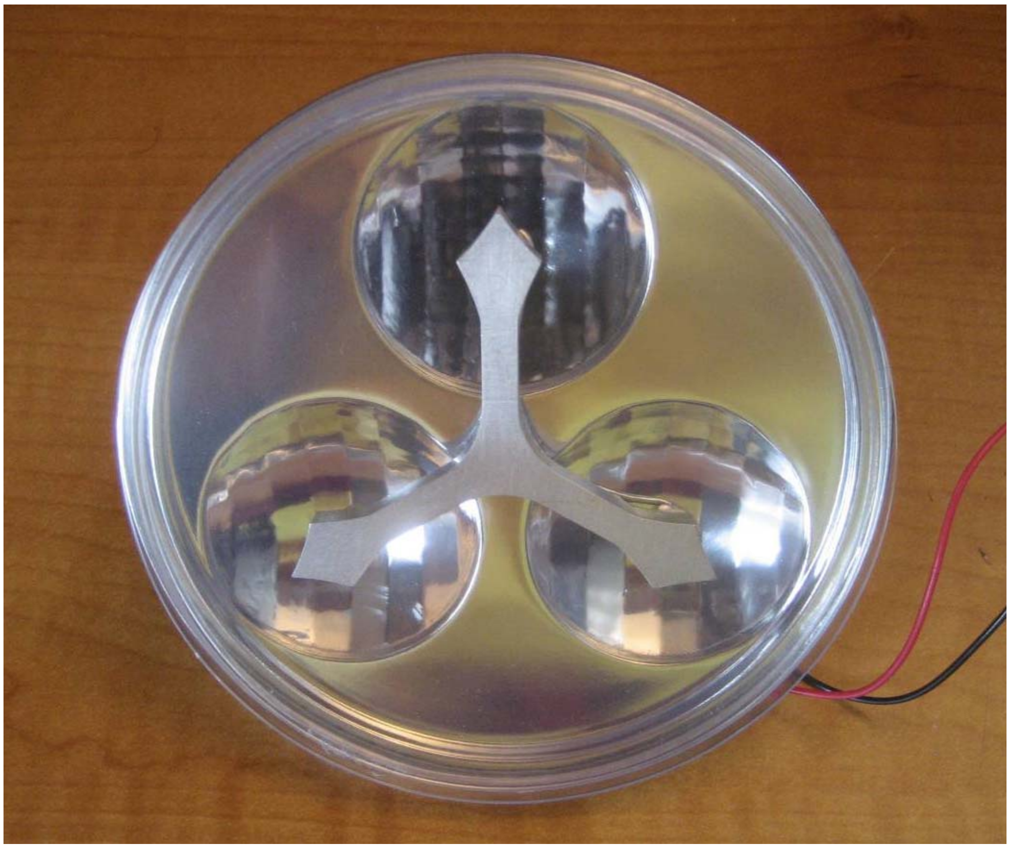
ME450 SENIOR DESIGN PROJECT
PROJECT #11



LED FOG LAMP DESIGN FOR AUTOMOTIVE APPLICATION FINAL REPORT

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March, 21 2008

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ABSTRACT

General Motors currently utilizes halogen bulb technology as the light source for front fog lamp applications. However, halogen bulbs have limited life, large warranty costs, and limit design creativity and size due to the physical construction. Light Emitting Diode (LED) technology has the potential to improve upon these areas. The objective of this project is to replace the traditional halogen light source with an LED for front fog lamp application. Our goal is to develop a robust LED front fog lamp design that meets the GM Design "Best Practices" and can be manufactured on a high volume basis for less than $13.50/part.

EXECUTIVE SUMMARY

DESIGN PROBLEM Halogen lamps have been used in vehicle lighting for more than 20 years with very few substantial improvements in lifetime or efficiency. Today, automakers are searching for new alternatives that will lower warranty costs from replacing defective or damaged fog lamps, improve fog lamp lifetime and allow for more design creativity. General Motors has requested a robust and legally compliant LED fog lamp design for providing forward illumination while driving under low visibility conditions. Additionally, it should be inexpensive, aesthetically pleasing, and have a lifetime exceeding that of the vehicle. LED fog lamps are more energy efficient than halogen lamps, have more than an order of magnitude longer lifetime, and their compact solid state nature makes them more durable while opening up novel design options.

SPECIFICATIONS Our LED fog lamp design should meet all requirements specified in the GM Best Practices document, the US SAE, the European ECE and the Canadian CMVSS. In addition, our design should be low profile, light weight, low cost, and aesthetically pleasing. Our final fog lamp design should meet all of the above requirements and also have a cost of $13.50 per unit on a high volume basis (approximately 5 million units).

CONCEPT GENERATION & SELECTION Each team member first generated fog lamp concepts falling into three different categories: aesthetic appeal, direct lighting, and indirect lighting methods. After narrowing this list of concepts and combining ideas, we arrived at a set of eight designs. For each design, factors such as manufacturability, ease of meeting legal requirements, cost, and aesthetics were evaluated using a concept scoring matrix. The highest point value was earned by the design incorporating hidden LEDs used in conjunction with a cone-based reflector. This design was selected as our alpha prototype.

PARAMETER ANALYSIS In order to verify the functionality of our design we used a combination of computer software simulations and physical testing. The reflector was designed using an iterative process. We used reflection theory along with a series ray tracing simulations with the help of OSRAM to predict the optical performance of our fog lamp. Based on these results, we redesigned the reflector to improve the light distribution pattern in order to meet the legal luminosity requirements. We used circuit analysis to design an appropriate circuit board for powering our LEDs. Using Finite Element Analysis software, Abaqus, we simulated the thermal performance of our heat sink, ensuring that our LEDs would not operate above the acceptable temperature range. Maintaining adequate protection from outside contaminants and moisture was addressed using adhesive seals and a GORE-TEX® patch.

FINAL DESIGN The initial ray tracing data from OSRAM indicated that we needed to redesign our chosen fog lamp. Our final design incorporates three separately aimed parabolic reflectors with vertical fluting to disperse light horizontally. A three pronged heat sink with a bottom mounted circuit board was chosen for positioning three Diamond DRAGON® LEDs at the focal points of each individual reflector. The reflectors' axes of symmetry were all aimed at the point where the fog lamp required the greatest amount of illumination. The flutes were each designed to angle light to a specific area of the luminosity testing zone in order to meet legal requirements. The optical simulation results indicated that future modifications are necessary for the reflector. We found that there is too much light above the horizontal and thus our solution is to redirect the light downward using reflector geometry. In addition, the thermal performance of our prototyped heat sink was inadequate; the temperature surrounding the LEDs was too high. Our solution was to manufacture the entire housing out of aluminum with integrated thermal dissipation fins on the back. The new design is predicted to keep the LEDs within their ideal temperature range and ensure that a long lifetime is achieved.

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APPENDIX

1 INTRODUCTION

The incorporation of Light Emitting Diodes (LEDs) in exterior automotive lighting applications has become a staple in the design of most concept vehicles for their aesthetic appeal. Recent breakthroughs in LED technology have considerably lowered their cost and increased brightness, thereby allowing automakers to pursue LED implementation in production vehicles. Currently, automobile fog lamps utilize halogen bulbs for their light source and therefore face many of the shortcomings inherent in halogen lighting technology. These include a relatively short bulb life (leading to large warranty costs) and limited design creativity due to the light dispersion of the bulb. The problem we've been assigned is to design a legally compliant fog lamp for providing forward illumination while driving under low visibility conditions, which is inexpensive, aesthetically pleasing, and has a lifetime exceeding that of the vehicle. To achieve this goal, we plan to replace the halogen light bulbs with LEDs. The use of compact-sized, relative low heat and long-lasting LEDs will remedy the aforementioned problems associated with halogen bulbs. Upon the project's completion, GM expects our team to deliver a mathematical model, as well as a LED fog lamp prototype. The final design should adhere to the legal lighting requirements for fog lamps set by the U.S., Europe, Canada and Japan. In addition, the final design's high volume production cost should not exceed $13.50/unit. A successful prototype design may lead GM to implement our fog lamp in a substantial fraction of its 9 million production vehicles per year [15].

2 ENGINEERING SPECIFICATIONS

During our discussion with GM, they stated that the most important specification for the fog lamp design was that it meets all fog lamp legal requirements for Europe, Canada, and the United States, thereby making it globally compliant. As stated in the project description from GM, the purpose of designing a LED fog lamp instead of a halogen fog lamp was to allow for greater design creativity and increased fog lamp life, which consequently reduces warranty costs. Due to the possibilities for new design creativity achieved by switching to a potentially smaller LED "bulb", GM requested a new aesthetic design that would not have been possible before. GM specified a high volume production target price of $13.50/unit. Lastly, minimizing weight would benefit the fuel economy, but was not deemed a requirement. The specifications are ranked by importance of design in Table 1, below.

Rank of Importance	Specification
1	Meet fog lamp legal requirements
2	Aesthetics
3	Increase life span of fog lamp
4	$13.50/unit price point
5	Minimize weight

Table 1: Customer Requirement Rankings

2.1 SCOPE OF REQUIRMENTS

For a fog lamp to be legally compliant, it must pass the tests outlined in numerous SAE and ECE documents shown in Appendix E on pg. 81. After discussing the legal requirements with GM we narrowed down the list of legal requirements for several reasons. First, we do not have enough time during the semester to complete our design, prototype it, and then run the numerous required tests. Second, our prototype will be made using rapid prototyping; the material used in rapid prototyping is not as strong or thermally resistant as the actual materials that would be used in a production fog lamp, thus making the test results unreliable. Finally, to meet legal specifications all testing must be done on production tooled parts, which we will not have. One of the legal specifications we were told to meet was the luminosity requirement, which may have to be met through simulation, due to the likelihood of a rougher surface finish and coating of our prototype reflector. We were asked to design for thermal consideration even though we will not be able to run the internal heat test and thermal cycle test. Our primary concern is that the performance of the fog lamp does not deteriorate with increasing temperature and prevent our design from meeting luminosity requirements. Although the voltage test will not be run, we should design the fog lamp such that it can operate under voltages between 12.8 V and 13.9 V as described in the electrical section (Section 2.4 on pg. 7).

2.2 QFD

To relate our customer needs to the technical requirements we constructed a Quality Functional Deployment (QFD) matrix. Using prescribed weights for each customer need and their respective relationships to different technical requirements, we ranked each requirement with respect to others by using a specific point value system. These rankings helped us determine the relative importance of individual technical requirements to our fog lamp design process with respect to customer needs. The results of this analysis allowed us to identify the most important technical requirements on which we should focus our attention. The three highest ranking requirements were: meeting the luminosity regulations, maintaining the acceptable LED operating temperature, and ensuring that we deliver an aesthetically pleasing final design. The following sections discuss the details behind the engineering targets. The QFD matrix can be found in Appendix C on pg. 79.

2.3 OPTICS

2.3.1 LUMINOSITY REGULATIONS

We are responsible for meeting the requirements for a harmonized fog lamp, which is designed to comply with the US SAE, the European ECE and the Canadian CMVSS specifications. To meet global luminosity standards, the light intensity distribution values, found in Table 2 and measured in candela (cd), must be met. Additionally, a tolerance of ±0.25° is permitted at any test point or line. The zone scans are to be conducted in 1° increments both horizontally and vertically [10]

Designation	Test	Vertical Position above h = (+) below h = (–)	Horizontal Position left of v = (–) right of v = (+)	Luminous intensity (cd) *Max*	Luminous intensity (cd) *Min*
Zone 1	Entire Zone	+ 10° to + 60°	-35° to +35°	125	---
Line 1	All Line	+ 8°	-26° to +26°	125	---
Line 2	All Line	+ 4°	-26° to +26°	150	---
Line 3	All Line	+ 2°	-26° to +26°	240	---
Line 4*	All Line	+ 1°	-26° to +26°	300	---
Line 5*	All Line	0°	-10° to +10°	400	---
Line 6	All Line	-2.5°	-10° to +10°	---	2400
Line 7	All Line	-6.0°	-10° to +10°	≤ 0.5 of Line 6 max	---
Line 8	A point on line	-1.5° to -4.5°	-22° & +22°	---	1000
Line 9	A point on line	-1.5° to -4.5°	-35° & +35°	---	400
Zone 2	Entire Zone	-1 ° to -3°	-10° to +10°	12000	---

Table 2: Photometric requirements for harmonize fog lamps [10]

* Some U.S. states require April 2001 metrics, and the luminous intensity values contained within designation lines 4 and 5 have been modified to account for this.

The photometric testing is accomplished by mounting the fog lamp on a test fixture that simulates the vehicle mounting system at a distance of 10 m from the photometer. The optical axis of the fog lamp is centered on the coordinate system at a position of 0º horizontal and 0º vertical on the flattened projection screen, illustrated in Figure 1. Figure 2, on pg. 5, represents the projection screen and illustrates the light distribution test points from the table.

In a discussion with GM, we found that the manufacturing process used for the prototype has a detrimental effect on the light dispersion of the reflector. Thus, the results from a physical test of the mock-up would be unreliable. In order to verify the optics for our design, we needed to rely heavily on simulation results with the help of OSRAM facilities. As a justification for this fact, we found there to be a 98% agreement between simulation results and actual fog lamp performance [22].

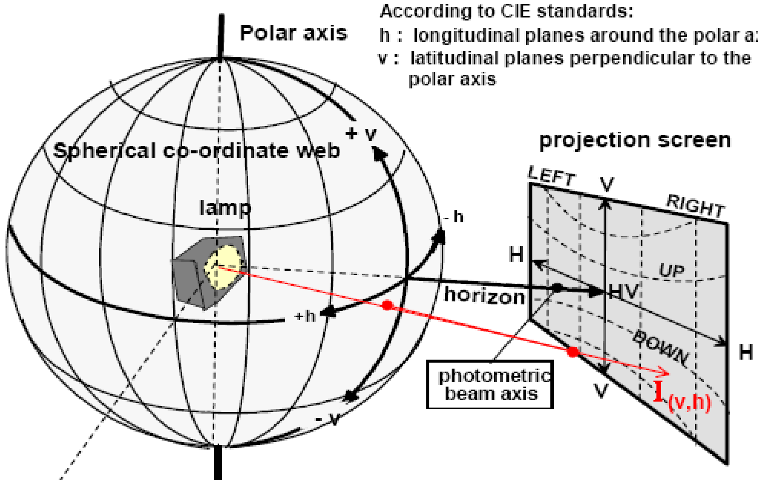


Figure 1: Measuring Screen Geometry [11]

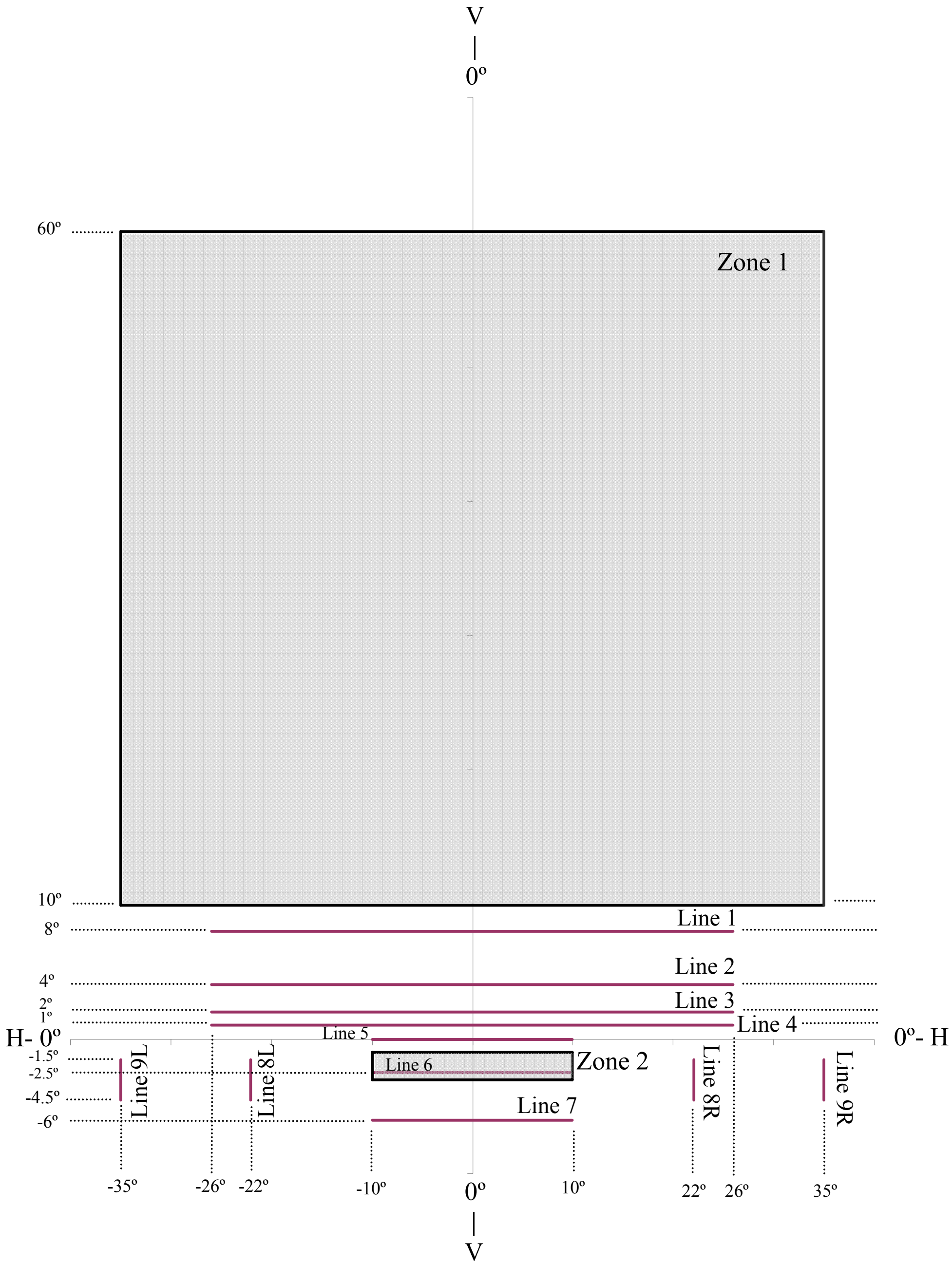


Figure 2: Light distribution testing points for harmonized fog lam requirements [10]

An additional consideration for front fog lamps is that we avoid glare for oncoming drivers. To ensure this condition is met, the gradient measurement procedure must be followed. A scan of the lamp beam pattern along the vertical line at 1 degree to the left and 1 degree to the right must be performed, while recording the light intensity (I, cd) at each position (α, degrees). The gradient (G_{log}) is calculated using below [10]. The location of the maximum gradient must fall within the range of 0.75° to 1.25° below the horizon.

$$G_{\log} = \log_{10} I(\alpha) - \log_{10} I(\alpha + 0.1) \quad \textbf{Eq. 1}$$

While this is an important check to ensure glare is avoided for oncoming traffic, we do not have the facilities on campus to accommodate this test. This test will need to be done in the future to verify the optics.

2.3.2 CHROMACITY REQURIMENTS

To comply with global fog lamp standards, the color emitted from the device must fall within a specified range of white. This is illustrated in the chromaticity diagram shown in Figure 3 on pg. 7. Chromaticity diagrams are essentially 2-D diagrams representing 3-D space. The Commission Internationale d'Eclairage derived the plot using positive and negative combinations of the blue, green, and red primaries; the values are a mathematical means of representing how different combinations of light within each color boundary are indistinguishable to the human eye. The coordinates are essentially normalized values derived from the spectral power distribution at each color's wavelength, where the x and y are color-coordinates, and the out-of-plane coordinate determines the luminance of the color [1].

We will use this as a guideline for selecting LEDs from the supplier such that all regulations are met. This is a metric that is provided to us by OSRAM as part of the specifications for each LED. As is illustrated in Figure 3, on pg. 7, the color of white light emitted from the device must fall within the following boundaries described in Table 3.

Boundary	Description
x = 0.310	blue
x = 0.500	yellow
y = 0.150 + 0.640x	green
y = 0.050 + 0.750x	purple
y = 0.440	green
y = 0.382	red

Table 3: Bounding equations defining SAE white color [1]

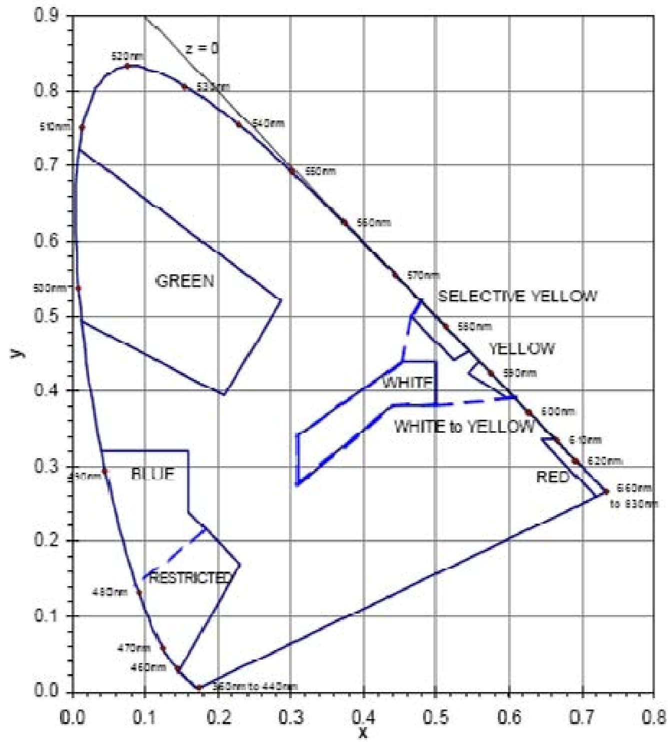


Figure 3: Chromaticity diagram with defined white color region [1]

2.4 ELECTRICAL

In accordance with the legal requirements, the photometry testing should be tested at a voltage of 12.8 ± 0.1 V DC, though our sponsor has specified that the lamp should sustain a maximum design voltage of 14.0 V DC.

2.5 THERMAL

Due to the prototyping material limitations, we cannot run thermal testing. Therefore we must do thermal design using simulations and heat transfer analysis. We should design the heat sink to keep the LEDs within an operating temperature range so that the photometric values do not change by more than ±20% from the nominal values before the test [16]. The operating temperature range of the LED is -40ºC to 85ºC; beyond these temperatures the LED luminosity changes by more 20% [8].

2.6 WEIGHT & SIZE

The weight of the fog lamp assembly should be minimized to improve vehicle fuel economy. GM currently has two low end fog lamps; fog lamp dimensions and weight are given in Table 4. The target weight does not count the heat sink or mounting hardware and is 82 g. The upper bound for weight is 340 g. While no target was given for the heat sink, weight should still be minimized with thermal and aesthetic considerations taken into account. GM design studio prefers smaller fog lamps so our target dimensions are a depth of 60 mm and a diameter of 100 mm target, but the only requirement GM actually gave us was that it be smaller than the current large fog lamp. This corresponds to a depth of 100 mm and a diameter of 140 mm.

	GM Small fog lamp	GM Large Fog Lamp
Depth (mm)	60	100
Diameter (mm)	100	140
Weight (g)	82	340

Table 4: GM fog lamp dimensions and weight

2.7 LIFETIME

GM wants the fog lamp to last the lifetime of the vehicle. Since a headlamp runs for approximately 5,000 hours over 10 years in a vehicle this is a reasonable goal since the fog lamp is operated less than the head lamp in standard vehicle use [3]. This target will not be tested, but will be verified with LED data taken by OSRAM.

2.8 COST

The cost of mass producing the fog lamp is $13.50/unit and should include the material and labor costs. We recognize this price point is volume dependent; we estimated a production volume of 5 million fog lamps. This correlates to 25% of GM's annual production of cars [15]. GM said the price point is a flexible target.

2.9 AESTHETICS

A major design criterion is that the fog lamp has to be aesthetically pleasing. Aesthetics are generally subjective, but we needed a method for rating the success of our design. We came up with the following set of criteria shown in Table 5, which was based on concepts from GM's "Perceived Quality" and GM design studio preferences [4]. For a design to be considered successful by our team, at least 4 of the 7 criteria must be rated with a positive score, resulting in at least an overall score of +1.

Aesthetic Criteria	**Score**
Minimize front profile (from front view of car)	
No visible bolts or glue	
No visible bulb	
Visible functional technical pieces	
See through lens	
Jeweled reflector (shiny)	
Aesthetic accent	
Total Score	
+ = (Criteria Met) - = (Criteria Not Met)	

Table 5: Metrics and Scoring of Aesthetics

2.10 CONTAINMENTS & MOISTURE

The dust, spray, and submersion tests are a means of verifying that contaminants and moisture are kept out of the assembly. This means that no dust shall enter the fog lamp when exposed in the dust test, and if dust does enter the luminous intensity of the fog lamp shall not decrease by more the 20% [11], **[16]**. During the submersion test no bubbles shall be seen exiting the fog lamp, and no water shall pool inside the fog lamp. Finally, for the spray test there shall be less than 2 ml of water in the fog lamp at the end of the test [16].We were not responsible for conducting these tests, but we were still expected to design the fog lamp with these specifications in mind. This means the fog lamp will be sealed to avoid containments from entering the assembly. However, in case moisture does get in, there needs to be a way for it to escape.

3 CONCEPT GENERATION

3.1 INITIAL BRAINSTROMING

We began our concept generation process with each group member independently brainstorming and then discussing and voting on the concepts. No limitations were placed on the design process in order to leave it as open ended as possible. The preliminary designs were voted on by our team. The concepts that we each came up with were numerous and varied. Each group member had a different idea about what a concept should consist of. Three of us drew shapes and profiles for the fog lamps, such as Figure G.6 in Appendix G on pg. 84, while one member drew different lighting concepts, such as Figure G.1 in Appendix G on pg. 84. We then decided we should go back and brainstorm more ideas using different fog lamp profiles, and lighting techniques. Even after our second brainstorming session the ideas were fairly unpolished and needed to be refined, to aid us we made a functional decomposition. This allowed us to track the material and energy flow through each of the fog lamp components.

3.2 FUNCTIONAL DECOMPOSITION

The main function of the fog lamp is to provide illumination in low visibility conditions. In order to satisfy this function, the following primary sub-functions must be considered; the functional decomposition can be found in Appendix D on pg. 80.

3.2.1 CONVERT ELECTRICITY TO LIGHT

The fog lamp must convert electrical energy into light energy. To perform the energy conversion from electrical to light energy, it is necessary to have an electrical interface. This interface must take the power supply of the car as an input and power the LED chip as the output. An LED is different from a halogen lamp in that it converts electrical energy directly into visible light, and thus no intermediate heating process is necessary [12]. However, it will be necessary to optimize the circuitry for the application.

3.2.2 DIRECT LIGHT

In order to comply with legal illumination regulations and avoid glare for the driver and oncoming traffic, it is necessary to redirect the light. The input to this component is photons emitted from each LED light source, and the output is reflected photons. According to optical physics, this can be accomplished either through the mechanisms of reflection or refraction. This could be done using lens optics and/or reflector optics. The light exiting the fog lamp assembly must comply with all specified luminosity requirements.

3.2.3 ABLE TO RESIST ELEMENTS AND ROAD CONDITIONS

The fog lamp assembly ensures that the unit can still function under the different conditions it will face during the vehicle's lifetime. The housing and the lens must prevent contaminants and physical factors such as moisture, vibrations, and small shocks from damaging the light source and reflector inside the fog lamp. The material inputs are contaminants and moisture, and the outputs are the deflection of contaminants and moisture.

3.2.4 PERFORMANCE DOES NOT THERMALLY DEGRADE

Since LEDs are very temperature sensitive, managing heat flow from the semiconductor will be very important [12]. The thermal management system must take heat energy input from the LEDs and circuit board components and dissipate heat to the surroundings in order to keep the LEDs within their ideal operating temperature range and meet luminosity requirements.

3.3 ADVANCED CONCEPT GENERATION

Generating the functional decomposition made it clear what components we could re-design. This also created more detailed and well thought out fog lamp concepts, see Appendix G on pg. 84. These designs were then presented and discussed with GM in a teleconference. The top five designs shown to GM that day are presented below.

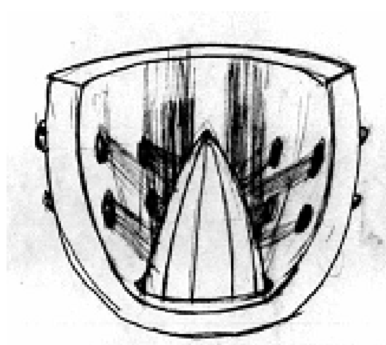


Figure 4: "Hidden LEDS with Cone" lighting method

Figure 4 above depicts a design using LEDs embedded in the housing in conjunction with a conical reflector. Since the light sources are not in plain view, this design was meant to draw the interest of anyone peering into the housing (since instead of seeing the usual halogen lamp they would see a cone surrounded by holes). As in most of the first sketches, this concept design should be treated more like an idea than an engineering drawing, since the number of LEDs, their orientation, and other specifications might change during the next steps of the design process.

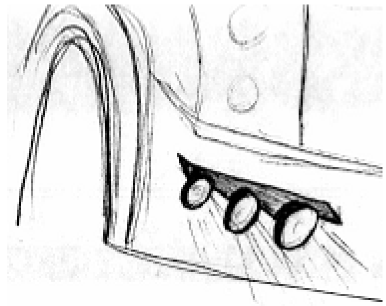


Figure 5: “Triple Decreasing” profile design

Figure 5 is a profile design, and thus its main purpose is to create a sleek outward appearance. Another positive is the unusual three “bulb” fog lamp design which is virtually nonexistent on production cars today. The fog lamp could be designed by first selecting a profile and then designing an appropriate lighting method to meet luminosity requirements.

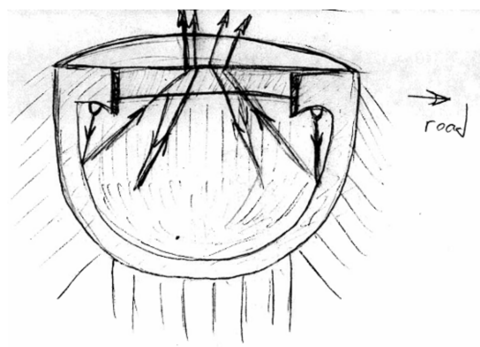


Figure 6: Side-sectional view of “Hidden under lip LEDs”

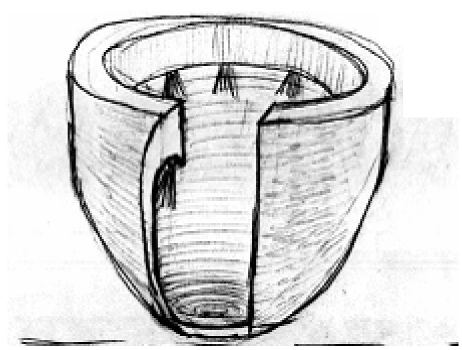


Figure 7: “Hidden under lip LEDs” lighting method

Figure 6 and Figure 7 above shows another lighting method which incorporates hiding the LEDs. However, whereas Figure 4 on pg. 10 will look like a cone surrounded by holes when viewed from the front, this design appears as an empty cavity from the same perspective. Figure 6 proposes modifying the mostly parabolic reflector (and/or altering lens optics) such that the light will meet luminosity requirements.

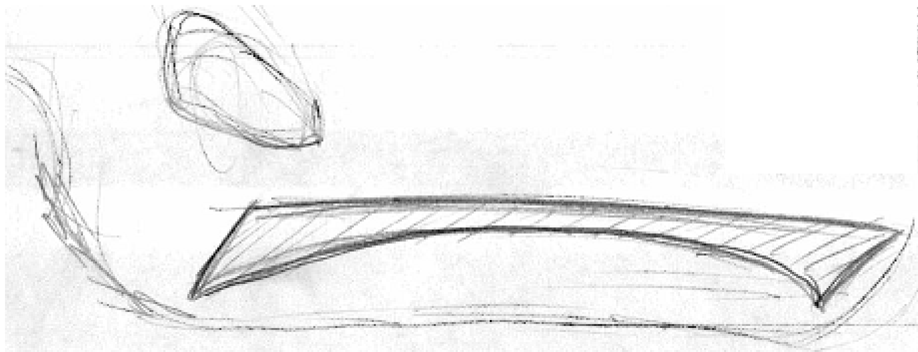


Figure 8: "Full Frontal" profile design

Figure 8 depicts a profile design which proposes replacing the two standard fog lamps with one large lamp spanning most of the width of the vehicle. This concept is a drastically different approach to fog lamps, and is meant to draw customers' attention by being radically different from other fog lamp designs currently on the market.

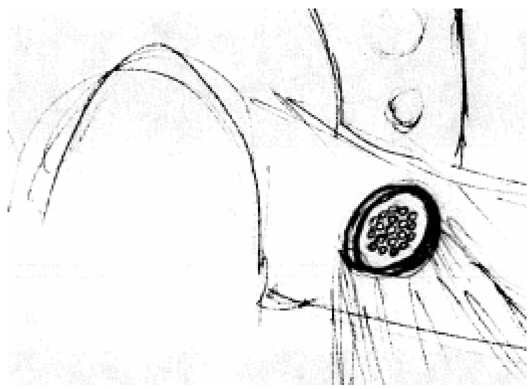


Figure 9: "Direct Cluster Lighting" lighting method

Figure 9 depicts a lighting method which became available because we switched from halogen to LED lighting. Since light emitted by LEDs can be directed, this lighting method takes advantage of this fact and discards the reflector component altogether. Figure 9 shows one possible arrangement of the LED cluster. In reality, the individual LEDs can be placed and directed in many possible ways allowing multiple possible looks for the fascia.

4 INITIAL CONCEPT SELECTION

Factors such as ease of manufacturing, ease of meeting legal requirements, cost, and aesthetic appeal played a major role in concept selections. In the end of the review, GM selected two lighting methods and asked for further refinement of the designs which incorporated these. The chosen methods were those which involved hiding the LED light sources and using direct lighting where the LED bulbs are visible. GM also requested several new designs based on these methods to have a larger pool of concepts to select from. Each team member came up with two fog lamp designs for each of these methods. The group voted to narrow down this list of sixteen designs to eight, based on the criteria discussed during the teleconference with GM. The sketches of the chosen eight can be found in Appendix H on pg. 89, and Appendix I on pg. 93. These concepts were evaluated using a Pugh chart (see Table 6 on pg. 14).

4.1 THE PUGH CHART

In the Pugh chart, the current GM halogen fog lamp was used as the datum for comparison and the design criteria were based primarily on the sponsor requirements. Since meeting the legal luminosity specifications determines whether a fog lamp can be placed on the market, and hence, whether we actually designed a functional product, this design criterion was assigned the most weight. It is important to note that luminosity in the Pugh chart does not refer to the light output of the devices, but rather to how easy or difficult it would be to make the given design meet luminosity specifications.

Aesthetics and "Cool Factor" were also two other heavily weighted categories. Fog lamps are easily noticed, since they are mounted on the fascia in the front of the car. Since a vehicle's exterior appearance has a large effect on whether a consumer purchases it or not, we wanted our design to attract customers. Aesthetics were based off of the GM "Perceived Quality" document and the GM design studio's opinion on what sort of appearance characteristics are desirable in exterior lighting **[17]**. Section 2.9 on pg. 8 covers these characteristics. The "Cool Factor" score was determined by team voting. It indicates how visually pleasing and sleek we perceived the design to be.

Lifetime, cost and manufacturability were given next priority. The main purpose of switching from halogen to LED lighting is to extend the lifetime of the fog lamp so that it will not need to be replaced during the vehicle's lifecycle. The reason lifetime was not assigned more weight is because all of our designs utilize LEDs as their light source, and hence, should not have a problem exceeding the halogen fog lamp's lifetime as desired by GM. Cost was assigned a weight of two because the $13.50/unit mass manufacturing cost was ranked fourth in the customer needs table (Table 1 on pg. 1). Finally, although manufacturability was not specifically mentioned by our sponsors, we deemed it a designed characteristic. Should our LED fog lamp prove to be satisfactory for GM, it will be manufactured on a large scale. GM produces over 9 million cars a year **[15]**. To equip even some of GM's vehicle models with fog lights would require millions of fog lamp units, thus the speed and ease of the manufacturing process for our designed fog lamp should be considered.

Assembly weight and the two size categories (the frontal area and depth of the fog lamp assembly) were included in the Pugh chart but were given minimum importance. Every part in a vehicle is designed so that its weight is minimized to maximize the vehicle's fuel economy, thus we could not exclude weight from the design criteria. However, since the eight designs considered in the Pugh chart do not vary significantly in mass, and since all of the designs' contribution to the overall vehicle weight will be less than 0.05%, not as much emphasis was placed on this criterion. The designs' frontal areas should be minimized. Lastly, the fog lamp's depth was considered since designs that are too great in depth will not work with GM's standard impact design.

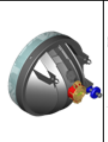
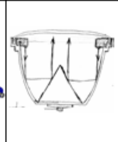
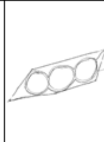
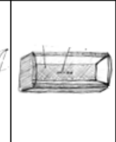
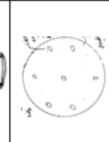
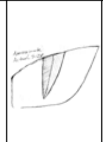
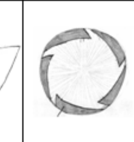
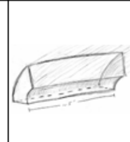
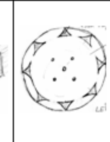
Design Criteria	Weight	DATUM	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6	Design 7	Design 8
	Sketches									
		Halogen lamp design	**The Mystery ver.2** (Pg 1)	The Trifecta (Pg 2)	The Cutest Button (Pg 3)	The points ver.2 (Pg 4)	The Cat Eye ver.2 (Pg 5)	The Vortex (Pg 6)	The Periscope (Pg 7)	The Desert Sun (Pg 8)
Aesthetics	3	·	**2.5**	0.5	-0.5	-0.5	2.5	2.5	0.5	0.5
"Cool Factor"	3	·	**1**	2.5	-0.5	-1	2.5	3	0.5	1.5
Cost	2	D	**-1**	-2	0	0	-2	-2.5	-1	-2
Weight	1	A	**-1**	-1	1	0	-1.5	-2	-1	-1
Lifetime	2	T	**3**	3	3	3	3	3	3	3
Luminosity	4	U	**-1**	0	-1.5	-1	-1.5	-1.5	-0.5	-0.5
Manufacturability	2	M	**-1**	-2	0	0	-2	-3	0	-1.5
Size (Depth)	1	.	**0**	1.5	3	3	0	0	-0.5	2
Size (Frontal Area)	1	·	**0**	-1	3	0.5	0	0	-1	0
			7.5	**6.5**	**4**	**1**	**5.5**	**3.5**	**2.5**	**4**

Table 6: Pugh Chart

4.1.1 PUGH CHART SCORING

Point values from -3 to 3 were assigned by our team in each category to each design in the Pugh chart using 0.5 increments. We determined the point values by each member deciding a score and then averaging these four scores and rounding the nearest .5. After multiplying all of the scores by their respective category weights and summing the results for each design, the design incorporating hidden LEDs with a cone-based reflector (The Mystery ver.2, which will hereby be referred to simply as "Mystery") earned the most points. Table 6 on pg. 14 summarizes the strengths and weaknesses of each of the eight designs evaluated using the Pugh chart.

4.2 THE TOP RANKED DESIGN

Mystery's 7.5 score came mostly from its high marks in the aesthetics and lifetime criteria (the latter being common to all eight designs since their LED light sources are far longer lasting than the halogen bulb of the datum). However, although it did not have any overwhelming disadvantages, it is important to note that it is by no means flawless. Mystery will be more expensive and harder to manufacture than the current halogen fog lamp. Furthermore, the light emitted from the LEDs has to reflect twice before exiting the assembly. This might make it difficult to meet luminosity requirements due to the uncertainty associated with a double reflection. Still the design's unique, neat look and long lifetime outweigh the aforementioned complications and place it well above the datum. Additionally, since it did not receive a negative score below -1 in any of the design criteria make it favorable to our other concepts which suffered from serious shortcomings.

4.3 THE RUNNERS UP

The following designs were the next four highest ranking designs in the Pugh chart.

4.3.1 THE TRIFECTA

The Trifecta (see Figure I.1 in Appendix I on pg. 93) was one point behind Mystery in the Pugh chart ranking system. When compared to Mystery, its design was deemed "cooler" and it boasted a smaller depth, however these characteristics failed to make up for its higher cost, lower aesthetics score, projected larger fontal area, and more complicated manufacturing process associated with incorporating three separate LED modules into one design.

4.3.2 THE CAT EYE VER.2

The Cat Eye ver.2 (see Figure H.4 in Appendix H on pg. 89) earned the third highest score of 5.5. Although it scored an impressive 2.5 in the aesthetics and "cool factor" categories due to its innovative and sleek design; the associated manufacturing complexity and cost caused it to lose points in comparison to Mystery. The asymmetric design of the Cat Eye make the optics of the fog lamp much more complicated than Mystery so it would be hard to meet luminosity requirements. Furthermore, the large centerpiece of the fog lamp assembly added to the design's total weight, lowering its score below that of Mystery in the respective category.

4.3.3 THE DESERT SUN

The Desert Sun (see Figure I.2 in Appendix I on pg. 93), with its score of four points, tied for fourth place in the Pugh chart rankings. Its distinguishing characteristic is the incorporation of accent lighting, which made it "cooler" than Mystery. In addition, it boasts a much thinner profile (i.e. smaller depth) than Mystery. The high price and manufacturing complexity of this design were simply too great to overcome. The lower scores in the cost and manufacturing categories, as well as the lower score as a result of the visible LEDs caused the Desert Sun to ultimately receive a lower rating than Mystery.

4.3.4 THE CUTEST BUTTON

The design that tied the Desert Sun was the Cutest Button (see Figure I.3 in Appendix I on pg. 93.). The design's name was jokingly assigned to it due to the incredibly small size, reflected in its maximum scores of 3 in both size categories (since smaller size earns a better score). The idea behind the Cutest Button was that a series of the smallest profile LEDs will be arranged into a line in such a manner than when the fog lamp is off, the light sources would not be noticed. Although originally this idea had great appeal, the Pugh chart revealed some serious shortcomings associated with it. For one, contradictory to the design's name, it was not as visually appealing as Mystery, trailing the chosen design in the "cool factor" category. Additionally, although the chosen LEDs would be extremely small, the LEDs would still be visible, thus the Cutest Button received a much lower aesthetics score than Mystery. Furthermore, it would be difficult for the Cutest Button to meet luminosity requirements due to the lack of reflector; this caused it to receive a lower score than Mystery in the luminosity category. The significant weight placed on the luminosity category caused the seemingly small point value deficit to have a rather large negative impact on the Cutest Button's final score. Thus, ultimately, this design, along with the other runners up, had to be discarded in favor of Mystery.

5 SELECTED CONCEPT DESCRIPTION

The fog lamp concept we chose with the major components is described by below in Figure 10. As illustrated, the design consists of a lens, reflector, housing, GORE-TEX® patch, heat sink, and LED circuit board.

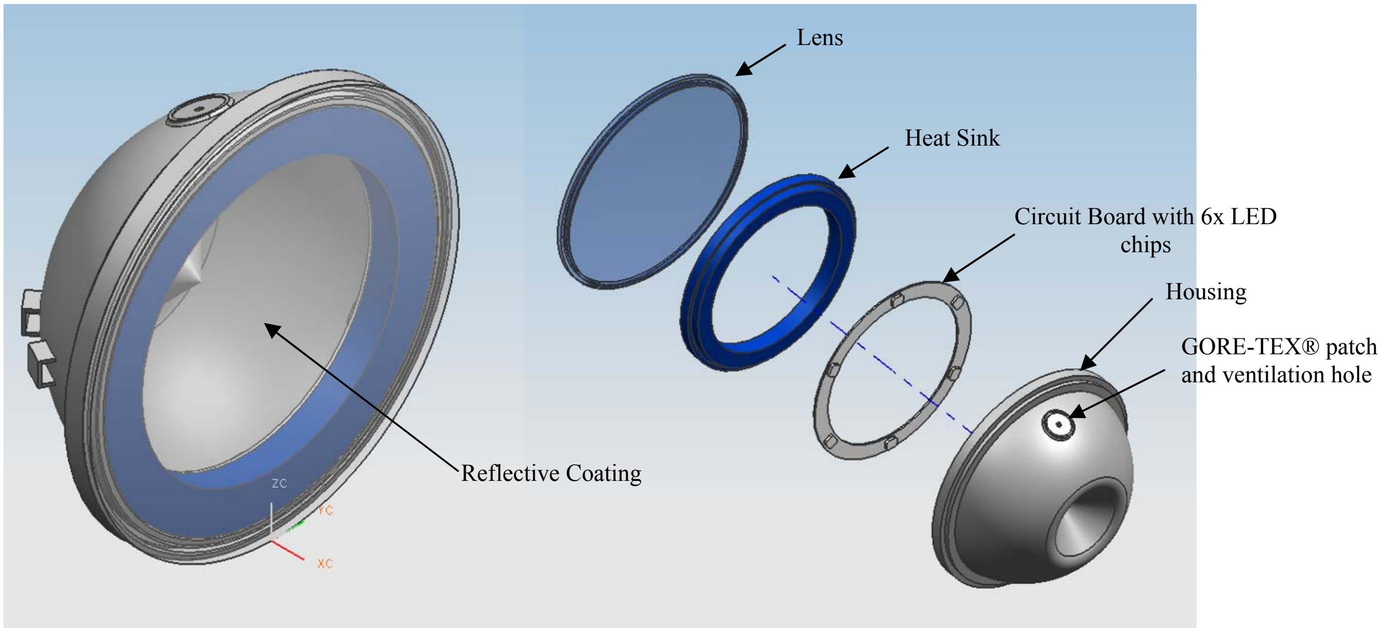


Figure 10: Assembled and exploded views of fog lamp showing major components.

5.1 LENS

The lens we chose was clear with no integrated optics to redirect the light. We selected a clear lens to give the fog lamp a jeweled look and to allow the viewer to see the unusual hidden LED design. The primary purpose of the lens in our design is to protect the fog lamp from the elements, and ensure that no debris or water enters the assembly from the front.

The preliminary material chosen was crystal polycarbonate, following the guidelines for lens material described in GM best practices GM.PC.009 [4]. However, further investigation will be done to make sure this material best fits our purposes.

5.2 HOUSING

The housing for the selected fog lamp is illustrated in Figure 11. The preliminary material chosen was a polycarbonate as described in GM.PC.001 best practices for housing materials [4]. However, further investigation is necessary to verify this material is best for our application.

A small ventilation hole was placed at the top of the housing. The purpose of this hole is to allow for pressure stabilization when the temperature inside the fog lamp assembly changes causing the air to expand or contract. When the fog lamp is turned on, the air inside the housing heats up and expands. As this air exits through the ventilation hole pressure within the fog lamp assembly is relieved. Air flow is reversed when the fog lamp is turned off after operating for a prolonged time. Air cools and contracts, creating a vacuum within the fog lamp assembly thereby sucking air from the outside into the lamp through the ventilation hole. In order to prevent this inflow of air from transporting moisture and other foreign contaminants into the fog lamp, a GORE-TEX® patch will be placed over the ventilation hole. This will also prevent any moisture that does get in from accumulating inside the housing by allowing it to evaporate out through the patch during fog lamp operation.

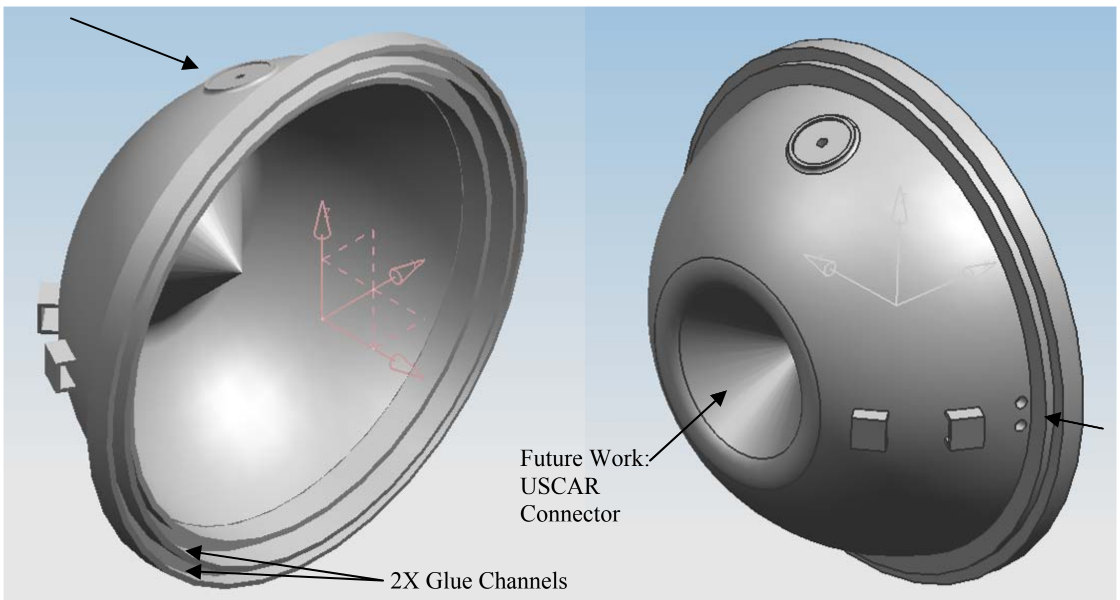


Figure 11: CAD model of housing

Additionally, we have two glue channels around the outer diameter of the housing. These will help seal the housing from the environment and prevent contaminants and moisture from entering the assembly.

The outermost glue channel holds the lens, and is designed in such a way as to prevent the lip of the lens from completely reaching the bottom surface of the channel. This ensures that the lens does not displace the glue, and a proper bond can form between the polycarbonate lens and housing. The inner glue channel is for the heat sink; the same glue channel design was employed here to ensure the heat sink adequately bonds to the housing. We must ensure the right glue is employed in each of these two cases by recognizing that one channel is for a plastic-plastic bond, and the other is for a plastic-metal bond. Another illustration of the interface between the glue channels and the lens can be found in Figure 12 on pg. 18.

We also have incorporated an initial solution to accommodate the wiring from the circuit board. Two wires are necessary for the power supply, and they will exit from the housing at the point shown in Figure 11, above. They will run along the outside of the housing and will be kept in place by the wire channels. The wires will need to attach to a USCAR connector, which we plan on integrating into the bottom portion of the housing. In addition, we will seal out moisture and contaminants at the exit point of the wires from the housing using sealant.

5.3 REFLECTIVE COATING

The reflector is integrated to the housing, and is illustrated by the cross-sectional view of the fog lamp assembly, shown in Figure 12. The coating used on the inside of the housing is aluminized for light reflectivity, following GM specification number 9984263. Essentially, the LEDs shine the light downward onto the parabolic reflector, which reflects the light towards the center conic shape and outwards, parallel to the axis. At this stage, the optics of the reflector need substantial refinement. We are currently in contact with OSRAM to discuss our options for the reflector. We will need to use their facilities and expertise to simulate and refine the optics and ensure that the geometrical distribution and intensity of the light will meet legal requirements before manufacturing our prototype.

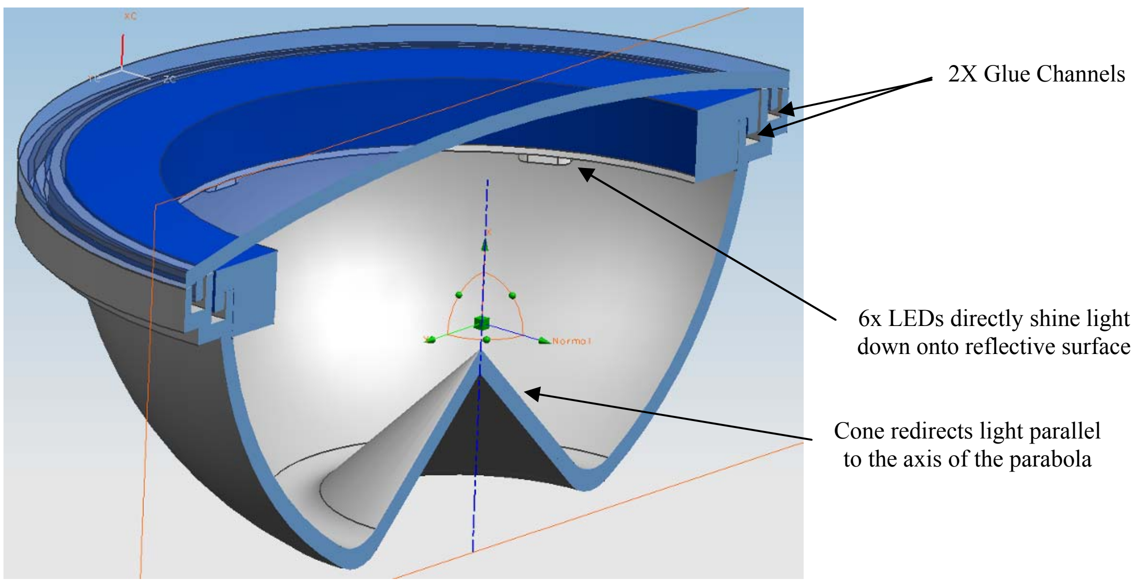


Figure 12: Cross-sectional view of fog lamp assembly

5.4 HEAT SINK

The heat sink is currently made of aluminum, though further analysis will be necessary to investigate the use of other materials. We will need to minimize the weight and cost of the heat sink, while optimizing the thermal properties. The purpose of the heat sink is to draw heat away from the LEDs and keep them within the operating temperature range specified by the manufacturer. The design of the heat sink is directly related to both the number and type of LEDs chosen. Optimization tests will need to be run to minimize the volume. Additionally, the heat sink has the ability to be designed for aesthetics. We plan on making the exposed surface of the heat sink aesthetically pleasing.

5.5 CIRCUIT BOARD

The circuit board (attached to the bottom of the heat sink using thermal adhesive) currently has 6 LEDs mounted on it. However, this portion of our design is very flexible, and we will need to discuss our options with OSRAM before we finalize the circuitry. After reviewing the specifications for the different LED choices, we have initially chosen to incorporate Platinum Dragon® white LED chips in our design. The primary reason for this choice was that it is brighter than other comparable chips due to better thermal management. This could allow the use of fewer LEDs and a smaller heat sink to save both weight and cost. The chip is shown below in Figure 13 . We will need to perform luminosity simulations to determine how many LEDs and which chip model would be necessary for our design.

Figure 13: Platinum Dragon® LED chip [8]

6 ENGINEERING DESIGN PARAMETER ANALYSIS

The following sections describe the approach and methodology used to determine the materials, dimensions, and tolerances associated with each component of our chosen design.

6.1 HOUSING

6.1.1 MATERIALS

The fog lamp housing needs to be stiff enough to withstand vibrations and shocks associated with driving under poor road conditions. Although we did not run FEA testing, through discussion with Mark Buffa at GM we determined appropriate material properties and dimensions [21]. After discussion, we determined it was important to choose a material with an appropriately large flexural modulus. Current GM fog lamps are composed from a bis-ethanol A polycarbonate – Makrolon® 2605, which has a flexural modulus of 2.4 GPa [20].

GM manufacturing practices specify a minimum thickness of 2.5 mm for housing components of all of its headlamps and fog lamps. This dimension is based on the injection properties and strength performance during testing of the Makrolon 2605 [21]. By using 2.5 mm as our minimal thickness in the housing design and by considering only materials with a similar or larger flexural modulus than that of Makrolon 2605, we undertook the first steps in ensuring our housing design would be adequately strong.

The material categories we considered for housing along with their properties are shown in Table 7 below.

Material Category	Flexural Modulus [GPa]	Density [kg/m^3]	Cost [$/kg]
Makrolon 2605 (datum)	2.40	1200	3.63
Polycarbonate	2.27-2.34	1190-1210	3.59-4.47
Polypropylene	1.33-1.61	898-908	1.67-1.84
Acetal (impact modified)	1.03-2.41	1320-1390	2.61-3.04
Polyester (impact modified)	1.93-2.23	1200-1220	4.1-4.9

Table 7: Material categories considered for housing [20], [30]

Discussing the considered material categories with GM's material science specialist revealed that only polycarbonate could be considered for housing manufacturing. Although some of the alternate choices presented in Table 7 had potential for cost reduction, the other materials were ruled out because the reflective coating poorly adhered to the surface of the material. Acetal's physical properties do not allow a reflective coating to stick to it. Polyester's crystallization would interfere with the fine tolerances necessary for the reflective coating to function appropriately. Lastly, polypropylene needs multiple surface treatments before a reflective coating can be applied to it, which causes a drastic increase in the housing's manufacturing cost [21].

Another housing consideration was the material color. The material color should be gray otherwise you need a thicker reflector coating to mask the housing color. The increase in reflector coating would consequently increase cost.

6.1.2 WEIGHT

As with most vehicle parts, the weight of the housing assembly should be minimized in order to limit its adverse effect on the vehicle's overall fuel economy. Currently, GM has two standard halogen fog lamp housing designs which differ in size. The smaller of the two housings weighed 44 g while the larger housing weighed 99 g. As mentioned earlier, Makrolon® 2605 is the current material standard used in the manufacture of GM fog lamps; it has a density of 1200 kg/m^3. While considering different material candidates, we attempted to choose one which had a density that was either equivalent or lower than this value.

We then determined the outer diameter and depth constraints as explained in Section 2.6 on pg. 7. While deciding on the size and shape of our housing, we ensured that we followed these size constraints and observed the minimal thickness requirement of 2.5 mm.

6.2 REFLECTOR

The following sections summarize the engineering approach used to determine the material, dimensions, and shape of the reflective surface. The primary driver to all of these parameters was meeting legal luminosity regulations.

6.2.1 MATERIALS

For a reflector to be functional, only materials with a high reflectivity should be considered. Either aluminum or chrome coatings would be suitable for our application. However, aluminum is the preferred material choice due to the high expense of chrome metallization and plating processes [21]. In addition, chrome metallization usually gives a darker, smokier look with a lower reflectance than aluminum. This would require a more powerful light source in order to get the same amount of light output as that for an aluminized coating, so we chose the aluminized coating.

There is no prescribed thickness of the reflector; only the minimum amount of coating should be applied to obscure the color of the housing underneath and produce the required amount of reflectance. Typically, the aluminum coating thickness ranges from 300 to 500 angstroms ($3x10^{-5}$ to $5x10^{-5}$ mm) [21].

To comply with GM Best Practices, the fog lamp reflector finish must be aluminized with a topcoat application to prevent oxidation of the metal [4]. The industry standard for the topcoat is a plasma treatment HNDSO for corrosion resistance [21].

6.2.2 TOLERANCE

To achieve predictable light dispersion, the reflector needs to have a significantly better tolerance than the other components of the fog lamp. Typically, a tolerance of ±.15 mm is suitable for the reflector [27]. In order to achieve the reflective finish, the reflectors need to be polished according to SPI/SPE #1. This is accomplished with an 8000 grit polish consisting of diamond particles of 3 microns in diameter **[21]**.

6.2.3 SHAPE

In order to comply with legal luminosity regulations, we focused our engineering analysis on the design needed to achieve optimal light dispersion. For aesthetic reasons, we have chosen to incorporate a lens with no integrated optics; thus, the reflector was the component where we focused our efforts for light dispersion. To determine the shape of the reflector, we used an iterative re-design process. Each iteration consisted of first a theoretical design, followed by optical simulation with OSRAM. We used the results of each simulation to refine our alpha design with the legal illumination requirements as our goal.

6.2.4 REFLECTION THEORY

Fermat's principle forms the foundation for the concept of reflection, and was the starting point in the design of our reflector. According to this rule, the angle of incidence (θ) is equal to the angle of reflection (θ'), illustrated in Figure 14, and by Eq. 2.

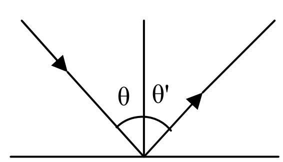


Figure 14: Illustration of Fermat's principle in reflection

$$\theta = \theta' \quad \textbf{Eq. 2}$$

This principle can be applied not only to a planar surface, as illustrated in the figure, but also to more complicated geometry such as a paraboloid (revolved parabolic surface). A parabola will focus rays parallel to its axis when a light source is located at the focal point [14]. Consequently, typical fog lamps utilize a parabolic reflector to redirect the light because the light dispersion can be controlled. However, the LEDs for our alpha design were not located at the focal point of the parabola, so we needed to make additional accommodations to redirect the light parallel to the axis. We thus utilized a basic parabolic surface in conjunction with a conic surface to redirect the light parallel to the axis (see Figure 15).

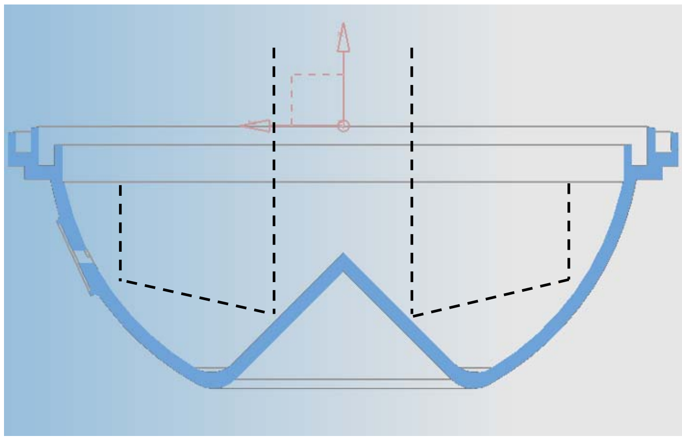


Figure 15: Cross-section of alpha design housing

However, this is a simplified 2-D ray trace, and was simply a starting point in our design process. In order to predict the scattering of the light in our 3-D setting we engaged in a series of simulations using optical software at OSRAM.

6.2.5 SIMULATIONS AND REFINEMENT OF THE MODEL

We worked closely with Doctor Hong Luo, a Senior Optical Engineer with OSRAM Sylvania. To simulate the light dispersion, OSRAM currently uses a ray-tracing program called ASAP® 2008. This program imports an IGES file from CAD to define the geometry of the reflector, and the user then inputs the optical properties of the material. A typical aluminized reflective surface generally reflects 85% of the incoming light, with 15% being absorbed into the material, and 0% of the light being transmitted through the material [26]. Thus, for our analysis, we specified 85% reflectivity, and 0% transmission. In addition, the program imports the properties of the chosen LEDs. OSRAM uses their technical data sheets to specify the LED physical geometry, ray data, and output angle. Each simulation was used to refine the model with the luminosity requirements in mind.

6.2.5.1 ALPHA DESIGN

Our alpha design, illustrated in Figure 16, was composed of 6 Platinum Dragon® LEDs, equally spaced around the base of the circuit board; each LED has an optical output of 75 lumens. Figure 17, below, illustrates the geometrical distribution of the reflected rays simulated by the program. A comparison of the light intensity values (cd) for our fog lamp with the legal luminosity requirements can be found in Appendix J on pg. 97.

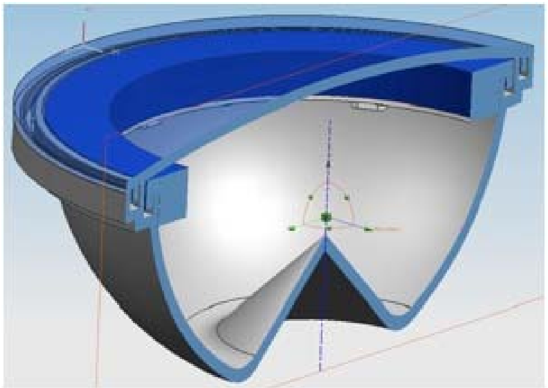


Figure 16: Alpha Design

From the ray distribution plot, below, it was evident that the cone was improperly designed. The central portion of the fog lamp exhibited very low intensity values and there were undesirable regions of high intensity outside of this range. Additionally, our design produced a symmetric beam pattern, which would ultimately fail to comply with legal standards.

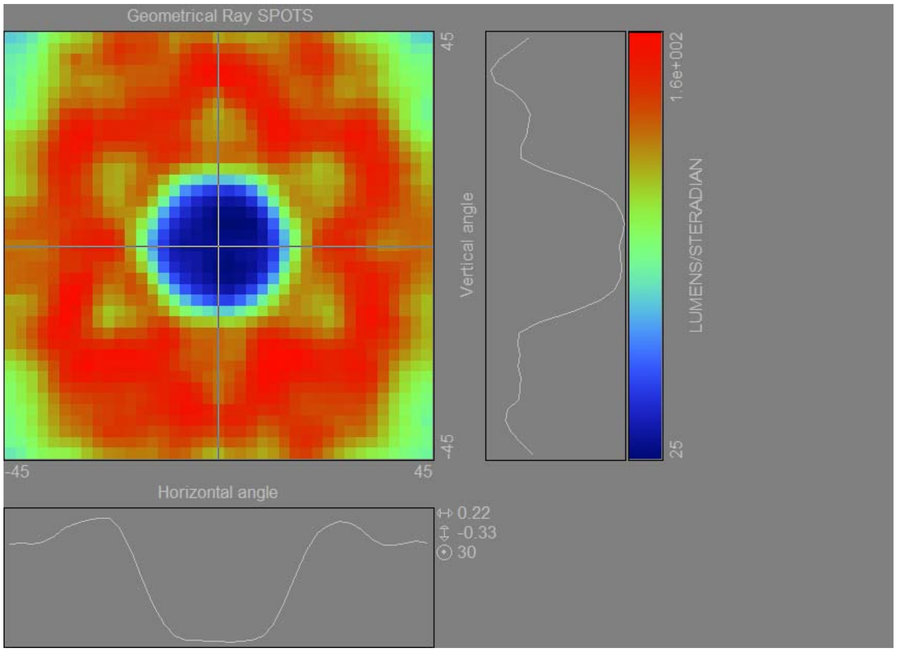


Figure 17: Geometrical Ray Data for Alpha Design

The failure of this design can be attributed to the simple conic surface, which only accounted for and redirected several rays of light parallel to the parabola's axis. The other rays were scattered thereby resulting in poor performance and a failure to meet requirements. In addition, our reflector design was rotationally symmetric, thereby producing a symmetric beam pattern. Asymmetry must be incorporated into the reflector if legal regulations are to be met.

6.2.5.2 MODIFICATION 1: REMOVAL OF CONE

For our first re-design of the fog lamp, we removed the conic surface to evaluate its effectiveness (see Figure 18). All other parameters such as LED orientation, placement, number and type remained the same.

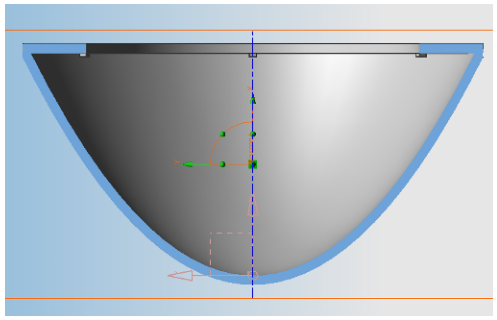


Figure 18: Cross-section of Modification 1

Figure 19, below, illustrates the beam pattern for this design, and the simulation results and comparison to legal requirements can be found in Appendix K on pg. 98. The removal of the cone actually improved the performance of our fog lamp, although the intensity values were still symmetric and well below the specified legal requirements. The design uniformly distributed the light and the focusing was not enough. The reason for this was due to the placement of the LEDs at a location other than the focal point with no additional surface to redirect the light.

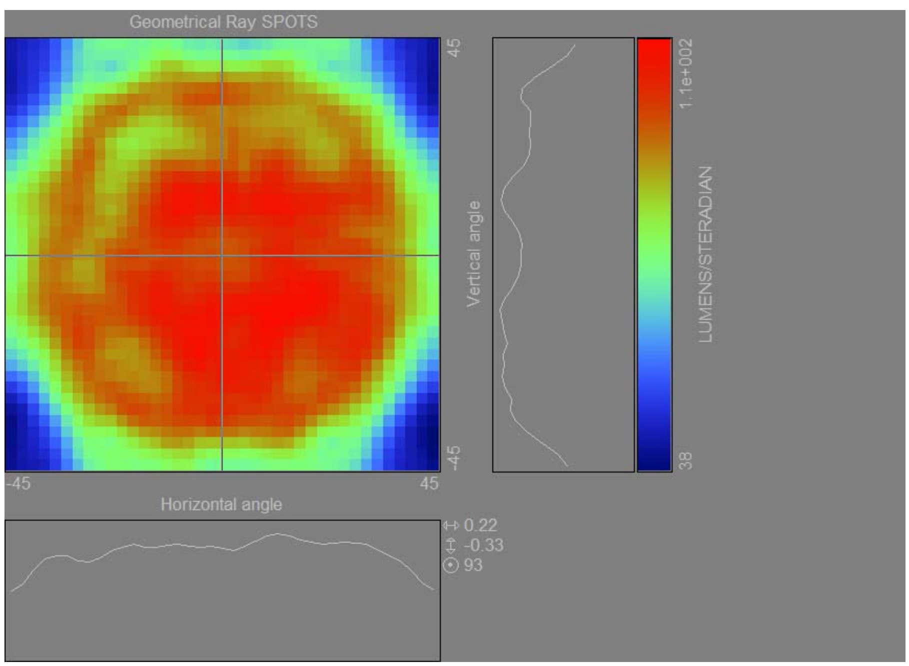


Figure 19: Geometrical Ray Data for Modification 1

6.2.5.3 MODIFICATION 2: ANGLED LEDS

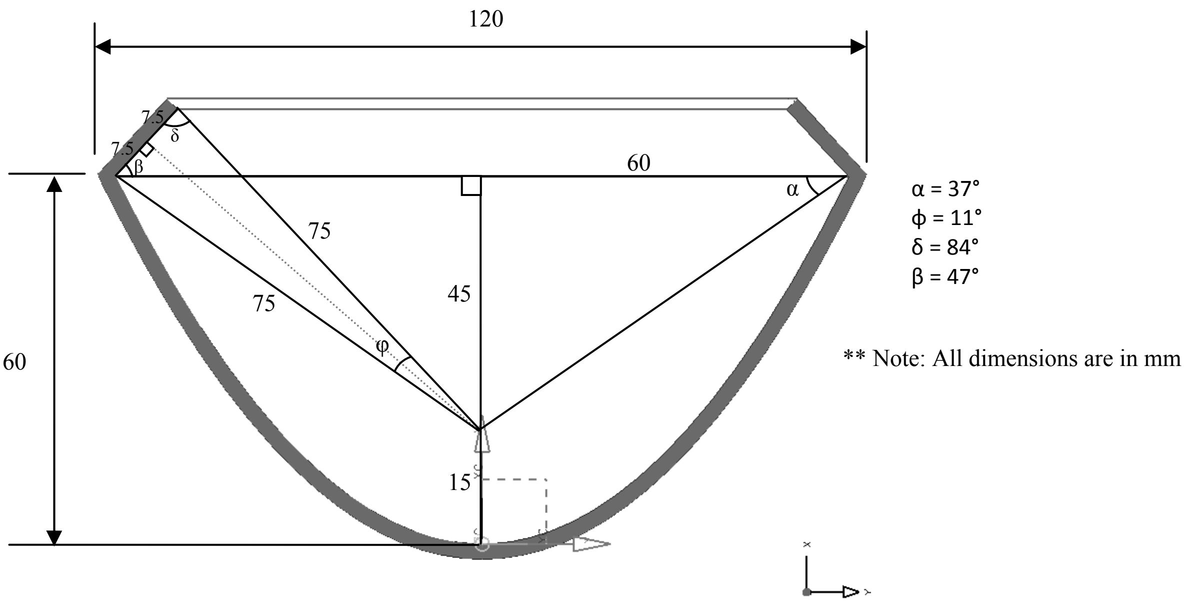
For our second re-design of the fog lamp, we oriented the LEDs towards the focal point of the parabola (see Figure 20). All other parameters such as number and type of LEDs remained the same.

The standard equation for a parabola with its vertex at the origin and its focus a distance *f* above the base is defined by Eq. 3, below [14]. Additionally, our parabola can be mathematically described by Eq. 4, below. From these two relations, we determined the focal point to be located at 15 mm above the base of the parabola in our CAD model, which we used as an input for the optical simulation.

$$y = \frac{1}{4f}x^2 \qquad \text{Eq. 3}$$

$$y = \frac{1}{60}x^2 \qquad \text{Eq. 4}$$

We determined the mounting angle necessary for this design by using the focal point of the parabola, the geometry of the parabola, in addition to basic trigonometric relations. We determined the mounting angle of the LEDs (*β*) to be 47°, as shown in Figure 20 below. The calculations can be found in Appendix L on pg. 99.



Figur **; angle**

The optical engineer at OSRAM, Hong Luo, was unable to complete the simulations for this design due to time constraints. However, she has advised us not to proceed with it because it has the same limitations associated with it as the previous designs. Because the LEDs are not located at the focal point, most of the rays will be scattered in an undesirable manner. Only the rays passing directly through the focal point will actually be redirected parallel to the axis.

6.2.5.4 MODIFICATION 3: THREE PARABOLIC DISHES

From the previous design, we recognized that it was necessary to locate the LEDs at the focal point of a parabola in order to scatter the light in a predictable manner. Thus, we decided to incorporate three parabolic surfaces, with two platinum dragons located at the focal point of each reflective surface (see Figure 21). We also recognized that to meet legal requirements we needed to make accommodations on the reflector to account for the “hot spot” and the asymmetric beam pattern defined by the legal requirements (see Table 2 on pg. 3). According to SAE and ECE specifications, the light needs to be focused below the horizontal and towards a high intensity region located within ±10º horizontal, and -1.5º to -4.5º vertical.

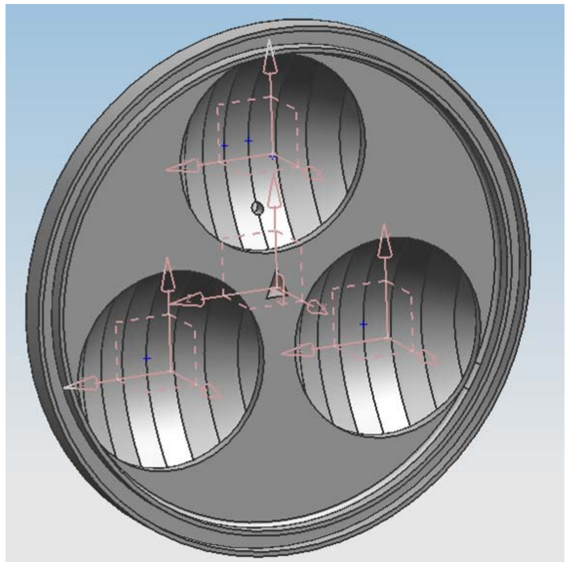


Figure 21: Illustration of Three Parabolic Dish Design

To define the focal point for each parabola, we used Eq. 5, below, where f is the distance of the focal point above the base of the parabola, D is the diameter of the parabola, and d is the height. The outer diameter of the housing excluding the glue channel and the space allocated for the heat sink determined the space left over for the three parabolic shape reflectors. These initial dimensions are shown in Figure 22 on pg. 27. Given the sizing constraints on our housing, we set the diameter of each of the three parabolas to be 47.5 mm.

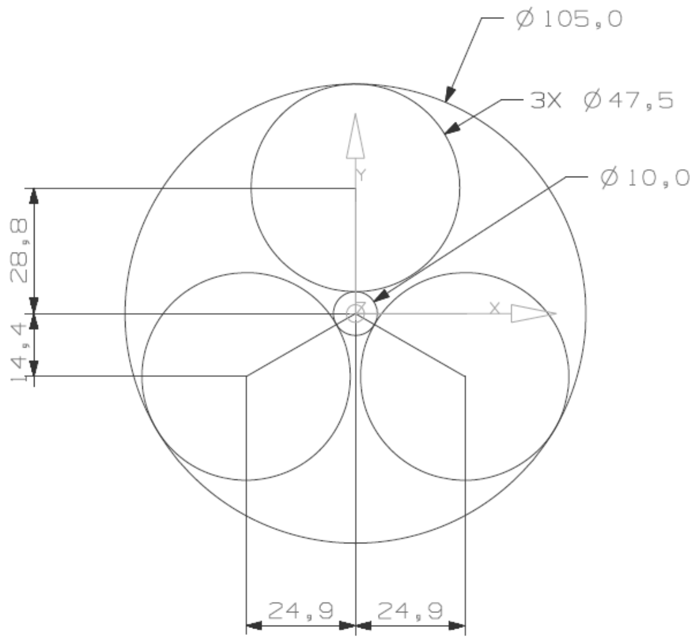


Figure 22: Initial dimensioning of the fog lamp housing; all dimensions are in mm

Additionally, we chose to place the focal point of each parabola at the top due to our proposed heat sink design (see Section 6.6 on pg. 31). Setting *d* equal to *f* in this formula, we determined the focal point to be located at 11.875 mm above the base of the parabola.

$$f = \frac{D^2}{16d} \qquad \textbf{Eq. 5}$$

We first focused our attention on the "hot spot", which according to Table 2 on pg. 3, is located at -2.5º below the horizontal at a distance of 10 m from the focal point of the fog lamp. We thus aimed the axis of each of the parabolic reflectors to hit this point, with the angles shown in Figure 23 below. Recognizing that our fog lamp dimensions may change over the course of the design process (i.e. locations of focal point with respect to the center of the assembly), we utilized a MATLAB code to output the axis angle for each of the parabolic dishes (see Appendix O on pg. 102). This code requests from the user geometrical information regarding the proposed fog lamp, such as overall outer diameter, parabolic dish diameter, in addition to the end location where we wish to aim our light. Basic geometric relations led us to determine the top parabola's axis angle to be 2.7° below horizontal, and the bottom two parabola's axis angles to be 2.4° below horizontal.

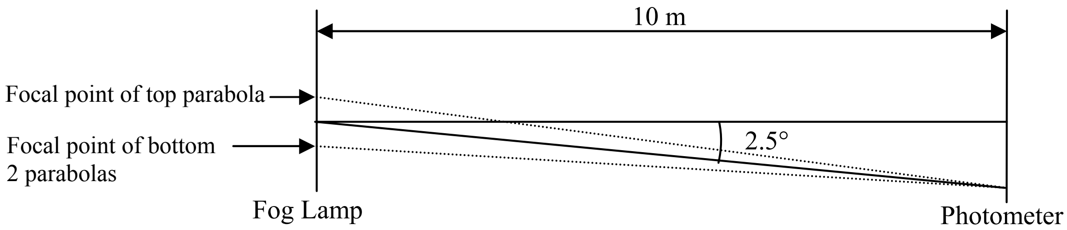


Figure 23: Setup of fog lamp for photometer test

In order to meet legal requirements, it is also necessary to spread the light horizontally, with the majority of the light falling within ± 20°. In order to achieve this, we decided to incorporate vertical fluting into our design. To account for any redesigning that may be necessary for the flutes, we used a MATLAB code to streamline the process (see Appendix P on pg. 103). The user inputs the radius and focal point of each parabolic reflector, the desired number of flutes, and the relative location of each reflector with respect to the center of the fog lamp.

For the ray calculations, we aimed the midpoint of each flute towards a target corresponding to a zone of high intensity in the photometry test. We chose to incorporate 4 flutes on each side of the parabola's center line, as illustrated in Figure 24, below. Each of the midpoints for the four flutes 1-4 are aimed at horizontal angles of 5°, 0°, 10°, and 20°, respectively, in order to achieve a wide distribution of light. Using basic trigonometric relations, we determined the inclination angle for each flute to achieve this distribution at a distance of 10 m from the center of the fog lamp.

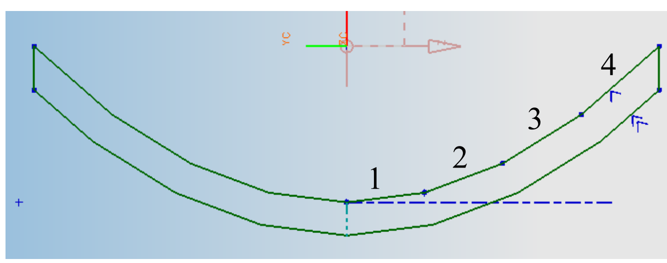


Figure 24: Illustration of fluting cross-section

For the following simulation, the two LEDs were placed side by side above each parabola. Figure 25, below, illustrates the resulting beam pattern; the simulation results and comparison to legal requirements can be found in Appendix N on pg. 101.

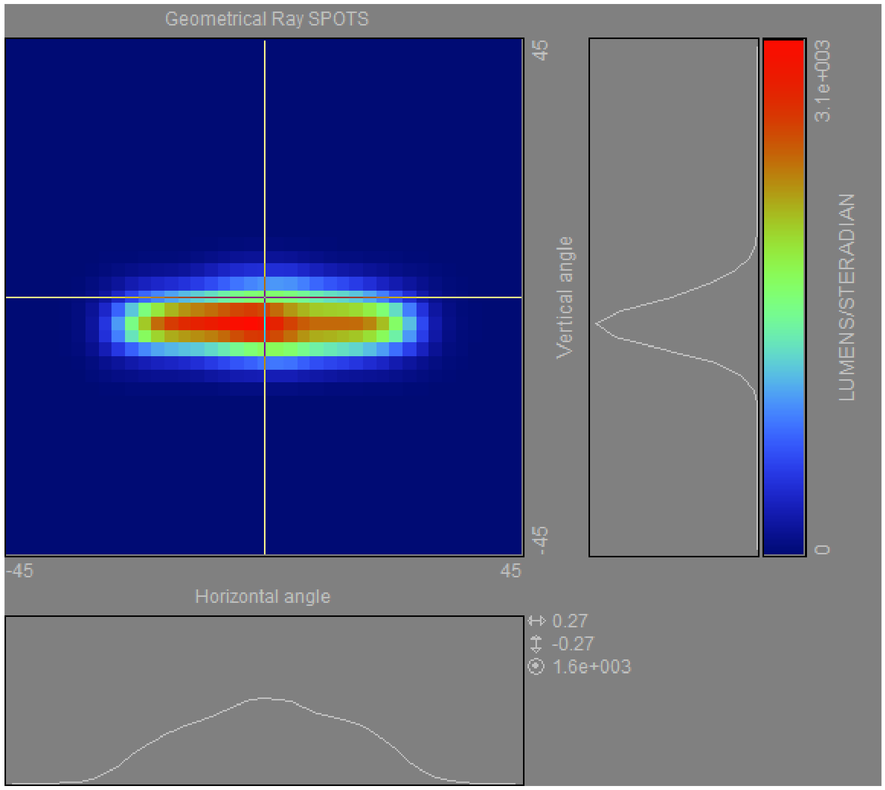


Figure 25: Geometrical Ray Data for Modification 3

The results are a substantial improvement over the previous re-design. We successfully produced an asymmetric beam pattern with respect to the vertical. The high intensity region corresponds to the hot spot found in Table 2 on pg. 3. However, our light intensity values above the horizontal exceed legal requirements. We thus need to devise a way to redirect the light being dispersed above the horizontal downward to achieve a sharper cut-off.

An additional downfall of our design is related to the geometry of the Platinum Dragons. Because of constraints associated with clean-rooms, you cannot simply handle the individual 1 mm by 1 mm chips and integrate them into a circuit. Instead, they come packaged in a module with dimensions described in Section 6.3 on pg. 29 (approximately 6 mm by 6 mm).

The spacing between each LED is too great to feasibly accommodate two modules on each arm of the heat sink. We will use Diamond Dragon® LEDs, which are brighter than the Platinum Dragon® LEDs. This would allow us to use fewer modules in order to better fit into our packaging constraints.

6.3 LEDS

6.3.1 NUMBER AND TYPE

In order to determine the number of LEDs necessary to meet the luminosity requirements, we used Eq. 6 below to determine the amount of lumens (lm) the LEDs will have to collectively produce (L). In this relationship, R is the required light output of a fog lamp in lumens (250 lm) as stated in a confidential GM document, α is the loss of light that occurs when light is bounced off of the reflector (15%), and ψ is the loss of light that occurs as light passes through a polycarbonate lens (12%) [22]. We calculated that we needed our LEDs to produce approximately 334 lumens of light.

$$L = \frac{R}{(1-\alpha)\cdot(1-\psi)} \qquad \textbf{Eq. 6}$$

We then divided 334 lm by the amount of lumens each of our three considered LED types were capable of producing. This gave us a rough estimate of how many LEDs would be required to make a fog lamp with sufficient illumination. Table 8 below displays our results (rounded up to nearest whole LED).

LED Type	Cost ($/unit)	Typical Luminosity (lm)	Approx. # Required
Golden DRAGON®	1.40	64	6
Platinum DRAGON®	1.90	75	5
Diamond DRAGON®	3.75	225	2

Table 8: LEDs' costs, luminosities, and required number

For the purpose of ray tracing we chose to use six Platinum DRAGON® LEDs. The reason we chose to add an extra LED was optical symmetry between parabolas (2 per parabola). The ray tracing results can be seen in Section 6.2.5 on pg. 22. After several redesigns of the reflector, we found that six Platinum DRAGON® LEDs provide sufficient luminosity for our fog lamp. The Platinum DRAGON® LEDs were chosen over the Golden DRAGON® LEDs because the Platinum DRAGON® LEDs have better thermal management [23].

It is important to note that the high performance Diamond DRAGON® LEDs are brand new technology, and were not available as an option until much later in the design process. However, in our final prototype, as well as our final design, Diamond DRAGONS® will be used. While discussing these LEDs with an OSRAM representative, we were told that it might be difficult to reach the specified luminosity of 225 lm [25]. However, we were assured that as a conservative estimate, the Diamond DRAGON® LEDs would provide at least double the luminance of their Platinum counterparts [23]. This allowed us to significantly cut down on the space required on the heat sink for LED placement, since 1 Diamond DRAGON® will be used on each heat sink arm instead of the two Platinum DRAGON® LEDs necessary before. All DRAGON® series LEDs have identical physical dimensions.

6.3.2 PLACEMENT

Throughout the iterative design and redesign process, the placement of the LEDs was pre-determined by the geometrical distribution of the reflector. Early designs, discussed in Section 6.2.5.3 on pg. 24 involved aiming our LEDs through focal points of parabolic reflectors. However, it was later found that more light can be captured and controlled if the LEDs were not aimed at, but positioned at the focal points of parabolic reflectors.

In our final design, we used the three fins of our heat sink to position three Diamond DRAGON® LEDs at the focal points of the three parabolic reflectors (Section 7.2 on pg. 40). The LEDs would be blanket soldered to a circuit board, which in turn would be mounted underneath the heat sink using a thermal adhesive. The details concerning this are discussed in Section 6.9 on pg. 34.

6.4 LENS

The following parameters were used to evaluate our options and select the optimal final design.

6.4.1 MATERIALS

There were two main materials considered for our lens composition. These materials were selected by evaluating durability, light transmittance, manufacturability, and cost. The two final materials were crystal polycarbonate and acrylic. Both materials are scratch resistant, but polycarbonate would still require a scratch resistant hard coating. Front lamps are regulated by the Federal Motor Vehicle Safety Standards Number 108 (FMVSS 108) to be constructed from crystal polycarbonate for safety and durability. Polycarbonate also requires a coating for protection from UV radiation. One coating can be used to achieve both requirements. A silicon or acrylic coating is most often used in industry. Acrylic is more brittle than polycarbonate, which makes it less desirable for a front fog lamp lens (manufacturers do not want fog lamps shattering on impact) [21]. Light transmittance for crystal polycarbonate is 88% while Acrylic is 92%, so acrylic is the best but the difference is negligible. In terms of manufacturability, both plastics can be injection molded, compression molded and extruded. Crystal polycarbonate is harder to injection mold due to its higher melting temperature. Using average costs found on the internet, the cost for crystal polycarbonate is $.84/kg. The cost for acrylic is yet to be determined by GM.

6.4.2 DIMENSIONS AND WEIGHT

The dimensions of our lens will be determined by the size or our housing. To fit the housing properly, the lens must have the same diameter as the outer edge of the housing. The lip of the lens must be shorter than the depth of the glue channel and thinner than the width of the channel to provide room for the glue to fill in the gap and create a good seal, see Figure 26. The lens will curve across the reflector providing protection from the environment while not interfering with the light dispersion from the reflector. The weight of the lens will be approximately 32 grams.

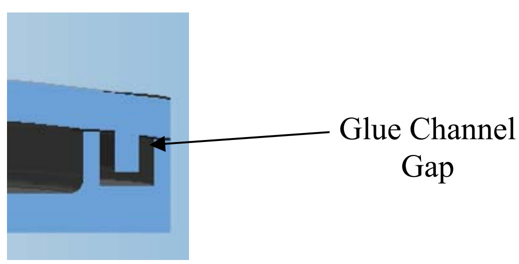


Figure 26: Lens glue channel gap

6.6 DIFFUSION MEMBRANE

The diffusion membrane allows for equalization of pressure between the interior of the housing and the surrounding environment to occur without contaminants and water entering the fog lamp assembly.

Since the air inside the housing gets heated up and cooled as the fog lamp gets turned on and off, it was necessary to place a small 2.5 mm diameter ventilation hole on the housing surface. Its location is discussed further in Section 7.5 on pg. 44. However, if this ventilation hole was simply placed in this housing without anything covering it, air flowing into the fog lamp to equalize pressure could easily transport small amounts of water or other contaminants into the unit assembly. Over time, water or contaminant accumulation could interfere with the performance of the reflector or even permanently damage the circuitry. To prevent this from happening, the ventilation hole was covered by a patch of GORE-TEX®. The specifics associated with this design feature can be found in Appendix Q on pg. 52.

6.4.3 MATERIALS

The diffusion membrane will be made from GORE-TEX® material due to its commercial availability and empirical effectiveness at maintaining humidity free internal fog lamp conditions [31]. The patch has a silicone adhesive backing to attach the patch to the housing.

6.4.4 DIMENSIONS AND WEIGHT

The patch diameter is prescribed by GORE-TEX® confidential documentation and testing [28]. The vent hole size was determined through testing done by GORE-TEX® and corresponds to patch size, where increased patch sizes correspond to larger vent hold diameters [32].

6.5 HEAT SINK

The purpose of the heat sink is to cool the circuit (including the resistors and LEDs), to support the circuit, and provide for proper LED placement. The following parameters were used to evaluate our options and select the optimal final design.

6.5.1 MATERIALS

There are several different metals that could work for heat sinks. Using the constraints of low cost and ease of manufacturing we narrowed the list down to a few materials. They included stainless steel, aluminum, and copper. Steel is roughly the same density as copper and both have a greater density than aluminum. Copper is more than two times heavier than aluminum. Stainless steel and aluminum are both corrosion resistant while copper would require a protective coating. Copper has the highest thermal conductivity at 401 W/m-K while aluminum is at 237 W/m-K and steel trails behind at 80 W/m-K [24], [30]. After weighing each pro and con discussed we decided to use 6061-T6 aluminum alloy, which has the best overall characteristics for our heat sink application.

6.5.2 DIMENSIONS AND WEIGHT

The heat sink has three arms, one for each parabolic reflector. At the center of the heat sink is a peg that is used to attach the heat sink to the lamp housing. The dimensions of the heat sink are determined by the size of the housing and positioning of the parabolic reflectors. The outer diameter of the heat sink will be sufficient to hold the LEDs at the focal point of the parabolic reflectors. Each arm was designed large enough to house the circuit board while blocking as little light from each reflector as possible.

6.5.3 THERMAL

Thermal analysis was done on the heat sink to determine if our prescribed dimensions were sufficient at maintaining the electrical circuit components at a safe operating temperature. To determine the appropriate heat transfer characteristics of the heat sink, we used convective heat transfer equations for plates and applied them to the faces of our heat sink. Each arm of the heat sink was approximated as a rectangle with 5 convective surfaces (top, bottom, sides and end). The equations used to calculate the convective coefficients are shown in Appendix R on pg. 107. We first found the Nusselt number as described by the appropriate equation, then used this value to calculate the convective heat transfer coefficient. These heat transfer coefficients were then averaged using an area weighted method to find a final convective heat transfer coefficient for our heat sink thermal analysis using Abaqus. Using the 8.6 W power consumption of the LEDs and an efficiency of 80%, it is reasonable to assume the remaining 20% of the 8.6 W power input is lost to heat generation (about 1.72 W). One resistor will also be used in the circuit and will be included in our model once our design is finalized. Given these conditions, the model was run using 6061-T6 aluminum alloy and its corresponding material characteristics. The LED heat flux of 1.72 W was applied at the end of the heat sink at the LED mounting locations, as shown in Figure 38 on pg. 46. Once the resistor design and placement is finalized, the analysis will need to be run again accounting for resistor heat dissipation. Further discussion and results can be found in Section 7.6 on pg. 45.

6.6 ELECTRICAL

6.6.1 CIRCUIT BOARD

A circuit board was used instead of wiring because it reduced mass production costs, since it production can be automated. The design of the circuit board was dictated by two factors: packaging within the heat sink (described above in Section 6.5.2 on pg. 32) and meeting electrical requirements of the LEDs.

6.6.1.1 ELECTRICAL REQUIRMENTS

LEDs need a minimal forward voltage to be functional. The standard Diamond Dragon threshold voltage is 3.5 V [25]. Once this voltage is met, the intensity of the LED light varies with current. Therefore, for equal brightness LEDs you want equal current, so it is recommended to put the LEDs in series [19]. We need to control the current through the LEDs so a current driver will be used [19]. The current driver will be outside of the housing in a small water tight box that will be a part of the power harness for the LED, and it will be set at 1.4 A, the nominal current for the LEDs.

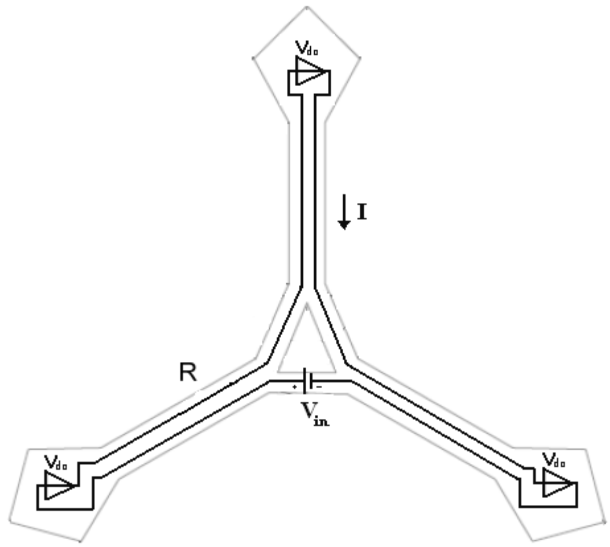


Figure 27: Circuit board circuit diagram

6.7 WIRING

The two wiring channels that connect the USCAR connector to the circuit board will be .361 mm in diameter to allow for 27 gauge wire to be used. Twenty seven gauge wire will be necessary to handle the maximum 1.4 A calculated above. The wire can is rated up to 1.7 A so there is a safety factor [33].

6.8 GT 150 2-WAY USCAR CONNECTOR

GM specified that we must use a 2-way GT 150 USCAR connector. USCAR facilitates cooperative research and development of automotive technologies. USCAR's main goal is to improve US auto technology. They also provide standardized designs to reduce development costs for automotive components such as electrical connectors [18]. Due to its standardized design and use in many automotive applications no problems are foreseen in the USCAR connector use.

6.9 ADHESIVES

The purpose of the adhesives in our design are to prevent contaminants from entering the housing, allow for thermal expansion between mated parts, and to securely attach the circuit board to the heat sink while maintaining good thermal contact. Numerous factors affect the design and application of adhesives in our fog lamp. The following parameters were used to evaluate our options and select the optimal final implementation.

6.9.1 MATERIALS

A few commonly used adhesives for sealing are polyurethane, acrylic, and silicone. All three sealants are highly corrosive resistant, element resistant, and have good adhesion to metals and plastics. Silicone adhesives have very high working temperatures (up to 315º C) and are resistant to heat related degradation. Polyurethane and Silicone both also form flexible bonds which will allow for differences in thermal expansion. We will be using an epoxy adhesive for attaching the circuit board to the heat sink due to its superior electrical insulation characteristics and good thermal conductivity [21].

6.9.2 APPLICATIONS

The sealants will be used in two main areas. Polyurethane adhesive will be used to attach the lens to the housing. A bead of polyurethane will be laid down the center of the glue channel; the lens and housing will then be pushed together to complete the seal. The glue channel is designed to allow excess glue to flow up the sides of the channel without spilling out of the channel. Silicone adhesive will be used to attach the heat sink to the housing. The adhesive will be spread on the outside of the heat sink peg and then the peg will be press fit into the asymmetrical triangular slot in the housing as shown in Figure 27. The epoxy adhesive will be used to attach the circuit board to the bottom of the heat sink and to insulate the circuit components from the electrical conducting heat sink surface.

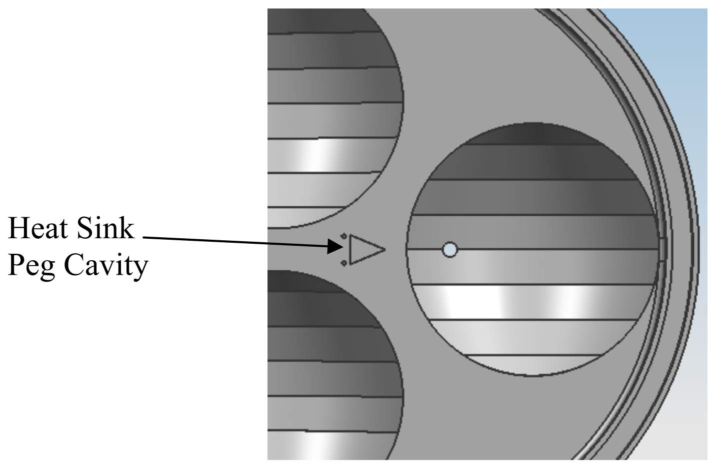


Figure 28: Heat sink peg cavity

6.10 TEAM ASSIGNMENTS SUMMARIES

The following sections outline the outcomes of the material selection, design for assembly, design for environmental sustainability, design for safety, and manufacturing process selection sections. The two components we chose to analyze were the housing and the heat sink. In Section 12.1.4 on pg. 67, we have outlined a new heat sink design and proposed material changes; throughout our analysis, we used these newest design changes.

6.10.1 MATERIALS SELECTION ASSIGNMENT

For our material selection analysis we selected the housing and heat sink to optimize. Using the CES software we determined the best materials for each part given the material constraints inherent to our design. Detailed results and complete assignment can be found in Appendix X.

Our analysis shows that the 7055 T77511 aluminum alloy is the best candidate for both the central heat sink material and for the housing material. One of the reasons for this is that it boasted the highest material index score. Furthermore, this is the same material as that chosen for the housing. Thus, the coefficients of thermal expansion for these two parts will be identical, a desirable factor since both parts are joined because of the housing / heat sink press fit.

6.10.2 DESIGN FOR ASSEMBLY

The purpose of design for assembly is to reduce the number of parts while simultaneously simplifying the assembly process of the remaining parts. Our original design needed a few improvements to optimize assembly efficiency in the final design. All of the designs for assembly (DFA) charts are in Appendix Y on pg. 120.

To optimize our assembly we first removed any unnecessary parts using the test for minimal number of parts. The heat sink could be incorporated into the bottom of the housing very easily. The extra aluminum will help with heat dissipation and aluminum is corrosion resistant so it will weather the elements well. To simplify the circuit, we will have the circuit board built as one piece with a flexible power ribbon connection between the two halves. This will allow us to assemble this as one piece and avoid any confusion on orientation or placement.

We also made design changes to increase our design efficiency. The heat sink triangular peg was made asymmetric to aid with insertion and help with circuit board orientation as well. The heat sink will also have clips along the bottom cavity to hold the circuit board in place while the thermal epoxy sets. We put clips on the lens to hold it in place while the polyurethane sealant sets.

Our overall assembly efficiency increased from 39% with seven total parts to 96% efficiency with 5 parts in our final design. This was a substantial improvement and shows the effectiveness of design for assembly.

6.10.3 DESIGN FOR ENVIROMENTAL SUSTAINABLITY

Although the final materials selected for the housing and heat sink were both determined to be 7055 T77511 aluminum alloy, we did the following analysis assuming the housing was made from the original design material of Makrolon 2605 and the heat sink from 7055 T77511 aluminum alloy as discussed. It may also be informative to use this analysis in the context of making the housing out of Makrolon 2605 vs. 7055 T77511 aluminum alloy as it applies to the impact on the environment.

The closest materials available in SimaPro were 7075 aluminum alloy, which has a similar composition, and traditional polycarbonate. We used Eco-Indicator 99 (I) V2.02 to analyze these two materials and to create the charts shown in Appendix Z.

From the environmental sustainability results we can see that using aluminum will be much worse for the environment during the manufacturing process. Therefore, our heat sink will contribute much more pollution than the housing. Unfortunately, PC does not have a high enough thermal conductivity to be used in place of aluminum for the heat sink. Our results also show that we should try to make our housing from PC instead of aluminum, although the heat sink would have to be increased in size to compensate for losing the cooling capacity of the housing. In this case, any emissions gains from using PC may be negated when the additional aluminum is added into the analysis.

From a lifecycle perspective, both aluminum and PC are similar in environmental impact. Both materials can be recycled and both have similar durability and lifetime. Aluminum has a high initial resource requirement, but most of this value is composed of water which could possibly be recycled or reused for another process. Furthermore, using aluminum for the housing may have a larger initial environmental impact but if it keeps the operating temperature of the LEDs lower than a comparable PC housing it may have an overall comparable impact given that the LEDs would fail less often and the unit would have to be replaced less frequently. Given these environmental considerations, we will take into account the environmental impact of our material choices and use this to make our final material selections.

6.10.4 DEISGN FOR SAFETY

For our design for safety analysis our prototype and final design will behave very similarly with regards to safety risks. The prototype will be less refined due to manufacturing constraints and cannot be made out of final materials. Overall, the safety risks associated with and LED fog lamps are very low given proper design and assembly. The complete design for safety chart is in Appendix AA.

The major hazards where due to sharp edges, failure during crash conditions, water damage and electrical overdrive. Sharp edges could cut the user or technician that services the fog lamp. During a crash the lamp could fall off and damage other components or shatter and lead to flying debris that could hit bystanders. Water entering the housing could cause corrosion of the electrical components or a short circuit that would damage the LEDs or possibly shock a technician. Also, failure during operation could cause low visibility for the driver. Voltage in vehicles is not constant and can cause the LEDs to be overdriven and damaged which would reduce lighting for the driver if failure occurred during operation.

All of the above risks were accounted for in our final design and their solutions are documented in the risk reduction column of the design for safety chart. We rounded the edges of our heat sink and housing to eliminate sharp edges. We manufactured our housing, lens and other parts out of high strength and impact resistant materials. Our design incorporates a GORTEX patch on the housing to allow water to escape and keep the housing dry and we used a constant current driver to maintain the appropriate power to our LEDs to eliminate overdriving the LEDs. The final redesign has low risk in all categories and therefore accomplished a balance between safety and function.

6.10.5 MANUFACTURING PROCESS SELECTION ASSIGNMENT

General Motors has requested for the end product to be able to be manufactured on a high-volume basis. We determined the appropriate production volume to be a minimum of 112,000 and a maximum of 4.4 million units for our LED fog lamp. Using this production volume and details regarding the material, geometry, and tolerances for both the housing and heat sink, we determined the optimal manufacturing processes. The best process for the housing turned out to be pressure die casting. An important consideration for this process is that the wall thickness needs to be as uniform as possible. The molten metal will cool in areas with the smallest cross sections, which may block the flow of metal to areas with thicker sections. Since our housing has varying thickness, it is recommended that feed paths be integrated into the mold to account for the solidification from thinnest to thickest sections **[35]**. This will generally add to the complexity and cost of the die. However, the process was still deemed to be economical for parts manufactured on a high volume basis.

We selected the heat sink manufacturing process by comparing the relative cost indices. The most cost-effective process for this component turned out to be die pressing and sintering. Since both parts are to be made from aluminum, which is very corrosion resistant, we do not foresee any surface treatment being necessary.

7 FINAL DESIGN DESCRIPTION

Figure 29 below, shows an exploded view of the fog lamp assembly. As can be seen, the LEDs mount to the heat sink, the electrical wires connect to the circuit board, the circuit board attaches to the bottom of the heat sink, the heat sink inserts into the housing, and the lens connects to the housing. Section 7 describes how all of these components function and come together.

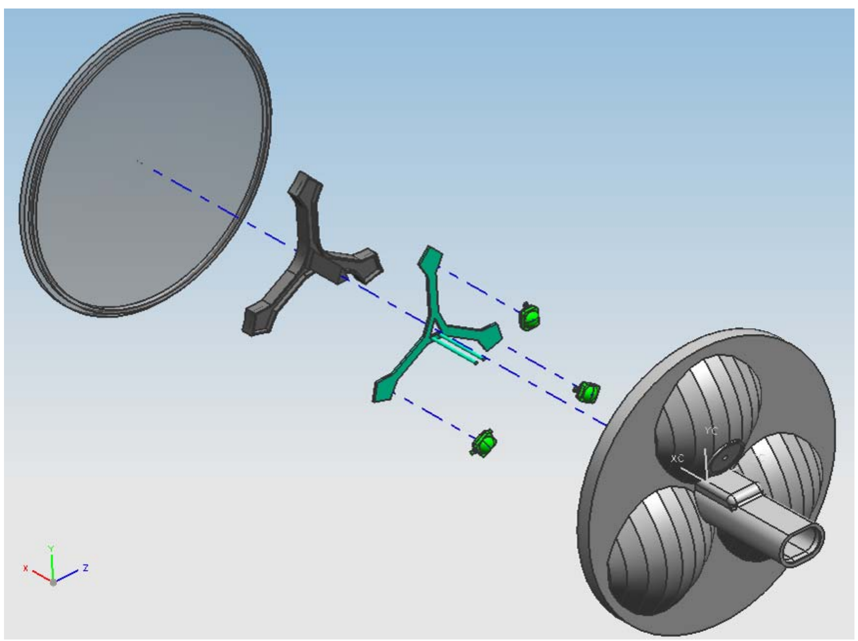


Figure 29: Exploded view of fog lamp assembly

7.1 HOUSING

Figure 30 displays different views and points out several features to help understand our housing design. Figure 31 displays the housing’s dimensions. As can be seen from the Figure 30, the housing design is circular and for the most part flat. The circular shape was chosen so that a regular shaped lens could be placed over it, with the lens ridges falling into the glue channel. The design was made as flat as possible, using the 2.5 mm thickness constraint, so as to cut down on the amount of material used thereby reducing the housing’s weight and cost. The outer diameter of the housing (113 mm) is 13 mm larger than that of smaller of the two current GM halogen fog lamps. Thus we stayed close to the frontal profile size requested by our sponsor. The additional housing depth in the middle was needed to accommodate the press fit of the heat sink and the USCAR connector. The two 1.3 mm diameter holes below the heat sink cavity in the center of the housing are meant for the wiring leading from the USCAR connector to the circuit board inside the housing. The small 2.5 mm diameter hole at the bottom of the top reflector is the ventilation hole discussed in 7.5 on pg. 44. The tolerances on the housing should be ±0.5 mm [27].

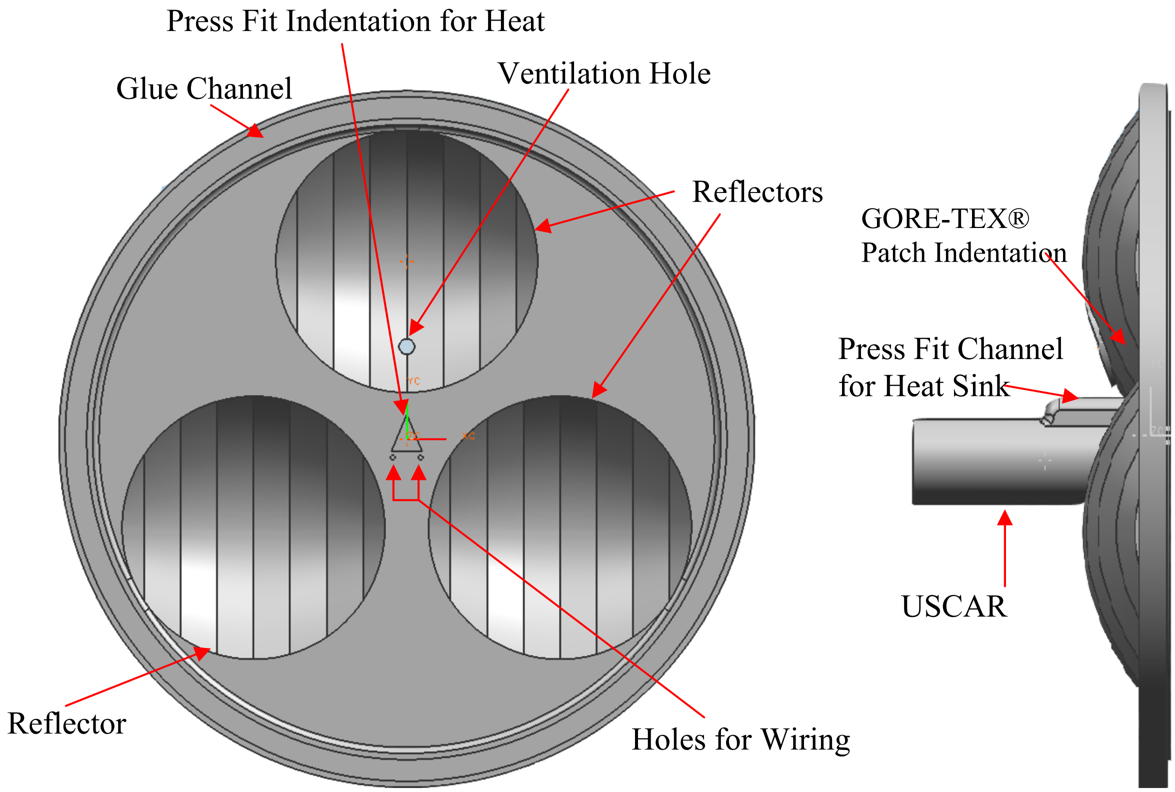


Figure 30: Front and side views of the housing with prominent features pointed out

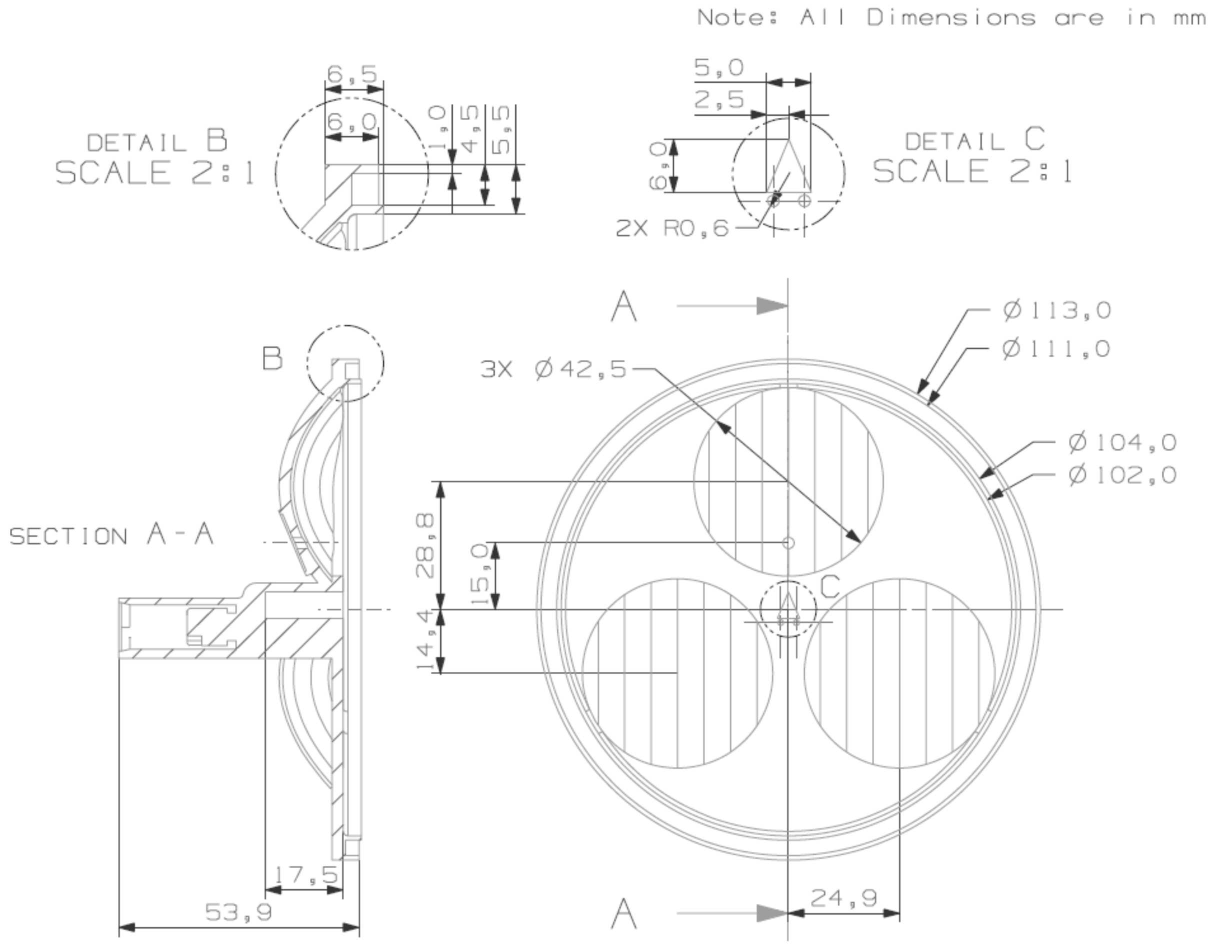


Figure 31: Housing engineering drawing

We chose to use Makrolon 2605, the current standard used for manufacturing GM halogen fog lamps and headlamps, as the material for our housing design. Not only do we know that this polycarbonate possesses adequate mechanical properties for fog lamp application, but it is also one of the two most commonly available materials in the industry along with Lexan 141 R. The cost of both Makrolon 2605 and Lexan 141 R is $3.63/kg. Since GM already uses Makrolon 2605 as its standard and since the two materials have equivalent flexural moduli and maximum long term service temperatures [24], we did not see any reason to choose Lexan 141 R. Lastly, the high 125 °C maximum long term service temperature of Makrolon 2605 ensures that the housing should have no problem with the heat given off by the LEDs.

7.2 REFLECTOR

The reflector material chosen was an aluminized coating with HNDSO topcoat, per GM Best Practices. The aluminum deposition will be accomplished using a sputter-coating process. The aluminum alloy used is typically 99.5% pure, with the remaining 0.5% containing trace impurities of copper, iron, gallium**,** manganese, silicon, and zinc [28]. The raw material used in the deposition process is typically aluminum clips, illustrated in Figure 32, below, courtesy of Lesker Products [29].

Figure 32: Aluminum clips for evaporation and deposition process

The part number is EVMAL1350U73, with a unit weight of 68-79 mg, and the cost for 10,000 pieces is $46.00. These clips were chosen as a result of their low unit weight and cost in comparison to comparable materials through this company.

The final design of our reflector incorporates both vertical aiming and horizontal spreading of the light. Figure 33, below, illustrates the angle at which the focal axis for each of the three parabolas must be located such that most of the light hits the hot spot of the beam pattern. The derivation of the axis angles can be found in Section 6.2.5.4 on pg. 25, and are summarized in Table 9 on pg. 42.

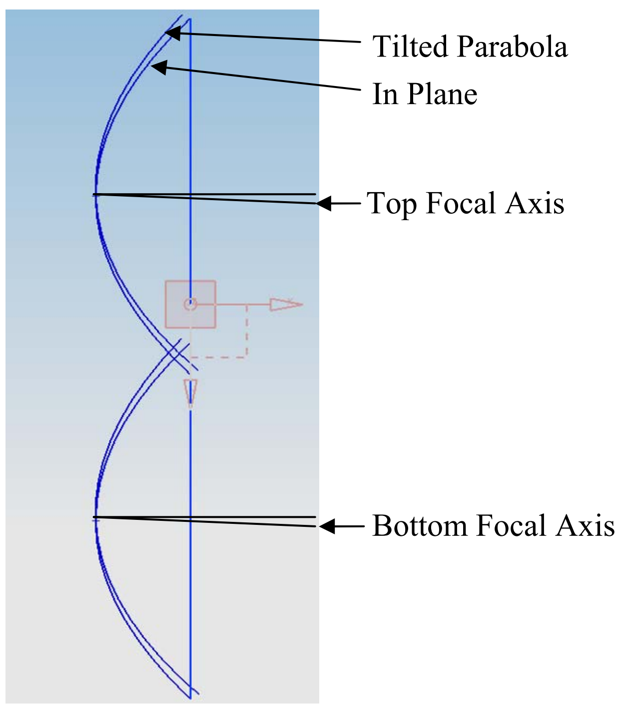


Figure 33: Illustration of Tilt Angles

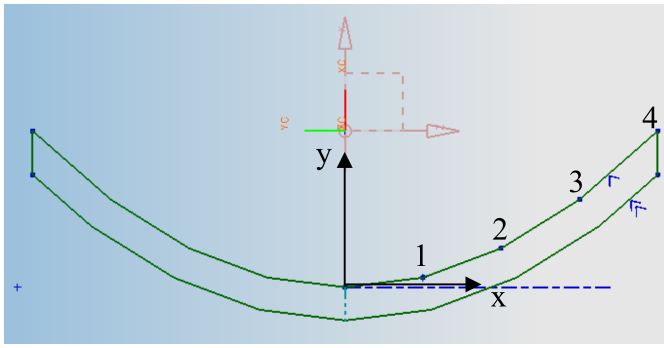


Figure 34: Illustration of Fluting Angles

Figure 34, above, illustrates a cross-section of the vertical flutes. Each flute was individually aimed to achieve the legally required horizontal light dispersion pattern, according to the calculations previously described in Section 6.2.5.4 on pg. 25. The fluting can be defined by points 1 through 4 illustrated in Figure 34 and Table 9. The x and y coordinates reported in Table 9 are with respect to the coordinate system shown in Figure 34. Notice that for the top and bottom parabolic surfaces, the flutes coincide. The final y-coordinate is located at 11.875 mm, which is equal to the height of the parabola. As previously determined in the engineering analysis section, we prescribed this point to be equal to the focal point of the parabola.

	Tilt Angle (below horizontal)	**Point 1 (x,y) [mm]**	**Point 2 (x,y) [mm]**	**Point 3 (x,y) [mm]**	**Point 4 (x,y) [mm]**
Top parabolic surface	2.7°	(5.930,0.737)	(11.868,0.960)	(17.805,6.660)	(23.75,11.875)
Bottom two parabolic surfaces	2.4°	(5.930,0.737)	(11.868,0.960)	(17.805,6.660)	(23.75,11.875)

Table 9: Tilt angles and fluting coordinates for reflective surfaces

Due to the complicated geometry associated with the reflector, it was necessary to clean up the edges where the reflector geometry intersected the housing to make the design more aesthetically pleasing from the front. Thus, the diameter of each reflector was smaller than the previously determined 47.5 mm; the diameter of each reflector is now 42.5 mm. The location of each parabolic dish with respect to the center of the fog lamp is the same as determined before (see Section 7.1 on pg. 38).

7.3 LENS

The lens in our final design will be made from injection molded crystal polycarbonate. A coating of acrylic will be applied to the surface of our lens to protect it from UV degradation and improve scratch resistance. The lens outer diameter will match the diameter of the housing glue channel and have a value of 113±0.5 mm, see Figure 36 below for full lens dimensions. The edge of the lens will have a 1 mm clearance on the edges and bottom of the glue channel as illustrated in Figure 35. This clearance allows the sealant to flow around the edge of the lens and fully seal the housing while providing a strong connection between the lens and housing. The curvature of the lens will be designed to minimize light refraction, so that reflector optics are not compromised.

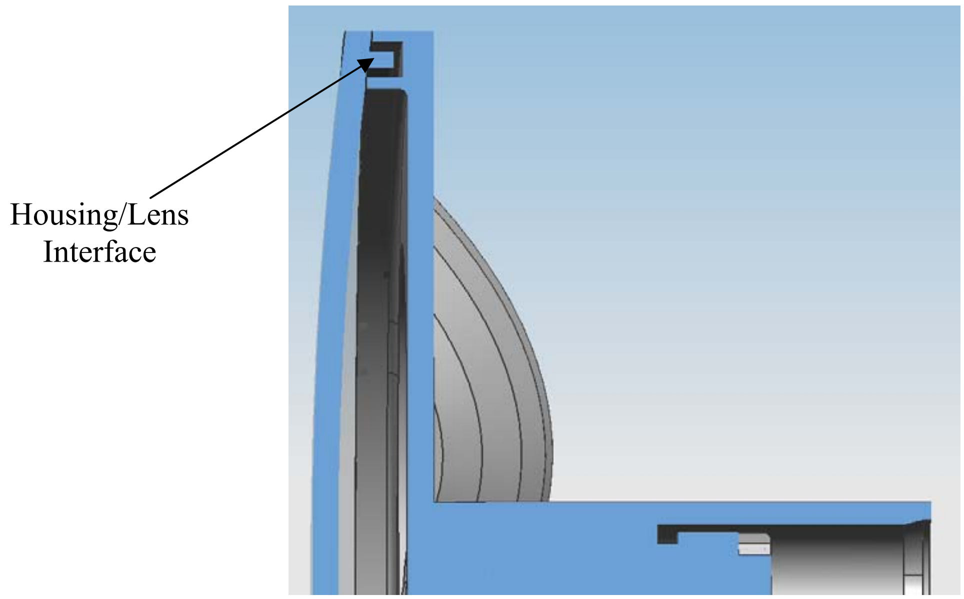


Figure 35: Seal location between housing/lens

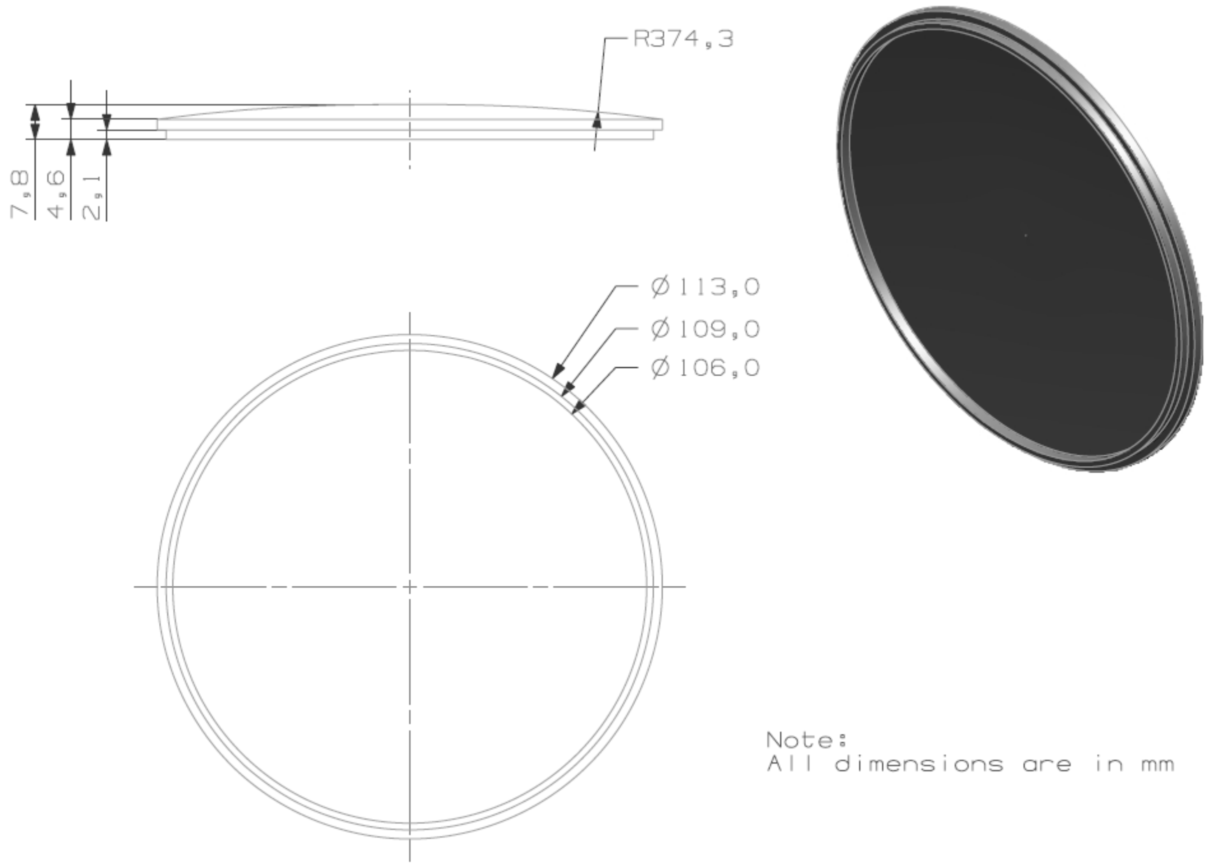


Figure 36: Lens engineering drawing

7.4 ADHESIVES

The seal between the housing and lens will be made using a flexible 2-part polyurethane sealant to fill the glue channel and prevent contaminants from entering the lamp. The flexibility of the polyurethane will help to minimize stress caused by differences in the thermal expansion coefficients between the lens and housing. We will need approximately 2,500 mm^3 to fill the glue gap around the edge of the housing as shown in Figure 35, above. The seal between the heat sink and housing will be made from silicone sealant. The sealant will be applied to the outside of the heat sink as showing in the diagram, to create an air-tight seal while also creating a thermal expansion buffer between the heat sink and housing. We will use 3M 2216 B/A Gray 2-part epoxy to attach the circuit board to the heat sink due to its availability and good bonding characteristics between circuit board and heat sink materials. The epoxy will be spread evenly across the entire circuit channel on the bottom of the heat sink to prevent electrical contact between the circuit board and heat sink.

7.5 DIFFUSION MEMBRANE

Our final design will have a 12.7±0.15 mm diameter 0.3±0.05 mm thick GORE-TEX® VE2035 patch as specified for a lamp of our size. This patch will be placed over the vent hole of diameter 4.0±0.1 mm in the position illustrated in Figure 37. The VE2035 patch has a minimum airflow rate of 3.0 L/h at 1 psi internal pressure, which is sufficient for our fog lamp as prescribed by GORE-TEX® proprietary documentation [31]. The GORE-TEX® patch used in our final design will be manufactured by GORE-TEX® and supplied to us as a final product. A fully dimensioned model of the GORE-TEX® patch and vent hole can be found in Appendix Q on pg. 106.

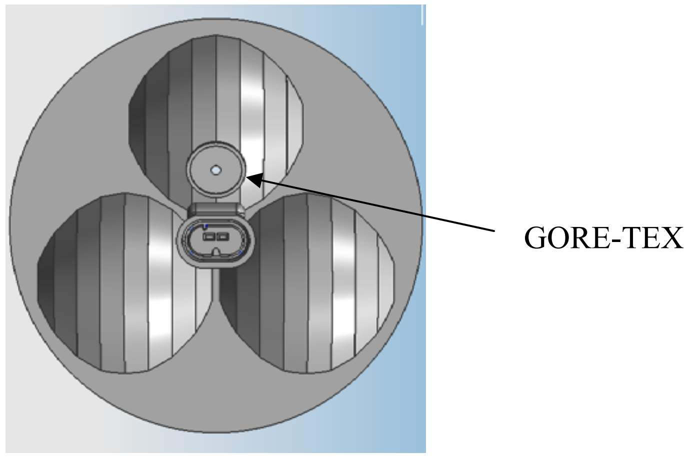


Figure 37: Back of housing illustrating diffusion membrane location

7.6 HEAT SINK

The heat sink in our final design will have three separate arms of length 35±0.05 mm; each arm has one LED that is attached to the circuit board. The arms are approximately 5mm thick by 5mm wide but have varied dimensions along their length as shown in Figure 38. The end is larger to allow room to mount the LED. To attach the heat sink to the housing, an asymmetrical triangular peg protrudes from the bottom center of the piece. This peg only fits into the housing in one orientation to avoid assembly mistakes.

To complete the thermal analysis we had to determine the overall convective heat transfer coefficient for our heat sink. As described previously, we used 4 different surfaces and calculated the coefficient for each, see Appendix R on pg. 107. We first found the Nusselt number for each surface using equations R1-R3, which gave: Nu_{top}=2.408, Nu_{bottom}=2.408, Nu_{sides}=2.408, Nu_{end}=2.408, where the Raleigh number and Prandtl Number are defined by equation R5 and R6, respectively; with *g* as gravity, β is Beta as defined by equation R7, T_s is the temperature of the heat sink surface, T_∞ is the temperature of the surroundings (for my simulation 25°C), *L* is the characteristic length, ν is the kinematic viscosity and α is kinematic diffusivity. Once these were all calculated, we used equation R4 to find the actual convective heat transfer coefficients: h_{top}=12.66 W/m^2-K, h_{bottom}=6.33 W/m^2-K, h_{sides}=15.63 W/m^2-K, h_{end}=6.38 W/m^2-K, where *k* is the thermal conductivity of air at T_∞. Finally, we weighted each corresponding convective heat transfer coefficient by the area they apply to and found the area weighted overall convective heat transfer coefficient of $h_{overall}$=12.22 W/m^2-K. This coefficient was used in all Abaqus analysis for the heat sink and should give a reasonable approximation of the convective heat transfer characteristics of our heat sink. From the thermal analysis, we determined that the difference in temperature between the ambient surroundings and hottest regions (LED placement points) was less than 0.1° C. This is well within the limits of the material used to make the fog lamp and of the LEDs and circuit.

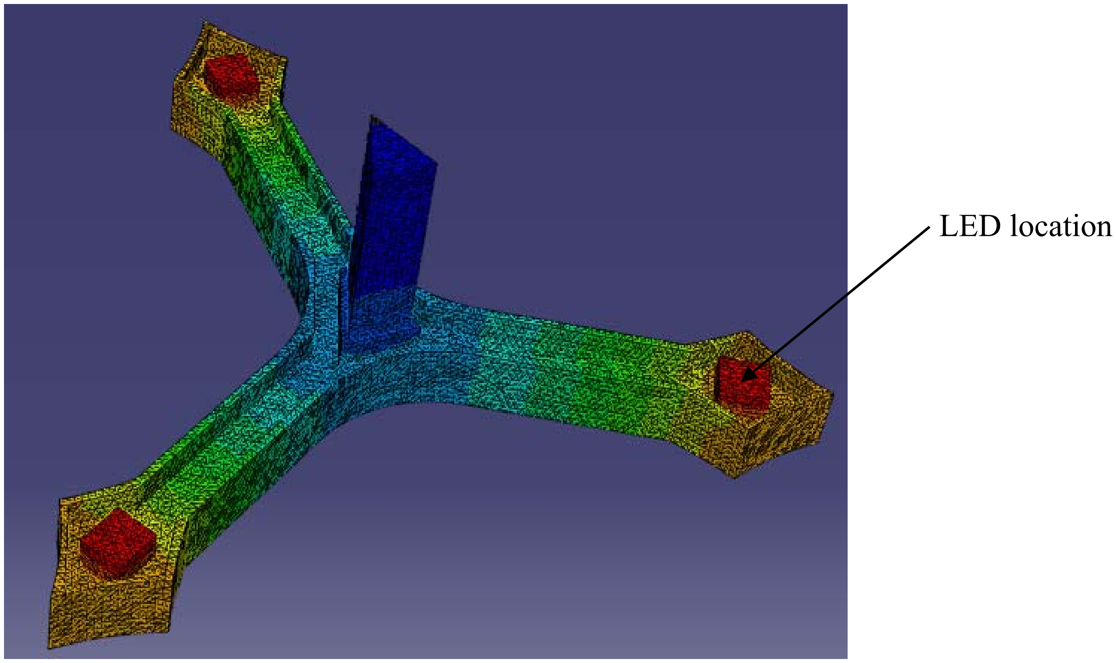


Figure 38: Thermal analysis of heat sink with temperature contours shown

Our final design will be die cast to achieve low cost high volume manufacturability. A fully dimensioned model of the heat sink can be found in Figure 39.

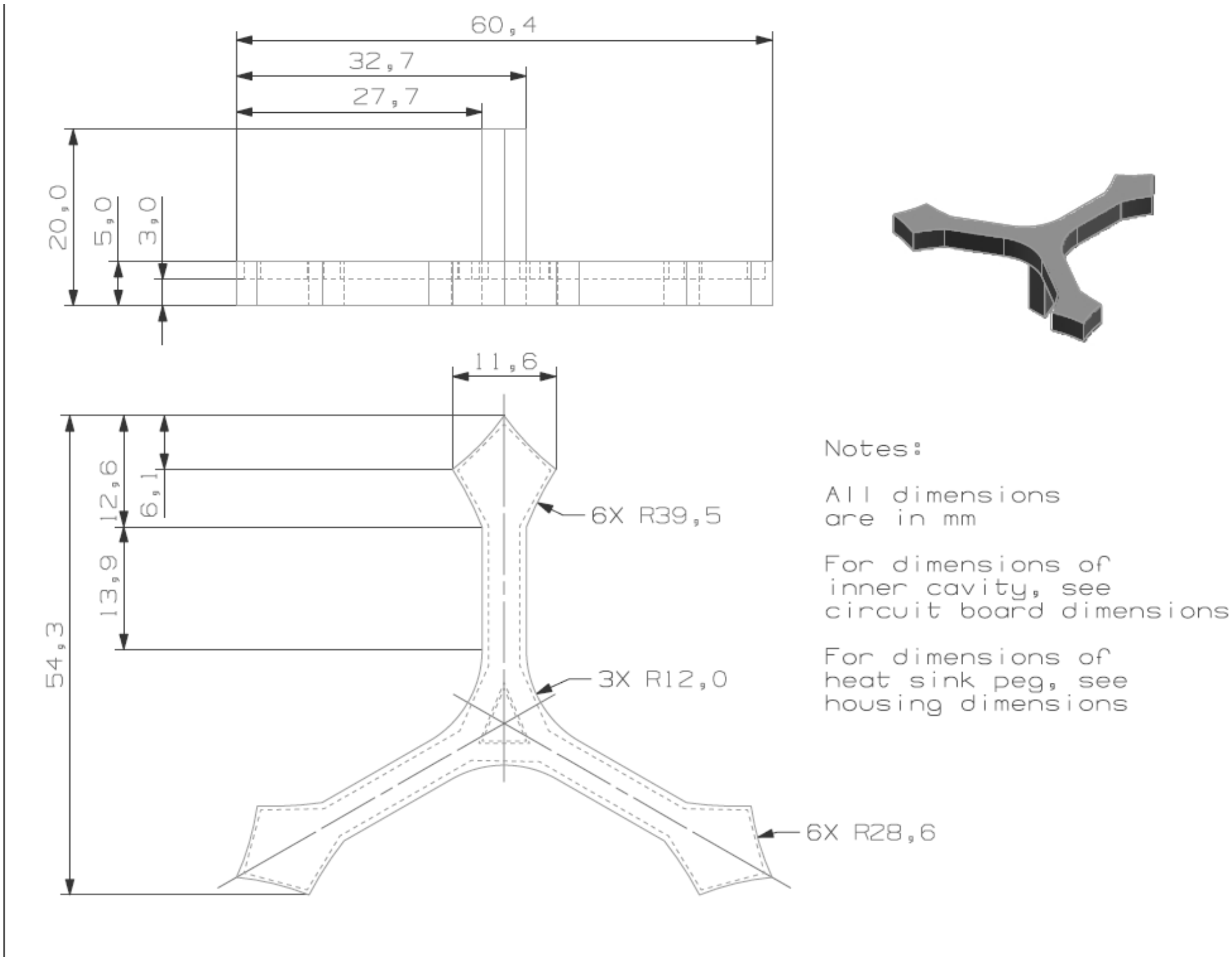


Figure 39: Heat sink engineering drawing

7.7 LEDS

Figure 40 on pg. 48 shows a photograph of the chosen Diamond DRAGON® LED and Figure 41 on pg. 48 shows its dimensions. As can be seen from these figures, the Diamond DRAGON® is a compact package with base dimensions of 6.3 mm x 7.3 mm. Despite its small size, it provides a significant amount of light. Its performance characteristics are summarized in Table 10 below.

Parameter	**Value**	**Unit**
Operating Temperature Range	-40 to 150	°C
Storage Temperature Range	-40 to 150	°C
Junction Temperature	160	°C
Power Consumption (at 25 °C)	8.6	W
Luminous Flux	150 to 280	lm
Typical Luminous Flux	225	lm
Viewing Angle	140	degrees

Table 10: Diamond DRAGON® performance characteristics [25]

As can be seen from the Table 10, three Diamond DRAGONS® will require 25.8 W and provide at least 450 lm. Once we take losses due to the reflector and lens into account using Eq. 6 on pg. 30, this luminous flux diminishes to 336.6 lm, which is still significantly larger than the required 250 lm. Therefore, we do not foresee insufficient luminosity stemming from lack of light coming from the LEDs.

Although the operating temperature goes up to 150 °C, in order to retain the lifetime requirement of at least 10,000 hours, we need keep the LED temperature below 85 °C [25]. This will be accomplished using a heat sink to draw heat away from the LEDs and is discussed in Section 7.7 on pg. 47.

Figure 40: Photograph of the Diamond DRAGON®

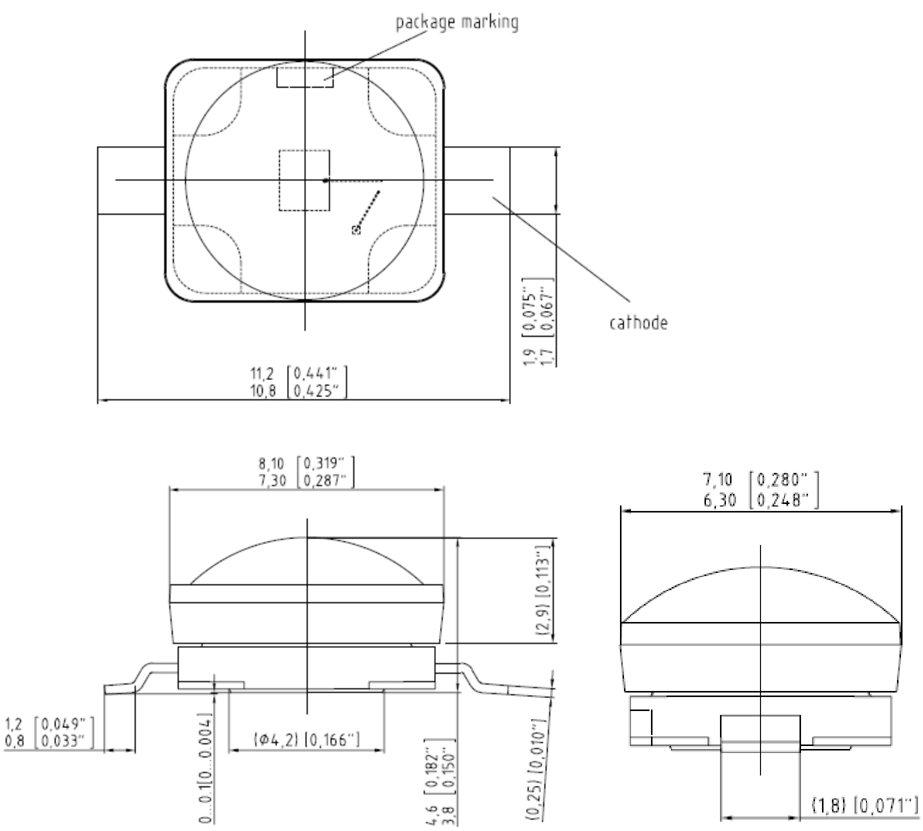


Figure 41: Dimensions of the Diamond DRAGON® LED; all dimensions are in mm

7.8 ELECTRICAL

7.8.1 CIRCUIT BOARD

The circuit board that will be used in the final design is shown with its dimensions in the engineering diagram in Figure 42. It will consist of the circuit diagram shown in Figure 27 on pg. 34, where the resistor's impedance will equal 1.7 ohms and must be able to with stand 16.4 W. The resistor dimensions are currently unknown and will be finalized after discussion with OSRAM's circuit prototyping department. The industry standard is ABS plastic, polycarbonate, or a mix. Polycarbonate will be used to prevent thermal degradation of the circuit [21]. Due to the unique resistance of the resistor it will most likely need to be produced specifically for this application. This series circuit will provide 1.4 Amps to each LED when 12.9 V is input. In this setup the current will vary by less than 5% within the 12.9±0.1 V range required by SAE for testing.

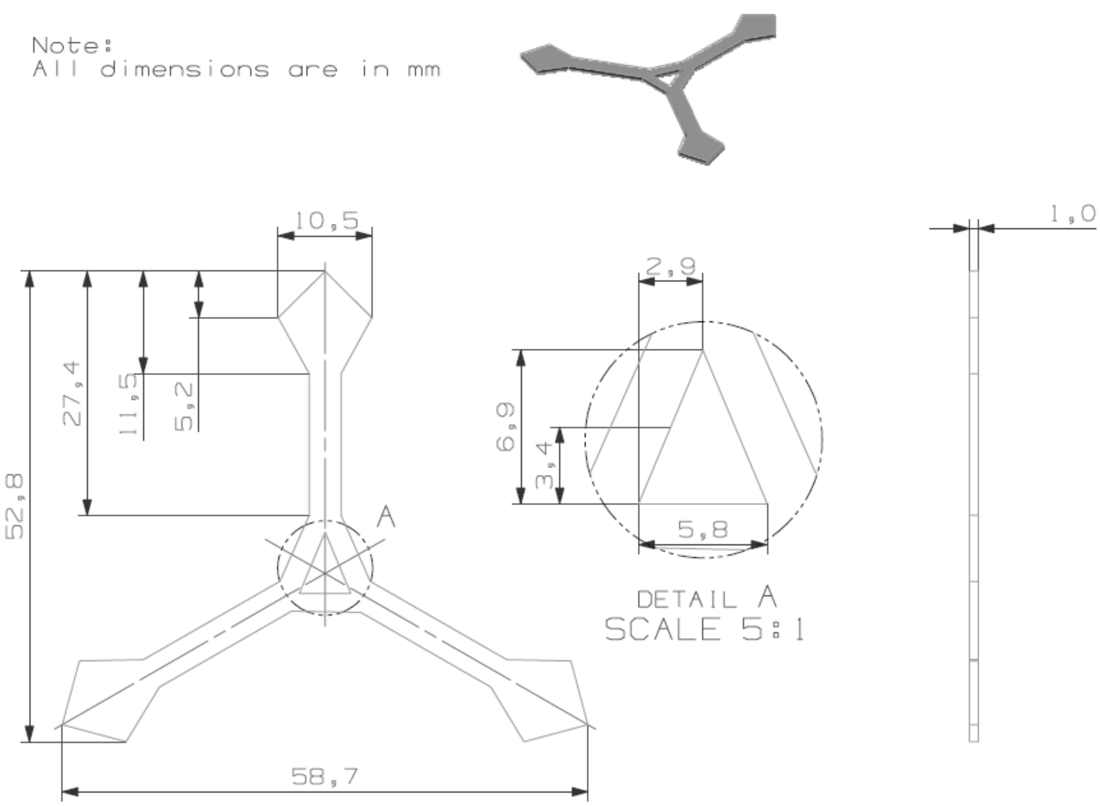


Figure 42: Circuit Board Engineering Drawing

7.8.2 CIRCUIT BOARD POWER CONNECTION

The GT 150 2-way USCAR connector is specified by USCAR (United States Council for Automotive Research). The connector used in our CAD model was made by reading dimensions from a Parasolid CAD model, and is an approximation of the actual connector. The major dimensions are shown in the engineering drawing in Figure 43.

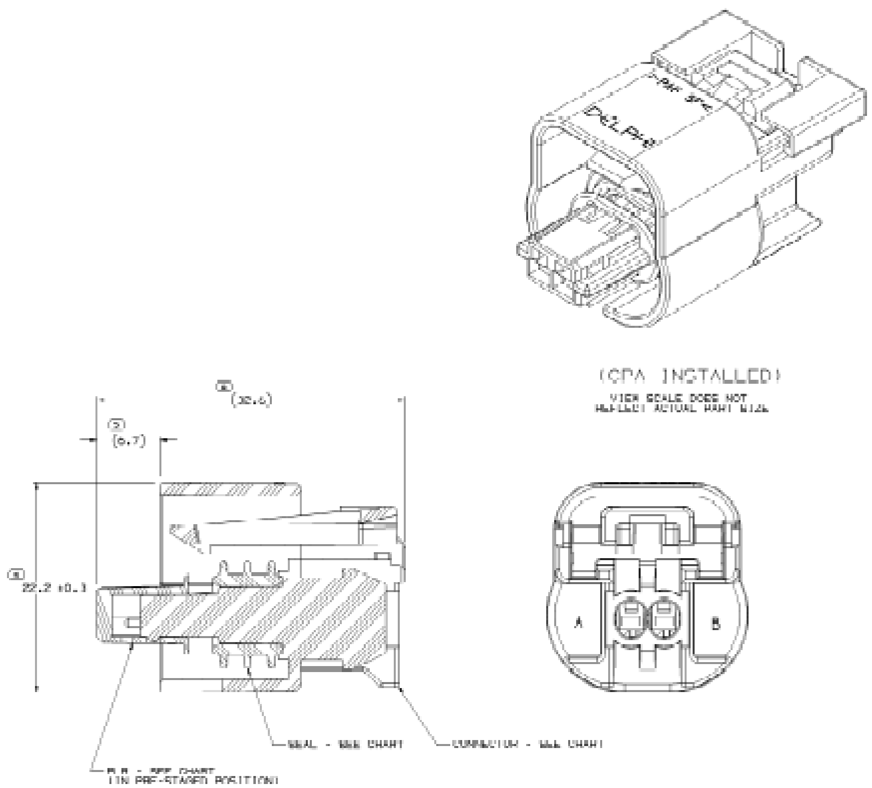


Figure 43: USCAR connector engineering drawings (courtesy of Delphi)

In order to simplify the assembly process, the electrical connections to the car power supply on the circuit board match those on the housing. Therefore when the heat sink LED and circuit board assembly are attached to the housing, the circuit board will not require further connection. This will further reduce labor costs and assembly time compared to wiring or soldering the connections. The wires coming out of the wire channels protrude out through the housing 1.0 mm.

8 PROTOTYPE DESCRIPTION

8.1 REFLECTOR

The reflector will be made of the same aluminized material as the mass manufactured part with the same aluminum deposition process. However, we will be unable to verify our prototype due to the low tolerances associated with rapid prototyping parts. The housing will need to be sanded prior to the aluminum deposition. This will severely alter the functionality of the component, and the light will no longer be scattered in a predictable manner. Thus, we will be unable to run the photometry test on the prototype. However, simulation results generally agree with the manufactured part with 98% confidence, so we will need to rely heavily on simulation to verify that legal requirements are met [22].

Despite this shortcoming, our prototype can still serve as a visual aid for the Design Expo, and will illustrate where our design is headed. Our final design will likely be different than the component shown at the expo due to time constraints placed on the manufacture of the assembly. Since our design is still being refined, we may need to begin prototyping before the reflector design is finalized.

8.2 HOUSING

One of the most important differences between our prototype and the final design is going to be the manufacturing method for the housing. Whereas our final design will be made by injection molding Makrolon 2605 into a cast for our housing's shape, our prototype will be constructed using stereolithography. Not only does this mean that the tolerances on the SLA prototyped housing will be much worse, but the material properties of the UV curable photopolymer resin are inferior to those of the Makrolon 2605 (see Table 11 below).

Material	Flexural Modulus [GPa]	Deflection Temperature at 1.8 MPa [°C]
UV-curable photopolymer resin (Stratasys® ABS)	1.834	76
Makrolon 2605	2.4	129

Table 11: Basic material properties for prototype and final design materials [24]

The combination of poor tolerances and inferior material properties of the prototype housing will not allow us to run most of the tests on the housing mentioned in Appendix E on pg. 81 on the prototype. Also, poor tolerances for the housing will require sanding down for the reflector surfaces. This will drastically lower the optical performance of the reflectors [22]. Therefore, most of the testing will have to be done on the final design once GM manufactures it.

8.3 LEDS

The number, type and geometrical distribution of our LEDs will be the only aspect remaining constant between manufacturing of the prototype and the final design. Both will use three Diamond DRAGON® LEDs placed at focal points of the three parabolic reflectors using the heat sink fins.

8.4 LENS

Our prototype will not have a fully functional lens due to the difficulty in manufacturing a lens with 88% transmissivity using prototype fabrication methods that we have available (stereolithography and CNC milling). A lens may be manufactured to serve as a representation of how the assembly will fit together and for running our modified internal heat test. However, the lens will not be used for luminosity testing. The prototype lens will be made from Plexiglas instead of crystal polycarbonate used in our final design. Our prototype lens will also be flat instead of slightly curved since we will be using stock Plexiglas sheets.

8.5 ADHESIVES

For our prototype we will not be using any sealants since we may have to take our prototype apart multiple times and both adhesive processes discussed in the final design section are permanent. Additionally, since we will not be able to run any of the contamination tests seals are not necessary in our prototype. We will be using the 3M 2216 B/A Gray 2-part epoxy to attach the circuit board to our heat sink so that we may test the thermal performance of our heat sink design.

8.6 DIFFUSION MEMBRANE

The prototype does not need a GORE-TEX® patch since we will not be doing any of the contamination or humidity tests. We are designing our prototype with a ventilation hole and a patch attachment surface so that the housing is geometrically similar to that of our final design and to give a rough idea as to how pressure equalization will occur. We may be able to acquire a few GORE-TEX® patches from GM to place on our prototype for a more authentic look.

8.7 HEAT SINK

The heat sink in our prototype will be made from the same 6061-T6 aluminum alloy as our final design. The difference between the prototype and the final design is that the heat sink will be machined from a solid piece of aluminum using a CNC mill for the prototype whereas it will be die cast for our final design. All other materials and dimensions will be the same as specified in our final design.

8.8 CIRCUIT BOARD AND POWER CONNECTION

The circuit will not have a current driver in the prototype but instead the LED will have to be run on a current limited power supply. The circuit will follow the diagram shown in Figure 44 below.

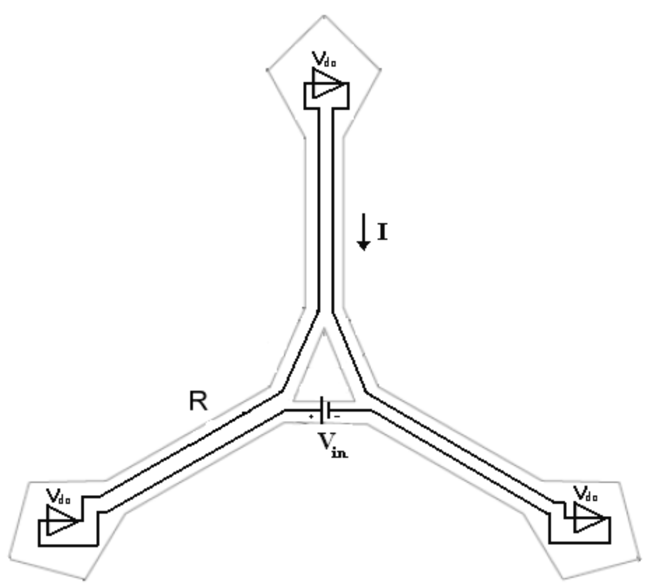


Figure 44: Prototype circuit diagram

The USCAR connector body will be molded into our prototype but it will not be functional. This is because our housing will be rapid prototyped and the connector dimensions input into CAD were only an approximation, as stated above (see Section 7.8.2 on pg. 49). Since the prototype is not actually being exposed to the elements and therefore does not need to be water resistant, we will run 28 gauge AWG wires through the housing. The wires will connect to a variable DC power supply with a current limiter that can supply 1 V to 14.0 V and .1 A to 1 A.

9 PROTOTYPE FABRICATION

9.1 HOUSING AND REFLECTOR

The housing (see Figure 45 below) was manufactured by GM's in-house prototyping shop using stereolithography (SLA). Essentially, this process utilizes a laser to cure a photopolymer resin layer-by-layer producing a 3D part based on the CAD model we sent to GM. The housing was then sanded with minimal sanding done to the reflector to attempt to preserve reflector geometry. Finally, GM applied the reflector coating using aluminum deposition.

Figure 45: Prototype Housing/Reflector

The wire guides had to be drilled out with a 1/16" drill bit because they were from an old CAD model. The peg receptacle on the housing also had to be sanded down to allow the heat sink to be removable.

9.2 LENS

The lens (see Figure 46 below) was also made by manufactured by GM's in-house prototyping shop. The lens was made from our CAD model using SLA with a clear resin, and then it was polished.

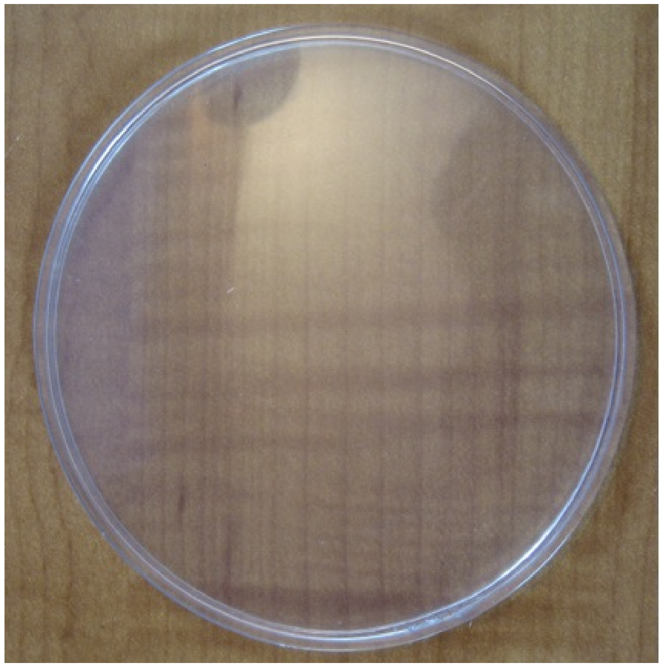


Figure 46: Lens Prototype

9.3 HEAT SINK

The heat sink (see Figure 47 below) was machined out of 6061-T6 aluminum using a mill. The process plan shown in Table 12 is used to describe the heat sink manufacturing process. Note: all dimensions within the process plane our in inches because the machine shop machines use inches.

Figure 47: Heat Sink Prototype

Operation	Machine or Device	Activity or Tool	Fixture	Parameters
1	Manual Mill	½ '' flat end	Mill Clamp	Using a 3"x3"x1" sheet of 6061-T6 Aluminum cut down the block to the dimensions shown in Figure 48 Spindle speed: 1400 rpm, with .1" steps
2	Manual Mill	¼" drill bit	Mill Clamp	Drill through work piece at points specified in Figure 49. Note: orientation of heat sink in diagram.
3	Manual Mill	¼" drill bit	Mill Clamp	Using a 3"x3"x½" sheet of scrap aluminum. Drill through piece at points specified in Figure 49. This piece will now be called the mounting piece.
4	Tap	#20 tap	Vice	Tap holes on work piece.
5	Tap	#20 tap	Vice	Tap holes on mounting piece.
6	EMCO Mill Model 55	¼ '' flat end	Mill Clamp	Clamp mounting piece with work piece attached using screw/washers in holes 1 & 2, see Figure 50. Run CNC operation to cut triangular peg out of work piece, Figure 51. Spindle speed=2000 rpm and cut depth=.1"
7	EMCO Mill Model 55	¼ '' flat end	Mill Clamp	Clamp mounting piece with work piece attached using screw/washers in holes 1 & 5. Run CNC operation to cut right side of heat sink, see Figure 52. Spindle speed=2000 rpm and cut depth=.1"
8	EMCO Mill Model 55	¼ '' flat end	Mill Clamp	Clamp mounting piece with work piece attached using screw/washers in holes 4 & 5. Run CNC operation to cut left side of heat sink. Spindle speed=2000 rpm and cut depth=.1"
9	EMCO Mill Model 55	¼ '' flat end	Mill Clamp	Clamp mounting piece with work piece attached using screw/washers in holes 3 & 4. Run CNC operation to cut bottom cut of heat sink. Spindle speed=2000 rpm and cut depth=.1"

Table 12: Heat sink prototype process plan

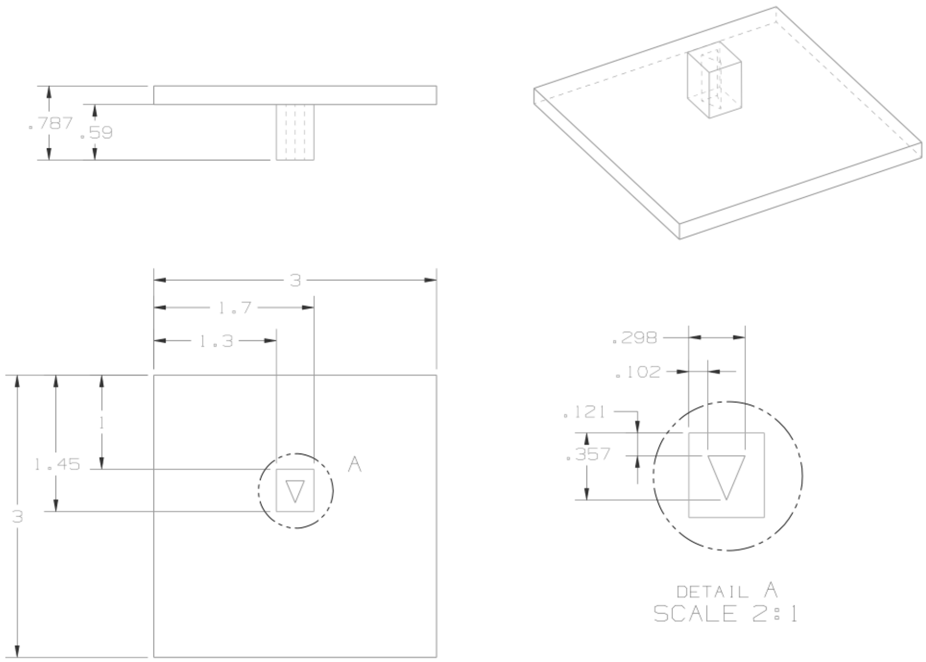


Figure 48: Engineering Drawing of work piece after operation 1

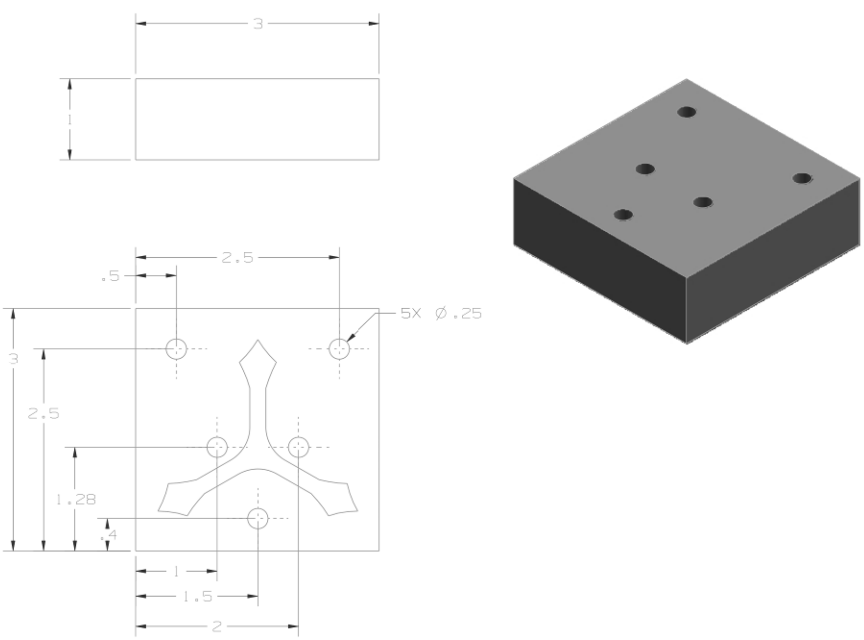


Figure 49: Engineering drawing of mounting piece after operation 2

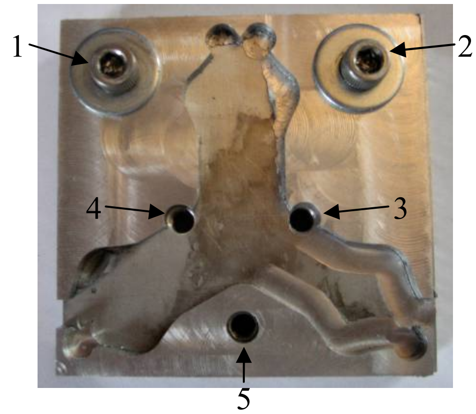


Figure 50: Heat sink mounting holes diagram

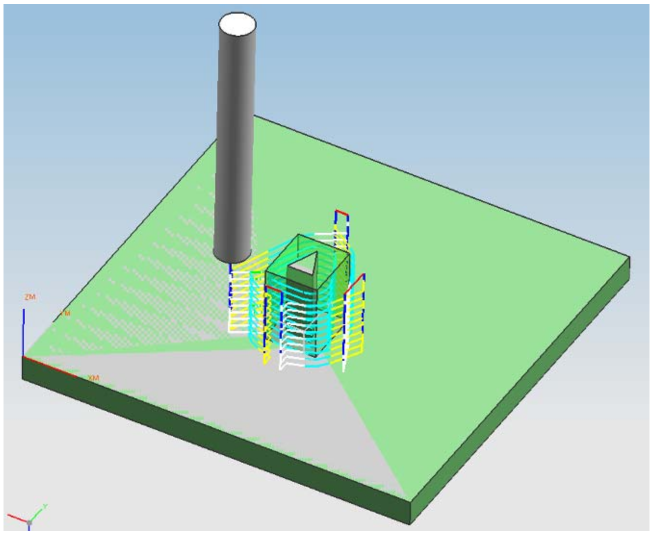


Figure 51: Heat sink peg tool path

Figure 52: Outer cut heat sink tool paths

The heat sink was then polished using a scouring pad. The peg also had to be lightly filed down to fit into the housing and still be removable.

9.4 ELECTRICAL

The electrical circuit was made at OSRAM. The LED model used in the prototype was the OSRAM Diamond Dragon® model number LW W5AP-LZMZ-5K8L, shown in Figure 53. The LEDs were attached on the bottom of the heat sink at the end of each arm using thermal adhesive, see Figure 54. Care must be taken so that the LEDs are insulated from the heat sink by the thermal adhesive otherwise the heat slug on the bottom of the LED will short circuit to the heat sink. The leads on the LEDs go along the arms as shown in Figure 55 on pg. 59 . With regards to placement, there was only one position the LED could be in and not overhang the edges of the heat sink. The LED circuit orientation and wiring matches Figure 55 on pg. 59; the LED orientation was carefully noted during construction. Note: The small white dot shown in Figure 53 means the cathode is on that side of the LED. Once the thermal adhesive had set we soldered the circuit together using 28 gauge AWG wire. The wires were then bent into place and glued down with epoxy. We then painted the wires with a paintbrush using silver model paint so that overhanging wires would not be noticeable from the front view of the fog lamp.

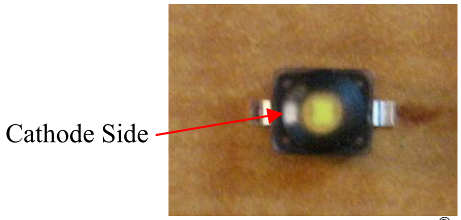


Figure 53: Diamond Dragon® LED

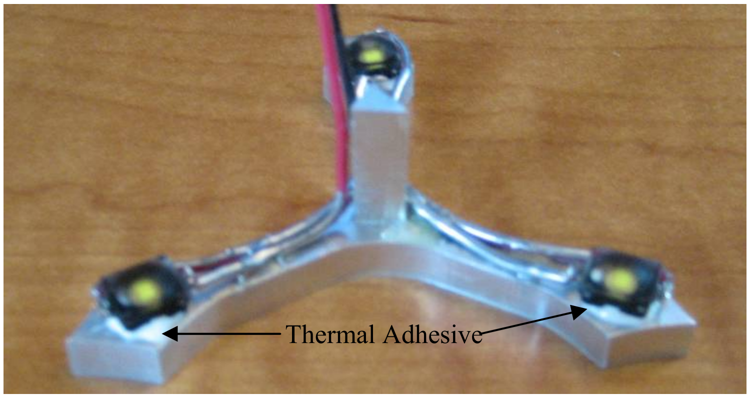


Figure 54: LED thermal adhesive application points

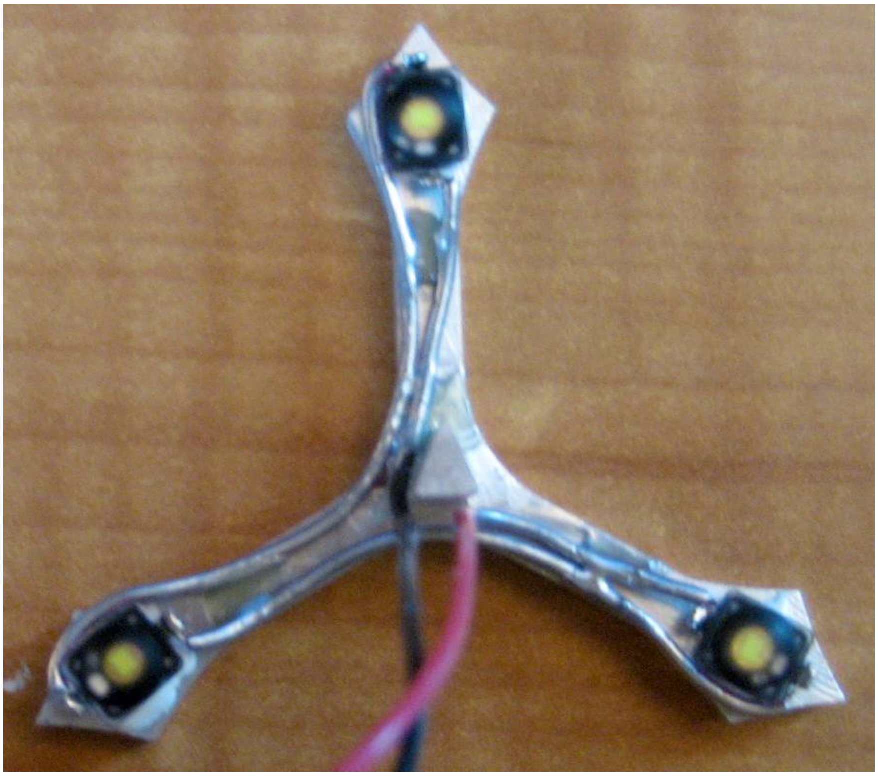


Figure 55: Prototype circuit

9.5 PROTOYPE ASSEMBLY

First, the wires were channeled through the wire holes. Then the heat sink peg was inserted into the heat sink peg hole on the housing. Since we removed the recess in the heat sink, the wires protruded from the surface of the part and prevented the heat sink from laying flush with the housing. Finally the lens was attached using rolled scotch tape in the glue channel. Although inelegant it was functional, barely visible, and allowed the fog lamp to be disassembled at a later time.

10 FINAL DESIGN FABRICATION PLAN

The fabrication plan we used to manufacture our prototype is significantly different from the fabrication plan we would recommend to GM for high volume production. Table 13, below, displays the cost distribution of raw materials and manufacturing processes of the fog lamp's components. It is important to note in this table the change in housing material from Makrolon 2605 to the 7055 T77511 wrought aluminum alloy. This material change was deemed necessary after validation results for our prototype were obtained, the details of which are outlined in Section 11.2.2 on pg. 63.

Part	Raw Material	Mass Required per unit (kg)	Total Raw Materials Cost ($)	Manufacturing Process	Total Manufacturing Cost, Labor Included ($)	Total Cost ($)
Housing	7055 T77511 wrought aluminum alloy	0.39	0.80	high pressure die casting	0.47	1.27
Central Heat Sink	7055 T77511 wrought aluminum alloy	0.0096	0.02	die pressing and sintering	0.38	0.40
Current Limiter	ON Semiconductor LT3517	Qty = 1	.38	N/A	0	0.38
Circuit Board	polycarbonate-based	0.002	0.01	circuit board printing	0.7	0.71
Lens	Polycarbonate	0.037	0.15	injection molding	0.27	0.42
LEDs	DIAMOND® Dragon LED: LW W5AP-LZMZ-5K8L	Qty = 3	11.25	N/A	0	11.25
Diffusion Patch	GORE-TEX® VE2035 patch	Qty = 1	0.18	N/A	0	0.18
Adhesives	3M 2216 Epoxy	45.3 mm^3	0.0043	N/A	0	0.043
	GM's silicon	22.5 mm^3	0.0009	N/A	0	0.0009
	2-part polyurethane	2500 mm^3	0.0892	N/A	0	0.0892
Assembly	N/A	0	0	N/A	0.9769	0.9769
				Total Cost of Fog Lamp Components:		15.72

Table 13: Cost distribution of fog lamp

From the table above, it is important to note some key manufacturing differences between the prototype and final design. Using the results from the manufacturing process selection assignment, we determined high pressure die casting would be the optimal process for the housing. This process will yield the necessary tolerances and produce the required shape of the component. The prototype was manufactured using stereolithography. In addition, a printed circuit board (PCB) will be utilized in place of wires for connecting the LEDs to their power source. The circuit board was utilized in place of wires to save on manufacturing time and labor costs when high volume production was needed.

Once the components and adhesives listed in Table 13, are manufactured, the fog lamp will need to be assembled. First, the Diamond DRAGON® LEDs will need to be soldered to the circuit board using tin or nickel (the cost of solder is included in the cost of the circuit board). After this is done, the circuit board with the attached LEDs will need to be mounted underneath the central heat sink using 3M 2216 Epoxy. Then the central heat sink, along with its attached components, will need to be connected to the housing with the help of GM's silicon adhesive. Finally, the GORE-TEX® patch will be attached to the back of the housing, using its adhesive coating, while the lens will be attached to the front of the housing with the help of a 2-part polyurethane adhesive poured into the glue channel. When considering all the cost contributing factors in Table 13, it's important to note that currently the dominating contributor to the fog lamp cost is the price of the LEDs ($11.25).

11 VALIDATION

11.1 METHODOLOGY

To verify the functionality of our design, we used a combination of physical testing and simulations. The ray tracing optical simulation done in ASAP 2008 was 98-99% accurate which is sufficient for validation of our design's optical performance [22].

The Abaqus simulation of the heat sink (Section 7.6 on pg. 45) is a partial validation that the heat sink is capable of drawing enough heat away from the LEDs such that their luminosity and lifetime are not compromised. For reasons previously mentioned in the final design description (Section 8 on pg. 50), there are numerous differences between our prototype and final design. Both the thermally inferior SLA housing and the non-standard lens would make thermal cycle tests unfeasible. However, since design verification was necessary, we conducted a modified thermal test to assess the adequacy of our heat sink. Because the testing procedure was significantly altered from the legally specified one, our test was meant to indicate whether our heat sink was close to being satisfactory rather than providing precise results.

Other components of our design are not as easily verified, and were deemed beyond the scope of our project based on discussion with GM. However, to set up our design for success, we still examined each component's ability to meet legal requirements. Our main concern with the validation process is whether the press fit/silicone sealant joining of the heat sink to the housing will prove to be adequate. Unfortunately, we don't have the expertise to run an FEA high frequency loading analysis on this seal, thus its strength and resistance to fatigue loading will have to be tested using the final design constructed using mass production methods and materials.

We know that the ventilation hole and GORE-TEX® patch combination used for pressure equalization and keeping water and contaminants out of the fog lamp assembly will be adequate. We can be certain of this since the same ventilation hole and GORE-TEX® patch combination is sufficient for both versions of the current GM halogen fog lamps, one of which is smaller than our fog lamp and the other larger.

Our final design employs the same crystal polycarbonate material for its lens as that used by the standard halogen fog lamps. Since our lens will employ GM standard material and will be smaller in size than the larger fog lamp lens (which passes the required tests), we can be fairly certain that it will pass the necessary validation.

11.2 RESULTS

11.2.1 REFLECTORS

Figure 56 displays the latest ray tracing results for our fog lamp, encompassing all of the most recent changes to the reflectors. As can be seen from this figure, the beam pattern is close to what is desired for a fog lamp – the light is spread out horizontally and the majority of the light falls below the 0° vertical line.

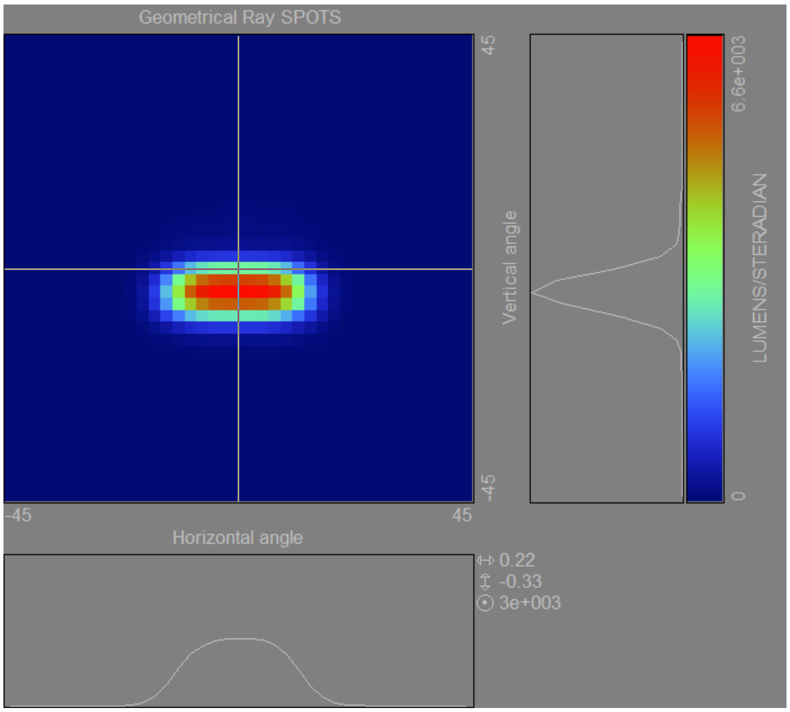


Figure 56: Beam pattern from the most recent ray tracing results

However, our optical results do not quite meet legal requirements. Table 14 shows a comparison between the luminous intensity provided by our fog lamp and the luminous intensity specified by the legal requirements. This chart shows that although our fog lamp meets the luminosity requirements below the 0° vertical line, its light output above this line is over the specified legal limits. However, since the simulated light pattern and total candela outputs are not far off of those required, we believe that the reflectors could be adjusted for the light to behave as needed. These adjustments are discussed in greater detail in the Section 12.1.2 on pg. 66.

Lateral angles							
	15 L	9 L	3L	0	3R	9R	15R
10 U	<125	<125	<125	<125	<125	<125	<125
	31	63	86	108	93	76	38
2U	<240	<240	<240	<240	<240	<240	<240
	347	1011	1248	1256	1241	1010	312
1U	<360	<360	<360	<360	<360	<360	<360
	538	1670	2080	2106	2092	1661	484
H	<480	<480	<480	<480	<480	<480	<480
	730	2330	2912	2955	2944	2313	655
1.5D		>1000	2000/10000		2000/10000	>1000	
		3646	4567		4549	3573	
3D	>1000						>1000
	1432						1261

Table 14: Simulated luminous intensity values (in candela) provided by our fog lamp (values in red) compared to luminous intensity values specified by SAE legal requirements (values in black)

11.2.2 HEAT SINK

The test was conducted using two thermocouple leads to measure the temperatures at one of the LEDs and at the end of the heat sink's peg, as shown in Figure 57 below. The main objectives were to estimate the temperature surrounding the LEDs and to assess the performance of the heat sink at diffusing the heat.

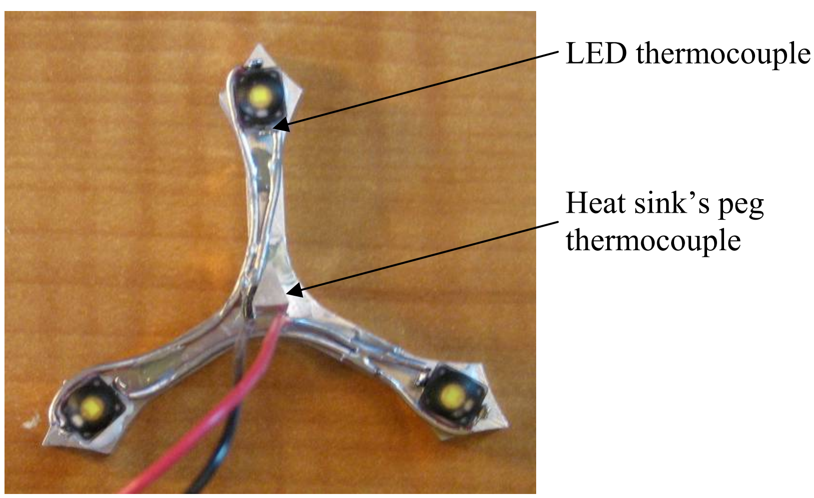


Figure 57: Thermal testing thermocouple locations

This arrangement was chosen so that we could see the temperature difference between these two locations and thus assess the heat sink's ability to conduct heat away from the LEDs. We conducted the test twice, once with a fixed voltage and once more with a fixed current.

Unfortunately, due to the limitations of our power supply, we were not able to run our testing configuration at a 1400 mA current and 12.9 ± .1 V voltage (nominal operation), the typical current and voltage values indicated in the Diamond® DRAGONS specifications sheet. However, even at the lower voltage and current values our test results indicated that the heat sink was inadequate and needed to be redesigned. The voltage was set to 9 V, while the power supply current varied due to increased heat as shown in Table 15. As can be seen from Figure 58, after eight minutes of operation, the temperature at one of the LEDs was already 76 °C and showed no sign of tending towards steady state. The test was discontinued at this point due to our concern for melting the wires' insulation.

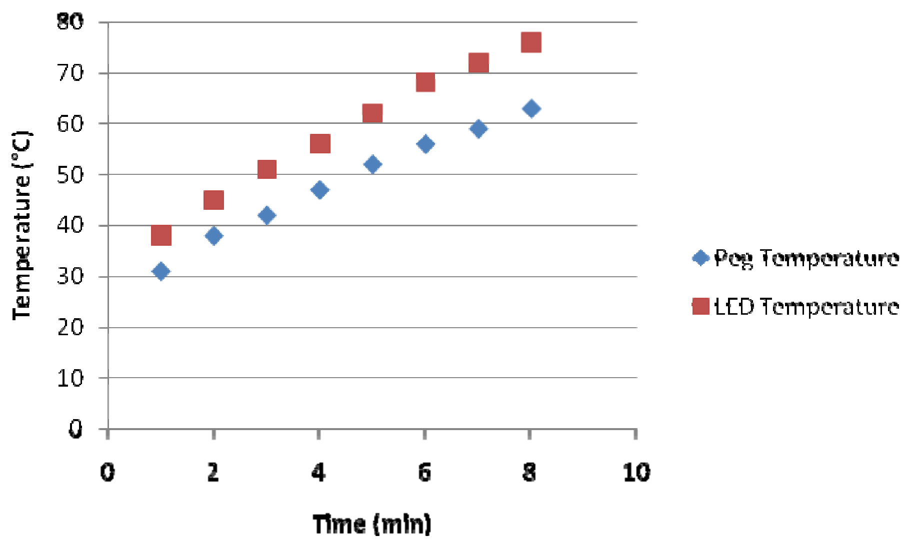


Figure 58: LED and peg temperatures as a function of time during first test

Time (min)	Voltage (V)	Current (A)
1	9	0.25
2	9	0.29
3	9	0.32
4	9	0.35
5	9	0.38
6	9	0.41
7	9	0.44
8	9	0.46

Table 15: Voltage and current provided to the LEDs during the first test

We conducted another test with higher power provided to the LEDs. The current was fixed at 0.7 A while the power supply voltage behaved as indicated in Table 16, below. These results can be seen in Figure 59, and further support the notion that the heat sink needs to be altered. After only four minutes at these power supply settings, the temperature at the LED solder point reached 80 °C and once again showed no indication that it was tending towards steady state. The test was discontinued at this point due to the concern for wire insulate and LED breakdown.

Time (min)	Voltage (V)	Current (A)
1	9.54	0.7
2	9.41	0.7
3	9.33	0.7
4	9.28	0.7

Table 16: Voltage and current provided by the power supply to the LEDs during the second test

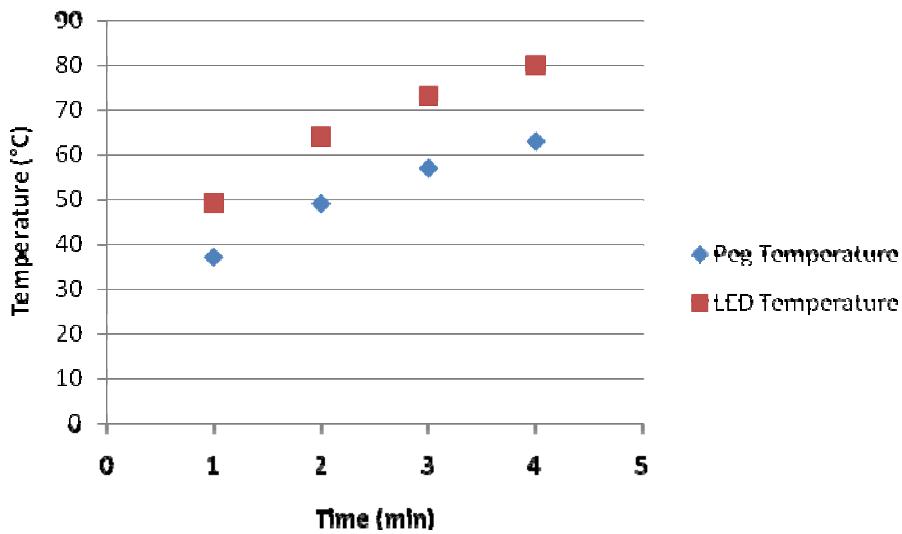


Figure 59: LED and peg temperatures as a function of time during the second test

Both tests indicated that our heat sink was not adequate enough to allow prolonged fog lamp operation and thus needed to be redesigned. The proposed redesign process is discussed in detail in the Section 12.

12 DISCUSSION OF FINAL DESIGN

General Motors had a list of requirements for our LED fog lamp, which are repeated for the reader's convenience in Table 17, below. We will critique our design based on how well each requirement was met.

1	Meet fog lamp legal requirements
2	Aesthetics
3	Increase life span of fog lamp
4	$13.50/unit price point
5	Minimize weight

Table 17: Customer requirements

12.1 LEGAL REQUIREMENTS

As previously discussed in Section 2.3.1 on pg. 2, we were only responsible for meeting the luminosity requirements and designing for thermal considerations. The biggest weakness of our design is that it currently does not meet either of these specifications, which was rated first in the customer requirements list.

12.1.1 OPTICS

Table 14 on pg. 63 displays the results of our latest ray trace from OSRAM. It is clear from our simulation results that our final design failed to meet the legal luminosity specifications. The results indicated that the intensity of our fog lamp's light output above the horizontal exceeded the targets specified by the harmonized SAE luminosity requirements. However, we had enough total light output such that the reflector has the potential to succeed with future modifications.

On the other hand, our design succeeded in meeting the chromaticity specifications for white light according to SAE standards. The color coordinates for the Diamond DRAGON® LEDs are x = 0.33, y = 0.33, which lies within the white region of the CIE 1931 color plot, according to Figure 60.

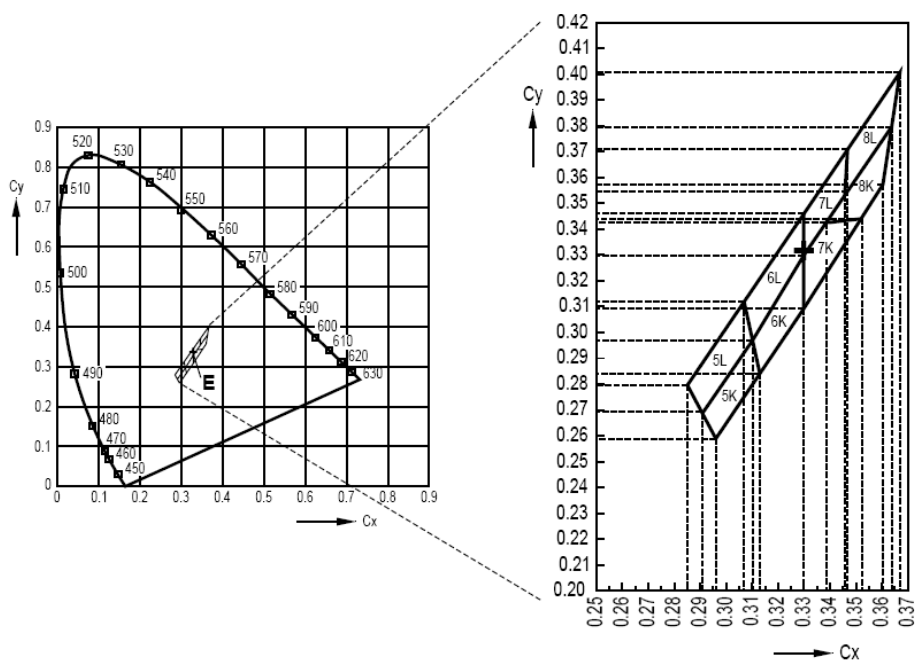


Figure 60: Chromaticity coordinate groups for Diamond DRAGON® LEDs [25]

12.1.2 OPTICS SUGGESTED IMPROVEMENTS

If we had more product development time, we would re-run the optics simulation using thermal roll-off of the LEDs. This would give us a better idea of how much light needed to be redirected to each portion of the hot-spot for the photometry test.

The next portion of the redesign would follow the iterative process we used for our reflector design. Since too much light fell above the horizontal, we would first suggest angling the top reflector down an additional 3.5°, making the new top parabola's axis angle 6.2°. The reason for choosing 3.5° is related to the simulation results. There was an intense band of light at 1° above the horizontal, and we wish to redirect this light towards 1.5° below the horizontal, the vertical location of the hot spot.

After obtaining these simulation results, there would likely need to be more modifications to the reflector. If there are still regions above the horizontal with too much light, we would need to incorporate a scattering mechanism on the surface of the reflector. GM's current reflector is illustrated in Figure 61, below. On the top region of this reflector is an additional feature to redirect light downwards. We would suggest integrating a similar feature onto the surface of each of the three parabolas to redirect undesirable light downwards.

With these two design changes, and possibly a few simulation iterations, we predict that the reflector will meet the luminosity specifications.

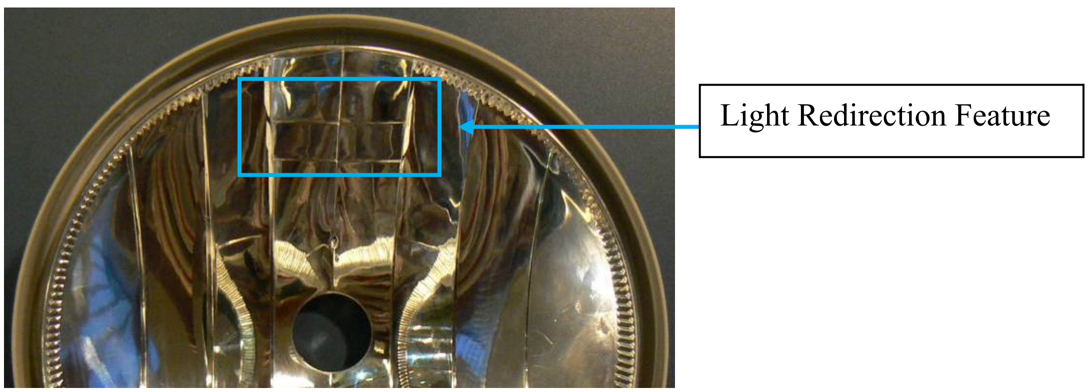


Figure 61: General Motors halogen fog lamp reflector

12.1.3 THERMAL CONSIDERATIONS

As indicated by our thermal validation results in Section 11.2.1on pg. 62, our current heat sink was inadequate. There was not enough surface area to transfer heat away from the LEDs, and the LEDs were projected to heat up beyond the target of 85°C rated by the manufacturer. This essentially means the light was predicted to degrade by more than 20%, which would mean a failure to meet legal requirements. Our fog lamp's heat sink therefore requires redesign in order to allow the LEDs to remain operational for a prolonged amount of time.

12.1.4 THERMAL SUGGESTED IMPROVEMENTS

Due to the thermal inadequacies associated with our final design, we had to redesign the thermal aspect of our fog lamp extensively. Our previous thermal analysis showed that there would be little difference between the temperature of the LEDs and the heat sink, which we verified with our thermocouple testing of the prototype (See Appendix T). Abaqus does not have the capability of predicting temperatures, only temperature differences, and thus we did not know until we conducted tests that the total system temperature would be above recommended operating conditions under our prescribed power input.

In an effort to solve our thermal issues, we recommend changing the housing material from Makrolon 2605 to 7055 T77511 wrought aluminum alloy and adding fins behind the housing for thermal dissipation.

To arrive at a new solution, we did a very conservative thermal analysis to ensure that our lamp would work under worst-case conditions. The analysis environment considered only thermal buoyant convective heat transfer (real world will have forced convective), with an ambient temperature of 50° C (120° F, close to the hottest temperature recorded on earth). For our analysis, we assumed that all power used by the LEDs is converted to heat (no light output, all heat) with a maximum allowable LED temperature of 80° C (so only a 30° C temperature gradient to drive heat transfer).

The results show that it is feasible to cool the LEDs under the above worst case conditions given the following design changes. The entire housing will need to be made from aluminum and will have long vertical fins on the back. The old heat sink component will function as a heat diffuser and will primarily transfer heat to the housing and fins for dissipation. Our model estimates the heat transfer as buoyant convective heat transfer on a vertical flat round plate in the front and back, and buoyant convective heat transfer between parallel vertical plates for the fins [38]. Equations for the Nusselt number, Raleigh number and other constants and supporting calculations are listed in Appendix U on pg. 110. Using fins with a base width of 0.002 mm, height of 0.040 mm and total overall length of 1.2 m (length if all fins were combined and lined up end to end), we were able to achieve a heat loss of 29.3 W. The plates contribute an additional 3.8 W for a total heat flux of 33.1 W from the system. This is well above the 25.8 W required to maintain the LEDs at 80° C, therefore, our redesign is more than adequate at cooling the LEDs even at worst case conditions. Thus, under normal operating conditions our fog lamp will be sufficiently cooled. We chose to use long vertical fins instead of pin fins for increased durability and to increase ease of manufacturability. The redesigned housing and heat sink combination is shown below in Figure 62 and the engineering drawing is shown in Figure 63 on pg. 69.

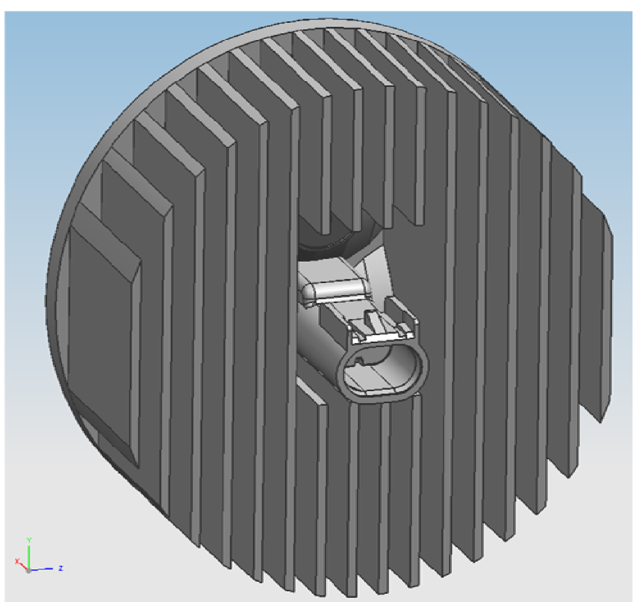


Figure 62: Heat sink re-design for final fog lamp

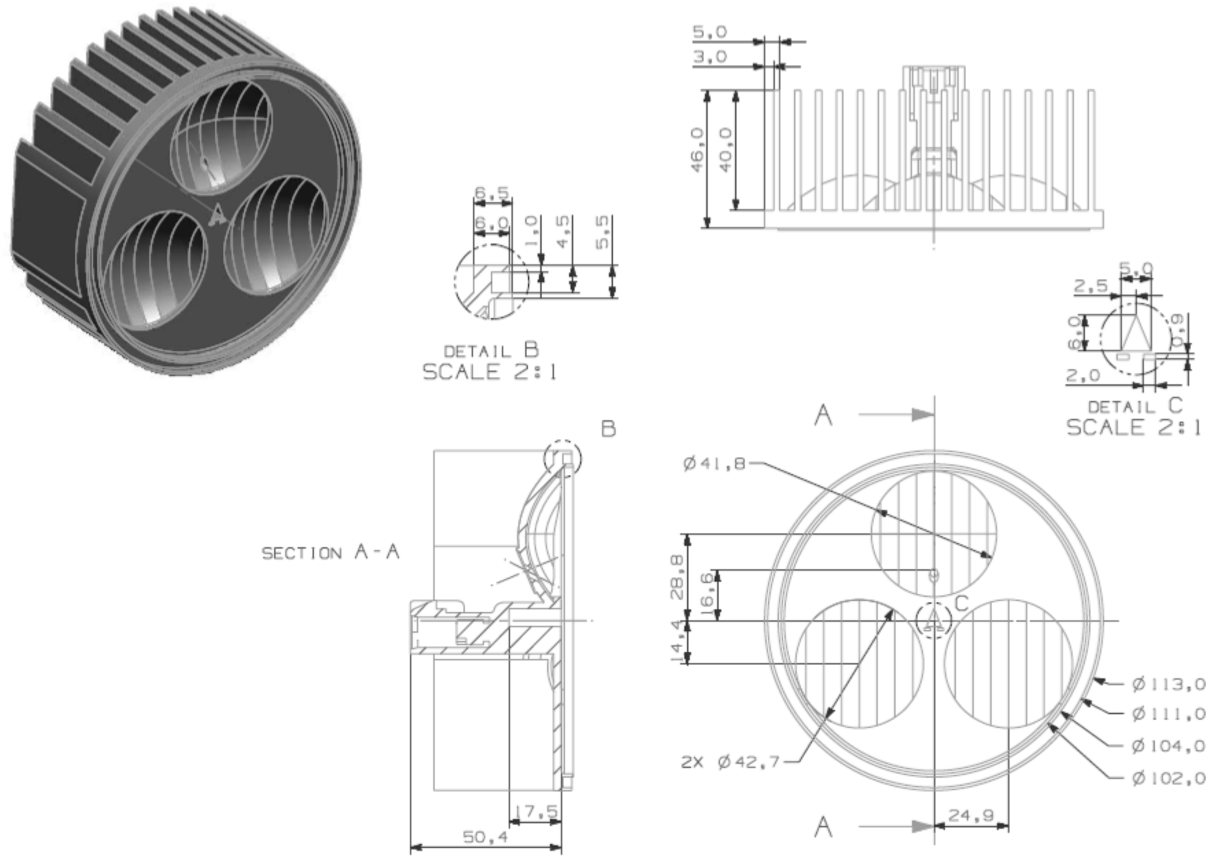


Figure 63: Engineering Drawing of Heat Sink/Housing Redesign

12.1.5 ELECTRICAL ACCOMODATIONS

Using the current design the current driver is separate from the housing. If time permitted we would have liked to redesign the USCAR connector/housing interface and move the current driver inside of the main housing assembly. Another option would be making a custom current driver that would fit on the circuit board under the heat sink, however this may not prove financially feasible.

12.2 AESTHETICS

One of the strengths of our design is that we came up with something new that has never been done before. Automakers today are looking to differentiate their products to appeal to customers. The advantage of LEDs is that new designs that have never been seen before can be created. Our product has the potential for tailored styling options that could potentially appeal to buyers. The heat sink shape and color can be modified, which appeals to GM's design studio. In addition, the non-functional portion of the front of the housing can be colored to match the fascia of the car. According to the perceived quality matrix determined in Section 2.9, the final design met all of the criteria and can thus be described as a success for GM design studios.

Aesthetic Criteria	**Score**
Minimize front profile (from front view of car)	+
No visible bolts or glue	+
No visible bulb	+
Visible functional technical pieces	+
See through lens	+
Jeweled reflector (shiny)	+
Aesthetic accent	+
Total Score	+7
+ = (Criteria Met) - = (Criteria Not Met)	

Table 18: Scoring matrix for aesthetics of final design

12.3 INCREASE LIFE SPAN OF FOG LAMP

One of the main reasons GM requested an LED fog lamp was to reduce warranty costs associated with the replacement of the current halogen lamps. As previously discussed, our LEDs are to be operated at a current of 1.4 Amps and temperature less than 85°C. According to the Diamond DRAGON® specification sheet provided by OSRAM, at a current of 1.6 Amps and temperature of 85°C, the LEDs are rated at 30,000 hours. Thus, with the proposed modifications to the heat sink, the LEDs will exceed the lifetime of a vehicle (~10,000 hours). We therefore succeeded in increasing the life span of the fog lamp such that the warranty costs to GM can be avoided altogether; the LED fog lamp would not need to be replaced during the entire lifetime of the vehicle.

12.4 TARGET PRICE

GM specified a price point of $13.50 per unit for mass manufacture of the fog lamp. We determined the price of our fog lamp to exceed this target point by close to 14%. The price of our proposed re-design was determined to be $15.72 (Table 13 on pg. 60), which includes raw material costs, labor, and machining costs. However, the three Diamond DRAGON® LEDs contribute 73% of the cost of our newest proposed design.

The LEDs are new technology and are not yet in production. Also, the price we were quoted from OSRAM was not necessarily for mass quantities. If the fog lamp is integrated on 5 million production vehicles, the order quantity would be 15 million LEDs. If GM were to use our fog lamp design, it can thus be projected that the price per LED would drop significantly if mass quantities were ordered in the future. Therefore, although our final design did not meet this customer requirement, we project that it has the potential to do so given that the LEDs are the primary cost driver.

12.5 MINIMIZE WEIGHT

Automakers are always looking to minimize the weight of each component in the car for fuel economy concerns. As a result, we were given the requirement that the final product weigh less than the larger of GM's fog lamps, excluding the weight of the heat sink (340.0 grams).

Table 19 summarizes the weight of each component of our fog lamp; the total weight including all components was determined to be 431 g. However, it is clear from this table that the weight of our proposed design without the integrated fins is less than the upper bound weight requirement; we determined this mass to be 160 g. However, when the fins are counted, the weight is exceeded by 27%. The most significant contributor to the total weight was the wrought 7055 T77511 aluminum alloy. Although we met our customer requirement, it is important to note the added weight associated with this fog lamp.

Part	Material	Mass (g)
Lens	Chrystal Polycarbonate	31.8
Housing with Fins	7054 T77511 Aluminum	390.6
Housing without Fins	7055 T77511 Aluminum	119.4
Heat Diffuser	7055 T77511 Aluminum	8.9
Reflector	EVMAL1350U73	negligible
Circuit Board, Current Driver, and GORE-TEX® Patch (approx.)	Polycarbonate	5.0
Lens/Housing Sealant	2-Part Polyurethane	2.7
Heat Sink/Housing Adhesive	GM Silicon	0.03
Diamond Dragon (3X)	Q65110A7506	0.9
	Total Mass (w/ heat fins)	**431.0**
	Total Mass (without fins)	**159.8**

Table 19: Fog lamp weight

12.6 PROBLEMS ENCOUNTERED

During the process of completing our prototype and validating our design, many problems were encountered. Given the limited amount of time we had to complete our project, it was difficult to fully optimize our fog lamp design and incorporate all design ideas. The main problem we had with the optics portion of our design is that we did not have the software to analyze our reflector and obtain ray trace data for further revisions. We therefore had to send subsequent CAD model revisions to OSRAM, where they are analyzed based our contact's availability. Often, this resulted in several days of delay. This severely limited the number of iterations we could complete through the course of the semester. The ray tracing results of our first alpha design proved that the team's lack of optics background limited the initial stages of the product development process. Although our theoretical calculations have greatly improved in accuracy with our acquired experience, we unfortunately ran out of time to do the necessary refinement to the reflectors.

We also had constraints on the time needed to fabricate the prototype. As previously described, we deemed the heat sink inadequate after running physical thermal tests with the LEDs in operation. However, after engaging in heat transfer analysis and redesigning, we did not have enough time to fabricate the newest design. Thus we could not verify the performance of the heat sink.

Our heat sink dimensions presented the biggest dimensional constraint problem for our project. The circuit board and Diamond DRAGON® LEDs should not be visible when viewing the fog lamp from the front due to GM studio's guidelines on aesthetics. We had some difficulty concealing the three LEDs under the heat sink, and as a result had to widen the arms on the heat sink. This resulted in a lower design luminous efficiency because the heat sink arms were blocking more of the light from the three reflectors. However, our simulation results indicated that this design change did not have a detrimental effect on the performance of our design.

13 CONCLUSIONS

The problem we have been assigned is to design a legally compliant fog lamp to be used under low visibility conditions, which is inexpensive, aesthetically pleasing, and has a lifetime exceeding that of the vehicle. To achieve this objective, our sponsors decided to replace the halogen light bulbs in their current fog lamps with LEDs. LED fog lamps are more energy efficient than halogen lamps, have more than an order of magnitude longer lifetime, and their compact solid state nature makes them more durable while opening up novel design options.

The initial ray tracing data from OSRAM indicated that we needed to redesign our first alpha design, the parabolic cone based reflector "Mystery". Our final design, "Trinity", incorporates three separately aimed parabolic reflectors with vertical fluting to disperse light horizontally as seen in Figure 21 on pg. 26. A three pronged heat sink with a bottom mounted circuit board was chosen for positioning three Diamond DRAGON® LEDs at the focal points of each individual reflector. The reflectors' axes of symmetry were all aimed at the point where the fog lamp required the greatest amount of illumination. The flutes were each designed to angle light to a specific area of the luminosity testing zone in order to meet legal requirements. The optical simulation results indicated that future modifications are necessary for the reflector. We found that there is too much light above the horizontal and thus our solution is to redirect the light downward using reflector geometry.

The thermal performance of our prototyped heat sink was inadequate; the temperature surrounding the LEDs was too high, as discussed in Section 11.2.1on pg. 62. Our solution was to manufacture the entire housing out of aluminum with integrated thermal dissipation fins on the back (shown in Figure 62 on pg. 69). Using heat transfer analysis, the new design was predicted to keep the LEDs within their ideal temperature range and ensure that a long lifetime is achieved.

14 ACKNOWLEDGEMENTS

We would like to give special thanks to the following individuals in particular, who gave us advice and guidance on our senior design project. We are very grateful for their support with the design process, and without their help this project could not have been possible. Thank you.

General Motors: Tony Micale, Matt Monden, and Mark Buffa

OSRAM: Mike Mott, Joe Jablonski, Mark Coykendall, Mike Godwin, Brent Pankey, and Hong Luo

University of Michigan: Professor Gregory Hulbert, Todd Wilber, Brooke Haueisen, and Bob Coury

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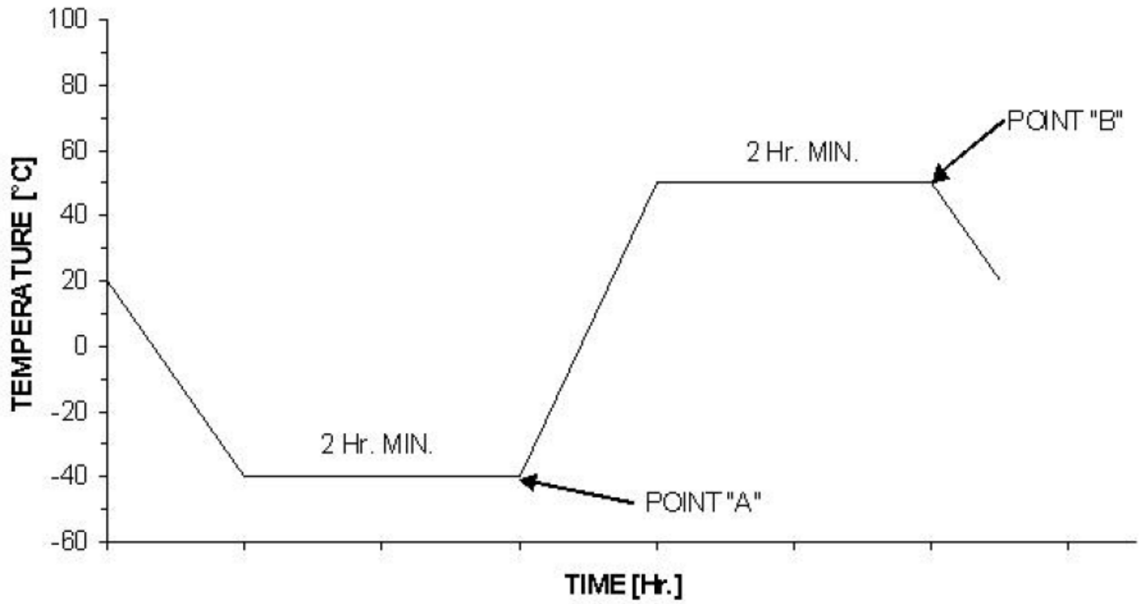
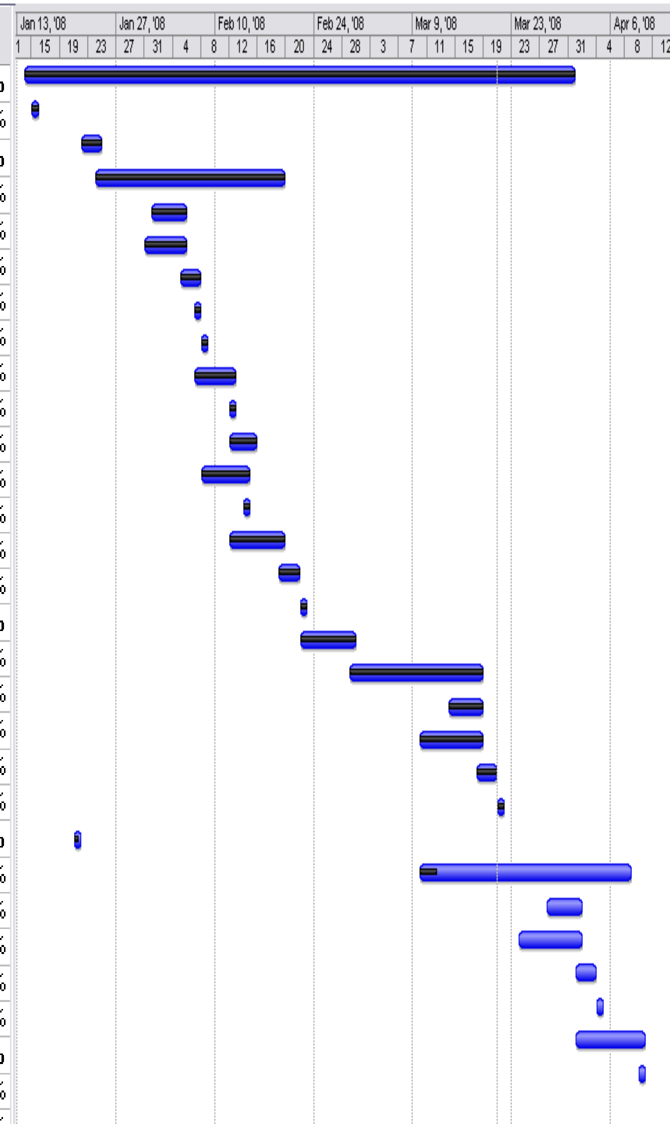
APPENDIX

Appendix A: Thermal Cycle Test Temperature Profile [16]



Appendix B: Gantt Chart

	Task Name	Duration	Start	Finish	% Task Complete
1	**Develop Design Requirments and Specifications**	**58 days**	**Mon 1/14/08**	**Mon 3/31/08**	**100%**
2	Meet with Sponsor	1 day	Tue 1/15/08	Tue 1/15/08	100%
3	**Design Review #1**	**3 days**	**Tue 1/22/08**	**Thu 1/24/08**	**100%**
4	Preliminary Design	19 days	Thu 1/24/08	Tue 2/19/08	100%
5	Create Pugh chart	3 days	Fri 2/1/08	Tue 2/5/08	100%
6	Work on Engineering Fundimentals and Func. Decomp	4 days	Thu 1/31/08	Tue 2/5/08	100%
7	Prepare for Informal Selection Process	3 days	Tue 2/5/08	Thu 2/7/08	100%
8	Informal Presentation 1: Best Prototype Design	1 day	Thu 2/7/08	Thu 2/7/08	100%
9	Meet with GM: Discuss Selected Design	1 day	Fri 2/8/08	Fri 2/8/08	100%
10	Write Preliminary DR2 document	4 days	Thu 2/7/08	Tue 2/12/08	100%
11	Meet with Professor, Review DR2 Document	1 day	Tue 2/12/08	Tue 2/12/08	100%
12	Talk With OSRAM and Work on Reflector/LEDs/Circuit	4 days	Tue 2/12/08	Fri 2/15/08	100%
13	Create Initial Engineering Drawings	5 days	Fri 2/8/08	Thu 2/14/08	100%
14	Informal Submission 2: CAD	1 day	Thu 2/14/08	Thu 2/14/08	100%
15	Revise DR2 Document	6 days	Tue 2/12/08	Tue 2/19/08	100%
16	**Design Review #2**	**3 days**	**Tue 2/19/08**	**Thu 2/21/08**	**100%**
17	Written DR2 Report Due 6pm	1 day	Fri 2/22/08	Fri 2/22/08	100%
18	Modify Selected Design For Alpha Design	6 days	Fri 2/22/08	Fri 2/29/08	100%
19	Decide on and Create Final Design. Check with Sponsor	14 days	Fri 2/29/08	Tue 3/18/08	100%
20	Prepare Presentation for DR3	3 days	Fri 3/14/08	Tue 3/18/08	100%
21	Write DR3 Document	7 days	Mon 3/10/08	Tue 3/18/08	100%
22	**Design Review #3**	**3 days**	**Tue 3/18/08**	**Thu 3/20/08**	**100%**
23	Turn in DR3 Report	1 day	Fri 3/21/08	Fri 3/21/08	100%
24	Prototype Final Design Iterations	1 day	Mon 1/21/08	Mon 1/21/08	80%
25	Prototype Construction	22 days	Mon 3/10/08	Tue 4/8/08	10%
26	Prepare Presentation for DR4	3 days	Fri 3/28/08	Tue 4/1/08	0%
27	Write DR4 Document	7 days	Mon 3/24/08	Tue 4/1/08	0%
28	**Design Review #4**	**3 days**	**Tue 4/1/08**	**Thu 4/3/08**	**0%**
29	Written DR4 Report Due	1 day	Fri 4/4/08	Fri 4/4/08	0%
30	Final Preperation for Design Expo	8 days	Tue 4/1/08	Thu 4/10/08	0%
31	**Design Expo**	**1 day**	**Thu 4/10/08**	**Thu 4/10/08**	**0%**
32	**Final Report**	**1 day**	**Tue 4/15/08**	**Tue 4/15/08**	**70%**

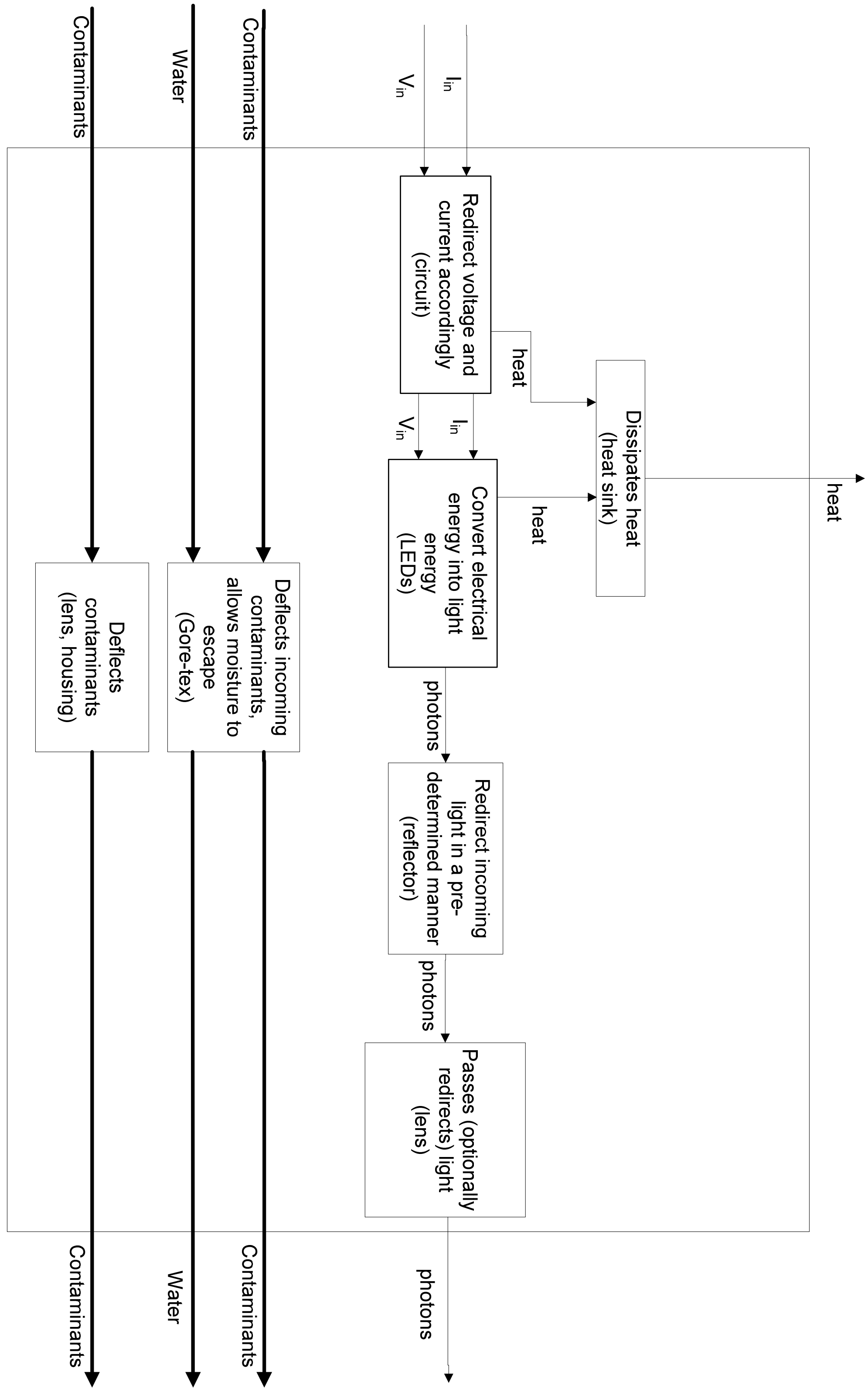


Appendix C: QFD

#	Technical Requirement		1	2	3	4	5	6	7	8
1	Luminosity Test									
2	Thermal Test		9							
3	Mass production price point			-3						
4	Diameter									
5	Depth					6				
6	Weight				6	3	3			
7	Lifetime of fog lamp			9						
8	Perceived quality									
9	Volume of fluid within housing									6

	Customer Needs	Customer Weights	Luminosity Regulations	LED Operating Temperature	Mass production price point	Diameter	Depth	Weight	Lifetime of fog lamp	Perceived quality	Volume of fluid within housing
			Technical Requirements								
1	Meets luminosity specifications	5	9	3		3	3		3		
2	Meets thermal specifications	5	3	9	3			6	3		
3	Aesthetics	5	6		6	3		3		9	
4	Increase life span of fog lamp	3		6					9		
5	Low cost	2	6	6	9	3	3	3	6	3	
6	Minimize weight	1		6		6	3	9	3		
7	Small footprint	1	3	3		9		3			
8	Allow humidity to escape inside of housing	3								6	9
9	Prevents contaminants from entering housing	3								6	9
	Raw score		105	99	63	51	24	63	72	87	54
	Scaled		1	0.943	0.6	0.486	0.229	0.6	0.686	0.829	0.514
	Relative Weight		17%	16%	10%	8%	4%	10%	12%	14%	9%
	Rank		1	2	5	8	9	5	4	3	7
	Technical Requirement Units		cd	°C	$/unit	mm	mm	g	hr	N/A	mL
	Technical Requirement Targets		see Table 2 on pg. 3	25	13.50	100	60	82	10,000	4	0
	Technical Requirement USL			85		140	100	340			2
	Technical Requirement LSL			-40							

Appendix D: Functional Decompositions



Appendix E: Test Specifications

Test	Description	Documentation
Abrasion	Lens rubbed in 20 cycles, and then checked if fog lamp still meets optical requirements.	SAEJ575, SAEJ1383, SAEJ2139, ECER19
Aiming	Meet aiming requirements including ± 5 ˚ in vertical and ± 2.5 ˚	SAEJ599, SAEJ1383, SAEJ2445, ECER19
Chemical corrosion	Windshield washer fluid, anti freeze, and gasoline wiped on lens in separate tests and left for 48 hours.	SAEJ575, SAEJ1383,SAEJ2139, ECER19
Color Band	Light emitted from fog lamp must fall within specified white region of color chart.	SAEJ575, SAEJ1383,SAEJ2139, ECER19
Dust	Fog lamp bombarded with dust in cycles for five hours, no dust must be inside, or light intensity cannot decrease by more than 10%.	SAEJ575, SAEJ1383,SAEJ2139
Humidity	Eight hour test at 35 ˚C and at least 95% humidity.	SAEJ575, SAEJ1383, SAEJ1455, SAEJ2139, ECER19
Impact	Lens hit with 23 mm diameter steel sphere (50g) dropped from 20 cm.	SAEJ575, SAEJ1383, SAEJ2139, ECER19
Internal heat	Lens coated with cement like material and fog lamp run for one hour	SAEJ575, SAEJ1383, SAEJ2139, ECER19
Labeling	Labeling of fog lamp specified.	SAEJ759, ECER19
Optical	Luminosity requirements for different points and lines measured from the horizontal and vertical axis.	SAEJ575, SAEJ1383, SAEJ2139, ECER19
Peel	The force required to remove tape from the lens is recorded.	ECER19
Salt Spray	Fog lamp sprayed for 240 hours with salt water, must still meet photometric requirements, and have less than 20% degradation in photometric test.	SAEJ575, SAEJ1383, SAEJ2139
Spray	Fog lamp sprayed for 12 hours with water, must have no less than 2 ml of water for a fog lamp with an interior volume<7000 ml.	SAEJ575, SAEJ1383, SAEJ2139, ECER19
Submersion	Fog lamp submerged, must not bubble, leak water, or have standing pools in fog lamp after the test.	SAEJ575, SAEJ1383, SAEJ2139
Thermal Cycle	Fog lamp runs for ten 8 hour thermal cycles ranging from -40 ˚C to 50 ˚C	SAEJ575, SAEJ1383,SAEJ1889, SAEJ2139
Vibration	Six hour test going from 10 Hz to 250 Hz with specified power density curve.	SAEJ577,SAEJ575, SAEJ1383, SAEJ2139, ECER19
Voltage	Transient voltage tested and polar reversal.	SAEJ573, SAEJ2560 or ECER37

Warpage	Fog lamp run for one hour at 25˚ C ambient temperature and must show no visible damage and meet luminosity requirements.	SAEJ575, SAEJ1383, SAEJ2139, ECER19
Inward Force	Aiming adjusters subject to a 222 N inward force.	SAEJ575, SAEJ1383, ECER19
Torque Deflection	222 N is parallel to the aiming reference plan and downward.	SAEJ575, SAEJ1383, ECER19
Adherence of Coatings	The reflector is scratched and then is taped. When the taped is removed, the luminosity cannot change by more than 30%.	ECER19

Appendix F: Advantages and disadvantages of the final eight design concepts based on hidden and direct LED lighting

Design	Advantage(s)	Disadvantage(s)
(#1) Mystery	*Unique look *Light sources not visible *Easier/cheaper to manufacture than other design with high aesthetics scores	*Meeting luminosity requirements may prove difficult
(#2) The Trifecta	*Pleasing to the eye *Does not sit deeply in the fascia	*High cost *Difficult/time consuming to manufacture
(#3) The Cutest Button	*Very compact size *Relatively cheap/easy to manufacture	*Difficult to meet luminosity requirements *Looks bland
(#4) The Points ver.2	*Does not sit deeply in the fascia *Relatively cheap/easy to manufacture	*Looks cheap *Visible light sources
(#5) The Cat Eye ver.2	*Intense, sleek look *Light sources not visible	*Costly *Difficult and time consuming to manufacture *Large weight *Difficult to meet luminosity requirements
(#6) The Vortex	*Fierce look *Light sources not visible	*Very costly *Large weight *Difficult/time consuming to manufacture *Difficult to meet luminosity requirements
(#7) The Periscope	*Light sources not visible	*Looks boring *Takes up more space behind the fascia
(#8) The Desert Sun	*Unique accent lighting draws attention	*Costly *Difficult/time consuming to manufacture

Appendix G: 1st Generation Concept Designs

Fog Lamp Lighting Methods

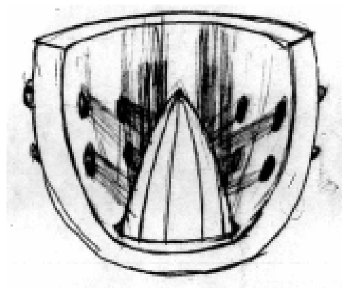


Figure G.1: "The Riddled"
Flush LEDs into housing, parabolic cone-based reflector

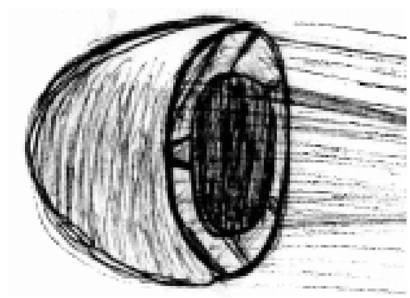


Figure G.2: "The Eclipse"
Hide LEDs behind planar surface, use reflector to emit light through opening between the planar surface and housing

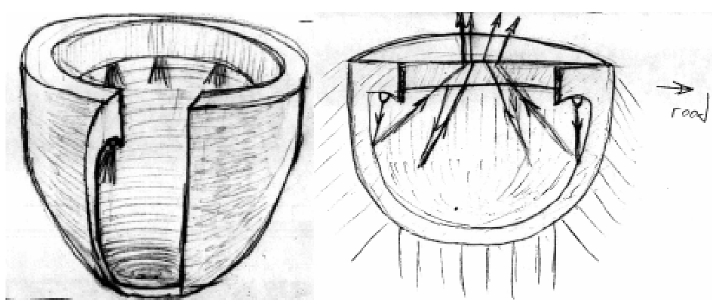


Figure G.3: "The Mystery"
Hide LEDs behind housing lip, use reflector to aim more of the redirected light towards the road than upward

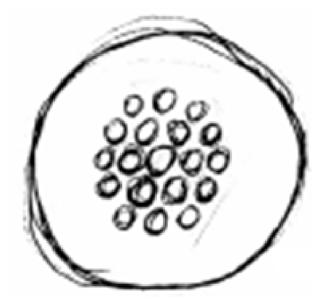


Figure G.4: “The Points”
Use a certain number of individually aimed LEDs in a certain geometrical distribution mounted on a planar surface; no reflector is used

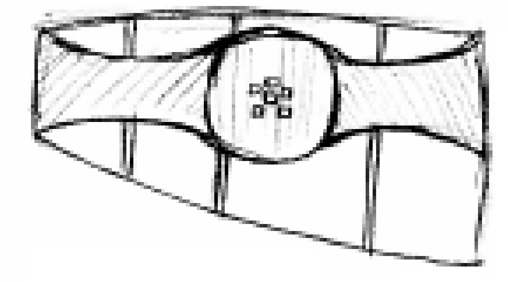


Figure G.5: “The Glow”
Use a certain number of individually aimed LEDs in a certain geometrical distribution mounted on a planar surface. Use a single LED mounted on the back of the planar surface and aimed towards the back at a reflector to provide accent illumination.

Fog Lamp Profiles

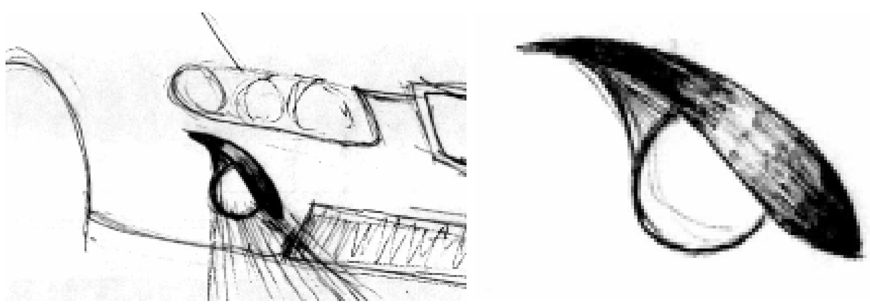


Figure G.6: “The Glare”
Circular lens with a differently colored fascia overhang

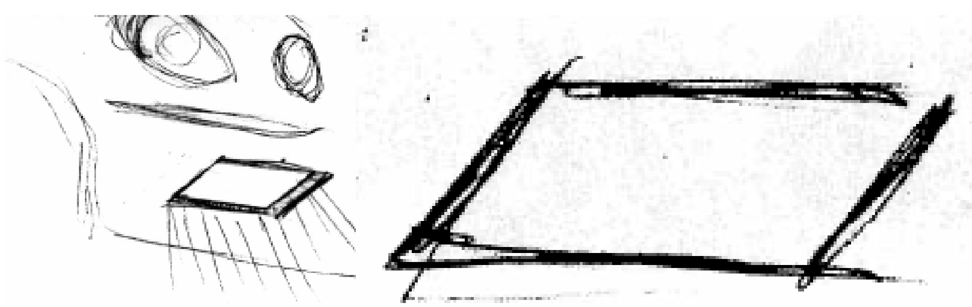


Figure G.7: “The Skew”
A parallelogram shaped lens slightly flushed into the fascia

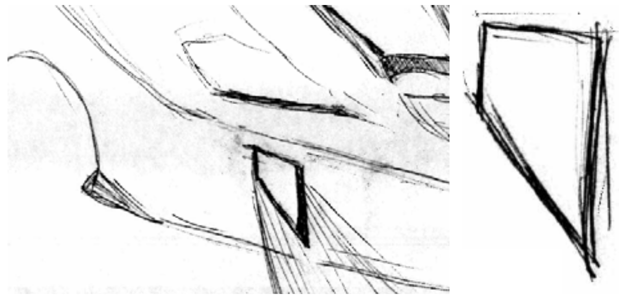


Figure G.8: “The Fang”
A trapezoidal lense with a sharp bottom corner slightily flushed into the fascia

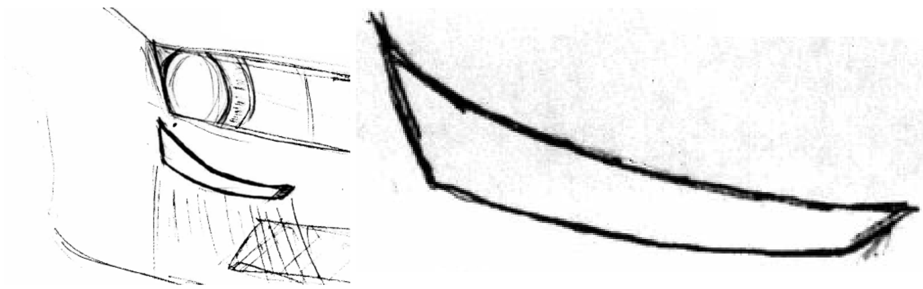


Figure G.9: “The Cut”
A narrow lens with sharp corners slighily flushed into the fascia

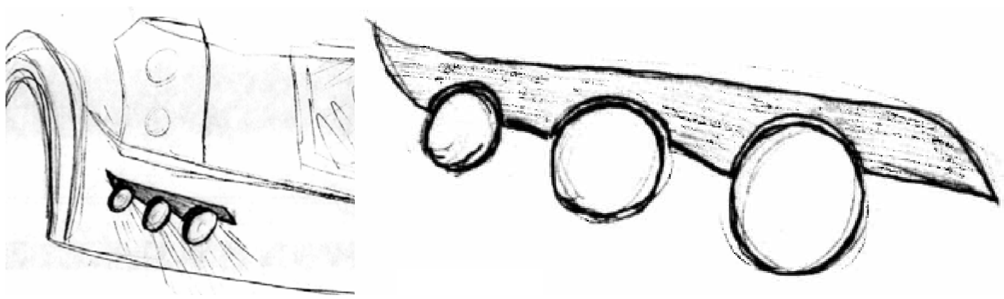


Figure G.10: “The Triple Eye”
Three circular lenses of progressively shrinking size with a strip for accent above

Figure G.11: “The Peek”
A three cornered lens covering a deep recess containing two short semi circular prisms which emit light

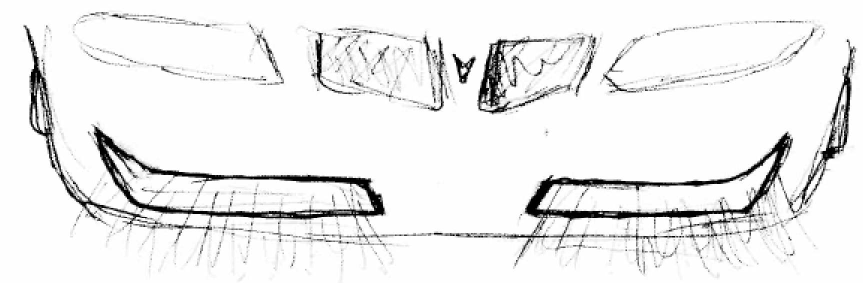


Figure G.12: “The Villain’s Mustache”
A very wide irregular shaped four cornered lens

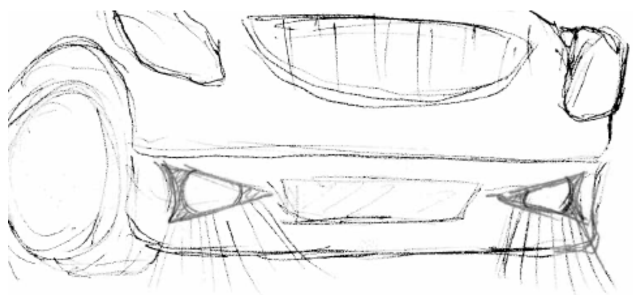


Figure G.13: “The Opposing Arrows”
A circular lens partially covered up set in a triangular fascia flush

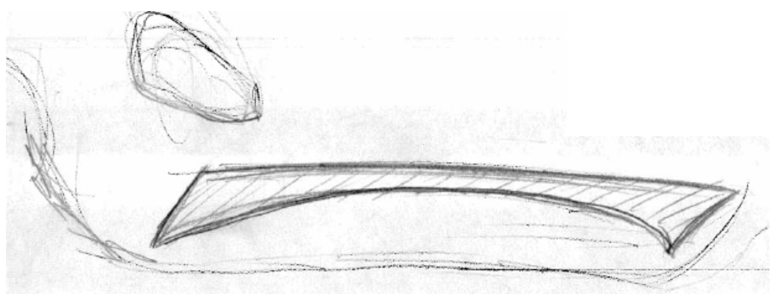


Figure G.14: “The Vampire”
A long single lens spanning the width of the car with sharp ends

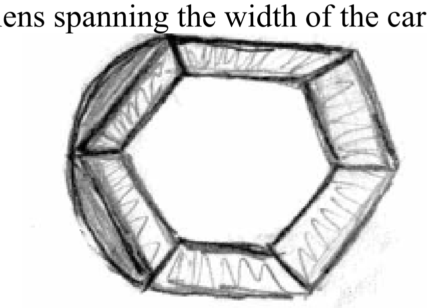


Figure G.15: “The Girl’s Best Friend”
A flat hexagonal lens flushed into the fascia; the fascia itself prvides an accent

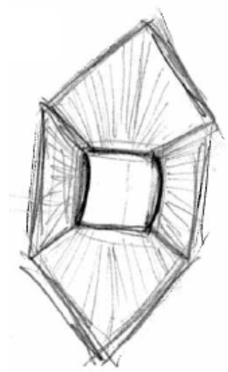


Figure G.16: “The Girl’s Best Friend ver.2”
A square lens flushed into the fascia; the fascia itself provides an accent

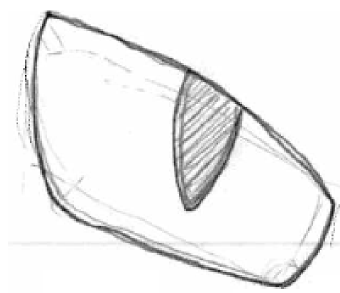


Figure G.17: “The Cat Eye”
An irregualr shaped lens covering a narrow strip placed in front of a reflector

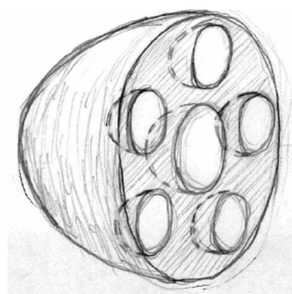


Figure G.18: “The Fiver”
A lens covering five parabolic recesses with a light source in each

Appendix H: 2nd Generation Concept Designs with Hidden LED Lighting Method

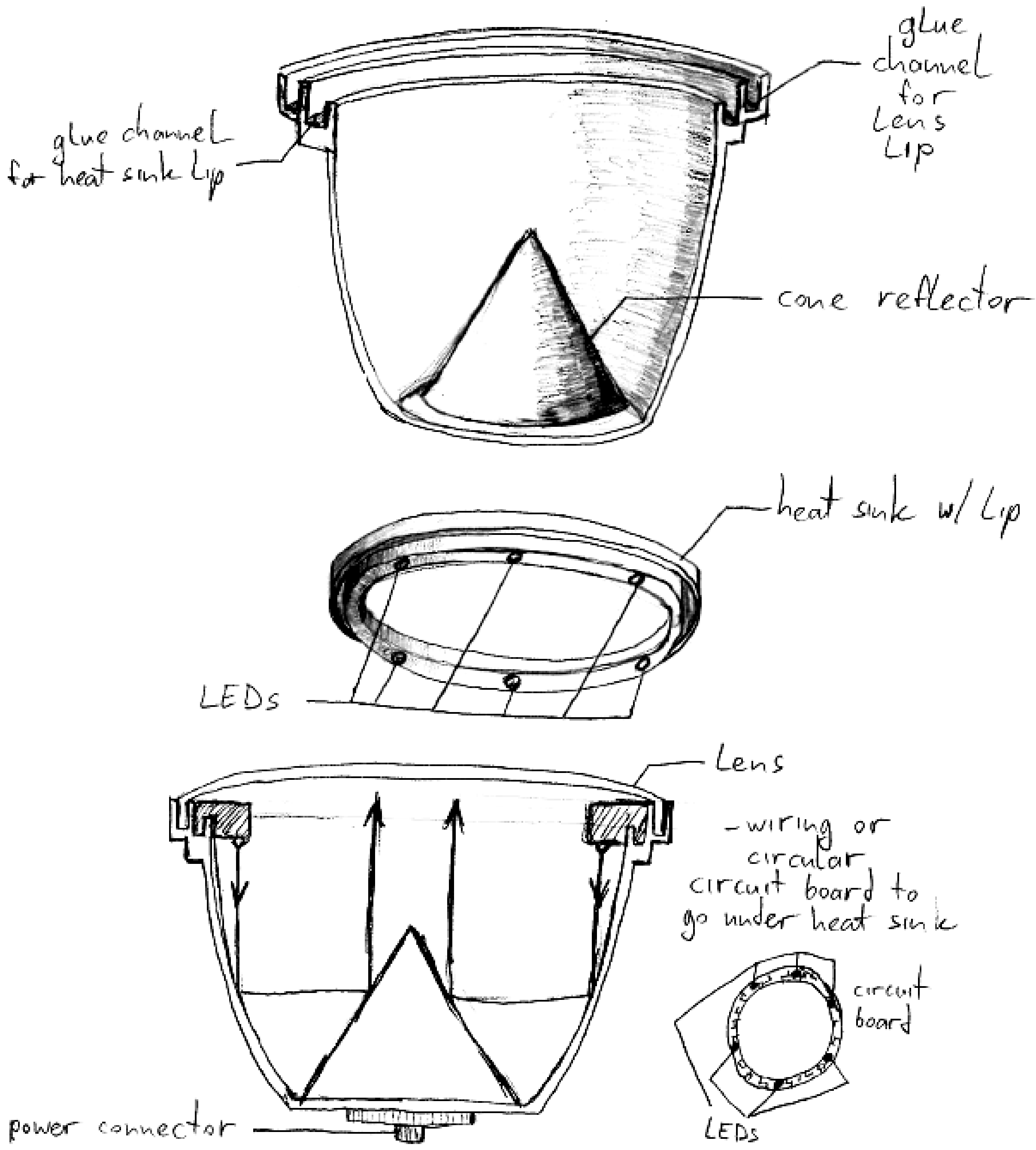


Figure H.1: Design 1, “The Mystery ver.2” or simply “Mystery” (chosen design)

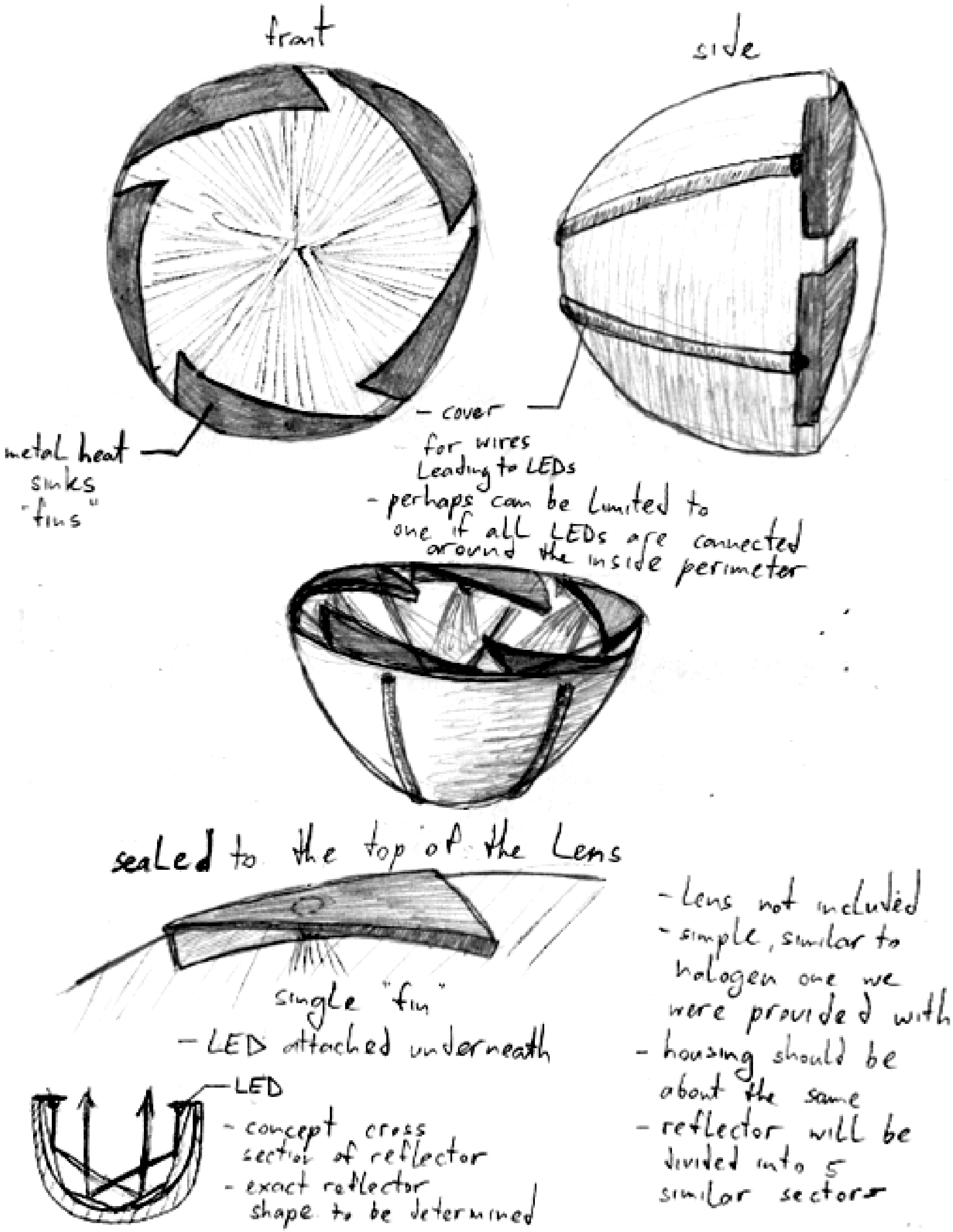


Figure H.2: Design 2, "The Vortex"

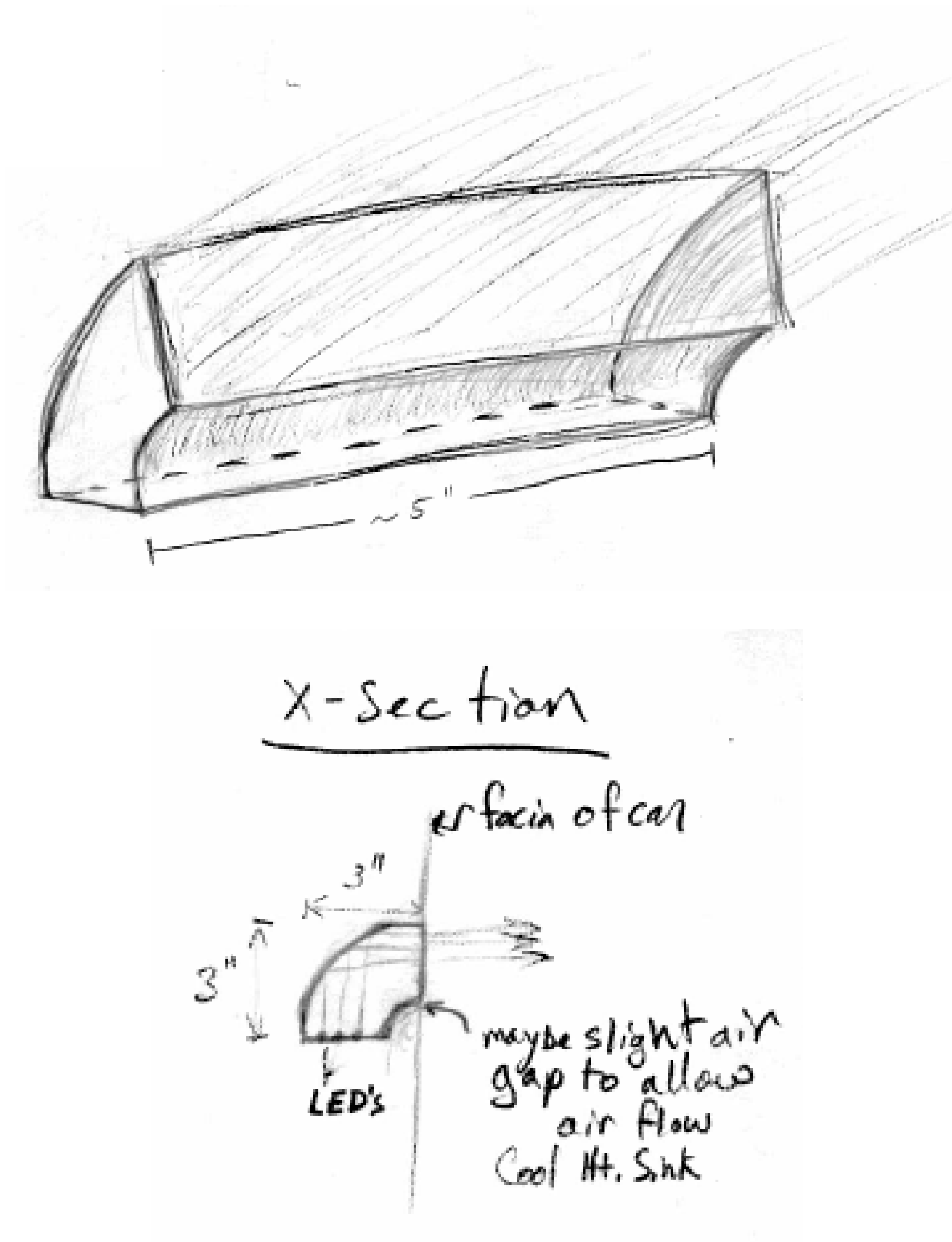


Figure H.3: Design 3, "The Periscope"

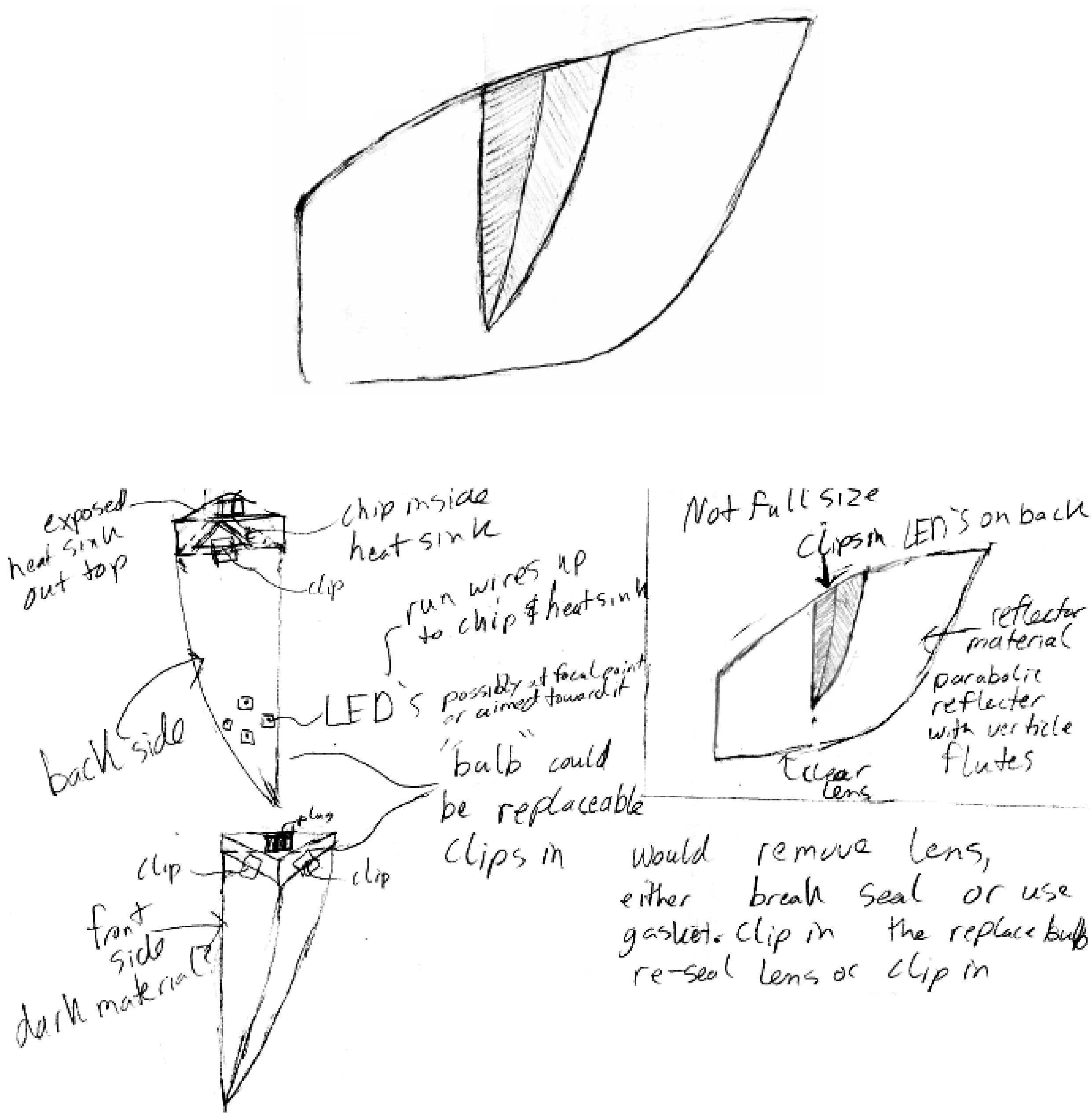


Figure H.4: Design Method 4, “The Cat Eye ver.2”

Appendix I: 2nd Generation Concept Designs Incorporating Direct Lighting

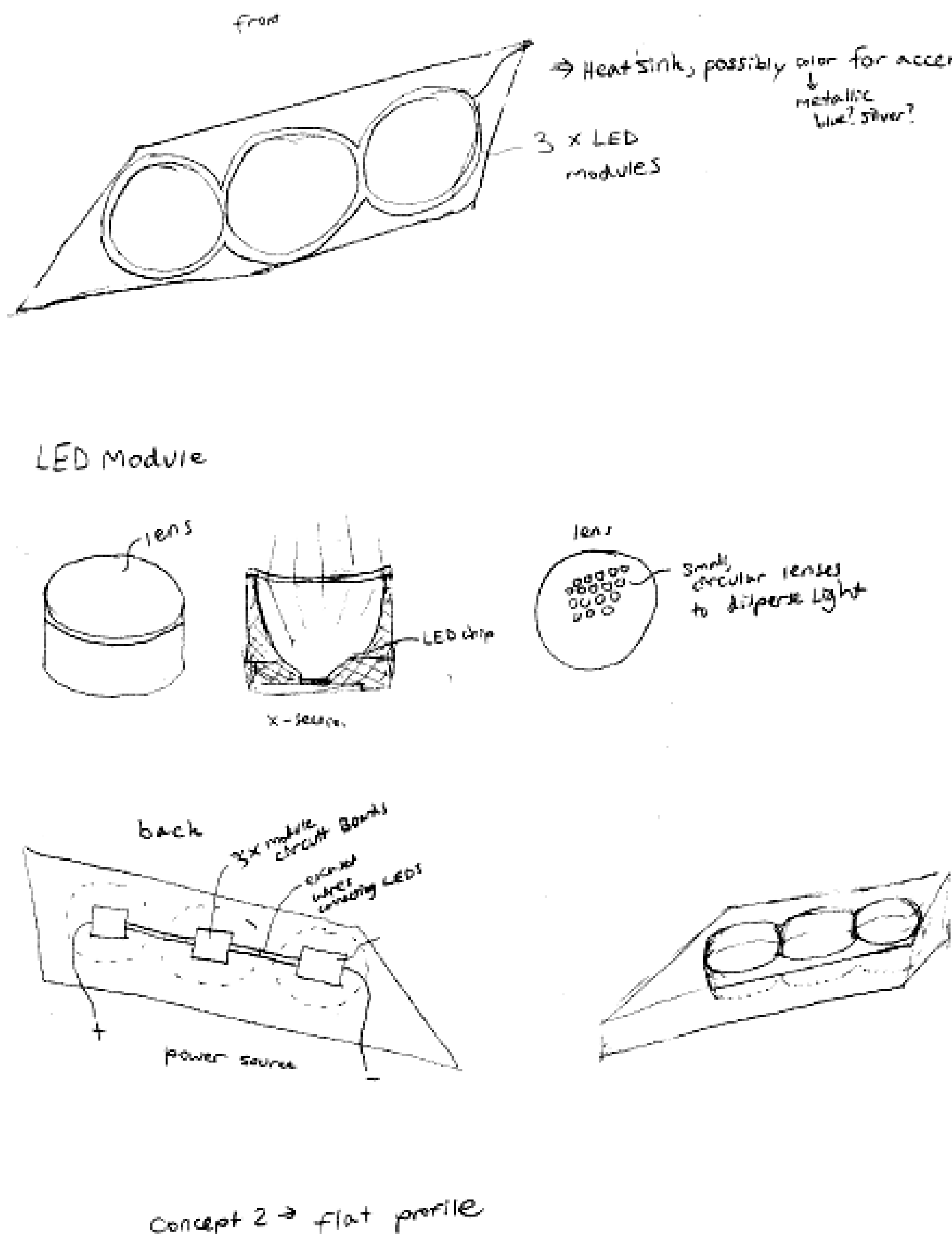


Figure I.1: Direct Lighting Method 5, "The Trifecta"

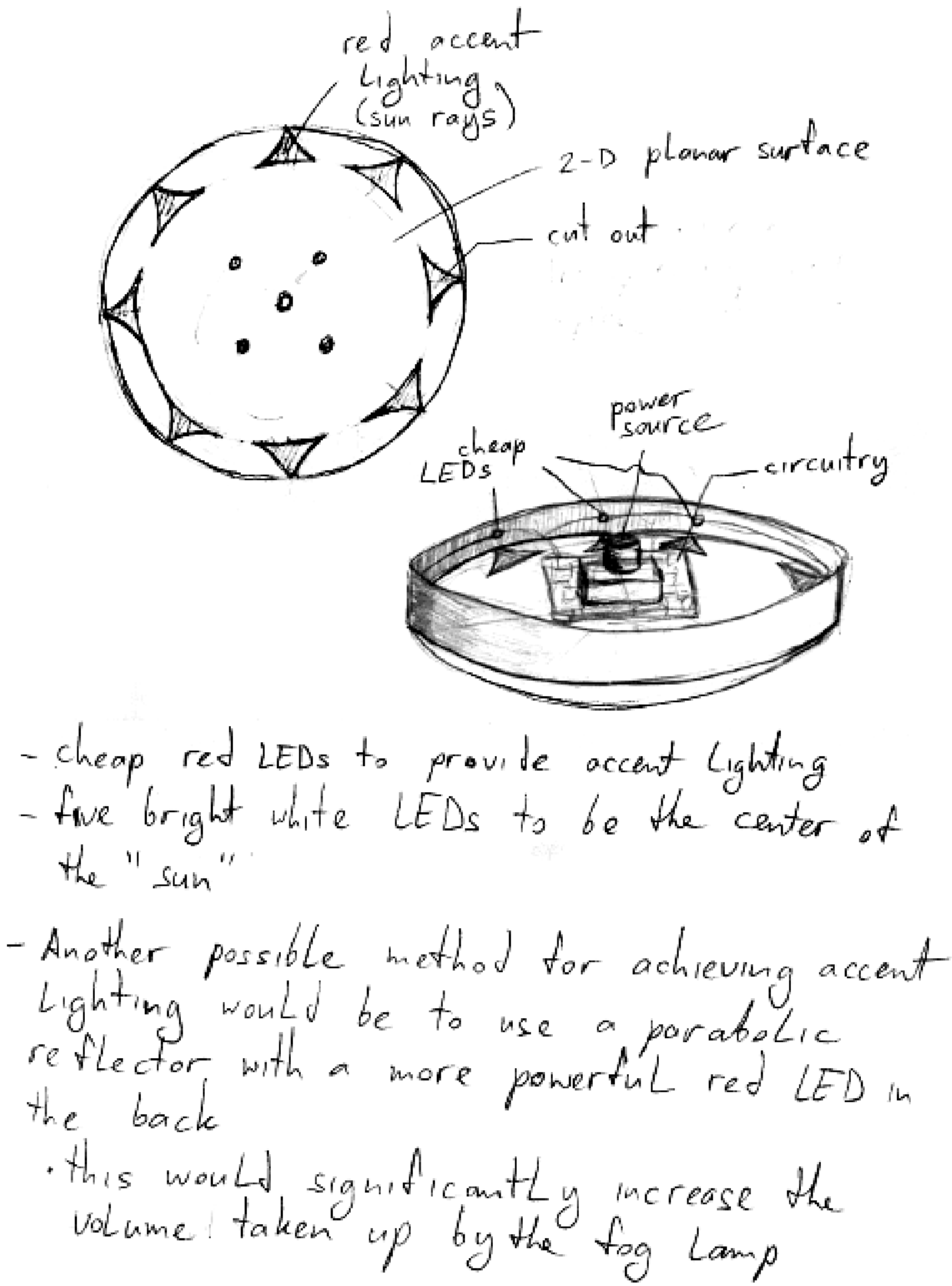


Figure I.2: Direct Lighting Method 6, “The Desert Sun”

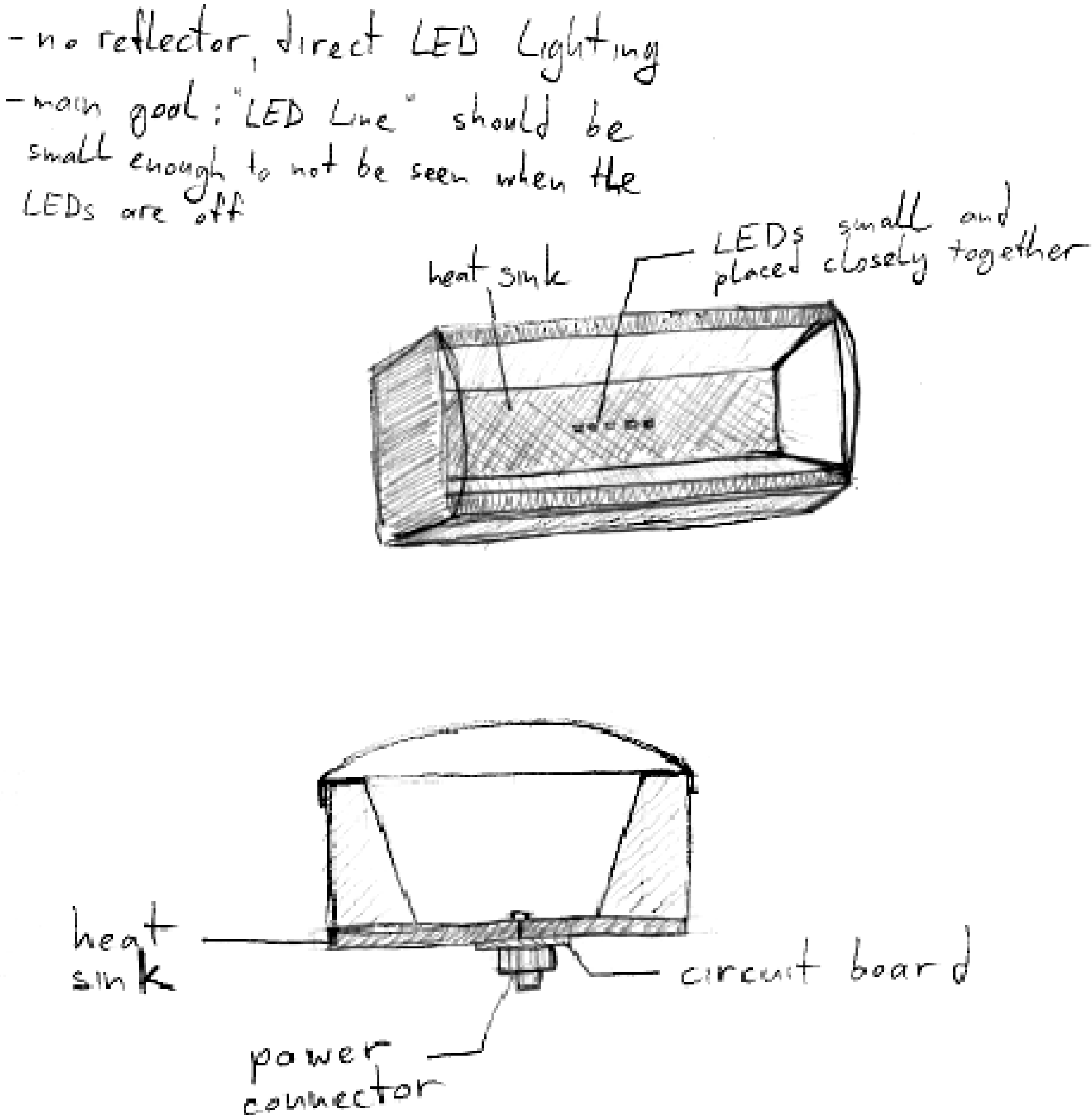


Figure I.3: Direct Lighting Method 7, "The Cutest Button"

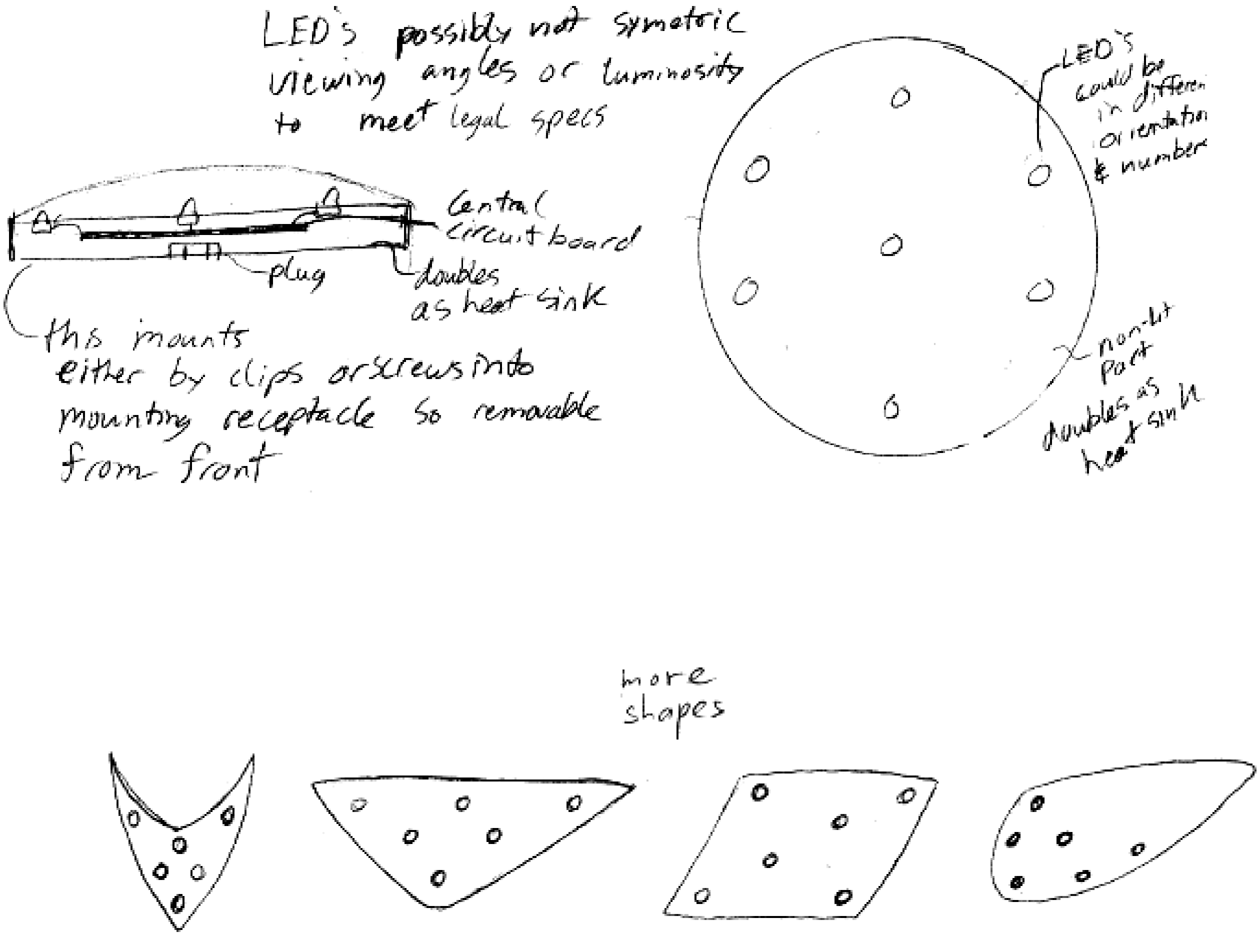
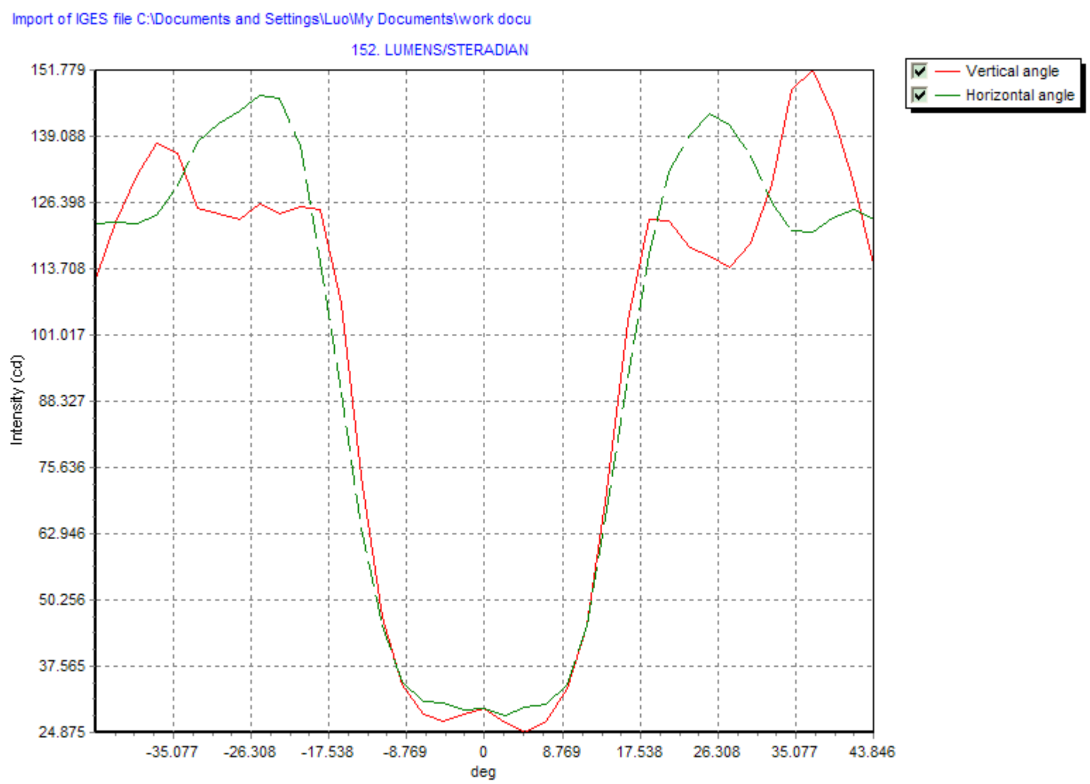


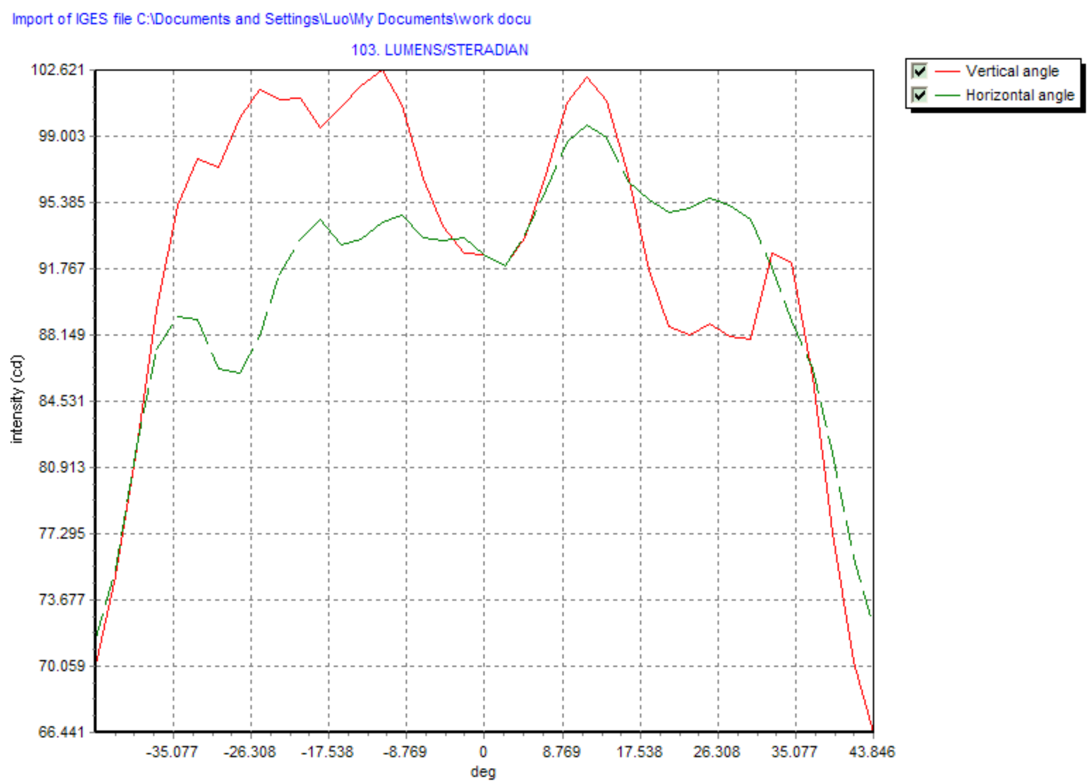
Figure I.4: Direct Lighting Method 8, “The Points ver.2”

Appendix J: Alpha Design Simulation Results



	Lateral angles							
		15 L	9 L	3L	0	3R	9R	15R
VERTICAL ANGLES	10 U	<125	<125	<125	<125	<125	<125	<125
		114	67	39	37	38	65	108
	2U	<240	<240	<240	<240	<240	<240	<240
		89	32	26	28	26	31	88
	1U	<360	<360	<360	<360	<360	<360	<360
		89	32	27	29	26	32	89
	H	<480	<480	<480	<480	<480	<480	<480
		90	33	27	29	26	32	87
	1.5D		>1000	2000/10000		2000/10000	>1000	
			35	26		26	32	
	3D	>1000						>1000
		94						89

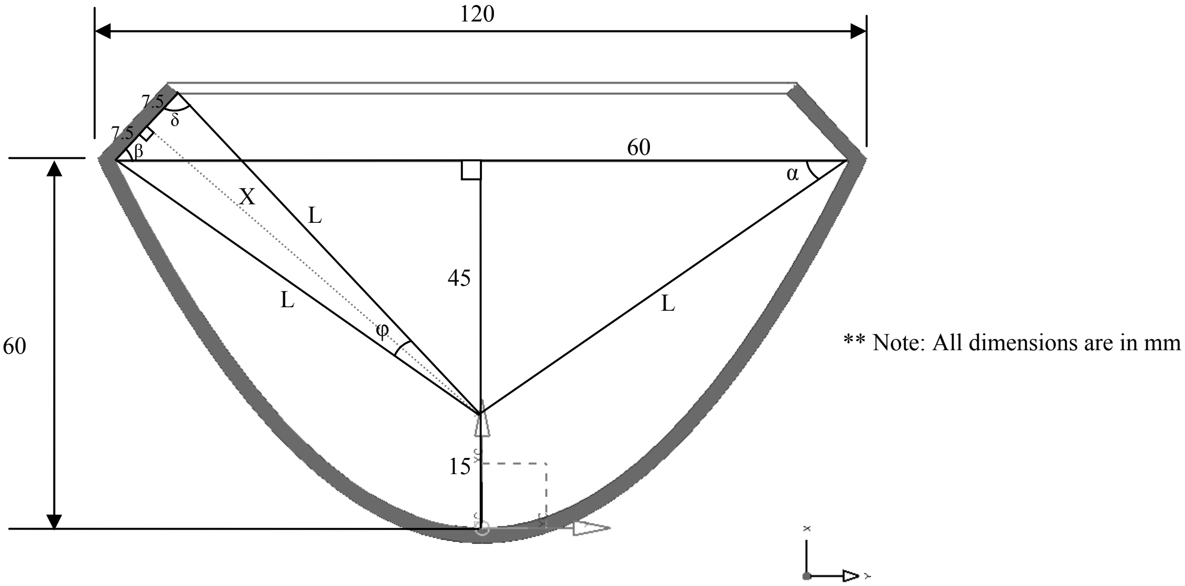
Appendix K: Modification 1 Simulation results



	Lateral angles							
		15 L	9 L	3L	0	3R	9R	15R
VERTICAL ANGLES	10 U	<125	<125	<125	<125	<125	<125	<125
		105	102	98	99	97	102	99
	2U	<240	<240	<240	<240	<240	<240	<240
		99	101	92	91	92	101	98
	1U	<360	<360	<360	<360	<360	<360	<360
		100	100	92	92	92	100	98
	H	<480	<480	<480	<480	<480	<480	<480
		101	100	93	92	92	100	98
	1.5D		>1000	2000/10000		2000/10000	>1000	
			100	92		92	101	
	3D	>1000						>1000
		102						99

Appendix L: Modification 2 Calculations

The figure below illustrates the lengths and angles used in calculations to determine the mounting angle of the LEDs.



Pythagorean Theorem:

$$L^2 = 60^2 + 45^2$$
$$L = 75$$

Trigonometric Identities:

$$\tan(\alpha) = \frac{45}{60}$$
$$\text{»}\ \alpha = 36.9°$$

$$\sin\left(\frac{\phi}{2}\right) = \frac{7.5}{75}$$
$$\text{»}\ \phi = 11.5°$$

Symmetric Triangle:

$$180° = 2\delta + \phi = 2\delta + 11.5°$$
$$\text{»}\ \delta = 84.3°$$

Definition:

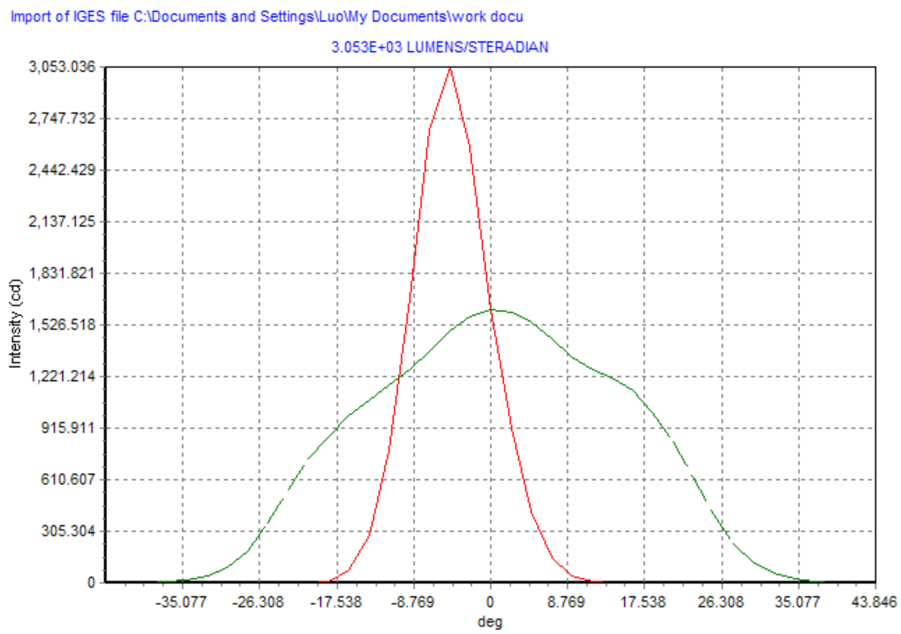
$$\beta = \delta - \alpha = 84.3° - 36.9° = 47.4° \approx 47°$$

Thus, the mounting angle is approximately 47° above the horizontal.

Appendix M: Modification 2 Simulation Results

Not Completed

Appendix N: Modification 3 Simulation Results



		Lateral angles						
		15 L	9 L	3L	0	3R	9R	15R
VERTICAL ANGLES	10 U	<125	<125	<125	<125	<125	<125	<125
		5	17	28	29	28	16	7
	2U	<240	<240	<240	<240	<240	<240	<240
		509	691	939	1010	1018	825	628
	1U	<360	<360	<360	<360	<360	<360	<360
		772	981	1246	1314	1301	1086	901
	H	<480	<480	<480	<480	<480	<480	<480
		1036	1271	1552	1618	1585	1347	1174
	1.5D		>1000	2000/10000		2000/10000	>1000	
			2003	2251		2081	1786	
	3D	>1000						>1000
		2329						2086

Appendix O: Fog Lamp Axis Angle MATLAB Code

```
D=110; %Diameter of overall lamp in mm
Ds=47.5; %Diameter of small lamps in mm
Db=10; %Diameter of "bulb" in middle
Dbot=14.4; %Distance of lower foci to center of overall lamp
M=10; %Distance light measured in m
M=M*1000; %Convert to mm
HotAng=-2.5; % Hot Spot Angle degrees
HotAng=HotAng/180*pi; %Rads

HotY=M*tan(HotAng); %Distance down from horizontal for hot spot

TopAng=atan(-(Ds/2+Db/2-HotY)/M);%Angle of top parabola in rads
TopAng=TopAng/pi*180 %Conversion to degrees

BottomAng=atan((HotY+Dbot)/M); %Angle of bottom parabola in rads
BottomAng=BottomAng/pi*180 %Conversion to degrees
```

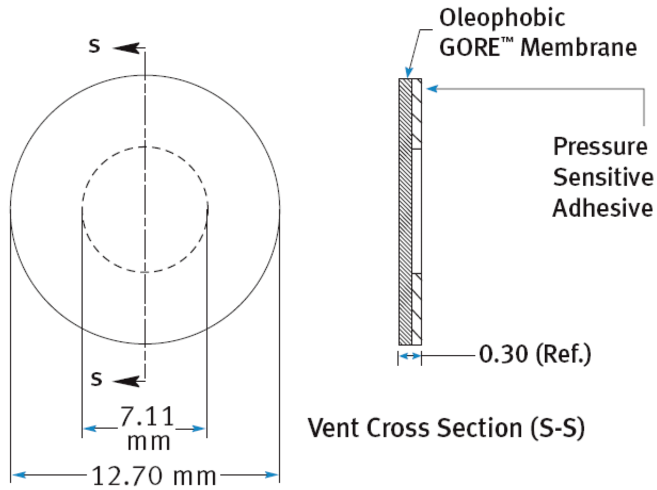
Appendix P: Vertical Fluting MATLAB Code

```
hold off
clear
% Defined as center of base as (0,0)
% Inputs
R=47.5/2; % Radius of parabola in mm
N=4; % Number of flutes
FullAng=179; %Viewing Angle of LED in degrees
F=11.875; %Focal length in mm

%%%% x Matrix%%%%%%%%%%%%
S=R/N; % Segment length of fluets in x direction
x=0:S:R;%Matrix of x coordinates start and finally end of each segment

%%%%%%%%%% Makes matrices of midpoint x & y values%%%%%%%%%%%
i=1;
% Ang(1)=0;
while i<(N+1)
    Mx(i)=(x(i)+x(i+1))/2;
    My(i)=1./(2*R)*Mx(i).^2; %Matrix of corrsponding midnpoint y values
    Ang(i)=atan(Mx(i)./(F-My(i)));
    i=i+1;
end

%%%%%%%%%%%%HotAng Calculation with shift%%%%%%%%%%%%%%%%
D=105; %Diameter of overall lamp in mm
Ds=2*R; %Diameter of small lamps in mm
Db=10; %Diameter of "bulb" in middle
% Dbot=14.4; %Distance of lower foci to center of overall lamp
M=10; %Distance light measured in m
M=M*1000; %Convert to mm
HotAng=[5 0 10 20]; %Desired angle from vertical in degrees
HotAng=HotAng./180*pi; %Rads

HotX=M*tan(HotAng); %Distance down from horizontal for hot spot
V=HotX-Mx;
T=M+F-My;
HotAng=atan(V./T);

%%%%%%%%Conversions and calculations%%%%%%%%%%%%%%%%%%%%%%%%%%

I=Ang./2-HotAng./2; %Angle from horizontal of "parabola" in rads

y(1)=0;

%Makes graphable matrix and plot it
hold
i=1;
q=0;
r=0;
slope=tan(I);
while i<(N+1)
    xLine(i,:)=x(i):.01:x(i+1);
    [xRow,xCol]=size(xLine);
    yLine(i,:)=slope(i).*(xLine(i,:)-r(i))+q(i);
    [yRow,yCol]=size(yLine);
    plot(xLine(i,:),yLine(i,:))
```

```
    q(i+1)=yLine(i,yCol);
    r(i+1)=xLine(i,xCol);
    i=i+1;
end

I=I./pi.*180; %Angle from horizontal of "parabola" in degrees
c=0:.1:R;
z=1./(2*R)*c.^2;
plot(c,z,'r')
xlabel('r')
ylabel('q')
axis equal

hold off
clear
% Defined as center of base as (0,0)
% Inputs
R=47.5/2; % Radius of parabola in mm
N=4; % Number of flutes
FullAng=179; %Viewing Angle of LED in degrees
F=11.875; %Focal length in mm

%%%% x Matrix%%%%%%%%%%%%
S=R/N; % Segment length of fluets in x direction
x=0:S:R;%Matrix of x coordinates start and finally end of each segment

%%%%%%%%%% Makes matrices of midpoint x & y values%%%%%%%%%%%
i=1;

while i<(N+1)
    Mx(i)=(x(i)+x(i+1))/2;
    My(i)=1./(2*R)*Mx(i).^2; %Matrix of corrsponding midnpoint y values
    Ang(i)=atan(Mx(i)./(F-My(i)));
    i=i+1;
end

%%%%%%%%%%%%HotAng Calculation with shift%%%%%%%%%%%%%%%%
D=105; %Diameter of overall lamp in mm
Ds=2*R; %Diameter of small lamps in mm
Db=10; %Diameter of "bulb" in middle
Dbot=24.9; %Distance of foci to center of overall lamp
M=10; %Distance light measured in m
M=M*1000; %Convert to mm
HotAng=[5 0 10 20]; %Desired angle from vertical in degrees
HotAng=HotAng./180*pi; %Rads

HotX=M*tan(HotAng); %Distance down from horizontal for hot spot
V=HotX-Mx-Dbot;
T=M+F-My;
HotAng=atan(V./T);

%%%%%%%%Conversions and calculations%%%%%%%%%%%%%%%%%%%%%%%%%%%

I=Ang./2-HotAng./2; %Angle from horizontal of "parabola" in rads

y(1)=0;
```

```
%Makes graphable matrix and plot it
hold
i=1;
q=0;
r=0;
slope=tan(I);
while i<(N+1)
    xLine(i,:)=x(i):.01:x(i+1);
    [xRow,xCol]=size(xLine);
    yLine(i,:)=slope(i).*(xLine(i,:)-r(i))+q(i);
    [yRow,yCol]=size(yLine);
    plot(xLine(i,:),yLine(i,:))
    q(i+1)=yLine(i,yCol);
    r(i+1)=xLine(i,xCol);
    i=i+1;
end

I=I./pi.*180; %Angle from horizontal of "parabola" in degrees
c=0:.1:R;
z=1./(2*R)*c.^2;
plot(c,z,'r')
xlabel('r')
ylabel('q')
axis equal
```

Appendix Q: GORE-TEX® Patch Dimensions



Appendix R: Thermal Calculations

$$\overline{N_u} = 0.54 * R_a^{\frac{1}{4}} \qquad \text{(Hot Plate Top Nusselt Number)} \qquad \text{R.1}$$

$$\overline{N_u} = 0.27 * R_a^{\frac{1}{4}} \qquad \text{(Hot Plate Bottom Nusselt Number)} \qquad \text{R.2}$$

$$\overline{N_u} = 0.68 * \frac{0.67 * R_a^{\frac{1}{4}}}{(1 + (\frac{0.492}{\Pr})^{\frac{9}{16}})^{\frac{4}{9}}} \qquad \text{(Hot Plate Sides Nusselt Number)} \qquad \text{R.3}$$

Where,

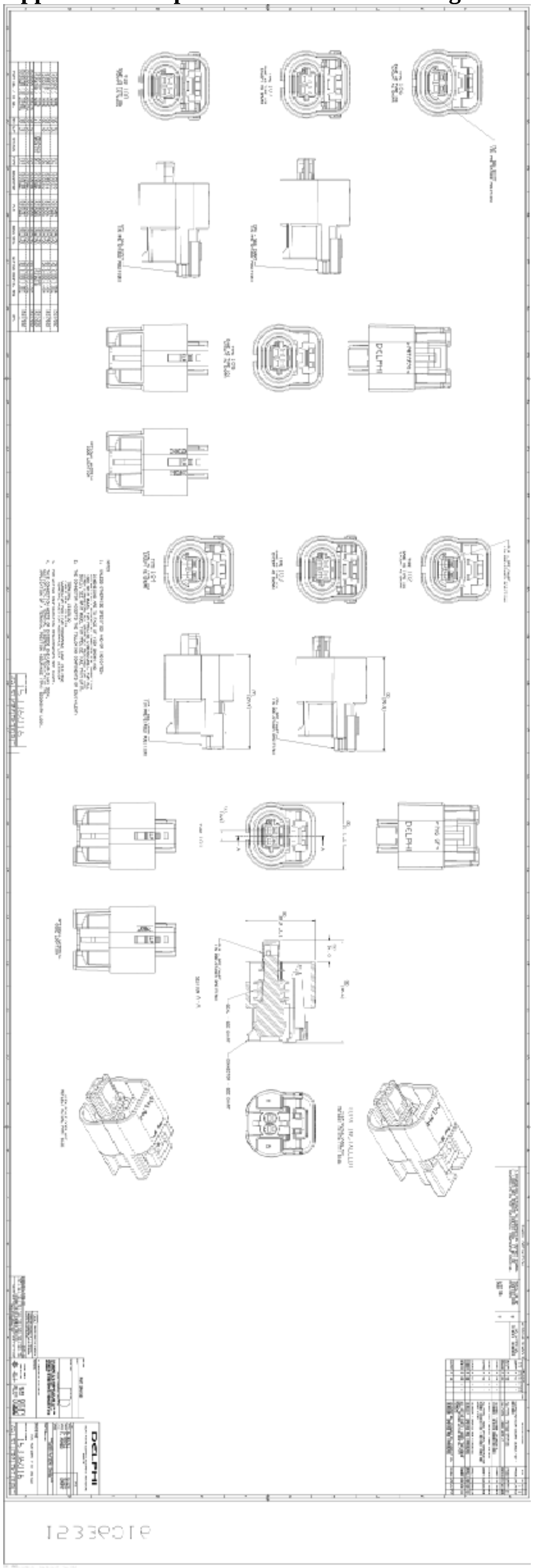
$$\bar{h} = \frac{\overline{N_u} * k}{L} \qquad \text{(Convective Heat Transfer Coefficient)} \qquad \text{R.4}$$

$$R_a = \frac{g * \beta * (T_s - T_\infty) * L^3}{\nu * \alpha} \qquad \text{(Raleigh Number)} \qquad \text{R.5}$$

$$\Pr = \frac{\nu}{\alpha} \qquad \text{(Prandtl Number)} \qquad \text{R.6}$$

$$\beta = \frac{1}{T_\infty} \qquad \text{(Beta)} \qquad \text{R.7}$$

Appendix S: Delphi USCAR Connector Engineering Drawing



Appendix T: Heat Sink Thermocouple Testing results

Voltage (V)	Current (A)	T1 (peg, C)	T2 (LED, C)	Time (min)
9	0.25	31	38	0
9	0.293	38	45	1
9	0.32	42	51	2
9	0.35	47	56	3
9	0.382	52	62	4
9	0.414	56	68	5
9	0.435	59	72	6
9	0.461	63	76	7

Appendix U: Thermal Redesign Calculations
[38]

$$Nu = \left[\frac{C_1}{(Ra * S/L)^2} + \frac{C_2}{(Ra * S/L)^{1/2}} \right]$$ (Parallel Vertical Plate Nusselt Number) Eq. U1

Where; C1=576, C2=2.87, S= fin spacing

$$Ra = \frac{g\beta(T_s - T_\infty)S^3}{\alpha\nu}$$ Eq. U2

$$Ra = \frac{g\beta(T_s - T_\infty)S^3}{\alpha\nu}$$ (Raleigh Number) Eq. U3

$$\bar{h} = \frac{\overline{N}_u * k}{S}$$ (Convective Heat Transfer Coefficient) Eq. U4

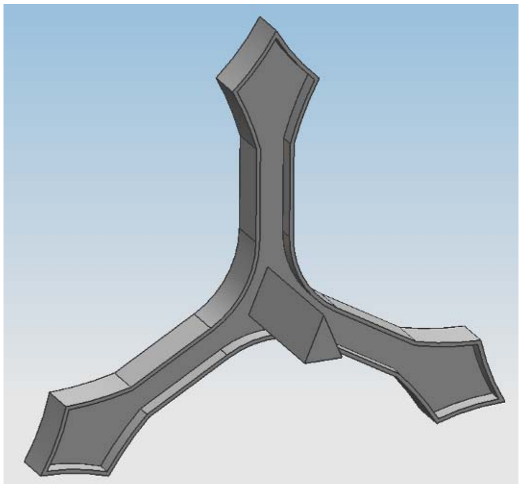
$$\beta = \frac{1}{T_\infty}$$ (Beta) Eq. U5

Appendix V: Bill of Materials

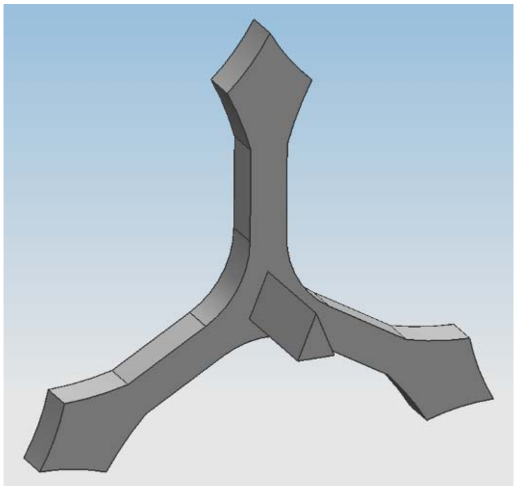
Item	Quantity	Source	Catalog Number	Cost ($)	Contact	Notes
LED	3	OSRAM	LW W5AP-LZMZ-5K8L	Donated	Mike Mott	
Lens	1	GM	SLA Part	Donated	Matt Monden	
Housing	1	GM	SLA Part	Donated	Matt Monden	
Aluminized Reflector	1	GM	Prototype Coating	Donated	Matt Monden	
28 Gauge Wire	2 feet	OSRAM	N/A	Donated	Joe Jablonski	
6061-T6 Aluminum 3”x3”x1” block	2	Arlo Metals Plus	6061-T6511	25.08	734-213-2727	Used for heat sink
Atlas Camel Bush	1	Rider's Hobby Shop	No. 32	0.99	734-971-6116	Used to paint wires
Model Master Silver Chrome Paint	1	Rider's Hobby Shop	2734	5.49	734-971-6116	Used to paint wires
Thermal Adhesive	<1	OSRAM	N/A	Donated	Joe Jablonski	
Solder	<1	OSRAM	N/A	Donated	Joe Jablonski	

Engineer Change Notice

WAS:



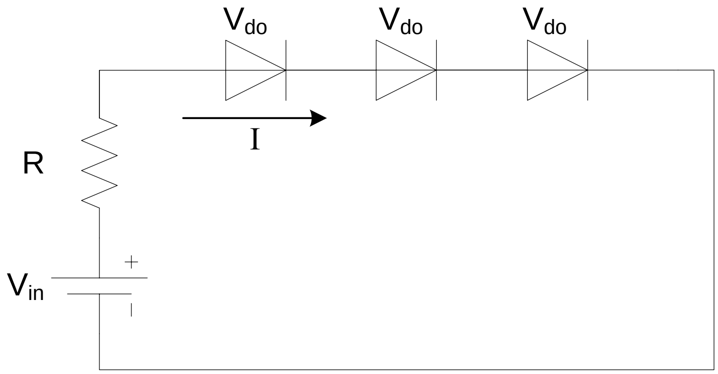
IS:



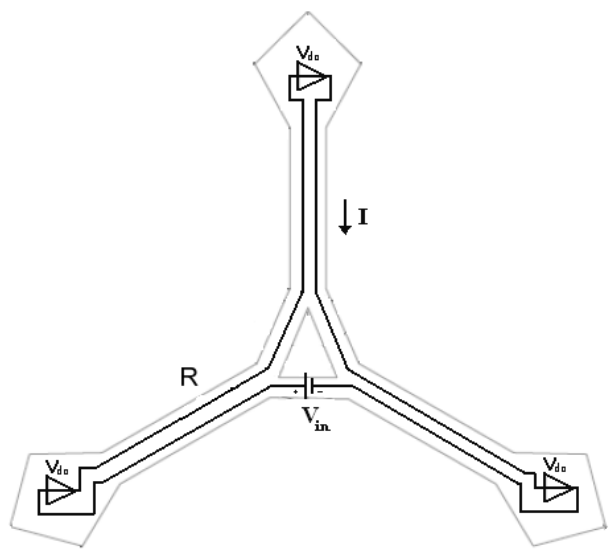
Note: Filled in circuit board cavity on heat sink because it was because it was unfeasible to make using the machine shop CNC mill. The fillets created by the mill bit would have made it so the LEDs could not fit.

Team 11	
Project: LED Fog Lamp	
Part Purpose: Prototype	
Engineer: Jessica Katterheinrich	3/27/2008

WAS: Circuit board under heat sink.



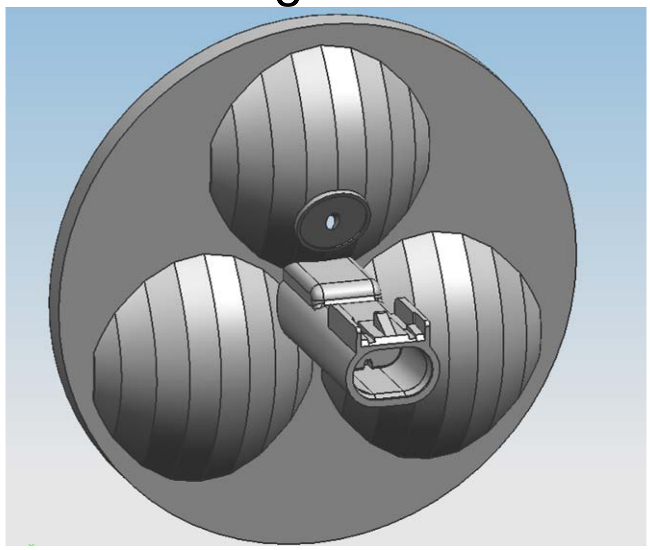
IS: Wire Connected LEDs



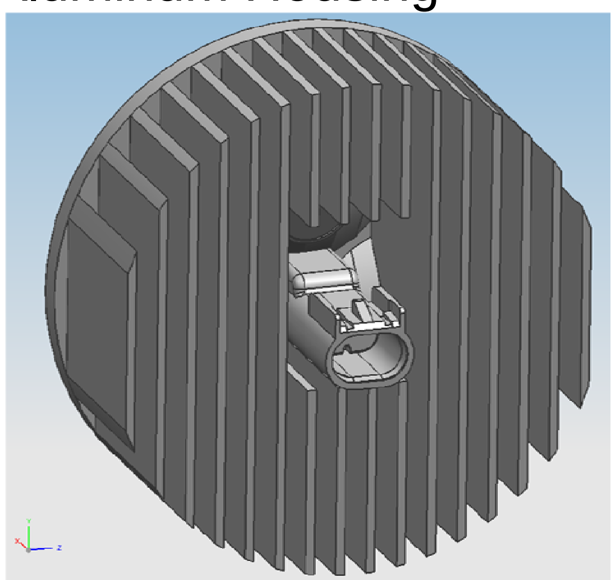
Note: The circuit board was not used with our prototype because it could not be manufactured in time for the design expo. Wires were used in its place. The resistor was removed from the original circuit due to OSRAM's warning that it would make it difficult to control the amount of power provided to the LEDs. A current limited power supply was used with our prototype.

Team 11	
Project: LED Fog Lamp	
Part Purpose: Prototype	
Engineer: Brett Stawinski	4/6/2008

WAS: Polycarbonate Housing



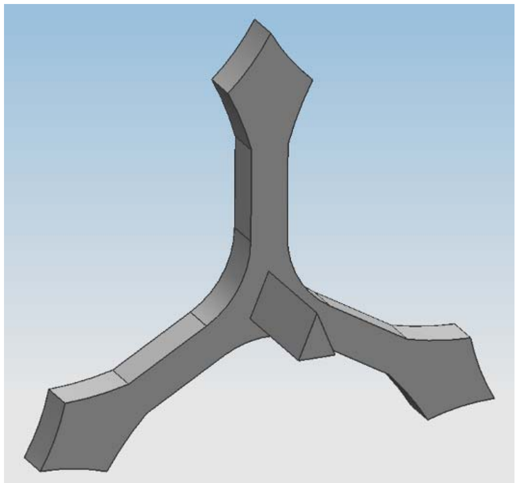
IS: 7055 T77511 Aluminum Housing



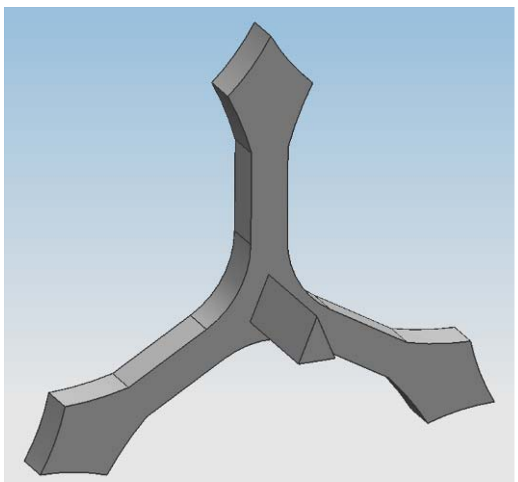
Note: The housing needed to incorporate aluminum heat fins to help dissipate heat from the LEDs. Due to the large number of fins needed, it was decided that it was more practical to make the entire housing out of aluminum.

Team 11	
Project: LED Fog Lamp	
Part Purpose: Mass Production	
Engineer: Josh Titus	4/12/2008

WAS: 6061-T6 Aluminum Central Heat Sink



IS: 7055-T77511 Aluminum Central Heat Sink

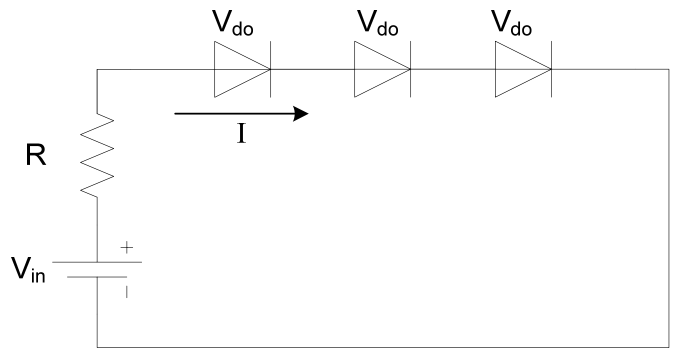


Note: The central heat sink was changed from 6061-T6 aluminum to 7055-T77511 because the latter material had the highest material index, while still meeting our minimum heat conductivity constraint. Also by using the same material as the housing we were able to match thermal expansion coefficients.

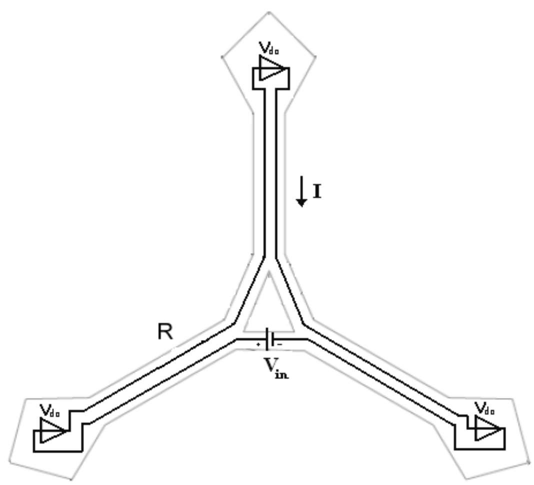
Team 11	
Project: LED Fog Lamp	
Part Purpose: Mass Production	
Engineer: Alex Pedchenko	4/12/2008

Engineer Change Notice

WAS:



IS:



Note: The resistor was removed from the circuit because OSRAM told us it would make it difficult to control the exact amount of power supplied to the LEDs. A current limiter (ON Semiconductor LT3517) was added to the power line downstream of the circuit to control current.

Team 11	
Project: LED Fog Lamp	
Part Purpose: Mass Production	
Engineer: Brett Stawinski	4/3/2008

Appendix X: Material Selection Assignment

X.1 Housing

Function:	Keep internal housing components fixed in place, prevent foreign substances form entering inside the fog lamp, and overall preventing the fog lamp from being damaged
Objective(s):	Minimize weight, maximize stiffness (flexural modulus), minimize cost
Constraint(s):	Weight ≤ 296.6 g Maximum long term service temperature ≥ 125 °C Thermal conductivity ≥ 170 W/m*K Waterproof Capable of accepting an aluminum coating*

Table X1: Material selection parameters for fog lamp housing

Material Index: $M = \frac{F}{C\rho}$, where F is the flexural modulus, C is the material cost, and ρ is density.

X.1.1 Housing Constraints

The geometry of our fog lamp housing, in conjunction with the chosen material's density, determines the housing's weight. Our design's housing volume was measured to be $4.1582*10^{-5}$ m^3 using Unigraphix NX 5.0. The upper weight constraint was derived by subtracting the weight of the central heat sink with the attached electrical components from the weight of the larger of the two currently used halogen fog lamps. Using this constraint, we found the maximum allowable density for our housing material to be 7132.9 kg/m^3.

The minimum maximum long term service temperature and minimum thermal conductivity were emplaced after the initial thermal validation of our final design demonstrated that the current heat sink at the time was inadequate. Speaking to engineers at OSRAM and studying heat sinks employed by OSRAM for their front head lamps, we decided a considerably larger heat sink which was exposed to the outside of the fog lamp was required. Thus, we decided to use the housing itself to aid in transferring heat away from the LEDs to the outside of the fog lamp assembly. This meant that the housing material should have similar thermal properties (specifically maximum long term service temperature and minimum thermal conductivity) to that of the material chosen for the central heat sink.

Finally, the housing material must be waterproof and capable of accepting an aluminum coating. The former is necessary so that the electrical components located inside the fog lamp do not get damaged. The latter is needed for the aluminum deposition process required for the fog lamp's reflectors.

X.1.2 Housing Final Material Choice

Top Five Material Choices

Material	Material Index Range [MPa/(USD/m^3)]
Wrought aluminum alloy, 7055, T77511	0.08-0.13
Wrought aluminum alloy, 7050, T7451	0.05-0.08
Wrought aluminum alloy, 7475, T761	0.05-0.07
Wrought aluminum alloy, 7010, T7651	0.04-0.07
Wrought aluminum alloy, 7050, T74511	0.04-0.07

Table X2 – Materials having the five largest magnitudes of the housing material index

Our analysis leads us to believe that using the 7055 T77511 aluminum alloy for our fog lamp's housing is the best choice. This decision is based on two factors. The more obvious of these two is that this material fulfilled the constraints listed in Table X1 on pg. 117, while scoring the highest housing material index out of all the eligible candidates, as can be seen in Table X2, above. A less apparent but equally important reason for choosing this particular material is that because it is also the foremost candidate for the central heat sink, as shown in Section X.2.2 below. To clarify, since the housing and the central heat sink are going to be joined together, it is desirable that their coefficients of thermal expansion are as close to each other as possible. Thus, choosing the same material for both parts is ideal. Lastly, as can be seen from **[40]**, aluminum alloys have a relatively low eco-indicator, when compared to that of other metals (materials which fulfill both the thermal conductivity and maximum long term service temperature constraints). Thus, this material choice is also good in terms of environmental impact.

X.2 Central Heat Sink

Function:	Draw heat away from the LEDs when they are on
Objective(s):	Minimize weight, maximize thermal conductivity, minimize cost, maximize stiffness (flexural modulus)
Constraint(s):	Maximum long term service temperature ≥ 125 °C Thermal conductivity ≥ 170 W/m*K

Table X3: Material selection parameters for central heat sink

Material Index: $M = \dfrac{k}{C\rho}$, where k is thermal conductivity, C is material cost, and ρ is density.

X.2.1 Constraints

The constraint on the central heat sink's maximum long term service temperature was assigned based on the DIAMOND® Dragons' temperature vs. lifetime performance. The specifications data sheet for these LEDs indicated that their median lifetime was only 200 hours when they operated at 125 °C. Since, as mentioned earlier in the report, a fog lamp's lifetime is require to be 10,000 hours for it to be considered that it will last the vehicle its entire life span, if the LEDs are operating for prolonged periods of time at temperatures reaching magnitudes close to 125 °C, the LEDs themselves will fail after a short period of time and the therefore the heat sink's long term temperature is not a concern at this point. For this reason the heat sink's maximum long term service temperature does not need to exceed 125 °C.

The minimum thermal conductivity constraint, 170 W/m*K, was based off of the 6061 series Aluminum alloys which are common, can be extruded, and are often used for heat sink application [39].

X.2.2 Final Material Choice

Material	Material Index Range [MPa/(USD/m^3)]
Wrought aluminum alloy, 7055, T77511	11.71-20.74
Wrought aluminum alloy, 7475, T761	7.69-12.49
Wrought aluminum alloy, 7010, T7651	7.54-12.52
Wrought aluminum alloy, 7050, T7451	7.53-12.26
Wrought aluminum alloy, 7050, T74511	7.30-11.94

Table X4: Materials having the five largest magnitudes of the housing material index

Our analysis shows that 7055 T77511 aluminum alloy is the best candidate for the central heat sink material. One of the reasons for this is that it boasted the highest material index score, as seen from Table X4 above. Another reason is that because this is the same material as that chosen for the housing, the coefficients of thermal expansion for these two parts will be identical, a desirable factor when separate parts are joined. Last of all, as discussed in Section X.1.2 the relatively low eco-indicator of aluminum alloys when compared to other metals makes choosing this material an environmentally conscientious decision.

Appendix Y: Design for Assembly

The purpose of design for assembly (DFA) is to reduce the number of parts while simultaneously simplifying the assembly process of the remaining parts. The following shows our original design and how we improved upon it to optimize assembly efficiency in the final design. The efficiency of our design will be evaluated using Eq. Y1, where N_m is the minimum number of parts needed and T_m is the actual assembly time (seconds). The DFA charts are shown at the end of this Appendix.

$$Eff. = 3 \bullet (\frac{N_m}{T_m}) \qquad \text{Eq. Y1}$$

Y.1 ASSEMBLY EFFICIENCY OF ORIGINAL DESIGN

Our original design has a total of 7 parts (lens, housing, heat diffuser, heat sink, LED circuit board, connector and power regulation circuit board). Using the DFA charts the assembly time for each part is summarized below in Table Y1.

The power regulation circuit board will have to be attached electrically to the circuit board holding the LEDs for the first operation. This requires one hand manual handling on each part with $(\alpha+\beta) < 360°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is secured immediately by metal clips between the circuit boards with plenty of clearance/visibility.

Next, we will attach the complete circuit board to the underside of the heat sink. This requires one hand manual handling on each part with $(\alpha+\beta) < 360°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is not secured immediately and attached using thermal epoxy (may need temporary clamps) with plenty of clearance/visibility.

Then, we will attach the heat diffuser to the housing. This requires one hand manual handling on each part with $360° \leq (\alpha+\beta) < 540°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is secured immediately by silicone adhesive with a press fit and with plenty of clearance/visibility. The heat sink will then be snap fit to the portion of the heat diffuser that passes through and extends out from the back of the housing.

Next, we will attach the connector to the heat sink. This requires one hand manual handling on each part with $360° \leq (\alpha+\beta) < 540°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is not secured immediately by silicone adhesive with a press fit and with plenty of clearance/visibility.

Finally, we will attach the lens to the housing to complete the assembly. This requires one hand manual handling on each part with $360° \leq (\alpha+\beta) < 540°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is not secured immediately with polyurethane sealant and with plenty of clearance/visibility.

This process leads to a total overall assembly time of 35.39 seconds, which corresponds to an overall efficiency of 39% using Eq. Y1. This efficiency is fairly low and therefore we will work to incorporate improved methods of assembly and remove unnecessary parts to improve this number for our final design.

Part	Handling Code	Handling (sec)	Insertion Code	Insertion (sec)	Minimum Parts	Assembly Time (sec)
LED Circuit Board	00	1.13	06	5.5	1	6.63
Power Regulation Circuit Board	00	1.13	30	2.0	0	3.13
Heat Diffuser	00	1.13	30	2.0	1	3.13
Heat Sink	00	1.13	31	5.0	0	6.13
Housing	10	1.50	31	5.0	1	6.50
Connector	10	1.50	31	5.0	1	6.50
Lens	10	1.50	06	5.5	1	6.50
					Total Time	**35.39**
					Efficiency	**.39**

Table Y1: Assembly time for original fog lamp

Y.2 ASSEMBLY REDESIGN

To optimize our assembly we first removed any unnecessary parts using the test for the minimal number of parts. The heat sink could be incorporated into the bottom of the housing very easily. The extra aluminum will help with heat dissipation and aluminum is corrosion resistant so it will weather the elements well. To simplify the circuit, we will have the circuit board built as one piece with a flexible power ribbon connection between the two halves. This will allow us to assemble this as one piece and avoid any confusion on orientation or placement.

We also made design changes to increase our design efficiency. The heat sink peg was made asymmetric to aid with insertion and this also helps with circuit board orientation as well. The heat sink will also have clips along the bottom cavity to hold the circuit board in place while the thermal epoxy sets. We put clips on the lens to hold it in place while the polyurethane sealant sets.

Y.3 ASSEMBLY EFFICIENCY OF FINAL DESIGN

Our original design had a total of 7 parts, where 2 parts were not needed and could be combined to improve efficiency. In our final design, we made the LED circuit board and power regulation circuit board into one part and incorporated the heat sink into the housing. This eliminated two parts and saved a significant amount of time. We also made a few minor assembly improvements as discussed in the assembly redesign section. Using the DFA charts the assembly time for each part is summarized below in Table Y2.

First, we will attach the complete circuit board to the underside of the heat sink. This requires one hand manual handling on each part with $(\alpha+\beta) < 360°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is secured immediately by clips and permanently attached using thermal epoxy with plenty of clearance/visibility.

Then, we will attach the heat diffuser to the housing. This requires one hand manual handling on each part with $(\alpha+\beta) < 360°$ and the parts are both thicker than 2 mm and larger than 15 mm.

Manual insertion will be done where the part is secured immediately by silicone adhesive with a press fit and with plenty of clearance/visibility. The connector will then be snap fit to the portion of the heat diffuser that passes through and extends out from the back of the housing.

Finally, we will attach the lens to the housing to complete the assembly. This requires one hand manual handling on each part with $(\alpha+\beta) < 360°$ and the parts are both thicker than 2 mm and larger than 15 mm. Manual insertion will be done where the part is secured immediately with snaps while the polyurethane sealant sets and with plenty of clearance/visibility.

This process leads to a total overall assembly time of 15.65 seconds, which corresponds to an overall efficiency of 96% using Eq. Y1. This efficiency is much higher than our original design and is a significant improvement.

Part	Handling Code	Handling (sec)	Insertion Code	Insertion (sec)	Minimum Parts	Assembly Time (sec)
Circuit Board	00	1.13	30	2.0	1	3.13
Heat Diffuser	00	1.13	30	2.0	1	3.13
Heat Sink/Housing	00	1.13	30	2.0	1	3.13
Connector	00	1.13	30	2.0	1	3.13
Lens	00	1.13	30	2.0	1	3.13
					Total Time	**15.65**
					Efficiency	**.96**

Table Y2. Assembly time for final design of fog lamp

Design changes can be seen below in Appendix W on pg. 112.

MANUAL HANDLING—ESTIMATED TIMES (seconds)

Key:

ONE HAND

			parts are easy to grasp and manipulate					parts present handling difficulties (1)				
			thickness > 2 mm			thickness ≤ 2 mm		thickness > 2 mm			thickness ≤ 2 mm	
			size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
			0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand without the aid of grasping tools	(α+β) < 360°	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
	360° ≤ (α+β) < 540°	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
	540° ≤ (α+β) < 720°	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
	(α+β) = 720°	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

ONE HAND with GRASPING AIDS

				parts need tweezers for grasping and manipulation								parts need standard tools other than tweezers	parts need special tools for grasping and manipulation
				parts can be manipulated without optical magnification				parts require optical magnification for manipulation					
				parts are easy to grasp and manipulate		parts present handling difficulties (1)		parts are easy to grasp and manipulate		parts present handling difficulties (1)			
				thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm	thickness > 0.25 mm	thickness ≤ 0.25 mm		
				0	1	2	3	4	5	6	7	8	9
parts can be grasped and manipulated by one hand but only with the use of grasping tools	α ≤ 180°	0 ≤ β ≤ 180°	4	3.6	6.85	4.35	7.6	5.6	8.35	6.35	8.6	7	7
		β = 360°	5	4	7.25	4.75	8	6	8.75	6.75	9	8	8
	α = 360°	0 ≤ β ≤ 180°	6	4.8	8.05	5.55	8.8	6.8	9.55	7.55	9.8	8	9
		β = 360°	7	5.1	8.35	5.85	9.1	7.1	9.55	7.85	10.1	9	10

TWO HANDS for MANIPULATION

		parts present no additional handling difficulties					parts present additional handling difficulties (e.g. sticky, delicate, slippery, etc.) (1)				
		α ≤ 180°			α = 360°		α ≤ 180°			α = 360°	
		size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm	size > 15 mm	6 mm ≤ size ≤ 15 mm	size < 6 mm	size > 6 mm	size ≤ 6 mm
		0	1	2	3	4	5	6	7	8	9
parts severely nest or tangle or are flexible but can be grasped and lifted by one hand (with the use of grasping tools if necessary) (2)	8	4.1	4.5	5.1	5.6	6.75	5	5.25	5.85	6.35	7

TWO HANDS required for LARGE SIZE

		parts can be handled by one person without mechanical assistance									two persons or mechanical assistance required for parts manipulation
		parts do not severely nest or tangle and are not flexible								parts severely nest or tangle or are flexible (2)	
		part weight < 10 lb				parts are heavy (> 10 lb)					
		parts are easy to grasp and manipulate		parts present other handling difficulties (1)		parts are easy to grasp and manipulate		parts present other handling difficulties (1)			
		α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°	α ≤ 180°	α = 360°		
		0	1	2	3	4	5	6	7	8	9
two hands, two persons or mechanical assistance required for grasping and transporting parts	9	2	3	2	3	3	4	4	5	7	9

MANUAL INSERTION—ESTIMATED TIMES (seconds)

Key:

- PART ADDED but NOT SECURED
- PART SECURED IMMEDIATELY
- SEPARATE OPERATION

PART ADDED but NOT SECURED

		after assembly no holding down required to maintain orientation and location (3)				holding down required during subsequent processes to maintain orientation or location (3)			
		easy to align and position during assembly (4)		not easy to align or position during assembly		easy to align and position during assembly (4)		not easy to align or position during assembly	
		no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)	no resistance to insertion	resistance to insertion (5)
		0	1	2	3	6	7	8	9
addition of any part (1) where neither the part itself nor any other part is finally secured immediately: part and associated tool (including hands) can easily reach the desired location	0	1.5	2.5	2.5	3.5	5.5	6.5	6.5	7.5
part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access or restricted vision (2)	1	4	5	5	6	8	9	9	10
part and associated tool (including hands) cannot easily reach the desired location: due to obstructed access and restricted vision (2)	2	5.5	6.5	6.5	7.5	9.5	10.5	10.5	11.5

PART SECURED IMMEDIATELY

		no screwing operation or plastic deformation immediately after insertion (snap/press fits, circlips, spire nuts, etc.)		plastic deformation immediately after insertion						screw tightening immediately after insertion (6)	
				plastic bending or torsion			rivetting or similar operation				
					not easy to align or position during assembly			not easy to align or position during assembly			
		easy to align and position with no resistance to insertion (4)	not easy to align or position during assembly and/or resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position during assembly (4)	no resistance to insertion	resistance to insertion (5)	easy to align and position with no torsional resistance (4)	not easy to align or position and/or torsional resistance (5)
		0	1	2	3	4	5	6	7	8	9
addition of any part (1) where the part itself and/or other parts are being finally secured immediately: part and associated tool (including hands) can easily reach the desired location and the tool can be operated easily	3	2	5	4	5	6	7	8	9	6	8
part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access or restricted vision (2)	4	4.5	7.5	6.5	7.5	8.5	9.5	10.5	11.5	8.5	10.5
part and associated tool (including hands) cannot easily reach desired location or tool cannot be operated easily: due to obstructed access and restricted vision (2)	5	6	9	8	9	10	11	12	13	10	12

SEPARATE OPERATION

		mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				non-fastening processes	
		none or localized plastic deformation				metallurgical processes					
							additional material required				
		bending or similar processes	rivetting or similar processes	screw tightening (6) or other processes	bulk plastic deformation (large proportion of part is plastically deformed during fastening)	no additional material required (e.g. resistance, friction welding, etc.)	soldering processes	weld/braze processes	chemical processes (e.g. adhesive bonding, etc.)	manipulation of parts or sub-assembly (e.g. orienting, fitting or adjustment of part(s), etc.)	other processes (e.g. liquid insertion, etc.)
		0	1	2	3	4	5	6	7	8	9
assembly processes where all solid parts are in place	9	4	7	5	3.5	7	8	12	12	9	12

Appendix Z: Design for Environmental Sustainability

Our design for environmental sustainability analysis will be done using the two parts analyzed in our material selection assignment. Although the final assessment resulted in both parts being made from 7055 T77511 aluminum alloy, for the purposes of this assignment (and recommended by professor Hulbert) the following analysis was done assuming the housing is made from the original design material of Makrolon 2605 and the heat sink is made from 7055 T77511 aluminum alloy. It may also be informative to use this analysis in the context of making the housing out of Makrolon 2605 vs. 7055 T77511 aluminum alloy as it applies to the impact on the environment.

Using the volume values from our CAD model, we found that 50.1 g of Makrolon 2605 and 271.3 g of 7055 T77511 aluminum alloy will be required for our final design. The closest materials available in SimaPro were 7075 aluminum alloy (has a similar composition, although not exactly the same) and traditional polycarbonate (they did not have the specific PC Makrolon 2605). We used Eco-Indicator 99 (I) V2.02 to analyze these two materials and to create the charts shown at the end of this appendix.

After running the analysis we found that there was a substantial difference between aluminum and polycarbonate (PC) with regards to emissions. Figure Z1 below, on shows the relative mass of each emission (raw, air, waste and water). Aluminum requires more than 45 Kg of raw materials for manufacturing, about 2.5 Kg of air pollutants and produces approximately 1 Kg waste. Polycarbonate, by contrast, requires only 7 Kg of raw materials for manufacturing, about 0.5 Kg of air pollutants and produces negligible waste. Both materials produce negligible water pollutants.

Another visualization of emissions is shown in Fig. Z2 below, which is the characterization tab in SimaPro. This chart shows a breakdown of specific emissions and environmental impact indicators (disaggregate damage categories) such as carcinogens, eco-toxicity and land use. Again, this chart clearly shows that aluminum has a much larger negative impact on the environment than PC, since it has the highest value in all categories and PC falls far behind (less than 15% of the magnitude of Aluminum) in all but one category (resp. organics) where it is only 35% of the magnitude of Aluminum. For land use and minerals categories aluminum dominates with insignificant contributions from PC.

The normalization chart shown in Fig. Z3 below, shows the relative impact on human health, ecosystem quality and resources of the two materials. Aluminum once again has a relatively larger impact in all categories, especially in resources. Because aluminum's normalized score in the resource category is notably high, this factor will be an important consideration when choosing the final material for mass production.

Figure Z4 below, combines the human health, ecosystem quality and resources values from the previous chart into two bars, one for each of the materials to show an overall Eco-Indicator 99 impact. This figure clearly illustrates the much larger detrimental impact of aluminum when compared to that of PC. The total impact of PC is approximately 10 mPt while the total impact of aluminum is approximately 1050 mPt, about 105 times greater.

From the environmental sustainability results we can see that using aluminum will be much worse for the environment during the manufacturing process. Therefore, our heat sink will contribute much more pollution than the housing. Unfortunately, PC does not have a high enough thermal conductivity to be used in place of aluminum for the heat sink. Our results also show that we should try to make our housing from PC instead of aluminum. However, since we know that our design requires the housing to supplement the central heat sink in heat dissipation, the housing will need to be made mostly from aluminum.

From a lifecycle perspective, both aluminum and PC are similar in environmental impact. Both materials can be recycled and both have similar durability and lifetime. Aluminum has a high initial resource requirement, but most of this value is composed of water which could possibly be recycled or reused for another process. Furthermore, using aluminum for the housing may have a larger initial environmental impact but if it keeps the operating temperature of the LEDs lower than a comparable PC housing it may have an overall comparable impact given that the LEDs would fail less often and the unit would have to be replaced less frequently. Given these environmental considerations, we will take into account the environmental impact of our material choices and use this to make our final material selections.

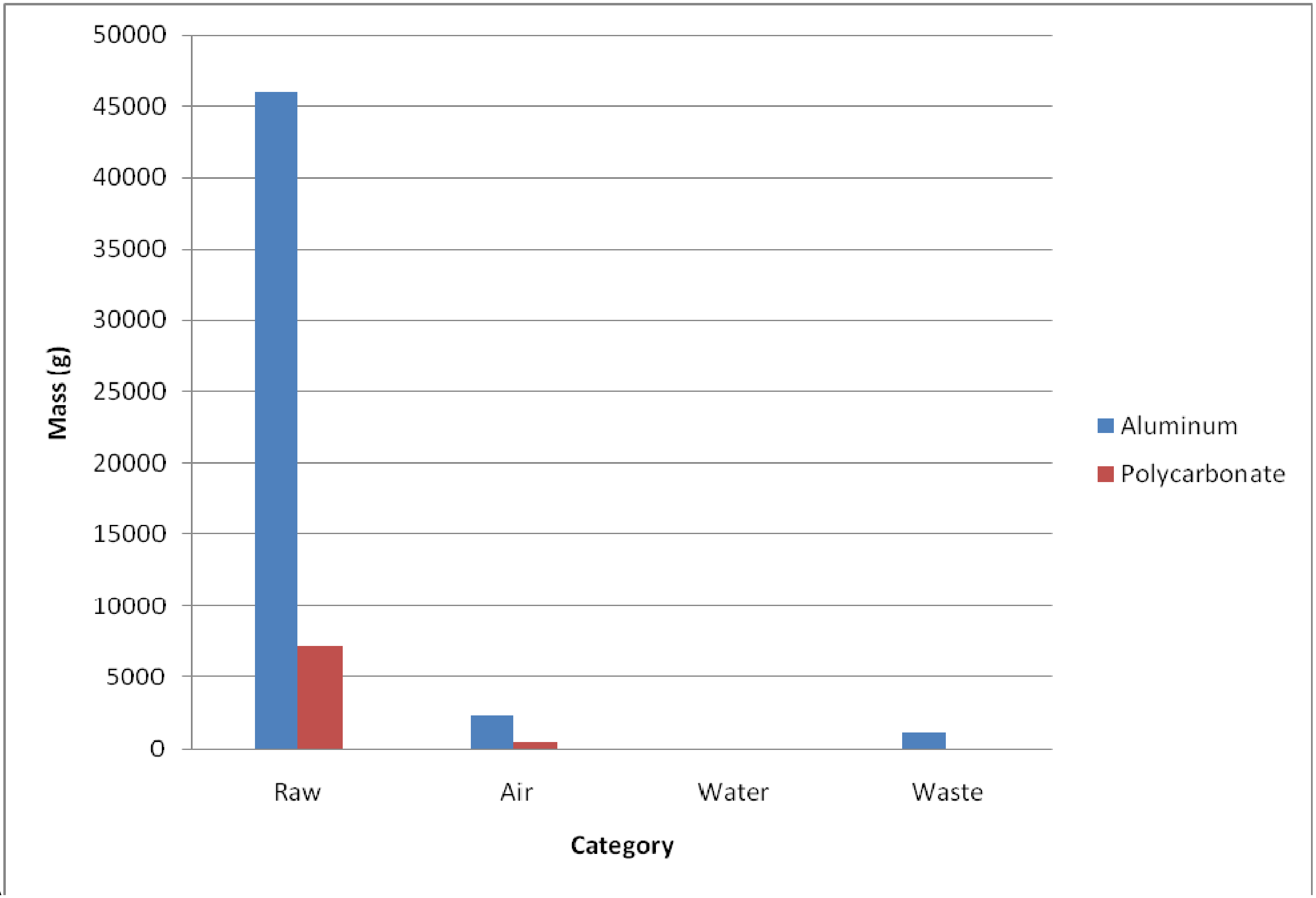


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Figure Z1: Total Emissions

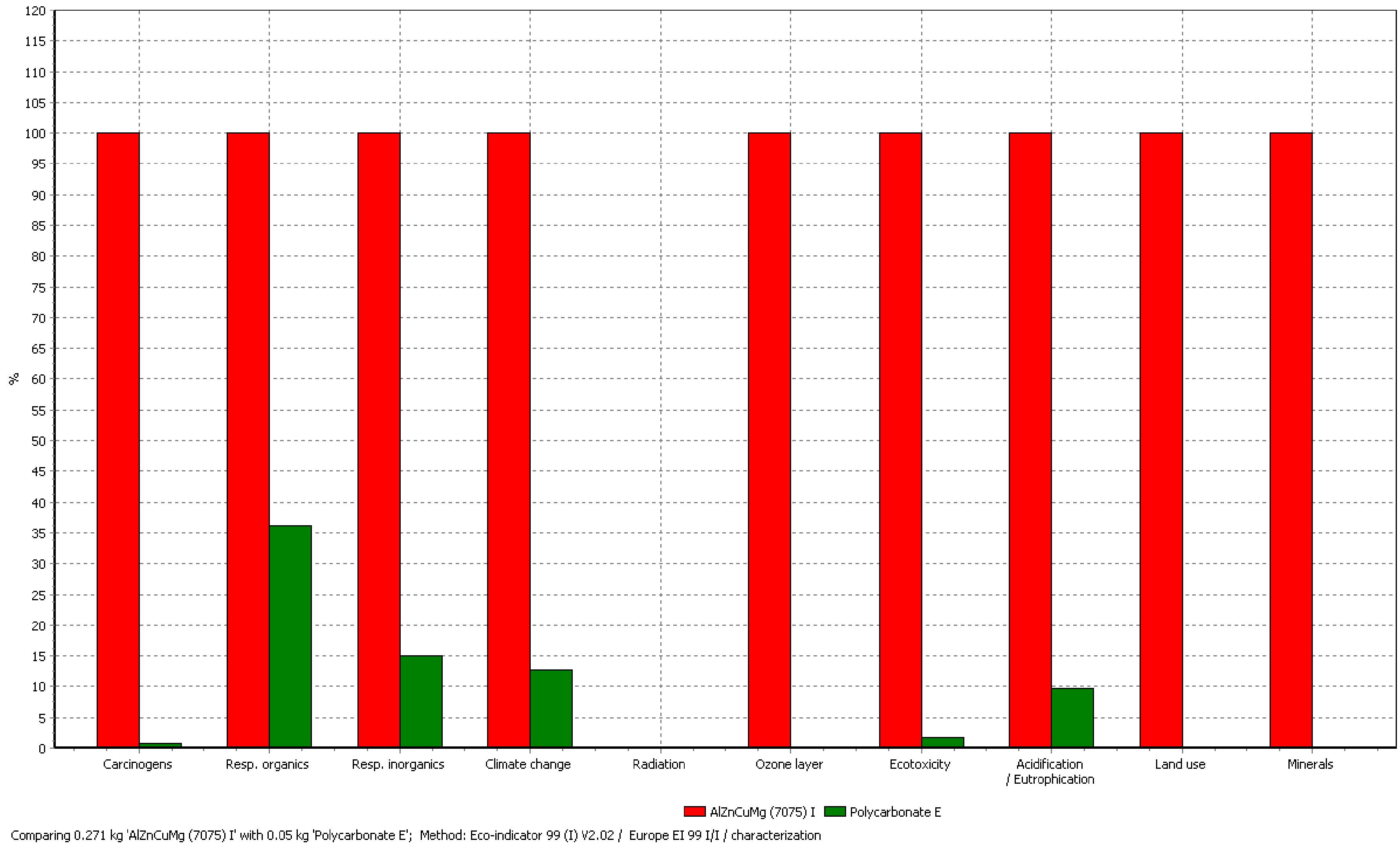


Figure Z2: Relative impacts in disaggregate damage categories

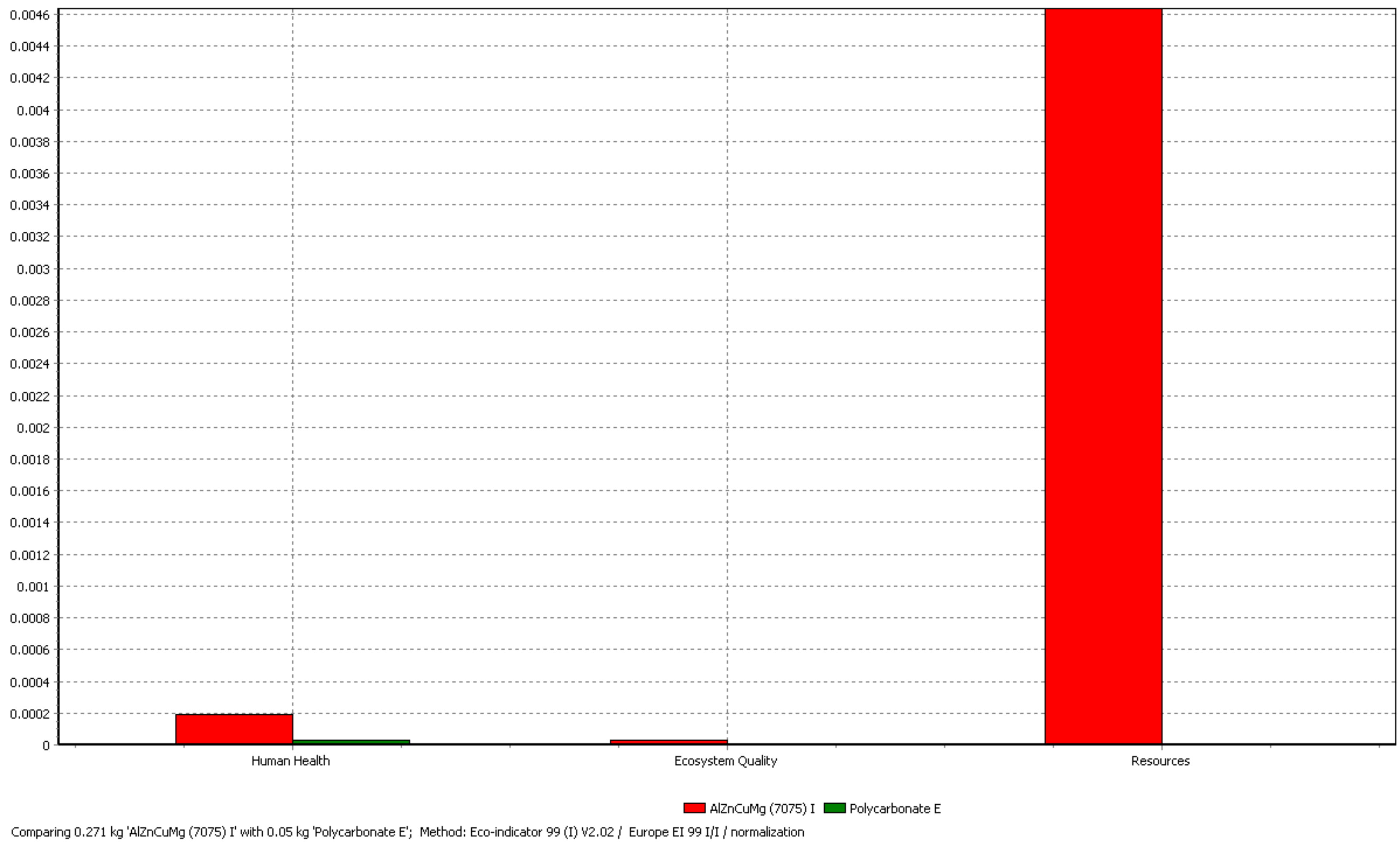


Figure Z3: Normalized score in human health, eco-toxicity and resource categories

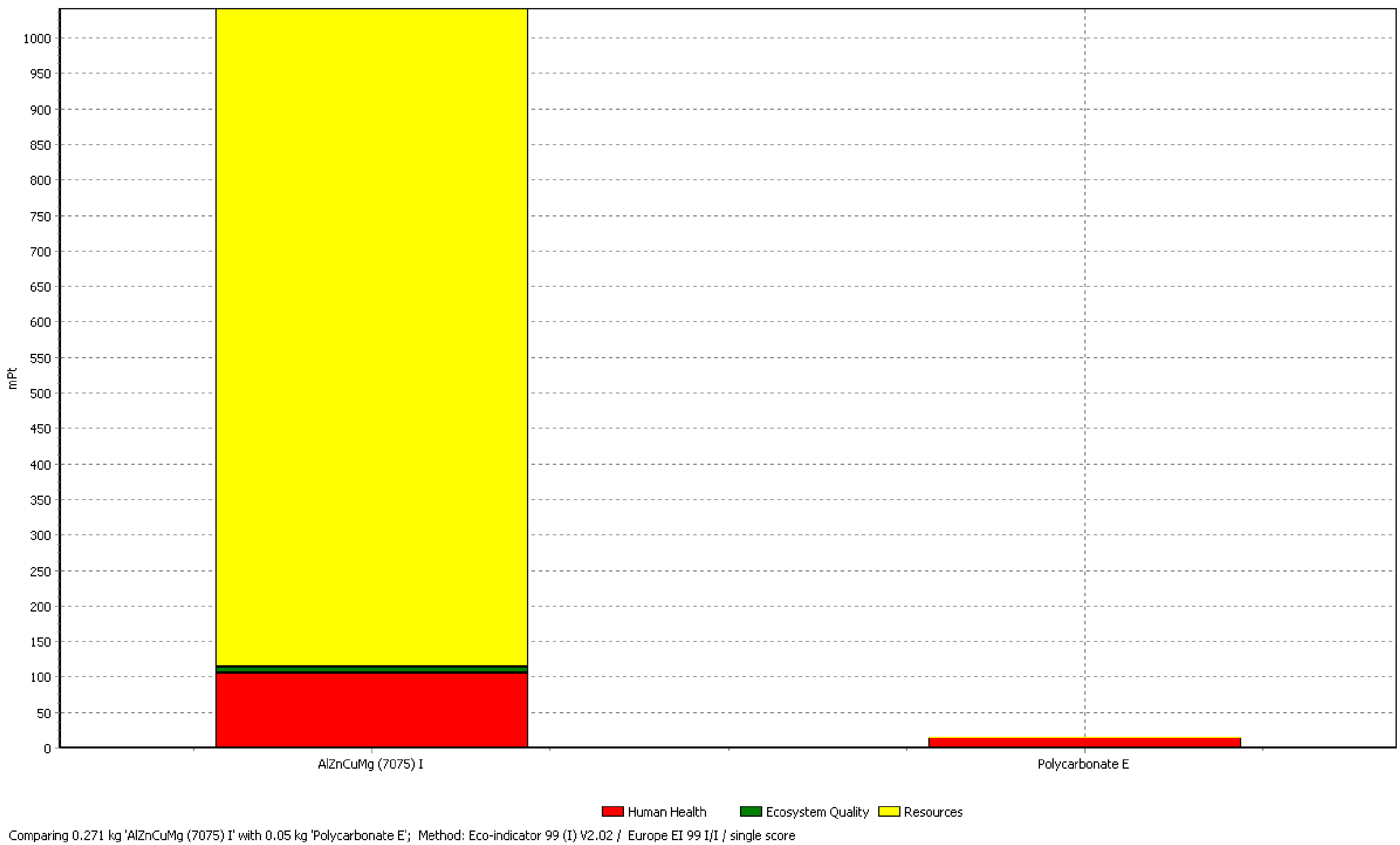


Figure Z4: Single score comparison in points

Appendix AA: Design for Safety

For our design for safety analysis our prototype and final design will have very similar safety risks. The prototype will be less refined due to manufacturing constraints and cannot be made out of final materials which are more durable because we used SLA. Overall, the safety risks associated with and LED fog lamps are very low given proper design and assembly. The complete design for safety chart is in Appendix X3.

The major hazards where due to sharp edges, failure during crash conditions, water damage and electrical overdrive. Sharp edges could cut the user or technician that services the fog lamp. During a crash the lamp could fall off and damage other components or shatter and lead to flying debris that could hit bystanders. Water entering the housing could cause corrosion of the electrical components or a short circuit that would damage the LEDs or possibly shock a technician. Also, failure during operation could cause low visibility for the driver. Voltage in vehicles is not constant and can cause the LEDs to be overdriven and damaged which would reduce lighting for the driver if failure occurred during operation.

All of the above risks were accounted for in our final design and their solutions are documented in the risk reduction column of the design for safety chart. We rounded the edges of our heat sink and housing to eliminate sharp edges. We manufactured our housing, lens and other parts out of high strength and impact resistant materials. Our design incorporates a GORTEX patch on the housing to allow water to escape and keep the housing dry and we used a constant current driver to maintain the appropriate power to our LEDs to eliminate overdriving the LEDs.

The difference between risk assessment and Failure Modes and Effects Analysis (FMEA) is that FMEA is based on potential failures of a system and the effects of that failure while risk assessment is a task-based hazard identification method to reduce risks. Both are useful tools for improving the safety of any design. FMEA is very effective at identifying possible failure methods in components and at creating a more robust design. Risk assessment is very effective at taking into account the human operator and user factors (tasks) that contribute to possible hazards. In many situations it would be beneficial to use both methods to increase the safety of the design and reduce risk early before it is a major problem.

In most cases we will not be able to reduce the risks to zero, therefore, we have to aim for acceptable risk. This allows us to maintain the function of our device while also minimizing the safety risks to all users. For our fog lamp, we will not be able to completely eliminate the risk of debris during a crash since there are so many variables and our fog lamp will likely be the least of concerns during a crash event (i.e. gas tank ignition and deceleration rates of vehicle and passenger are much greater concerns). We will also never be able to completely eliminate assembly error or defective parts, but through the processes discussed above we can make their occurrence rare and overall risk low. With our redesign we reduced all risk categories and therefore accomplished a balance between safety and function.

designsafe Report

Application:	FogLamp	Analyst Name(s):	Josh Titus
Description:		Company:	LED2008
Product Identifier:	LEDFogLamp	Facility Location:	NA
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Fins have pointed edges	Slight Remote Unlikely	Low	Round corners and Edges	Minimal Remote Negligible	Low	
All Users All Tasks	mechanical : impact during crash could fly off or shatter	Slight Occasional Possible	Moderate	Increase strength of attachment, Use shatter resistant materials	Slight Remote Unlikely	Low	
All Users All Tasks	electrical / electronic : energized equipment / live parts If insulation fails could short circuit, only 12v, 1.4A	Minimal Remote Negligible	Low	unlikely to occur during normal operation	Minimal Remote Negligible	Low	
All Users All Tasks	electrical / electronic : insulation failure If insulation fails could short circuit, only 12v, 1.4A	Minimal Remote Negligible	Low	unlikely to occur during normal operation	Minimal Remote Negligible	Low	
All Users All Tasks	electrical / electronic : shorts / arcing / sparking If the insulation fails or improperly built could short circuit	Minimal Remote Negligible	Low	not very high power, would not be very hazardous	Minimal Remote Negligible	Low	
All Users All Tasks	electrical / electronic : improper wiring could cause short circuit and ruin lamp	Minimal Remote Negligible	Low	prevent energy release			
All Users All Tasks	electrical / electronic : lightning LED lighting failure, defective part or overvoltage	Minimal Remote Negligible	Low	Quality testing should eliminate this	Minimal Remote Negligible	Low	
All Users All Tasks	electrical / electronic : water / wet locations Water entering housing could ruin components	Slight Occasional Unlikely	Moderate	Gortex patch used to keep interior dry and to equalize pressure	Slight Remote Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	electrical / electronic : overvoltage /overcurrent Surge in voltage could overdrive LEDs if current limiting driver is not installed correctly	Slight Occasional Possible	Moderate	Use current limiting driver to eliminate overdriving LEDs	Slight Remote Negligible	Low	
All Users All Tasks	electrical / electronic : power supply interruption If power is cut the lamp will not operate	Minimal Remote Unlikely	Low	Unlikely to happen	Minimal Remote Negligible	Low	
All Users All Tasks	electrical / electronic : electrostatic discharge Static electricity could damage circuit board or LEDs	Minimal Remote Unlikely	Low	ESD equipment used to eliminate static buildup	Minimal Remote Negligible	Low	
All Users All Tasks	ergonomics / human factors : human errors / behaviors Bad wiring, improper sealing, assembled incorrectly	Minimal Remote Unlikely	Low	Design for Assembly used to make assembly easier and harder to do improperly	Minimal Remote Negligible	Low	
All Users All Tasks	fire and explosions : hot surfaces heat sink could be hot, up to 80 degrees C max	Slight Remote Negligible	Low	under normal operating conditions the heat sink should be well below 80 degrees C and will not cause injury.	Minimal Remote Negligible	Low	
All Users All Tasks	ingress / egress : inadequate lighting Not enough light output could cause low visibility and impare the driver's vision	Minimal Remote Negligible	Low	LEDs should last entire life of vehicle	Minimal Remote Negligible	Low	
All Users All Tasks	chemical : reaction to / with chemicals Components of lamp will react with certain chemicals, though not with most found naturally in the environment so should not be large concern	Minimal Remote Negligible	Low	housing, lens and sealants are all corrosive and chemical resistant	Minimal Remote Negligible	Low	
All Users All Tasks	radiation : bright visible light Light from the lamp is very bright and could temporarily degrade vision of oncoming drivers	Slight Remote Unlikely	Low	Light is aimed downward to minimize oncoming driver exposer.	Minimal Remote Negligible	Low	

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	lasers : eye exposure Temporary blindspots and could cause retinal damage if directly stared at for long periods of time	Minimal Remote Unlikely	Low	person would look away well before damage occured, to damage retina one would have to intentionally stare into light for extended period of time.	Minimal Remote Negligible	Low	

Appendix BB: Manufacturing Process Selection

BB.1 Estimated Production Volume

General Motors has requested for the end product to be able to be manufactured on a high-volume basis. In 2006, GM sold approximately 9.1 million cars and trucks globally **[36]**. Generally, consumers have the option of choosing to add fog lamps to their vehicle upon purchase, and thus not every vehicle sold has this feature. According to our sponsors, the production volume for our fog lamps would depend on their final price. Since our product is predicted to cost less than $15.00 per unit after cost reduction of the LEDs, it would be integrated onto approximately 80% of GM's vehicles. In addition, fog lamps typically have 30% penetration on average, meaning that 30% of a vehicle model would be sold with fog lamps added as an option **[22]**. Following the above logic, the maximum production volume for our project should be 4.4 million units.

However, the newest technology is typically reserved for GM's high end cars. If we restrict our attention to the Cadillac CTS, General Motors sold approximately 56,000 vehicles of this model in 2004 **[37]**. Thus, as a minimum production volume, we will use 112,000 units. These values were utilized to determine the optimal manufacturing process for both the housing and the heat diffuser piece.

BB.2 Component Process Selection

We utilized the CES Manufacturing Process Selector to determine the optimal manufacturing processes for both the housing and the heat sink at the production volume discussed above. Since both of these parts are to be made from aluminum, we do not foresee the need for a surface treatment to prevent corrosion resistance. Aluminum is highly resistant to corrosion, and will be able to withstand the elements under operation of the vehicle.

BB.2.1 Housing

The design requirements to manufacture the proposed aluminum housing are described in Table BB1, below. We used these parameters to determine the most appropriate shaping process from the Process Universe contained within the CES software.

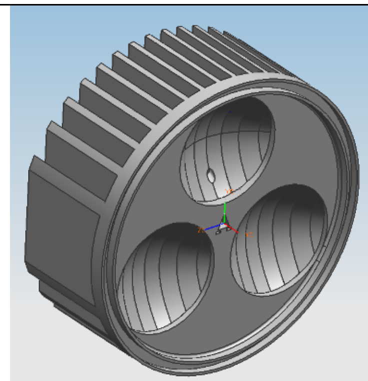
Housing	
Material Class	Non-ferrous metal
Process Class	Primary, discrete
Shape Class	3D-Solid
Mass	0.217 kg
Minimum Section	1 mm
Precision	0.15 mm
Batch Size	Minimum: 112,000 units Maximum: 4.4 million units

Table BB1: Design Requirements for Housing

To determine the most appropriate manufacturing process, we first determined a primary shaping process best suited for manufacturing the housing. Essentially, this type of process takes an unshaped material and gives it the final shape of the part. Specifying the prescribed surface tolerance from Table BB1 above, we narrowed down the list of primary shaping processes significantly. We then specified the material to be shaped as a non-ferrous metal with a mass of 0.217 kg. Because of the complexity of the housing shape, we specified that it was a solid 3-D shape with complex transverse features to help narrow down the manufacturing processes. We wanted to be sure the manufacturing process could handle intricate features, such as the USCAR connector piece protruding from the back of the housing. Finally, the manufacturing piece needed to handle a high economic batch size of between 112,000 and 4.4 million units, as determined in Section BB.1.

Using the parameters described above, the remaining processes were die casting and high pressure die casting. We chose to manufacture the housing using high pressure die casting. For this process, the molten metal is injected under high pressure into a metal die, and the pressure is maintained during solidification **[30]**. Afterwards, one of the die halves is moved away, and the component is removed. For an aluminum alloy, a ‘cold chamber’ process is employed, whereby the metal is melted in a separate furnace and transported to the die casting machine, according to Figure BB1, below.

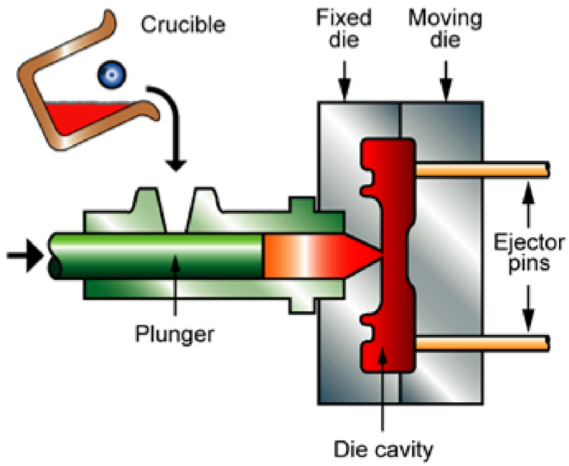


Figure BB1: Process Schematic for Pressure Die Casting [30]

One of the benefits of this process is that it can accommodate complex shapes. On average, high pressure die casting exhibits lower surface roughness values and higher tolerances than regular die casting. Table BB2 describes a few of the cost modeling parameters associated with this process. The capital and tooling costs associated with the system are significant primarily due to the precision machined dies. However, the capital cost for producing 4.4 million units per year is only $0.04 - $0.21 per fog lamp. In addition, the tooling cost per fog lamp is $0.002 - $0.03. Thus, the production volume will help to overcome the large costs associated with the system.

Parameter	Value
Capital cost	$188,500 – $942,600
Material utilization fraction	0.75 – 0.85
Production rate (units)	20 – 600 /hr
Tool life (units)	2,000 – 1,000,000
Tooling Cost	$8,483 – $122,500

Table BB2: Cost Modeling Table

Because of the internal porosity associated with this manufacturing process, die castings cannot be heat-treated. However, we do not foresee heat treatments being necessary for our housing as the strength of the 7050 T77511 aluminum should be sufficient.

An important consideration for this process is that the wall thickness needs to be as uniform as possible. The molten metal will cool in areas with the smallest cross sections, which may block the flow of metal to areas with thicker sections. Since our housing has varying thickness, it is recommended that feed paths be integrated into the mold to account for the solidification from thinnest to thickest sections [35]. This will generally add to the complexity and cost of the die.

BB.2.2 Central Heat Sink

To select the ideal manufacturing process for this component, it was first necessary to define the shape it must be able to make for our application. The single-unit heat sink is considered a solid-3D shape, since there is no axis of symmetry, it cannot be extruded, and it cannot be stamped from a flat sheet. In addition, we used the previously determined minimum production volume of

112,000 units and maximum of 4.4 million units. We determined the tolerance needed for this component to be ±0.15 mm (see Section 7.6 on pg. 45).

We also refined our search to processes which can handle primary shaping. This means that the process is able to take an unshaped material and give it a shape. We restricted our attention to discrete manufacturing processes. Also, the physical size of the heat sink comes into play in the manufacturing process. Using our CAD model, we approximated the mass of the heat sink to be a maximum of 0.01 kg, further reducing the number of appropriate processes.

Table BB3 summarizes the design requirements used in selecting the manufacturing process for the heat sink.

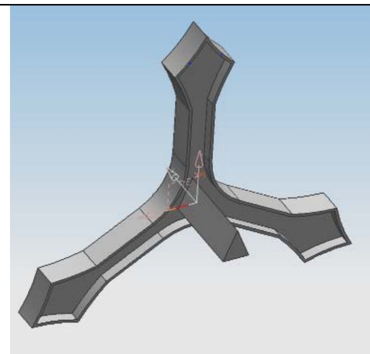
Heat Sink	
Material Class	Non-ferrous metal
Process Class	Primary, discrete
Shape Class	3D-Solid, parallel features
Mass	0.01 kg
Minimum Section	1 mm
Precision	0.15 mm
Batch Size	Minimum: 112,000 units Maximum: 4.4 million units

Table BB3: Design Requirements for Heat Sink

Using the above requirements, we determined the top four manufacturing processes for the central heat sink. The automotive industry is always interested in low-cost products, and thus we used the relative cost index per unit to compare each of these processes. The relative cost index is calculated using the materials, capital, time, energy, and information costs per unit manufactured. This flow of resources is illustrated in Figure BB2 **[30**].

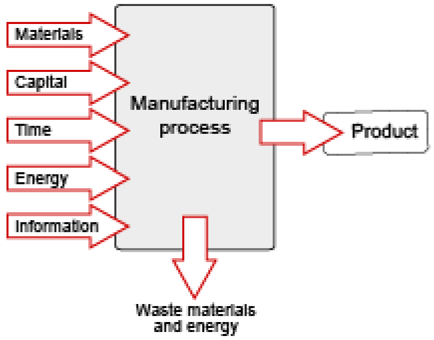


Figure BB2: Flow of resources associated with manufacturing process

Table BB3, below, lists the relative cost index per unit manufactured for each of the remaining processes. On average, the die pressing and sintering process has the lowest relative cost index. Although the CES program did not quote a relative cost index for the forging/rolling process, we eliminated this process primarily because it is appropriate for circular prismatic pieces, and thus does not lend itself to the central heat sink's geometry..

Process	Relative Cost Index (per unit)
Cold closed die forging	18.92 – 36.98
Die pressing and sintering	15.83 – 26.95
Forging/rolling	n/a
Powder injection molding	21.78 – 50.42

Table BB3: Costs associated with each manufacturing process

Thus, the optimal manufacturing process is die pressing and sintering for our heat sink. For this process, metal or ceramic powders are blended and then pressed in a closed die to form the shape, as illustrated in Figure BB3, below. It works well with the shape we are producing because all of the sidewalls are parallel, and the undercuts would be at right angles to the pressing direction. In addition, the parts can achieve relatively good surface tolerances and the process can accommodate small massed objects, making this process ideal for our heat sink.

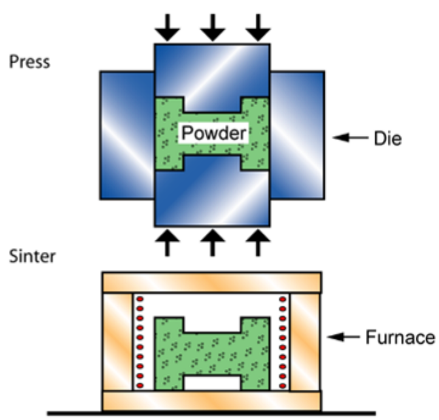


Figure BB3: Process Schematic for Die Pressing and Sintering

As with most of the manufacturing processes, the dies for this process are expensive. The capital cost ranges from $659,800 - $2,639,000; this equates to $0.15 - $0.60 per unit for 4.4 million units. In addition, the tooling cost ranges from $4,713 - $15,080, which equates to $0.001 - $0.003 per unit for 4.4 million units. Thus, this process will be economical for mass manufacture, overcoming the large capital costs in the long run.