at critical angles to direct light only where it is needed. The replacement kit has been built and tested to be the most efficient walkway lighting system with comparable light distribution characteristics to Metal Halide fixtures. The system achieves an even light distribution pattern at 1/3 of energy consumption when compared to metal halide lamps. This lighting system was developed with current technology, but with the expectations that LED technology will improve considerably by 2012. It is the goal of this paper to describe the development process of a new five board LED replacement kit for walkway lights.

NOMENCLATURE

kWh: kilowatt-hour
PCB: printed circuit board
Ft-cd: Foot candle

INTRODUCTION

RIT is dedicated to environmental issues and sustainability. This project entails developing a product that will conserve electrical energy, and reduce Maintenance costs to meet the requests of RIT Facilities Management Services. Current exterior lighting technologies are resource intensive and not electrically cost effective. RIT spends about $6 million per year in electrical costs, which half is due to lighting. RIT also dedicated a large portion of resources in the maintenance of exterior lighting. A new Light Emitting Diodes (LED) replacement kit that is easily implemented in existing light fixtures will provide a more robust and energy efficient lighting system.

It was found from project P07421 that off-the shelf LED light fixtures are inadequate due to their small lit area. This lit target area needs to be comparable with the current lighting system in order for the replacement kit to be successful. The new design relies heavily on the performance of LED's and their directional placement. It is expected that LED efficiencies will continue to increase to a point where this concept can be adapted to more powerful applications, such as parking lot lights.

PROCESS

Light Modeling

Light, or any electromagnetic wave, in a vacuum obeys an inverse square law: $I = \dfrac{I_0}{4\pi r^2}$ where I is the intensity at a distance r from a given intensity source I_0. This describes how the amount of light needed at the source to give a certain illumination quadruples as the distance to the target doubles. For simplification of the model, it can be assumed that light has the same characteristics in air as it does in a vacuum[1].

It was decided to use computer-based modeling tools once we discovered the impracticality of modeling light with hand-calculations. Contacting Dr. Robert MacIntyre in the College of Imaging

Science led us to examine Lambda Research Corporation's OSLO software as a possible solution. OSLO did not provide the needed capabilities, but another Lambda product TracePro, seemed to be a good fit.

Lambda was contacted and provided a license copy of TracePro through their University Gratis Program. TracePro can import physical models from Pro/ENGINEER and then apply surface properties (such as reflectivity, absorptivity, etc) and also make surfaces into light sources. TracePro then traces a user defined number of rays and wavelengths for each source (usual simulation ran 500 rays per wavelength per source, with a total of 25 wavelengths sampled). We were able to create models of our LEDs and fixtures, apply properties, and find the overall lighting distribution.

Experimental testing on our alpha prototype was carried out in a dark room with the use of a light meter to determine if the prototype met our customer's needs of 0.5ft-cd light density over a 12ft x 80ft coverage area. The prototype was positioned 14 feet away from a surface to simulate the height of the fixture when installed. Light intensity measurements were taken at four points on the target surface. These points included the center of the light pattern, six feet below the center, forty feet laterally from the center, and forty feet laterally and six feet down from the center of the light pattern.

The experimental data obtained did not validate the anticipated results of the computer simulation. Later investigation showed that the simulation inputs had been entered incorrectly and that the small-angle collimating lenses, which consolidate the light output into a tighter pattern, were not performing as shown on the manufacturer's specification data sheet:

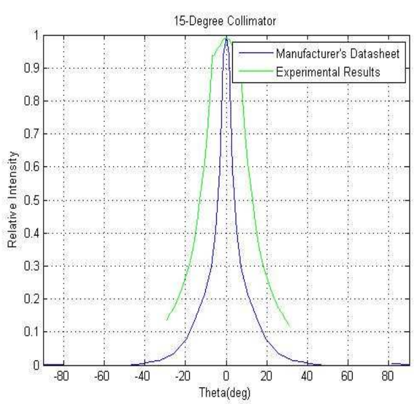

Figure 1: Light distribution curve for 15-Degree Collimating Lens

As can be seen in Figure 1, the actual result from the 15-degree lens is a much wider spread than the data sheet indicates. Note that the LEDs used in the alpha prototype had a 120-degree viewing angle. For the first prototype, we also had used a 30-degree collimating lens for the shorter-distance LEDs, which produced the following photometry data:

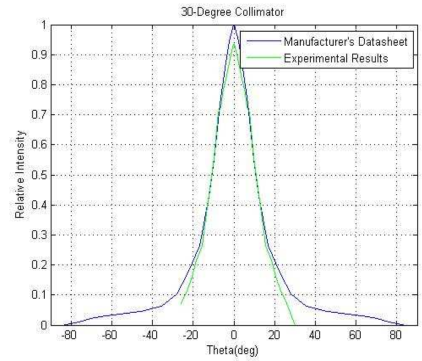

Figure 2: Light distribution curve for 30-Degree Collimating Lens

The lens described in Figure 2 produced a light pattern that was considerably closer to the manufacturer's data sheet; however, we needed the 15-degree lens for the longer-distance illumination. Overall, the far edges of the light pattern were at roughly ¼ of our specified intensity. The intensity results for the first prototype ranged from ½ ft-cd to $1/10^{th}$ of a foot-candle.

TracePro produces a number of outputs, but only one type was useful for our purposes. Our latest lighting "scenario" shows an illuminance map of the same area as the walkway using CREE XLamp LEDs and custom elliptical reflectors.

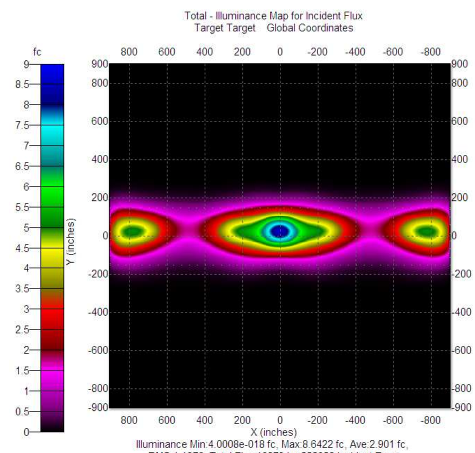

Figure 3: Illuminance Map of 3 fixtures

Figure 3 shows the incident flux on a large plate. The walkway in this scenario is a rectangular area with opposing corners at coordinates (480,120)in. and (-480,-24)in.

Due to difficulties in manufacturing custom reflectors, we are substituting a new collimating lens made by FraenSRL. Our beta prototype was tested using two types of the Fraen lenses: one with a 28-degree viewing angle and one with a 20-degree viewing angle. Again, the smaller-angle lenses were used to illuminate the areas further away. The beta prototype test was successful with a minimum measurement of 0.61 ft-cd at the farthest corner of the test area; overlap between fixtures will increase this value to 1.22. The maximum measured value was 3.0 ft-cd.

One other customer requirement was to reduce light pollution. Usually, this is defined by luminance, further defined as the incident intensity multiplied by the reflectivity of the surface. As the surface is not changing, the reduction of total incident light on the surface using our fixture meets this requirement by default.

Mechanical Design

The focus of the mechanical design was to deliver a light fixture assembly that was easy to install, was durable, and was cost efficient. This took the form of a "drop in" replacement for the internal components of the existing light fixtures, reusing the exterior structure of the fixture housing, including the glass cover. This "retrofit" assembly uses the same mounting features as the bulb reflector it replaces, eliminating the need for modification to the fixture housing.

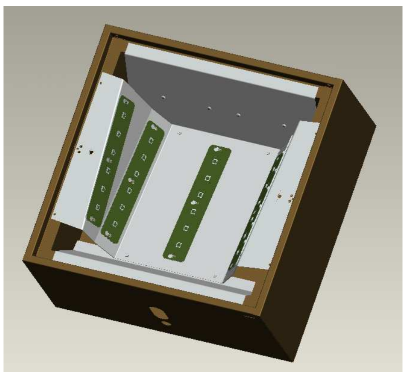

Figure 4: Fixture Assembly

Figure 4 shows the 3D model of the insert assembly mounted in the fixture housing. The insert assembly consists of three pieces of sheet aluminum, .063" thick, formed to provide mounting surfaces for the Printed Circuit Boards (PCBs), transformers, and to provide good thermal grounding with the fixture housing. Earlier revisions consisted of a single aluminum plate, which did not provide enough surface area for good thermal dissipation. The three plate configuration also provides better mechanical stability. The PCBs are attached to the base plate using three 6-32 screws, providing good clamping pressure to minimize thermal contact resistance between the PCB and the base plate.

A concern with mounting the PCBs to the base plate was that they be easily replaced when needed. Although the LEDs have a longer lifetime than the metal halide bulb, they will need to be replaced during the lifetime of the fixture. The most efficient means of replacing the LEDs is to replace the entire PCB. This was accomplished using a "keyhole" design, whereby the screw is retained in the base plate, and the PCB can be simply slid over and pulled up. This eliminates the chances of losing fasteners, which was a concern to our customer. The screws also have a standard #P2 drive, eliminating the need for special tools.

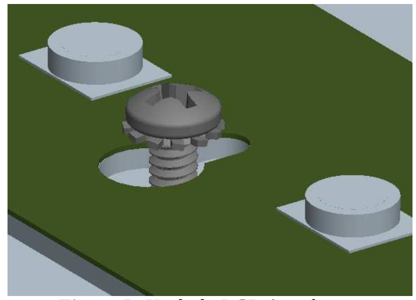

Figure 5: Keyhole PCB Attachment

The three pieces of sheet aluminum are attached to each other using 8-32 screws and press in "clinch" nuts. These fasteners provide a very strong connection and eliminate any possibility of damaged threads. The .063" aluminum plate is sufficiently thick to use a self-tapping screw, which could be implemented in a cost-reduction effort. This three plate configuration is ideal for prototype purposes, but for production quantities, a one-piece stamping could be used.

Thermal Analysis

Thermal analysis was completed in several stages. Quick hand calculations were first performed to evaluate the feasibility of the project. A simple 1-D thermal resistance network was formed. Heat flux and temperatures were first set at assumed values so that natural convection coefficients could be calculated. After the properties were established, an iterative process could be used to solve for temperatures at various points [4].

The second form of thermal analysis used was a finite element (FE) model. The 3D computer model made in Pro/Engineer was imported into Pro/Mechanica. Material properties were assigned, and boundary conditions applied. Contact resistances were modeled using thin solids. The values for natural convection coefficients found in the hand calculations were used as boundary conditions in the FE analysis.

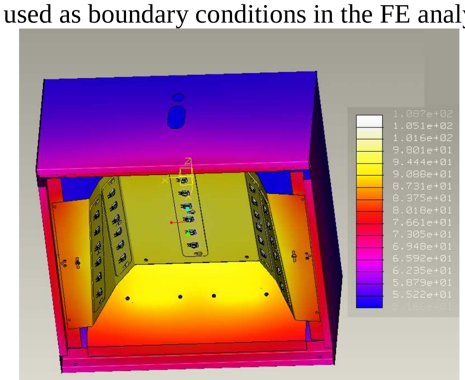

Figure 6: Thermal Analysis

In this thermal simulation, the ambient temperature was held at 50°C, the bulk temperature inside the fixture was assumed to be 86°C. Each LED was assumed to dissipate 1.4W, each transformer 4W, and the average natural convection coefficient was 12W/m^{2}K. Maximum case temperature of the LEDs was measured at 109°C under this "worst case" scenario. Using the datasheet value of thermal resistance of the LED, junction to solder point of 8°C/W, this gives a maximum junction temperature of 120°C. The maximum junction temperature for these LEDs is 150°C.

Once the prototype fixture was assembled, thermal tests were run using thermocouples. Data was recorded at several points on the assembly. A test on an early prototype which consisted of a single base plate supporting the PCBs and transformers revealed a high thermal contact resistance between the PCB and the base plate, which was remedied using the "keyhole" and screw attachment method, and a high thermal resistance between the base plate and the ambient conditions, which was remedied with the two additional end plates. These plates allowed the transformers to be mounted away from the PCBs, increased the surface area of the assembly, and increased the contact area between the insert assembly and the fixture housing. Subsequent thermal testing showed a 20°C drop in temperature at the LED solder point under identical conditions with the revised configuration. This second round of testing agreed very closely with the FE analysis.

Circuit Design/Power Conditioning

The overall circuit design meets the engineering specification with the total power of 60 Watts, and is designed to run on a standard 120VAC input. Using a 120/208/240V - 24VAC step-down transformer provides the proper operating voltage for each of the 5 LED board modules. A bridge rectifier was used to rectify this 24VAC signal. This entailed changing the 24VAC signal to a 24VDC signal usable for LED applications. An RC filter was used to eliminate the ripple voltage. Ripple voltage is a small amount of AC signal that remains on a rectified voltage. In other words, instead of having a purely DC voltage (straight line), there are peaks and valleys in the shape of a sine wave, but much less than that of a purely AC signal. The current control system, or "ballast" in this system is a simple network of resistors used to maintain the desired 400mA current through each array of LEDs. A total of 12.73 W from the five circuit boards is dissipated due to the resistive LED drivers. Each board consumes 10.65 W.

Figure 7 displays a circuit design with the solder pad footprints of the Cree LEDs and circuit components. The production board's layout contains most of the copper top surface to maximize heat transfer

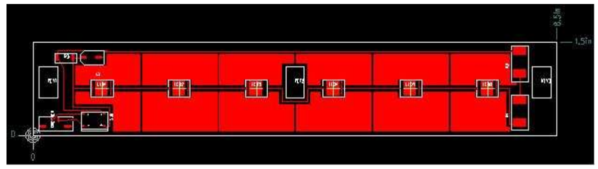

Figure 7: PCB layout

Figure 8 shows the circuit design for one LED board. The AC line in voltage source is representative of the 120VAC to 24VAC transformation. The RC circuit reduced the ripple voltage from the full bridge rectifier. The ripple was reduced to 57.6 mV.

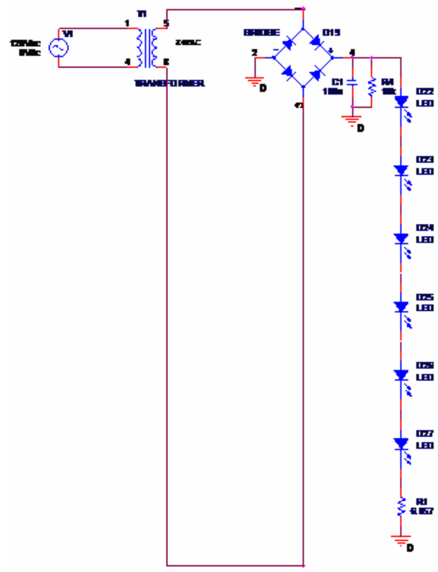

Figure 8: Single LED board schematic

Each LED is 1.34W, 400mA, 3.35VDC drop. Each current limiting resistor dissipates ~2.4W. The 15 ohm resistor limits the drive current through the LEDs to 400mA. The RC circuit reduces the ripple voltage from the full bridge rectifier.

TESTING

LED High Temp Test

This test was designed to verify the thermal models and performance of the LED lighting system under high temperature (66°C) operating conditions in the fixture. The LED lighting unit was powered by a 120VAC input supply. The unit was monitored with a thermocouple placed at the LED/PCB junction (Tj) via a soldered connection. The temperature inside of the fixture (Tsur) was measured with another thermocouple placed in the middle of the fixture. The voltage to an LED was measured to check the status of the LED's and confirm that they are still lit when inside the heat chamber. The temperature outside the fixture (Ta) was recorded at the start of the test. The duration of this test was for 60 minutes.

Measurements were taken every minute and recorded. Failure occurred if the LED/PCB junction temperature (Tj) rose above 110°C. The test proved to be successful, since no failures occurred.

LED Low Temp Test

This test was designed to verify the thermal models and performance of the LED lighting system under low temperature operating conditions in the fixture (-30°C). The LED lighting unit was powered by a 120VAC input supply. The unit was monitored with a thermocouple placed at the LED/PCB junction (Tj) via a soldered connection. The temperature inside the fixture (Tsur) was measured with another thermocouple placed in the middle of the fixture. The voltage to an LED was measured to check the status of the LED's and to confirm that they were still lit when inside the heat chamber. The temperature outside the fixture (Ta) was recorded at the start of the test. The duration of this test was 60 minutes. Measurements were taken every minute and recorded. Failure occurred if the LED/PCB junction temperature (Tj) rose above 120°C. The test proved to be successful, since no failures occurred.

Ease of Installation

One specification is that the fixture can be easily replaced. The current fixture type is estimated at taking two hours to prepare and install. Maximizing the number of pre-assembled parts was vital in making sure the new fixture could be installed quickly and easily.

A time study was designed to test the time it took to install components into the current metal halide fixture versus removing old components and installing the new retrofit materials. Each test assumed the fixture already had metal halide components which needed to be removed. The metal halide test required removing the bulb, disconnecting all wires then removing the diffuser assembly and ballast assembly. A new ballast assembly would have been put together in the workshop before working at the pole. A new diffuser assembly, ballast assembly, and bulb would be placed in the fixture. All wires would need to be connected between the pole and the fixture.

The LED retrofit required disconnecting and removing all metal halide components. The new components would come fully assembled to the base plate. Electrical components would be connected; the base plate would be set into the fixture and attached to the fixture with screws.

It was assumed that certain aspects between the two situations were similar, such as driving to the fixture pole and climbing a ladder. Therefore the only difference was the components themselves. The test was performed on a table top indoors, not at a fixture pole. The average time to install the LED system in ideal conditions was 75.19s.

Ease of Replacement

In order to reduce replacement time, the steps to replace the current boards needed to be mistake proof. This led to standardization of similar boards and making visual distinctions on different components to make sure they were placed properly. The testing covered two metal halide replacement situations, the bulb only and the bulb with ballast, and LED circuit board replacement.

The bulb test requires removing the old bulb and screwing in a new one. The second metal halide test requires removing the bulb, disconnecting the diffuser and ballast, removing the ballast assembly and replacing the ballast, capacitor, and igniter, connecting the wires, and zip tying components in place, and finally placing all components back in the fixture. The LED board replacement requires each of the five boards to be disconnected from the power then loosened from the base plate. New boards are placed in position and connected to the power supply.

The replacement test followed many of the same principles as the installation test. The average time to replace the bulb with ballast was 569.0s. The average time to replace the LED system was 104.31s, which resulted in a time savings when compared to the metal halide system.

AC Rectification

This test was designed to verify the usability of a rectified AC source with the LED lighting system. LEDs being DC operated devices require a rectification circuit in order to run on RIT's power grid. Using a bridge rectifier, a DC voltage was attained from the AC source. However, rectified signals are not purely DC. Rather, a small to moderate ripple voltage remains. Depending on the application, this ripple voltage may be an issue. To test the usability of this rectified signal in a lab setting, the 24VAC transformer output was rectified. Using a digital oscilloscope, the output of this rectified circuit was monitored, and values for peak and ripple voltages were measured. The test was then repeated using an RC filter with calculated values for the Resistor and Capacitor: 10kOhms and 100uF, respectively. After the second set of measurements were taken, both tests were repeated visually by connecting the rectified circuit to a 6-LED board module. A visual check was made to discern failure. Failure occurred if the LEDs did not turn on or there was a noticeable flicker occurring in the LEDs during operation. The test proved to be successful, since no failures occurred.

Power Consumption

This test was designed to verify the customer's need of creating a new lighting system that is more energy efficient than the current system. The LED lighting system was powered while the current and voltage were recorded. The duration of this test was 10 minutes, and occurred after the system reached steady state. Failure occurred if the LED lighting system requiring more power than the metal halide system. The test proved to be successful, since no failures occurred.

RESULTS AND DISCUSSION

Emissions

In the early phases of the design it was decided that powering the retrofitted fixtures by a separate energy source, such as wind or solar, would not be cost effective. The goal instead was to reduce the total energy each fixture requires. RIT does receive its energy from a number of different sources. The breakdown is show in Table 1.

Biomass	<1%
Coal	31%
Gas	23%
Hydro	11%
Nuclear	23%
Oil	12%
Solar	0%
Solid Waste	<1%
Wind	<1%

Table 1: RIT Fuel Sources from Amerada Hess

Using LEDs reduced the power from 165 watts to 60 watts. This also led to a reduction in carbon emissions. Table 2 shows the changes in CO_2 emissions from metal halide to LED for one fixture. The factor for New York was 0.86 lbs/kWh, but based on RIT's fuel sources the factor was increased to 1.1868 lbs/kWh.

	LED	**Metal Halide**
kWh/year/fixture	262.80	722.70
Total lbs/kWh/fixture	311.89	857.70
lbs/kWh for Hess/RIT	1.1868	

Table 2: CO_2 Emissions per Fixture [3]

All tests that were conducted have met the customers' specifications. This results in an end product that will be implemented at RIT. The success of the product at RIT's campus suggests that other campuses might have interest in the LED replacement kit for walkway lighting systems.

CONCLUSIONS AND RECOMMENDATIONS

The LED replacement kit for walkway lights has proven to be highly successful in reducing power consumption with a comparable light distribution. All customer needs have been addressed with the design of the five board LED replacement kit, but there is still room for improvements. The increase of LED efficiencies and luminance output will allow for a greater energy savings while having larger possible lit target areas. A pivotal component in maximizing the light output from the LED's is specific elliptical reflectors that was not included in the replacement kit due to the high costs and long lead times. More investigation is needed in the development of the manufacturability of the reflector before the LED lighting fixture can be optimized further.

While choosing not to optimize the light distribution more, we are meeting our customers' concerns regarding initial costs. The product would not be successful in the market if we did not consider the initial cost and its affects on the customers' return on investment.

The product is truly a viable alternative lighting solution for walkways. It allows the customer to implement a robust and moderately priced system without a major replacement of all current fixtures. This relates in a reduced time to see savings, as well as reusing old fixtures in an effort to promote sustainability.

Two fixtures have been retrofitted with the LED replacement kit on the RIT campus. The two fixtures are located next to a high pressure sodium (HPS) fixture and a metal halide fixture to compare the different lighting systems. The site chosen for implementation is on the residential side of campus in an effort to generate interest in new lighting technology.

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Personal conversations with Dr. Robert MacIntyre, various dates.
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