7. DESIGN OVERVIEW

Fig. 5 shows a solid model of our final design, and Fig. 6 shows a picture of our final prototype.

Our design is relatively simple. A total of 30 LEDs are used in the luminaire—achieving predicted luminaire output of 1315 lumens. They are divided equally among two heat sinks and spaced 2.8 inches apart. All the LEDs face upward towards a diffuse reflective surface.
in the shape of a double parabola. Each row of LEDs is strategically located at the foci of the parabolas—resulting in even light distribution from the luminaire. An example of this is shown in Fig. 7:

![FIG. 7. EXPECTED LIGHT DISTRIBUTION](image)

The heat sinks themselves were designed to maximize the natural convection heat transfer coefficient across their fins. Their slotted design allows for buoyancy driven channel flow across the fin surfaces and also minimizes the blockage of light reflected from the parabola. Fig. 8 illustrates the natural convection streamlines across the heat sink fin surfaces:

![FIG. 8. NATURAL CONVECTION STREAMLINES ACROSS HEAT SINK FIN](image)

The heat sinks each comprise four fins which are 1” in depth and 1/8” in thickness. The fins are separated by three 1/4” thick spacers at each of the 30 LED mounting locations. Fig. 9 shows a rendering of a heat sink cross section and an LED junction.
All components of the luminaire fit inside a 2’ X 4’ envelope.
8. CONCEPT GENERATION AND SELECTION

3M allowed the team freedom to design any lighting component we desired. This freedom made the scope of the project very open ended. It also meant that a large amount of time had to be put into the concept generation and selection process, to ensure the team selected the best possible concept for our final design. To narrow down the scope of this project, the team went through three separate concept generation and selection phases. The team started with general light applications, then focused on a specific fixture category, and finally chose a final fixture design. The following sections will discuss separately the processes used in each concept generation and selection phase.

8.1 GENERAL LIGHTING APPLICATION

The team decided to research all general lighting applications that would be feasible candidates for LED technology. Some examples of the lighting applications considered include overhead spot lighting, outdoor lighting and desk lamps. Fig. 10 illustrates examples of these lighting applications.

(A) SPOT LIGHTING    (B) OUTDOOR LIGHTING    (C) DESK LAMP

FIG. 10. LIGHTING APPLICATIONS
8.1.1 Concept Generation

The team discussed possible lighting applications that would benefit from LED technology, and also have a large market. Each team member was assigned specific lighting applications to research and was instructed to find out all areas where the lighting application is used, what products are already on the market using LED technology, and what patents exist for these products. Team members used the internet, patent searches, and consultation with 3M sponsors to gather information.

8.1.2 Concept Selection

Once a sizeable amount of information was found, the team discussed the pros and cons of each lighting application. Each team member shared what they had found with the rest of the group and made a recommendation of how feasible each application would be to build. After a thorough discussion, the team decided to design a 2’X4’ light fixture for commercial applications. The team decided on this type of fixture because there are no 2’X4’ commercial light fixtures on the market, utilizing LED technology, and because commercial lighting offers a large potential market.

8.2 SPECIFIC FIXTURE CATEGORY

Once the team decided upon a commercial light fixture, the next step was to determine a specific fixture category. The team determined that the different fixture options included direct lighting, indirect lighting, side lighting, recessed fixtures, and hanging fixtures. Examples of the first three fixture options are illustrated in Fig. 4. Recessed and hanging are illustrated in Fig. 11.

The following sections will talk about each category along with the pros and cons of these fixtures ending with an explanation of how the team chose the recessed fixture with indirect lighting.
8.2.1 Concept generation

The team first researched different fixtures available on the market. A web search was done by each member of the group on a specific commercial lighting manufacturer. The team found that commercial fixture designs were either recessed into the ceiling or hanging down into the room. Upon talking to an expert in purchasing commercial light fixtures, the team was told that recessed fixtures were more commonly used than hanging fixtures in most commercial buildings. This information, paired with a large market, helped the team to decide on a recessed fixture for our project. The next step was to have each team member come up with at least ten design concepts to share with the group in the next meeting. After all the concepts were shared with the team, a group brainstorming session took place to determine strengths and weaknesses of the designs. Team members were instructed to come up with additional design concepts to be reviewed in the next meeting. At the next meeting the team shared their concepts and participated in a final brainstorm session to ensure all ideas had been exhausted.

8.2.2 Concept Alternatives

After brainstorming sessions and research, the team came up with several concepts. We were able to group these concepts into three categories based on the way each design distributed light. These categories were direct lighting, side lighting and indirect lighting. Each category is discussed in the following sections.
8.2.2.1 Direct lighting

The first category that will be discussed is direct lighting. An example of one of our direct lighting concepts is illustrated in Fig. 12. This group of concepts is designed to emit light directly from the LED to a particular area. This type of design is the simplest of the three because there is no use of a reflective surface. The LEDs are simply positioned uniformly within the fixture, pointing downward toward the desired illuminated area. A diffusing material is used to cover the base of the fixture so that all light is spread evenly and the LED source cannot be distinguished.

![FIG. 12. DIRECT LIGHTING CONCEPT](image)
8.2.2.2 Side Lighting

The second category to be discussed is side lighting. A side lighting example concept is illustrated in Fig. 13. Side lighting concepts were designed to redirect light from the LED’s positioned on the edges of the fixture up to the top of the fixture. The top of the fixture is covered with a white diffusing reflective material that redirects the light to the desired area. The LED’s on the side of the fixture cannot be seen due to a cover placed below the LED’s so that the point sources are not immediately visual. The advantage of side lighting is the ability to hide the source of the light without restricting air movement in the fixture. The disadvantage of side lighting is the inability to distribute light evenly.
8.2.2.3 Indirect Lighting

The final category to be discussed is indirect lighting. An example of one of our indirect lighting concepts is illustrated in Fig. 14. Indirect lighting concepts were designed to place the LEDs in the center of the fixture on top of a heat sink directing light upwards. The top of the fixture is covered with a reflective material to redirect the light to the desired illuminated area. In these designs the light source is hidden and there is free air movement around the entire fixture and heat sink. This gives these fixtures a great advantage in cooling capabilities. A disadvantage of this category is the heat sink blocking light distribution in the center of the fixture.

FIG. 14. INDIRECT LIGHTING CONCEPT
8.2.3 Concept Selection

Once the team gathered sufficient data and generated concepts, a weighted concept selection matrix was used to choose the best fixture category. The concept selection chart is illustrated in Table 6. To build this selection chart, the team reviewed the PDS to determine the most important design requirements for our project. The requirements the team decided upon and the reason the team chose them are discussed in the following paragraph.

The six categories used to determine the benefits of each fixture were: 3M film usage, thermal management, cost, light distribution, construction feasibility and air handling capability. The team decided that 3M film usage was very important to our design because one of the main goals of our project is to utilize 3M technology in the design of a light fixture. Thermal management is also a crucial requirement because LEDs must be cooled properly in order to give off consistent bright natural light and to maintain their long life. The air handling capabilities of the fixture relates to how easily the fixture design supports natural convection flow. Since cheap, efficient commercial light fixtures already exist on the market today, fixture cost plays a large role in determining the final fixture category. To be competitive with current fixtures it is essential that light is distributed evenly across the intended illuminated area. Feasibility addresses the team’s ability to realistically design and build the final concept over one semester.

The requirements were then weighted in relation to their importance to the final design. The team decided that 3M film, thermal management, and distributing light evenly were the most important and therefore were given a weight of 5. 3M film was important because 3M was the team sponsor for the product and as our customer they wanted their technology incorporated into the design. Thermal management was also important because LED’s are very susceptible to heat and therefore it is vital that they are cooled properly. Distributing light evenly is important because without properly doing so, the fixture is useless to the end user. Cost, feasibility and air handling capabilities were given a weight of 2 because the team felt these were requirements that could be a factor in choosing between two promising designs.
Finally, the team was able to compare the three concept categories. The team determined, through a group scoring exercise, that an indirect light fixture design would be the best candidate to accomplish the primary design requirements.

<table>
<thead>
<tr>
<th>TABLE 6. WEIGHTED CONCEPT SELECTION CHART FOR FIXTURE CATEGORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>3M Film</td>
</tr>
<tr>
<td>Thermal Management</td>
</tr>
<tr>
<td>Cost</td>
</tr>
<tr>
<td>Distribute Light Evenly</td>
</tr>
<tr>
<td>Feasibility</td>
</tr>
<tr>
<td>Air Handling Capability</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

8.3 FINAL CONCEPT

Now that our project had been narrowed down to an indirect light design, the next step was to find the best indirect light concept. The differences between concepts had to do with various heat sink designs, and parabolic reflector layouts.

8.3.1 Concept Generation

Each team member came up with as many indirect light fixture concepts as possible for the next meeting. In the next meeting the new and old indirect designs were shared with the team. A final team brainstorming activity took place to ensure all ideas had once again been exhausted. The team then laid all the concepts out on the table and grouped them in similar design categories. Each team member went around and initialed the designs they liked the best. There turned out to be three designs with four initials or more, and several that had three initials. Each team member explained why they liked the designs they chose and why they felt it would be a good candidate for the final concept. After all ideas were shared, the team unanimously decided on the top three designs.
8.3.2 Concept Alternatives

The team was able to narrow the extensive list of concepts down to the three most promising ideas. These ideas were a floating double parabola, a single heat sink, and a third option the team named Option #3.

8.3.2.1 Floating Double Parabola

The Floating Double Parabola concept uses two separate heat sinks to dissipate the heat from the LEDs. These heat sinks are “floating” in the center of the fixture and are held in place by the outer frame. The design also has a double parabolic top to distribute the light evenly. The LEDs are located directly at the focus point of each parabola. This concept can be seen below in Fig. 15.

![FIG. 15. FLOATING DOUBLE PARABOLA CONCEPT](image)
8.3.2.2 Single Heat Sink

The single heat sink design has a single “floating” heat sink placed in the center of the fixture. This design is open to having either a single or double parabolic top. The design, illustrated below in Fig. 16, shows it with a double parabolic top and the LEDs angled to distribute light evenly to each parabola.

FIG. 16. SINGLE HEAT SINK CONCEPT
8.3.2.3 Option #3

Option #3 incorporates the heat sink and parabolas into one single piece. The heat sink becomes a part of the fixture which gives it a very large surface area to dissipate heat. A water cooling system was also presented with this concept but was rejected due to noise, plumbing and feasibility issues. Option #3 is illustrated below in Fig. 17.

FIG. 17. OPTION #3 CONCEPT
8.3.3 Concept Selection

The final weighted concept selection chart retained many of the same requirements used in the previous concept selection chart shown in Table 6. This is because these requirements are just as important in deciding the final concept as they were in deciding the fixture category. However, with a narrowed down field of concepts and similar designs, some of the requirements no longer made a difference in concept selection. Weight and the depth dimension of the fixture were added as additional requirements.

After selecting the most appropriate requirements, the concept selection matrix was constructed. To keep any bias out of selecting the final concept, each member of the team ranked each concept individually. All individual rankings were tallied up and averaged to come up with the overall group ranking. The individual concept selection charts can be found in the Appendix, Section 16.3.2 - Individual Concept Selection Charts. The final average matrix is shown below in Table 7. The floating double parabola concept received the highest weighted score.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Weight</th>
<th>Floating Double Parabola</th>
<th>Floating Double Parabola Weighted</th>
<th>Single Heat Sink</th>
<th>Single Heat Sink Weighted</th>
<th>Option #3</th>
<th>Option #3 Weighted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light distribution</td>
<td>5</td>
<td>4</td>
<td>20</td>
<td>4</td>
<td>20</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Thermal management</td>
<td>5</td>
<td>4</td>
<td>20</td>
<td>3</td>
<td>15</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>3M technology use</td>
<td>5</td>
<td>4</td>
<td>20</td>
<td>4.4</td>
<td>22</td>
<td>3.4</td>
<td>17</td>
</tr>
<tr>
<td>Weight</td>
<td>2</td>
<td>4.8</td>
<td>9.6</td>
<td>4.2</td>
<td>8.4</td>
<td>3.2</td>
<td>6.4</td>
</tr>
<tr>
<td>Air Handling capability</td>
<td>3</td>
<td>3.6</td>
<td>10.8</td>
<td>4.4</td>
<td>13.2</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Depth dimension</td>
<td>2</td>
<td>4.8</td>
<td>9.6</td>
<td>4.2</td>
<td>8.4</td>
<td>3.8</td>
<td>7.6</td>
</tr>
<tr>
<td>Feasibility</td>
<td>4</td>
<td>4.4</td>
<td>17.6</td>
<td>4</td>
<td>16</td>
<td>2.6</td>
<td>10.4</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>42</strong></td>
<td><strong>107.6</strong></td>
<td><strong>103</strong></td>
<td><strong>88.4</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.4 CONCEPT JUSTIFICATION

After the intensive generation and selection process, the team determined that the floating double parabolic concept was the best design for this project. This concept complied with our requirements better than the rest of the proposed concepts. The floating double parabola concept distributes light evenly across the entire desired area whereas concepts such as Option #3 have trouble doing this with such a wide center heat sink. It is the best design for thermal management due to separating the LEDs onto two different heat sinks which increases surface area for heat dissipation. This could possibly have been a problem using any concept that only utilized a single heat sink. The design utilizes 3M’s white diffuser/reflective material along with 3M adhesives. These 3M materials turned out to be common throughout almost all concepts generated. The overall weight of the fixture was estimated to be within 4 pounds of any other concept considering the only major difference was an added heat sink. Air handling capability was the best possible by using a double parabolic top and two separate heat sinks. The side lighting would have trouble dissipating the heat without the heat sinks being in an open air region.
9. DESIGN DESCRIPTION

The Design Description section provides documentation for engineering analysis and modeling, outlines experiments run during the course of the design, discusses the prototype construction, and outlines manufacturability, cost, environmental impact of the design, and regulatory analysis. The Design Description is intended to provide the necessary in-depth design considerations encountered during the design of the light fixture.

Evaluation of the thermal characteristics, light output and electrical load of the final prototype is found in section 10 - Prototype Evaluation. Section 11 - Design Evaluation provides an evaluation of the overall design taking into consideration the prototype evaluation. A reflection on the design process, including the success of the project management is included in section 12 - Design Process Evaluation.
9.1 MODELING AND ANALYSIS

Thermal management, light distribution, and electrical wiring and load analysis were considered for the successful creation of an LED based light fixture.

The thermal analysis primarily considered one dimensional, steady state heat transfer analysis to approximate the performance of the light fixture. This analysis was used for sizing the heat sink, and during discussions of potential light fixture designs. Testing of thermal performance was completed to verify the thermal analysis (Section 10.1.1 - Temperature Testing).

A ray tracing program was created to approximate the pattern of light emanating from an LED. The analysis was used in concept selection as well as creation of the final prototype. The light distribution of the luminaire was not tested due to time constraints. The light output and spectral distribution were tested to confirm the expected values (Section 10.1.2 - Light Distribution/Output).

Electrical wiring and load analyses are necessary for the design of an energy efficient light fixture that will provide the expected performance. The wiring and load analyses were used during the construction of the final prototype, and to determine expected power usage of the light fixture. The electrical loads were tested to confirm the analysis (Section 10.1.3 - Evaluation of Electrical System).

A three dimensional solid model was created to confirm component placement for construction of the final prototype. The model considered the fixture housing, heat sink, LEDs, and wiring (Section 9.1.4 - Solid Model).
9.1.1 Heat Transfer/Heat Sink Sizing

9.1.1.1 LED Thermal Background

Thermal management is extremely important when working with high power LED’s since 75% to 85% of the power dissipated through an LED is converted into heat [4]. Fig. 18 displays the percentage of power converted to heat for the most common types of lights.

![Power Conversion for “White” Light Sources](image)

The useful life of the LED is dependent on the rate at which this heat is dissipated. The temperature inside the LED, referred to as the junction temperature, is one factor that determines the lifetime of the LED. Fig. 19 shows that both the useful life and relative light output decrease as this junction temperature increases.
The LEDs are commonly mounted on a heat sink from which heat is dissipated by conduction, radiation, and natural or forced convection. Aluminum is the material of choice for most high power LED heat sink applications because of its light weight, high thermal conductivity, and reasonable price. Consequently, aluminum was chosen as our heat sink material. A copper heat sink was considered, but was determined to provide little benefit compared to its significantly higher costs. Our verification of a lumped capacity assumption for our aluminum heat sink, explained in Section 16.4.2 - Lumped-Capacity Calculations, tells us that a heat sink material with a higher thermal conductivity is not needed for our design.

9.1.1.2 Design Goal

Our design goal was to construct a luminaire that maintains 70% lumen maintenance at 50,000 hours of operation, listed as metric #24 in our product design specification (Table 5). The manufacturer of our LEDs (CREE) states that this goal can be achieved if the LED junction temperature is maintained at or below 80 °C [6].

An ambient air temperature of 35 °C is used throughout our analysis. This temperature is based on qualitative assumptions that room temperature air (~20 °C) will be trapped and heated in the parabolic section of our luminaire (Fig. 20).
No quantitative analysis was performed to determine the transient temperature characteristics of the luminaire.

**9.1.1.3 Lumped-Capacity Simplification**

We simplified our thermal analysis by approximating our heat sink as a lumped-capacity body. A lumped capacity simplification is applicable when the *internal* thermal resistance of a body due to conduction is much lower than its *external* thermal resistance due to convection. Consequently, a lumped capacity analysis assumes a uniform temperature distribution throughout the solid body [5]. This uniform temperature assumption is advantageous because it allows us to simplify our analysis into a one-dimensional problem by analyzing only a cross section of our heat sink. Calculations for the lumped-capacity assumption are available in Section 16.4.2-*Lumped-Capacity Calculations*

**9.1.1.4 Heat Sink Dimension Constraints**

There were a number of dimensional constraints which helped shape the design of our heat sink. The first constraint was the heat sink length. Each heat sink was assumed to be 42” long, with 15 LEDs distributed over its length. This length allowed three additional inches on each side of the heat sink for the fixture housing and mounting hardware—making the overall length of the luminaire 48”. By spacing the LEDs equally over the heat sink, the
length of heat sink available to each LED, for heat dissipation, is 2.8 inches. Fig. 21 reveals an illustration of a heat sink section

The second constraint was the *maximum* heat sink width. As a heat sink gets wider it blocks out more reflected light from the parabolic surface. Hence, narrower heat sinks are preferable for light distribution. Any width less than 3 inches was deemed acceptable. Heat sink widths greater than 3 inches would take up more than ¼ of the 2’ by 4’ luminaire footprint—blocking too much light.

The third dimensional constraint was the *minimum* heat sink width. If the heat sink is too narrow, the LEDs will be visible from wide viewing angles. It was approximated that any width over 1 inch would effectively block the light source from all but the widest of viewing angles.

---

1 The appearance of the heat sink in Fig. 21 does not reflect our final design; it is merely an illustration to reveal the length and adiabatic faces of each heat sink section.
The last dimensional constraint was that the heat sink could not extend above the LED. Doing so would block light emitted from the LED—reducing light output.

9.1.1.5 Thermal Schematic and Resistance Network

The thermal characteristics of the LED and heat sink were analyzed under steady state conditions. A thermal schematic and associated resistance network was used to set up the quantitative thermal analysis. Fig. 22 reveals the cross section of a heat sink segment.

Fig. 23 shows the associated thermal resistance network for the schematic shown in Fig. 22.
Equation (1) describes this thermal resistance network.

\[
P_{\text{LED}} = \frac{\Delta T}{\sum R_{\text{th}}} = \frac{T_{\text{junction}} - T_{\text{ambient}}}{R_{\text{LED}} + R_{\text{mount}} + R_{\text{heat sink}}} \tag{1}
\]

Our goal for using Eq. (1) is to determine the maximum value of the total thermal resistance required for our heat sink. \( T_{\text{junction}}, T_{\text{ambient}}, \) and \( P_{\text{LED}} \) (the power dissipated by the LED), are constants. \( T_{\text{junction}} = 80 \, ^{\circ}\text{C}, \, T_{\text{ambient}} = 35 \, ^{\circ}\text{C}, \) and \( P_{\text{LED}} = V \times I = (3.4 \, \text{V}) \times (0.7 \, \text{A}) = 2.4 \, \text{Watts}. \) Rearranging Eq. (1) to solve for \( R_{\text{th}} \) we obtain Eq. (2):

\[
\sum R_{\text{th}} = R_{\text{LED}} + R_{\text{mount}} + R_{\text{heat sink}} \leq \frac{T_{\text{junction}} - T_{\text{ambient}}}{P_{\text{LED}}} = \frac{80\, ^{\circ}\text{C} - 35\, ^{\circ}\text{C}}{2.4 \, \text{W}} = 18.75 \, ^{\circ}\text{C}/\text{W} \tag{2}
\]

Equation (2) informs us that the maximum thermal resistance, \( R_{\text{th}} \), between \( T_{\text{junction}} \) and \( T_{\text{ambient}} \) must be less than 18.75 \( ^{\circ}\text{C}/\text{W} \) to maintain a junction temperature below 80 \( ^{\circ}\text{C} \) with an ambient temperature of 35 \( ^{\circ}\text{C} \). The three components that comprise \( R_{\text{th}} \) will be described in more detail:

**R\text{LED}:**
The thermal resistance \( R_{\text{LED}} \) is a property of the LED and is referred to as the *Internal Thermal Resistance*. The value of this internal thermal resistance ranges from \( 5^{\circ}\text{C}/\text{W} \) to \( 15^{\circ}\text{C}/\text{W} \) depending on the power output of the LED and the manufacturer. Our LEDs have an internal thermal resistance of \( 8^{\circ}\text{C}/\text{W} \), taken from our LED manufacturer’s data sheet [6].

**R\text{mount}:**
The mounting resistance between the LED and the heat sink depends upon the thickness and thermal conductivity of the mounting substrate. LEDs are commonly mounted using one of three methods: thermal tape, solder, and thermal grease. All three methods will be explained in further detail.
The first method, thermal tape, involves compressing a thermal pad between the LED and the heat sink. An example of this is 3M 8010 Thermal Tape. This tape is 10 mils (0.254 mm) thick and has a conductivity of 0.6 W/m°C. Rearranging Fourier’s law of heat conduction,

\[ q = -kA \frac{\Delta T}{\Delta x} \]  

(3)
to solve for \( \Delta T/q \), the conduction resistance, \( R_{\text{mount}} \), can be described by:

\[ R_{\text{mount}} = \frac{\Delta T}{q} = \frac{\Delta x}{kA} \]  

(4)

With an LED base area of 36mm\(^2\) (equivalent to our LED) such a thermal pad has a mounting resistance of

\[ R_{\text{mount, thermal tape}} = \frac{\Delta x}{kA_{\text{LED}}} = \frac{0.000254 \text{m}}{(0.6 \text{ W/m°C}) \times (36 \times 10^{-6} \text{m}^2)} = 11.7 \text{ °C/W} \]  

(5)

This thermal resistance is much too great for our application, noting that total thermal resistance must be less than 18.75 °C/W. For this reason, we chose not to use the 3M Thermal Tape as our primary means of mounting the LEDs. During the prototype construction, six LEDs required the thermal tape for mounting because of electrical shorting problems.
The second common method of mounting an LED to a heat sink is by soldering the LED to a Printed Circuit Board (PCB). This method provides the least thermal resistance assuming that hard solder \((k = 94 \text{ W/m°C}, \text{ EngineersEdge.com})\) is used with an estimated thickness of 5 mils \((0.127 \text{ mm})\). The computed thermal resistance through the solder is

\[
R_{\text{mount, solder}} = \frac{\Delta x}{kA_{LED}} = \frac{0.000127m}{(94 W/\text{m°C}) \times (36 \times 10^{-6} \text{m}^2)} = 0.04 ^\circ \text{C}/\text{W}
\] (6)

In this case, such a small thermal resistance is negligible. Hence, it is the preferred method of mounting an LED to a heat sink. The disadvantages of this method include the technical difficulty of soldering such a small area and expense of manufacturing a PCB specifically for this application. For these reasons our LEDs were not mounted in this fashion.

The third method of mounting an LED to a heat sink involves using thermal grease. Thermal grease is comprised of micronized silver dust suspended in silicon grease. One such grease has a thermal conductivity of 9.4 W/m°C (DYNEX Silver-Based Thermal Compound). An advantage of using thermal grease is that it can be applied in an extremely thin layer, estimated to be 1 mil \((0.0254 \text{ mm})\), and is readily available at electronics hardware stores. The thermal resistance through the thermal grease is:

\[
R_{\text{mount, thermal grease}} = \frac{\Delta x}{kA_{LED}} = \frac{0.0000254m}{(9.4 W/\text{m°C}) \times (36 \times 10^{-6} \text{m}^2)} = 0.08 ^\circ \text{C}/\text{W}
\] (7)

Although not as small as the thermal resistance through solder, the thermal resistance of the thermal grease is still small enough to be neglected. Our LEDs were originally mounted using this thermal grease because of this small resistance and commercial availability. During prototype construction, it was found that this type of thermal grease produced electrical shorting problems. A different thermal grease (RadioShack Heat Sink Compound) comprised of silicon and zinc oxide was substituted for the original thermal grease because it provided better electric isolation of the LED from the heat sink. The thermal conductivity of
our new thermal grease was unknown, but is estimated to be between 0.7 W/m°C and 3 W/m°C based on the thermal conductivities of common silicon based heat sink compounds (Omega OT-201 Silicon Grease, ~2 W/m°C). One disadvantage of using thermal grease is the fact that it does not provide a permanent bond. Our solution to this problem is to fix LEDs to the heat sink by screwing a piece of spring steel across the LED surface. This method is described in further detail in Section 9.3.2 - Heat Sink.

\[ R_{\text{heat sink}} \]

The thermal resistance of the heat sink is determined by the surface area of the heat sink and the natural convection heat transfer coefficient across that surface area. Equation (8) reveals the thermal resistance from the heat sink to its surroundings, neglecting conduction and radiation.

\[
R_{\text{heat sink}} = \frac{1}{h_{\text{natural convection}}A_{\text{heat sink}}} \tag{8}
\]

With \( R_{\text{LED}} \) known (8 °C/W) and \( R_{\text{mount}} \) assumed to be zero, Eq. (2) can be rearranged to determine the required value of \( R_{\text{heat sink}} \):

\[
R_{\text{heat sink}} \leq 18.75^\circ\text{C/W} - R_{\text{LED}} - R_{\text{mount}} = 10.75^\circ\text{C/W} \tag{9}
\]

Radiation from the heat sink is neglected in this analysis because preliminary calculations showed that radiation contributed only a small amount to the total heat transfer, lowering our junction temperature estimates by less than 1%. Program code and solution of the thermal analysis which includes radiation is available in Sections 16.4.3 and 16.4.4. These results can be compared to the program code and solution without radiation in Sections 16.4.5 and 16.4.6. The design of the heat sink and calculation of the natural convection heat transfer coefficient are explained in Section 9.1.1.6 - Heat Sink Design.
9.1.1.6 Heat Sink Design

Numerous heat sink designs were considered including horizontal, radial, and vertically finned surfaces. Initial calculations revealed that a simple flat plate would provide insufficient surface area to effectively transfer heat by natural convection. A vertically finned design was chosen because it provided adequate surface area for natural convection and was feasible to construct. A radially finned heat sink was considered but was determined to be too difficult to construct given our time constraints. A section of the vertically finned heat sink is illustrated in Fig. 24.

A slotted fin design is advantageous because it allows air to flow through its channels, increasing the natural convection heat transfer coefficient, $h$. An example of the natural convection currents is shown in Fig. 25.
Only the sides of the fins, highlighted red in Fig. 25, are included in the heat sink surface area. The top and bottom surfaces of the fins are assumed to be adiabatic. Doing so provides a conservative estimate of the thermal resistance.

A Nusselt number correlation for buoyancy driven channel flow was used to determine the average natural convection heat transfer coefficient across the fin surfaces [7].

\[
\overline{Nu_s} = \frac{1}{24} Ra_s \left( \frac{S}{L} \right) \left\{ 1 - e^{\left[ \frac{-35}{Ra_s (S/L)} \right]} \right\}^{3/4}
\]  

(10)

In this equation, \( S \) is the gap between the fins, \( L \) is the height of the fins, and \( Ra_s \) is the Rayleigh number based on the fin gap, given by Eq. (11).

\[
Ra_s = \frac{g \beta (T_{fin} - T_{ambient}) S^3}{\alpha v}
\]

(11)

In this equation, air is treated as an ideal gas, atmospheric pressure is assumed, \( \beta \) is the thermal expansion coefficient of air, \( \alpha \) is the thermal diffusivity of air, and \( v \) is the kinematic viscosity of air. Fluid properties are evaluated at ambient temperature in accordance with the correlation constraints [7]. The natural convection heat transfer coefficient, \( h \), is computed using Eq. (12):

\[
\bar{h} = \frac{k_{air} \overline{Nu_s}}{S}
\]

(12)

A thermal analysis program was written in EES which included the three equations above in addition to the equations for the thermal resistance network. The program code is available in Section 16.4.3 - Thermal Analysis Program Code. Different fin lengths and fin gaps are inputted and the program outputs the thermal resistance of the heat sink along with all other temperatures and thermal resistances in the resistive network. The procedure for finding the
correct number of fins and fin length to obtain a heat sink thermal resistance below 10.75 °C/W was found by manual iteration.

A heat sink design was established which gave us a heat sink thermal resistance, $R_{\text{heat sink}}$, of 9.35°C/W. This gives us an LED junction temperature of 76.83°C—4% lower than our maximum temperature of 80°C. The final cross-sectional dimensions of our heat sink are shown in Fig. 26.

![Final Heat Sink Cross Section](image)

\[ h_{\text{natural convection}} = 7.4 \frac{W}{m^2\circ C} \]

\[ A_{\text{fins}} = 0.01445 \ m^2 \]

\[ R_{\text{heat sink}} = \frac{1}{hA} = 9.35 \ ^\circ C/W \]

**FIG. 26. FINAL HEAT SINK CROSS SECTION**

To provide a mounting surface for the LEDs, spacers were placed in-between the fins at every LED junction location. The spacers allowed heat transfer from the LED to all four fins. A cross section of the heat sink at the LED junction location is shown in Fig. 27.
Each fin spacer is 1” long, 0.5” deep, and 0.25” thick. The spacers are assumed to not affect the natural convection flow across the fin surface. The fins and fin spacers are bolted together using 1.5 inch long #10 bolts. DYNEX Silver-Based Thermal Compound is applied to the mating surfaces of the fins and spacers to decrease the contact resistance between the surfaces. A detailed schematic of the final heat sink design can be found in Appendix Section 16.4.1 - Heat Sink Schematic.
9.1.2 Ray Tracing

To meet the design specification of distributing light evenly, in Table 5, it was necessary to determine how well concept light fixtures distributed light. It would have been expensive and time consuming to make physical prototypes of more than one design. So to determine the approximate light distribution of each possible concept without building a physical prototype, the team used a program written in MATLAB. The program approximates how the light produced by the LEDs will be reflected by the light fixture. The complete code for this program can be found in section 16.5.1 - MATLAB Code and section 16.5.2 - MATLAB functions.

The program uses the law of reflection which states: the angle a light ray makes with a normal to a surface will be equal to the angle the reflected ray makes with the normal. This is illustrated in Fig. 28.

The law of reflection would precisely describe the light distribution of the luminaire if the surface the light is reflected from is an ideal specular reflector. However, the surface used for this light fixture is not ideal and it actually diffuses light that strikes it. This is much more complicated to describe than specular reflection because it requires knowing how the light diffuses in three dimensions once it hits the surface. Fortunately, two-dimensional specular reflection gives an approximation of the how the light rays are distributed once they are reflected.
The program is given an input of the location of the LED, and a parabola describing the upper surface of the light fixture. Next, rays are projected out of the LED location for a range of angles and their intersection with the parabola is determined. Using the derivative of the parabolic equation the slope is determined at each intersection. Then, the angle the parabola makes with the horizontal is determined using the arctan function. The law of reflection and basic geometry are applied to determine the angles of the reflected rays. The angle of the reflected rays is converted into slopes and is plotted (Fig. 29). The parabolic profile is then printed to scale, and can be used as a stencil for making the light fixture.

The development of this software allowed the team to quickly see the effect of changing the parabolic shape or moving the LED location without having to construct multiple prototypes. The team decided that the best light distribution would be when all of the reflected rays are pointing straight down. This required placing the LEDs as close as possible to the focus of the parabola.
9.1.3 Electrical Load Analysis

9.1.3.1 Design goals

The electrical system is the mechanism that will determine the overall performance of the luminaire. The design goals include the use of efficient power and zero current draw when the lights are turned off. First, some background information will provide the basis for the electrical design. Second, the electrical circuit layouts will be described. Lastly, the final design and its components will be explained.

9.1.3.2 Electrical Properties of LEDs

In addition to the design goals, LEDs have electrical properties that need to be met in order for them to operate. LEDs typically have a voltage range that allows current to flow. If the supplied voltage is not in that range, the LED will not emit light. LEDs also have a nominal operating current which determines the luminous output, color temperature, and forward voltage [21]. As an example of these relationships, data from the CREE X-Lamp XR-E LEDs is shown in Fig. 30 and Fig. 31. The plots show the forward current versus forward voltage, and forward current versus luminous flux, respectively.

![FIG. 30. LED OPERATING VOLTAGE VS. CURRENT](image-url)
The supplied LED forward current is a very important consideration. LEDs heat up when they are turned on. With this, the forward voltage will rise and fall, causing the forward current to change if the driving electrical circuit is improperly designed. Thus, the electrical circuit that will drive the LEDs will have to compensate for this temperature change and vary the supply voltage in order to deliver a constant current. If the forward current is allowed to swing, the LED brightness will fluctuate [15].

9.1.3.3 Circuit Layout

In order to obtain a specified lumen output, a certain number of LEDs needed to be connected together. The electrical circuit that will power the LEDs has a few different possibilities. A series connection, parallel connection, and a combination series–parallel connection were considered.

A series connection inherently allows the same current to flow through each LED. Consequently, the supply voltage increases to an intolerable value when connecting a significant number of LEDs. This can be seen from Fig. 32 and from using Eq. (13), where $I_f$ is the forward current, $V_f$ is the forward voltage, $R_{bs}$ is the ballast resistance, and $V_{supply}$ is the voltage delivered to the LEDs. If by chance an LED fails short-circuit, a series circuit will have a smaller resistance and the current will increase. With this concern in mind, the
current must be both controlled and be constant. In the case an LED fails open-circuit, the serial LEDs will simply shut-off [15].

\[ I_f = \frac{V_{\text{supply}} - \sum V_f}{R_{bs}} \] (13)

A parallel connection allows the supply voltage to be much lower than in a series connection, but the total current increases with each LED added to the circuit. This can be seen from Fig. 33 and Eq. (14). Where \( V_f \) is the forward voltage, \( R_{bs} \) is the ballast resistance, \( I_{\text{tot}} \) is the total current delivered, \( I_f \) is the forward current, and \( V_{\text{supply}} \) is the voltage delivered to the LEDs. Current sharing is more difficult to control in this configuration, since LEDs’ forward voltage can vary from a nominal value by 20%. Current sharing describes the circuit’s ability for each parallel loop to have the same current. In the case of an LED failing open-circuit, a parallel connection will deliver increased current to the remaining LEDs, thereby reducing their overall life span. If an LED fails short-circuit in a parallel configuration, the remaining LEDs will shut-off [15].
The series-parallel connection has the flexibility to accommodate many different LED configurations. By selecting how many LEDs are needed, a simple calculation allows the circuit to be created. This can be seen in Fig. 34 and by using Eq. (15). Reliability is increased when using parallel strings of LEDs, while voltage loss is reduced when LEDs are in series [14].

\[
I_{tot} = n \cdot \frac{V_{supply} - V_f}{R_{bs}} = \sum_{1}^{n} I_f
\]  

\[
I_{tot} = n \cdot \frac{V_{supply} - \sum V_f}{R_{bs}} = \sum_{1}^{n} I_f
\]
9.1.3.4 Power Supply

To allow the use of a standard power supply, a reasonable voltage range needs to be set. Power supplies in the 12V to 32V range are sufficient to power the LED circuit. High power white LEDs typically have a 3.5 V$_{dc}$ forward voltage; this relates to approximately three to nine LEDs in series strings. The power supply voltage needs to be slightly higher than the voltage drop across all the LEDs to accommodate differences in LED voltages, as well as to cover resistance losses in the connections. The power supply should also have the highest achievable efficiency to keep the overall luminaire efficiency as high as possible.

9.1.3.5 Efficiency

LEDs have a relatively high efficacy compared to other common sources of light. LED manufacturers publish the efficacy of specific LEDs in lumens per watt. The efficiency of the electrical power circuit can be described by Eq. (16), where useful power is the power the LEDs consume to emit light. As long as the circuit does not include resistors or other power dissipating components, all the power delivered to the LEDs will be useful power. As a result, this will maximize the efficiency. The use of a DC-DC converter, such as a Buck or Boost voltage regulator, reduces the overall efficiency by the inefficiency of the regulator. The efficiency of the AC-DC power supply will also reduce the overall effectiveness of the luminaire. Efficiency calculations can be found in the Appendix section 14.6.

\[
\eta = \frac{\text{Useful Power Output}}{\text{Total Power Input}}
\]  

(16)
9.1.3.6 Proposed electrical system

The final electrical system design is depicted in Fig. 35. The DC-DC converter is a current regulated device which is made specifically for driving high power LEDs.

A specific DC-DC converter from LUXDRIVE™, the 3021 BuckPuck, was used for the team’s light fixture. The BuckPuck driver varies the output (LED) voltage to maintain constant current to the LEDs for constant luminance. The BuckPuck realizes high efficiency, up to 95%, but is reduced with higher input voltages as depicted in Fig. 36 [17].
The BuckPuck has built in short circuit protection for up to 15 seconds, and open circuit protection. The BuckPuck can interface with a microcontroller if you wanted to have the circuit sense failure and turn off the power. The microcontroller can act as an electronic switch to effectively eliminate current draw when the luminaire is turned off. A manual switch can also be connected across the adjustable current potentiometer for turning off the current supply [17].

Since LEDs require direct current, the polarity must be carefully controlled when connecting series strings of LEDs. The positioning of the LEDs along the length of the heat sink lends itself to alternating the positive and negative sides of the LED to reduce the wire needed, and to allow for all the wires to be straight. This can be seen from the solid model in Fig. 40.

The number of LEDs to use in the luminaire was determined through current availability of the most efficient super-bright white LED on the market, specifically the CREE X-Lamp XR-E. The actual values of the LED light output of 114 lumens was reduced to 100 lumens as a conservative measure to help offset the losses in reflected light in the fixture. The total lumen output from the fixture is desired to be 3000 lumens, so about 30 LEDs would be sufficient. The LEDs used in the prototype were supplied by 3M and happened to be CREE X-Lamp XRs, but of a later model with an output around 70 lumens. The forward current needed to power the LEDs in the prototype is 700mA, and as such requires each series string to have its own BuckPuck [6].
9.1.4 Solid Model

A SolidWorks model of the light fixture was made initially for use in the team’s midterm design review. Once a more comprehensive design had been selected, the model was refined to assist with component placement for the final prototype.

The initial SolidWorks model was a rough sketch of how the final light fixture design would look. This model was used in the team’s midterm design review to provide the audience with a visual description of what the fixture should resemble for the design show. This model can be seen in Fig. 37.

After a final design was selected the SolidWorks model was rebuilt. The new model included all the parts used in the prototype. These parts include: the LEDs, wiring assembly, prototype frame, led holder and heat sink assembly. The updated model was used to determine the correct dimensions of each part in order for everything to fit properly into the prototype fixture. The entire model is illustrated in Fig. 38. Each individual part can be found in the appendix Section 16.7. Building the final model led to the team resizing some of the fixture parts in order to obtain the best fit possible between each component, resulting
in a quality end product. The parts resized were the heat sink lengths and the height of the parabolas.

9.1.4.1 Electrical wire layout

A 3D SolidWorks model was created to aid in the arrangement of wiring the LEDs. The model was also used to visualize the placement of the wires in the prototype. This is shown in Fig. 39 and Fig. 40.
The positive and negative lead wires should fit along the width of the fins on each side of the LEDs, as you can see from the top-down view in Fig. 40. This placement allows the view from underneath the heat sink to be of only the fins and fixture, ensuring light distribution from the parabolic surface be more even and the fixture itself less distracting.
9.2 EXPERIMENTS

A couple of experiments were performed to verify the electrical systems operation. Specific experiments include resistive network testing and electrical performance testing. The resistive network testing is described below. The key concept found from the test was the voltage loss attributed to the simple circuit. The details and results of the performance test are found in the appendix.

9.2.1.1 Resistive circuit test

The resistive circuits in section 9.1.3.3 - Circuit Layout describes how to connect multiple LEDs in series and parallel using a ballast resistor to limit the current supplied to the LEDs. To test if the equations correctly describe the circuit, a sample of green indicator LEDs salvaged from a broken router were wired up to an old cell phone battery charger, shown in Fig. 41.

![Fig. 41. Test setup](image)

**TEST:** Light 4 and 8 green indicator LEDs.

**LED SPECIFICATIONS** - FORWARD VOLTAGE: 2 $V_{dc}$  FORWARD CURRENT: 20 mA

**POWER SUPPLY:** AC/DC Transformer, output: 8 $V_{dc}$, 350 mA

**CIRCUITS NEEDED:** 1 series & 1 series – parallel combination, see Fig. 42.
CALCULATIONS: Using Eq. (13) and solving for the ballast resistance, a resistor is not required for this simple circuit.

\[ R_{bs} = \frac{8V - 8V}{0.02A} = 0 \Omega \]

RESULTS: The equations proved to be valid and all the LEDs lit up in both configurations. The voltage drop across each individual LED is found in Table 8. The series – parallel LEDs are shown in Fig. 43.
TABLE 8. TEST RESULTS

<table>
<thead>
<tr>
<th>LED</th>
<th>Voltage drop ($V_{dc}$)</th>
<th>LED</th>
<th>Voltage drop ($V_{dc}$)</th>
<th>LED</th>
<th>Voltage drop ($V_{dc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.96</td>
<td>1</td>
<td>1.98</td>
<td>5</td>
<td>1.87</td>
</tr>
<tr>
<td>2</td>
<td>2.08</td>
<td>2</td>
<td>1.88</td>
<td>6</td>
<td>1.98</td>
</tr>
<tr>
<td>3</td>
<td>2.00</td>
<td>3</td>
<td>1.93</td>
<td>7</td>
<td>1.91</td>
</tr>
<tr>
<td>4</td>
<td>2.04</td>
<td>4</td>
<td>1.91</td>
<td>8</td>
<td>1.95</td>
</tr>
<tr>
<td>Total</td>
<td>8.08</td>
<td>Total</td>
<td>7.70</td>
<td>Total</td>
<td>7.71</td>
</tr>
</tbody>
</table>

The measured LED voltage supply from the transformer was 8.10 $V_{dc}$ in the series circuit and 7.75 $V_{dc}$ in the series–parallel circuit. The voltage loss using 4 LEDs was $8.10 - 8.08 = 0.02$ $V_{dc}$. The voltage loss in the series–parallel circuit with 8 LEDs was $7.75 - 7.70 = 0.05$ $V_{dc}$. The voltage loss in the two circuits shows that there needs to be a higher supply voltage then the sum of the voltage drops across series LEDs.
9.3 PROTOTYPE

The luminaire prototype was manufactured to verify and display the working principles of our design. Fig. 44 and Fig. 45 reveal the final prototype in both power states.

The prototype was constructed in three sections: the fixture housing, the heat sink, and the electronics. All three will be explained in further detail.
9.3.1 **Fixture Housing**

An existing luminaire fixture was purchased and modified to house all the components. Fig. 46 shows the original light fixture before it was modified.

![FIG. 46. ORIGINAL LIGHT FIXTURE HOUSING](image)

All electrical components were removed from the light fixture. The parabolic surface was constructed by screwing sheet metal onto five wood brackets cut in the shape of the calculated optimum parabolic shape. The sheet metal was then covered in poster board to provide a uniform white surface prior to the application of the 3M Diffuse Reflective film. Fig. 47 shows this component under construction.

![FIG. 47. PARABOLIC SURFACE CONSTRUCTION](image)

The top of the light fixture was then removed to accept the constructed parabolic surface.
9.3.2 Heat Sink

A number of machining operations were required to construct the heat sinks. The fins and spacers were cut to the dimensions of the detailed heat sink schematic, Fig. 65, in Appendix Section 16.4.1 - Heat Sink Schematics and Detailed Drawings, using a hydraulic shear and a band saw. All touching surfaces of the fins and spacers were covered in a thin layer of silver thermal grease before they were bolted together to reduce the contact resistance between the surfaces. Fig. 48 shows a section of the completed heat sink.

To hold the LEDs in place, spring steel clips were manufactured. The clips were necessary to hold the LEDs in place and provide the mounting force needed to reduce contact resistance between the LED and the heat sink. A layer of 3M Electrical Tape was applied to the bottom surface of the clips to provide electrical isolation from the LED and wiring components. Fig. 49 shows a picture of a mounting clip next to a permanent marker.
The clips were manufactured to be 38 mm long by 19 mm wide. Their corners were cut so they would not be visible from below the luminaire. Holes were drilled and tapped in the heat sink to accept size 4-40 screws which held the clips in place.

9.3.3 Electronics

Wire leads were soldered to the LEDs by a master bonder. The LEDs were then soldered to copper wires in the arrangement outlined in Section 9.1.4.1 - Electrical wire layout. The LEDs were originally mounted on the heat sink by applying a DYNEX Silver-Based Thermal Compound to the heat sink surface and the LED base. This grease proved to provide insufficient electrical isolation of the LED base from the heat sink. Nearly half of the LEDs shorted upon initial powering of prototype. To combat this problem, a different thermal grease (RadioShack Heat Sink Compound) was applied in a much thicker layer. This thicker layer of thermal grease provided a greater thermal resistance between the LED and the heat sink and most likely accounted for the difference between predicted and measured heat sink temperatures during thermal testing of the prototype. A number of LEDs (6) continued to give us electrical shorting problems. These LEDs were secured in place using the 3M’s 8010 Thermal Tape. The LEDs were secured in place by attaching the spring steel clips to the heat sink, shown in Fig. 50.

FIG. 50. LED MOUNTED ON HEAT SINK
9.4 MANUFACTURABILITY

The project is primarily for early stage R&D. Cost and manufacturing were not heavily considered during the design phase. In order to produce the final design in a manufacturing setting, a few key considerations could ease the complexity.

The fixture frame is easily made using thin sheet metal by cutting out templates for the end caps and the main span. Bending operations on the sheet metal would finalize the metal forming. Giving the whole frame a few coats of rust prevention and paint will provide the fixture a long life of care-free maintenance. The parabolic surface is included in the span and a stamping process could shape the profile of the parabola. Application of the diffusing film on the parabolic reflector finishes the fixture frame. The frame would undoubtedly be inexpensive per unit in a mass produced quantity.

The heat sinks could be created from a single extruded die using aluminum. The gaps between the fins could be machined out to allow the light to pass through them, though may not be needed at all if the wall thickness were thinned out, making the width smaller. The thickness of the solid section shown in Fig. 51 could also be reduced so that less material is wasted in the machining process. The extruded aluminum would also be inexpensive to produce on a mass quantity scale, after the initial investment for the equipment is recovered.
The LEDs could be reflow soldered to the heat sink, eliminating the need for any mechanical strap to hold the LEDs in place. The soldering of the LEDs to the heat sink would also improve the thermal characteristics and allow for a smaller sized heat sink, in turn effectively reducing the amount of material needed. Reflow soldering is generally used in mass production and is an inexpensive process.

The electrical connections to the LEDs could use a thin film printed circuit placed along the center of the heat sink, thereby creating a low profile design. These considerations are depicted in Fig. 52 where the printed circuit is shown in orange. Thin film printed circuits are also inexpensive, although in order to reflow solder the LEDs to the heat sink and to the printed circuit, the substrate in the printed circuit may need to be made of polyimide to handle the temperatures safely.
9.5 COST ANALYSIS

A bill of materials for the prototype can be seen below in Table 9. This BOM shows all incurred costs, with the exception of labor, to manufacture the prototype. The team was told by 3M that the product would not be sent into production. Instead, the design would be used for product development purposes later on by 3M. Knowing this information, the team concentrated on building a prototype that would best demonstrate the uses of 3M technology, rather than primarily focusing on cost competitiveness. Since the prototype was not designed to be going into production, a cost analysis for mass manufacturing the fixture would be difficult and inaccurate.

TABLE 9. PROTOTYPE BOM

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Price ($)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED's #XR7090XT L1-0002*</td>
<td>30</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Aluminum Sheeting</td>
<td>2</td>
<td>$10.00</td>
<td>$20.00</td>
</tr>
<tr>
<td>White Poster board</td>
<td>3</td>
<td>$0.99</td>
<td>$2.97</td>
</tr>
<tr>
<td>65 ft “Bell” wire</td>
<td>1</td>
<td>$4.99</td>
<td>$4.99</td>
</tr>
<tr>
<td>Buckpuck #03021-D-E-700*</td>
<td>5</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Light Fixture</td>
<td>1</td>
<td>$34.00</td>
<td>$34.00</td>
</tr>
<tr>
<td>Aluminum (lb)**</td>
<td>5</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>1.5” #10 machine screws (30 pack)</td>
<td>1</td>
<td>$4.00</td>
<td>$4.00</td>
</tr>
<tr>
<td>#10 nuts (packaged with screws)</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>DYNEX Silver thermal compound</td>
<td>2</td>
<td>$10.00</td>
<td>$20.00</td>
</tr>
<tr>
<td>3M electrical tape**</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>0.005” thick spring steel**</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>#40 allen head machine screws**</td>
<td>60</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>#40 washers**</td>
<td>60</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>#6 metal screws (30 pack)</td>
<td>1</td>
<td>$2.39</td>
<td>$2.39</td>
</tr>
<tr>
<td>3M super 55 adhesive</td>
<td>1</td>
<td>$10.00</td>
<td>$10.00</td>
</tr>
<tr>
<td>3/4” OSB Plywood</td>
<td>1</td>
<td>$11.00</td>
<td>$11.00</td>
</tr>
<tr>
<td>3M white diffuse film*</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>** TOTAL</td>
<td></td>
<td></td>
<td><strong>109.35</strong></td>
</tr>
</tbody>
</table>

* Provided by 3M at unknown cost

** Parts from ME shop
9.6 ENVIRONMENTAL ANALYSIS

A design for the environment analysis is required to address the product design specification of sustainable materials and recyclability found in Table 5. Because this prototype is not intended to be mass produced many of the manufacturing techniques and materials used in the prototype would not be used in a production model. The prototype is intended to be used by 3M Research and Development to determine if an LED based commercial light fixture is a viable product. An in-depth look at the environmental impacts of this prototype will not accurately address the environmental concerns for when this product is inevitably redesigned for mass production. However, it is still important to look at how the prototype’s design affects the environment to make sure components that will be reused in a final product will have minimal environmental impact. The team decided that the design for the environment questionnaire adequately addressed the aforementioned product design specs so no further analyses were performed.

9.6.1 Design for the Environment Questionnaire

RAW MATERIALS

Do any of the raw materials have high environmental impact?

- The steel, aluminum and plywood used in construction do not have a high environmental impact.

Are any recycled raw materials used?

- No.

Has the amount of raw materials been minimized?

- Yes.

Did the transport of the raw materials require significant energy use?

- Yes. Because the raw materials we used were not produced locally energy was required to transport them from where they were produced to where we purchased them.

Are any of the raw materials hazardous or toxic?

- No.
PURCHASED COMPONENTS

Do any of the purchased components have high environmental impact?

- No.

Are recycled materials used in any of the purchased components?

- No.

Did the transport of the purchased components require significant energy use?

- Yes.

Do any of the purchased components contain materials that are hazardous or toxic?

- No.

MANUFACTURING

Have you minimized the creation of solid or liquid wastes in your product manufacturing process?

- The only significant wastes created by the manufacturing process are the scraps from cutting raw materials, and they are minimal.

Does the manufacturing process create toxic waste (airborne, solid or liquid)?

- No.

Have you minimized the number and type of parts?

- The number of separate parts has not been minimized because this is a prototype luminaire. If the objective of this project had been to mass produce light fixtures, the numbers and types of parts would have been minimized.

PACKAGING AND TRANSPORT

Are packaging materials green?

- No packaging is used.

Is the weight of the packaging much less than the weight of the product?

- Not applicable.

Does the customer throw away the packaging?

- Not applicable.

Can the product be shipped using minimal energy?

- Yes.
PRODUCT USE

Is the product energy efficient?
- The luminaire has an efficiency of 17.3 lumens/Watt, and while this is not phenomenal, with more efficient LEDs the efficiency could be greatly improved.

Are consumables required for product use?
- No.

Has the environmental impact of consumables been minimized?
- Not applicable.

RE-USE

Is the product designed for easy take-apart?
- Yes.

Can the product be easily separated into appropriate waste and recycling streams?
- No.

Does the product contain liquids or gasses that are difficult to capture during disassembly?
- No.

Is it clear to the end-user what must happen to the product at the end of its life?
- No.

REGULATIONS

Are there local or state green regulations that apply to the product?
- There are rebates available from Excel Energy for installing energy efficient light fixtures. This is made possible by a state law requiring electric utilities to invest 1.5% of their revenue in energy efficiency programs [18]. However there are currently no rebates available for LED based light fixtures.

Are there green regulations in other states that might apply to the product?
- Other states have similar programs to Minnesota

Are there federal green regulations that apply to the product?
- The Leadership in Energy and Environmental Design (LEED) rates how “green” buildings are. For commercial interiors LEED offers points toward LEED certification for keeping the Watts/square foot used for lighting a building below the
ASHRAE standards for lighting[19]. Our product was not designed to directly meet this but, any energy efficient light fixture would be helpful in accomplishing LEED certification.

- The federal government gives products an energy star if they meet certain energy efficient criteria.[20] However for LED based lighting, these criteria are very demanding, and our luminaire does not meet the qualifications to be given an energy star.

Are there international green regulations that apply to the product?

- Yes. The restriction of hazardous substances directive (RoHS) prohibits the uses of certain materials in new electrical equipment to be sold in the European Union[10]. All purchased components used in the light fixture are RoHS compliant.

Are there green regulations that apply to the process used to manufacture the product?

- No.
9.7 REGULATORY ANALYSIS

One of the customer requirements of this project was that the luminaire would be designed to meet all applicable codes and standards Table 4. Our research indicated that the applicable standards were those established by: Canadian Standards Association, Underwriters Laboratories, European Union (CE), and Minnesota State Building Codes. Due to the nature of these regulations, some regulatory agencies required that copies of the standards be purchased to gain access to them. Tom Corrigan advised the team not to consider some regulations due to their cost. Therefore the only regulations that were analyzed were those freely available to the public. The 2007 Minnesota State Building Code was available for free online, and it specified that equipment for electric light must meet the regulations contained in the 2005 National Electrical Code[8].

The following is a list of all the sections of the 2005 National Electrical Code applicable to luminaires and how our design meets each:

- **410.3 Live Parts**: The luminaire has no live parts normally exposed to contact[9].

- **410.22 Luminaire (Fixture) Wiring—General**: The wiring in the luminaire is neatly arranged[9].

- **410.24 Conductor Insulation, 410.67(A) Wiring, General**: The luminaire uses conductors with insulation rated for the operating conditions[9].

- **410.35 Luminaire (Fixture) Rating**: The luminaire is marked with the maximum lamp wattage, manufacturer’s name, and wire temperature rating[9].

- **410.38 Mechanical Strength**: The thickness of the outer metal outer structure is greater than .016 in[9].

- **410.68 Temperature**: The luminaire does not subject the adjacent materials to more than 90°C[9].

- **410.71 Solder Prohibited**: No solder was used in the construction of structural components of the luminaire[9].

- **410.74 Direct Current Equipment**: The luminaire is marked for dc operation [9].
10. PROTOTYPE EVALUATION

The prototype evaluation section outlines testing performed on the LED based luminaire. During the design process several analyses were performed to approximate the characteristics of the luminaire. Each of these analyses made simplifying assumptions to explain things that would be difficult to model analytically. For example in the thermal design it was assumed that the lumped capacity solution could be used to describe the heat transfer in the heat sink. To test this, thermocouples were attached to the luminaire in different places to determine steady state temperature at several locations so they could be compared to the analytical results.

In the light distribution design, it was assumed that the light could be modeled in two dimensions. Unfortunately, testing to verify this analysis could not be performed due to time constraints, but the light output of the luminaire was verified with testing. The light output testing let the team determine how much light the luminaire actually produced, compared to the specifications sheet for the LEDs.

For the electrical section, it was assumed that the components performed with the characteristics reported in the product specification sheets. The actual power input to the luminaire was measured allowing the team to identify the actual power consumption.

By testing our prototype in these areas we are able to validate the assumptions we made as well as, determine how the luminaire’s actual performance compares to the product design specifications. The testing compares the actual characteristics to the expected values and explains any discrepancies between the two.
10.1 TESTING

10.1.1 Temperature Testing

Controlling LED temperature is important for LED life and consistency of light output. The thermal characteristics of the final prototype were tested over three hours.

The team attempted to verify the analytical calculations for heat sink temperature and air temperature above the heat sink. To accomplish this, temperature was recorded at one location on and above each heat sink. For discussion of testing results the heat sinks are called out as “left heat sink” and “right heat sink.” Fig. 53 outlines the placement of type-T thermocouples utilized in temperature measurement. Note that the heat sink in Fig. 53 is highly simplified and only serves to illustrate thermocouple placement. Fig. 55 shows the actual placement of the thermocouples on one of the heat sinks. TC 1 in Fig. 53 (a), represents the thermocouple location on each heat sink. Thermocouples on the heat sink were placed on the outside of the heat sink approximately 0.25 inches below the level of the LED. The thermocouples were attached to the surface of the heat sink with a small piece of adhesive. TC 2 represents the thermocouple location above each heat sink. TC 2 is located directly above the LED between the LED and the top of the fixture.

Temperature measurement was achieved with a C++ language data acquisition program, Keithley channel scanner, and multimeter. Type-T special limit thermocouples (28 gauge, ±0.5°C) were used to measure temperature. A thermistor located in an isothermal box was used for the thermocouple reference temperature. Data were acquired every 8 seconds. The data acquisition program is found in Appendix Section 16.8 - Data Acquisition Program For Thermal Testing. To perform the testing the light fixture was placed in a false ceiling, 7 ft above the ground. Fig. 56 shows the light fixture placed in the false ceiling. The computer, scanner, and multimeter are shown in Fig. 57. A sample output is show in Fig. 58.

Three LEDs on the left heat sink shorted before testing. Due to time constraints the LEDs were not repaired before temperature testing occurred. Fig. 53 shows the location of the broken LEDs.
A plot showing the first 100 minutes of testing is shown in Fig. 54. Table 10 gives the average steady state values for each temperature measurement. At 47.9 °C, the average steady state temperature of the right heat sink is approximately 3 °C higher than the average steady state temperature of the left heat sink. The temperature difference has two possible explanations. The most likely explanation for the temperature difference is the three broken LEDs on the left heat sink. These LEDs did not input any energy into the heat sink, reducing the heat sink temperature. Also, the method of attaching the thermocouples to the heat sink was not ideal. Adhering the thermocouples to the side of the heat sink with tape did not make up for the contact resistance between the thermocouple junction and the heat sink. The contact resistance creates additional uncertainty in the temperature measurement of the heat sink.
The estimation of steady state air temperature above the heat sinks (35 °C) was very close to the measured values (34.9 °C and 35.0 °C).

The measured heat sink temperatures (44.8°C and 47.6°C) were approximately 20% lower than the expected value (57.4 °C). This difference is likely explained by improper bonding of the LED to the heat sink. At the time of temperature testing, the LEDs were secured to the heat sink as shown in Fig. 50 of section 9.3.3. The spring steel clip holding down the LEDs was not fully tightened because the LEDs were shorting when the team was using the original thermal grease (the thermal grease would displace, providing direct contact with the heat sink). Because the LEDs were not fully tightened down, the resistance between the heat sink and LEDs was likely higher than the predicted resistance, which provided a lower than expected heat sink temperature. The method of thermocouple attachment also creates a small temperature drop from the surface of the heat sink to the thermocouple, because of the contact resistance. Because of this, the actual heat sink temperature would be slightly higher than the measured value. The final potential explanation for lower than expected heat sink temperature is better than expected thermal performance. The high uncertainty associated with empirical heat transfer correlations could have underestimated the thermal performance of our system.
FIG. 54. RESULTS OF THERMAL TESTING (FIRST 100 MINUTES)

TABLE 10. ACTUAL AND EXPECTED STEADY STATE TEMPERATURES

<table>
<thead>
<tr>
<th>Steady State Temperatures (°C)</th>
<th>Tested</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Heat Exchanger</td>
<td>44.8</td>
<td>57.4</td>
</tr>
<tr>
<td>Right Heat Exchanger</td>
<td>47.6</td>
<td>57.4</td>
</tr>
<tr>
<td>Air Above Left Heat Exchanger</td>
<td>35.8</td>
<td>35.0</td>
</tr>
<tr>
<td>Air Above Right Heat Exchanger</td>
<td>34.9</td>
<td>35.0</td>
</tr>
<tr>
<td>Average Temperature of Ambient Air</td>
<td>22.9</td>
<td></td>
</tr>
</tbody>
</table>
FIG. 55. THERMOCOUPLE PLACEMENT ON HEAT SINK

FIG. 56. LIGHT FIXTURE PLACED IN FALSE CEILING
FIG. 57. COMPUTER SCANNER AND MULTIMETER USED TO PERFORM TESTING

FIG. 58. SAMPLE OUTPUT
10.1.2 Light Distribution/Output

The testing of light distribution and output is necessary to validate the luminaire design and determine if it meets the product design specifications for even light distribution, proper color temperature, and proper light output as listed in Table 5. The color temperature and the light output in lumens are mostly based on the LED characteristics. The light output test allows us to see how the actual performance of the LEDs compares to the manufacturer’s data sheets. The results of our testing can be used to benchmark other 3M technologies that could be utilized in this type of application.

The testing of light distribution compared against the program described in section 9.1.2 - Ray Tracing would show how accurate a two dimensional approximation of the luminaire is. Unfortunately, there was not sufficient time to test the light distribution of the fixture. Also, the intensity of the light produced by the LEDs varies depending on the angle the LEDs are viewed from. Directly over the top of the LED’s the relative luminous intensity is about 100%, but closer to horizontal the relative luminous intensity drops to about 10% [6]. This property was not included in the ray tracing program, so the program’s output does not give approximate luminous intensity at different locations. This would make comparing the actual light distribution to the ray tracing program difficult because the actual luminous intensity at various locations would be difficult to compare to the graphical results of the program.

Light output testing was performed at the 3M Display & Graphics Lab using an Optronic OL-770 LED Measurement System and is shown in Fig. 60 and Fig. 64.
FIG. 59. LUMINAIRE IN LIGHT INTEGRATING SPHERE

FIG. 60. LIGHT OUTPUT TEST EQUIPMENT AND SETUP
The most important characteristics from testing were lumen output, color temperature, steady-state lumen depreciation, and spectral distribution. The lumen output of the luminaire was measured at the instant the luminaire was turned on and at steady state. The initial lumen output was found to be 1315 lumens with a color temperature of 6593 K. The steady-state lumen output is 1227 lumens with a color temperature of 6840 K. The color temperature of sunlight is approximately 6500 K. From the LEDs’ data sheets the maximum lumen output would be less than 1380 lumens, therefore 1315 lumens and 1227 lumens are reasonable results [6]. The data sheets for the LEDs’ also gave a range of 5000K to 10000K for color temperature, and the measured color temperatures fit within this range.

Steady-state lumen depreciation describes how well the LEDs light output is maintained during normal operation compared to the instant the fixture is turned on. Our fixture obtained a well regarded, 9.3 percent lumen depreciation. All too often manufacturers of LED light fixtures publish the initial light output from a luminaire and not the depreciated value which can be in the vicinity of 15 to 50 percent of the initial. Quality luminaires are typically in the 5 to 15 percent range.

The initial spectral distribution of the luminaire is shown in Fig. 61. The spectral distribution of the LED itself is very similar to the luminaire and is shown in Fig. 62.
FIG. 61. LUMINAIRE SPECTRAL DISTRIBUTION

FIG. 62. LED SPECTRAL DISTRIBUTION [6]
Chromaticity coordinates describe the apparent color of the light and are shown in Fig. 63 and are from the initial prototype test. The circle in the middle of the figure is a reference white light lamp that has a special power supply that makes sure the light’s output is extremely accurate. The black dot shows where the prototype’s light output is and the line connecting it to the outside of the color band shows where the dominant wavelength is tending towards. This means that the light is white but has a slight blue-ish tint to it. The dominant wavelength is 479.7 nm and the peak wavelength is 446.7 nm.

FIG. 63. CHROMATICITY COORDINATES OF LUMINAIRE
10.1.3 Evaluation of Electrical System

The electrical system determines how efficient the prototype actually is. Electrical system testing was performed at the student prototyping lab using a KillaWatt. The power the luminaire consumes is 89 Watts. The efficiency of the system is calculated from Eq. (16), and is 74 percent resulting from inefficiency in the power supply and constant current LED driver. The LEDs consume 65.8 Watts.

In comparison to the electrical characteristics of the test results, the LEDs used have a nominal 3.4 V forward voltage and a desired 700 mA forward current resulting in 2.38 Watts dissipated per LED. The power consumed by the LEDs is theoretically 71.4 Watts and the luminaire theoretically consumes 96.6 Watts. The difference of 7.6 Watts is from the combination of a few variations in actual operating conditions. The LED forward voltage can vary by 0.8 V and the exact current output of each BuckPuck will be slightly off from 700 mA. There are also small losses in the length of wire between connections and from the connections themselves.

10.1.4 Summary of Prototype testing results

The estimation of steady state ambient air temperature above the heat sink (35.0 °C) was very close to the measured values (35.0 °C average). The measured heat sink temperatures (44.8°C and 47.6°C) were approximately 20% lower than the expected value (57.4 °C). The difference between the expected and measured heat sink temperature was primarily attributed to poor LED bonding with the heat sink at the time of testing, and the inaccuracy in the temperature measurement.

The light output of the luminaire was found to be less than what was expected, 1315 lumens compared to 1380 lumens. This can be attributed to the use of less efficient LEDs. The luminaire was initially designed to use LEDs that had twice the lumen output and half the power of the current LEDs. The CCT of 6593 K for the luminaire achieved a very good comparison to sun light of 6500 K.
The power consumed by the luminaire is 89 watts. The electrical circuit efficiency of 87 percent is from the use of the Buck Puck. The overall luminaire efficiency of 74 percent could be increased if a more efficient power supply were found. Light distribution testing had to be put aside due to time constraints and was never tested.
11. DESIGN EVALUATION

For our luminaire design to be successful it needs to satisfy the product design specifications. To determine how well the design met these requirements thermal, optical, and electrical testing was performed. From the results of these tests the team was able to establish the actual specifications of the luminaire. This section compares the test results and prototype's specifications to the product design specifications.

11.1 COMPARISON OF TEST RESULTS TO ANALYSES

Testing showed that the team’s analyses conservatively predicted fixture performance. A direct comparison between expected values and measured values is shown in Table 11. The reasons for discrepancies between the expected and measure values are discussed in depth in Section 10.1 - Testing.

<table>
<thead>
<tr>
<th>Property</th>
<th>Expected</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat sink temperature</td>
<td>57.4 °C</td>
<td>47.6 °C</td>
</tr>
<tr>
<td>Temperature of air above heat sink</td>
<td>35 °C</td>
<td>35 °C</td>
</tr>
<tr>
<td>Light output</td>
<td>1380 lumens</td>
<td>1315 lumens</td>
</tr>
<tr>
<td>Color Temperature</td>
<td>5000K-10000 K</td>
<td>6593 K</td>
</tr>
<tr>
<td>Power Input</td>
<td>96.6 Watts</td>
<td>89 Watts</td>
</tr>
</tbody>
</table>
11.2 COMPARISON OF PRODUCT DESIGN SPECIFICATIONS TO FINAL PROTOTYPE SPECIFICATIONS

The properties of the final prototype were determined through multiple tests and are listed in Table 12.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
<th>PDS Marginal Value</th>
<th>PDS Ideal Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular dimensions</td>
<td>47.5x24</td>
<td>48x24</td>
<td>12x24</td>
<td>Inches</td>
</tr>
<tr>
<td>Initial light output</td>
<td>1315</td>
<td>1000-4000</td>
<td>2000-3000</td>
<td>Lumens</td>
</tr>
<tr>
<td>3M diffuse reflector use</td>
<td>yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Binary</td>
</tr>
<tr>
<td>Power input</td>
<td>76</td>
<td>50</td>
<td>25</td>
<td>Watts</td>
</tr>
<tr>
<td>Cost</td>
<td>109.35</td>
<td>&lt;600</td>
<td>&lt;200</td>
<td>Dollars</td>
</tr>
<tr>
<td>Color temperature</td>
<td>6593</td>
<td>3000-7000</td>
<td>5000</td>
<td>Kelvin</td>
</tr>
<tr>
<td>Steady state light output</td>
<td>1227</td>
<td>1000-4000</td>
<td>2000-3000</td>
<td>Lumens</td>
</tr>
<tr>
<td>Ceiling compatibility</td>
<td>1</td>
<td>1</td>
<td>all</td>
<td>Quantity of types of ceilings</td>
</tr>
<tr>
<td>Depth dimension</td>
<td>5.625</td>
<td>2-7</td>
<td>3-6</td>
<td>Inches</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>17.3</td>
<td>&gt;45</td>
<td>&gt;80</td>
<td>Lumens/Watt</td>
</tr>
<tr>
<td>Maximum fixture temperature</td>
<td>47.6</td>
<td>90</td>
<td>60</td>
<td>°C</td>
</tr>
</tbody>
</table>

The rectangular dimensions of the fixture are very similar to the marginal dimensions detailed in the product design specifications (Table 5) of 2’x4. The depth dimension of the final prototype is 5.625 inches which falls into the ideal range of three to six inches described in the product design specifications. These dimensions are set by the purchased light fixture that acts as a framework for the luminaire. The light fixture does use 3M’s diffuse reflective film to break up the light from the LED’s so that individual bright points of light are not visible. The final cost of the prototype not including labor is $109.35. This cost does not factor in the materials donated by 3M. The light fixture is compatible with only drop ceiling because the purchased fixture that is used as a frame is compatible with drop ceiling. The color temperature of the output is 6593 K, this fits in the range of marginal values of 3000 to 7000 K mentioned in the product design specifications. The color temperature is
predominantly controlled by the LED that is used, and there are LEDs available in several
different color temperatures. A maximum measured temperature of 47.6°C was found on the
heat sink and it was less than the ideal value of 60°C for maximum fixture temperature. The
actual operating temperature of the LED was not measured because there was not a good way
to attach a thermocouple to the LED.

The initial light output of the luminaire is only 1315 lumens. The light output reduces to
1227 lumens at steady state. This is lower than the ideal value of 2000-3000 lumens in the
product design specifications Table 5 because the LEDs used in the fixture (Cree XR’s) are
not as efficient as the LED’s the team wanted to use (Cree XRE’s). The power input to the
luminaire is 76 Watts. This value does not include the losses for power conversion from AC
to DC. The marginal value for power input was much lower at 50 watts in the product design
specifications. The efficiency of this fixture is 17.3 lumens/watt compared to the desired 45
lumens/watt for the marginal value in the product design specifications. This discrepancy in
efficiency can be caused by two things, the efficiency of the LEDs and how well the fixture
reflects light. The LEDs used in the fixture are less efficient than the LEDs we were planning
on using so the maximum value of efficiency is the efficiency of the LEDs. Also, not all of
the light produced by the LEDs leaves the fixture, some of the light is absorbed by the light
fixture further reducing efficiency.

Not all of the product design specifications were validated with testing. This is due to time
constraints and lack of sophisticated testing equipment. Things like testing fixture life or
lumen maintenance at 50000 hours would have required destructive accelerated life testing.
Also, some of the product design specifications were overly optimistic. For example, the
team only used 3M diffuse reflective film despite listing several 3M products in the product
design specifications. Using all of the products listed would have made the design overly
complex.