

# **Fabricating Replacement Glass Prisms for the Piedras Blancas Lighthouse**

**Daniel Garcken**

**Advisors: Dr. Kathy Chen and Prof. Lee McFarland**

**Materials Engineering**

**California Polytechnic  
State University, San Luis Obispo**

# Approval Page

Project Title:           Fabricating Replacement Glass Prisms for the Piedras Blancas Lighthouse

Author:                   Daniel Garcken

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CAL POLY STATE UNIVERSITY  
Materials Engineering Department

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Prof. Kathy Chen  
Faculty Advisor

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Signature

Prof. Trevor Harding  
Department Chair

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Signature

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## **Acknowledgements**

- Prof. Lee McFarland
- Dr. Kathy Chen
- Dr. Richard Savage
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- Eric Dandurand – Harmony Glassworks
- Piedras Blancas Lighthouse Staff
- Cal Poly Craft Center – Associated Students, Inc.

## **Abstract**

The objective of this project was to design and create a process for manufacturing replacement glass prisms for the Piedras Blancas lighthouse and several other lighthouses nationwide. The prisms were designed to be in multiple metal arrays spread across the floor of the beacon room (the topmost room of the lighthouses). The prisms functioned to transmit extra, radiant light from the beacon light through the floor of the beacon room and disperse it into the maintenance room below. Using computer aided drafting (CAD) software, an original prism was measured and modeled; the corresponding mold was also modeled. G-codes for controlling the movement of a computer numerically controlled (CNC) mill were created to machine the two halves of the mold. A donated block of graphite was machined according to the developed G-codes. As a proof of concept method for casting these prisms, I used a lampworking setup – consisting of a propane-oxygen torch, the associated hoses, regulators, and tanks, an annealing kiln, and the necessary lampworking tools – to melt one end of a borosilicate glass rod into a large gather of molten glass. I forced this gather into the mold, thereby filling the mold, and allowed the glass to solidify. Then I opened the mold, removed the prism, melted off the extra rod, and flattened the top face of the prism. This method, although suitable for the proof of concept, will not be efficient for casting the needed quantity of prisms due to the additional, time consuming steps required. For producing large quantities of these prisms, suggested future work may involve pouring molten glass into the mold via the use of a crucible.

**Keywords:** glass, borosilicate, prism, lighthouse, Piedras Blancas, cast, manufacture



## 1. Introduction

The Piedras Blancas lighthouse, located about 5 miles north of San Simeon Bay on the central coast of California, needs replacement glass prisms. These prisms will also be used in multiple additional lighthouses nationwide (one such lighthouse is San Island lighthouse in Alabama). This project's objectives were to create accurately dimensioned engineering drawings of the prism and of the mold used to cast the prism, manufacture the mold, and cast glass into the mold, thereby creating replacement prisms.

The topmost room of most lighthouses is the beacon room, in which a light turns 360° emitting the beacon light. Below this beacon room is a maintenance room. To illuminate the maintenance room, the lighthouse designers incorporated metal arrays of these glass prisms (**Figure 1**) into the floor of the beacon room (the ceiling of the maintenance room). The prisms – the top surface flush with the beacon room's floor and the bottom facets protruding into the maintenance room – transmit and disperse ambient light from the beacon light into the maintenance room.



**Figure 1:** Each metal array holds 19 prisms, with a total of 14 arrays in the floor of the beacon room (266 total prisms).<sup>1, 2</sup>

### 1.1 Stakeholders

There are multiple people who are affected by the success or failure of this project including:

- Myself
- My advisors:
  - Kathy Chen (Materials Engineering Faculty)
  - Lee McFarland (Mechanical Engineering Faculty)
- The lighthouses in need of replacement prisms.

Funding for this project is supported by the Materials Engineering Department of California Polytechnic State University, San Luis Obispo and by the Piedras Blancas lighthouse staff board. I have completed this project on my own, aside from assistance received from my advisors and three other important people:

- Richard Savage (Materials Engineering Faculty)
- Sam Kaplan (Manufacturing Engineering Student)
- Eric Dandurand (Harmony Glassworks)

## **1.2 Broader Impact**

Due to the important safety aspects of lighthouses, their proper function and maintenance is critical. Proper function of these prisms may ensure the possibility of effective maintenance, which in turn will ensure the effective function of the lighthouse. The Piedras Blancas Lighthouse staff board intends to maintain the historical integrity of the lighthouse; therefore, it is important to ensure that the replacement prisms are as historically accurate as possible. This project requires an understanding of the union between the scientific and artistic aspects of making glass for practical applications.

## **1.3 Design Constraints**

Funding may be limited for this project; therefore all efforts will be made to decrease the cost of completing this project. The material used for the prisms must have high resistance to degradation from ocean air (salt water), ultraviolet (UV) radiation, temperature fluctuations, and possibly mechanical oil or cleaners/solvents. The purpose for the prism is to be a sustainable form of lighting. Therefore, ideally the processing would utilize sustainable methods. The prism's manufacturability is a question of the feasibility of casting glass into the desired shape without excessive (if any) post casting cold work such as grinding and polishing.

There are several safety concerns in terms of the fabrication processes. Melting glass requires extreme temperatures; therefore, precautions should be taken to avoid burns. In addition to the molten glass and the torch's flame, the tools and molds used to manipulate the molten glass can get hot enough to burn flesh. While working with glass, one must always be aware that everything in the studio has the potential to be hot enough to cause a burn. Other safety concerns include the risk of incisions due to sharp, razor-like edges of broken glass and the risk of inhaling harmful fumes given off by the torch (such as NO<sub>x</sub> gases).

## 2. Background Literature

When the lighthouse was first built, the beacon light was illuminated by a kerosene lamp. As opposed to installing multiple kerosene lamps throughout the maintenance room, these prisms utilized the light from the main beacon lamp. When the kerosene beacon lamp was replaced by an electric light bulb, these prisms eliminated the need for additional electrical lines to power additional light bulbs for illuminating the maintenance room.

Prisms such as these were first used as “deck prisms” in sea faring vessels. Vessels such as brigs or schooners – vessels that lay low on the water – had no room on their sides for the placement of portholes to let daylight into the lower compartments.<sup>3</sup> In place of portholes on the sides, deck prisms were placed in the top decks to transmit and disperse light into the lower rooms. There were multiple shapes of these deck prisms (**Figure 2**) but all the shapes were similar in that they all had flat tops that were flush with the surface of the deck and faceted or spherical bottom surfaces that acted to disperse the transmitted light.

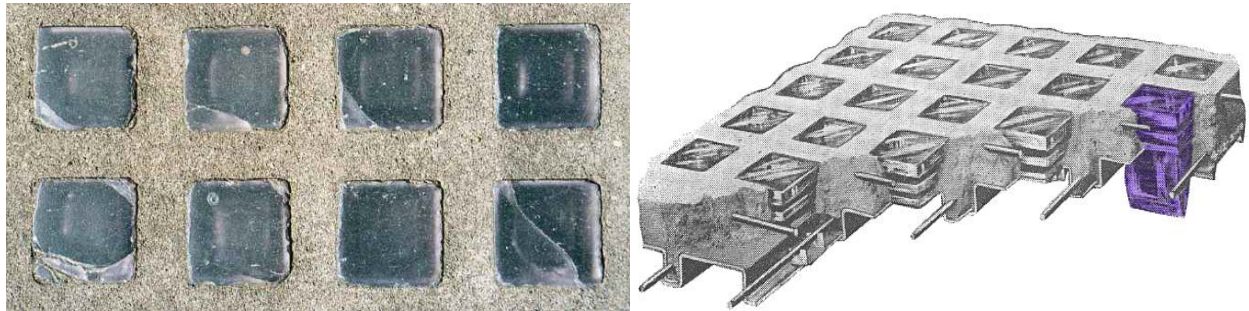


**Figure 2:** Some deck prisms were rectangular or hexagonal, and others were hemispherical.<sup>4</sup>

These deck prisms also improved the safety of sea vessels. Without these deck prisms, the lower compartments of the ship were illuminated by use of oil, kerosene, or whale blubber lamps (all of which

were open flames). These lamps presented obvious fire hazards to the wooden ships, especially those carrying gunpowder, coal, or other flammable/explosive materials. The utilization of these deck prisms eliminated the need for lamps in the lower compartments, thereby reducing the chance of fire.

Deck prisms have also been used in some cities' streets. They are installed in the cement sidewalk to illuminate cellar rooms below (**Figure 3**). Similar to the deck prisms of sea vessels, these sidewalk prisms are flush with the top surface of the sidewalk and have faceted bottoms to disperse the transmitted light.



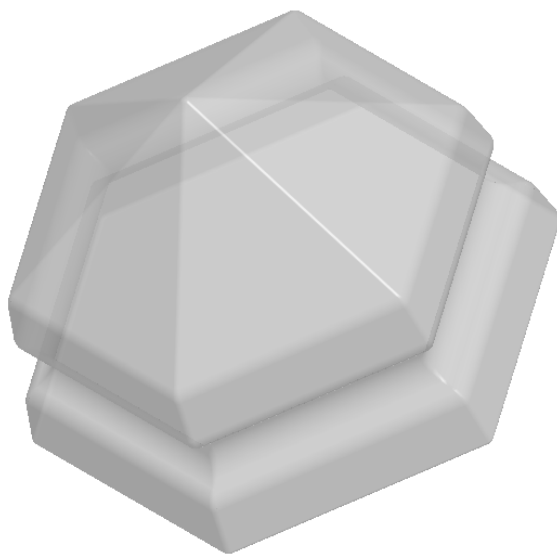
**Figure 3:** Sidewalk prisms supply daylight to the cellars below.<sup>5</sup>

### 3. Methods and Materials

#### 3.1 The Original Prism

The first step to manufacturing replacement prisms was to produce a 3-dimensional model of the original prism using computer aided drafting (CAD) software (Creo Pro-Engineer). This model needed to accurately represent the shape and dimensions of the original prism. The original prism, provided to us by the Sand Island lighthouse in Alabama, was in poor condition; some of its edges were chipped and its surfaces were worn and scratched. In addition to the chipped edges, the rounds on all edges made extrapolating the corners difficult.

To measure the prism's dimensions I first used digital calipers. I then created a CAD model based on these rough dimensions. To obtain more accurate dimensions I utilized an optical comparator; a machine normally used by inspectors that magnifies an image of the part, thereby allowing more accurate measurements.<sup>6</sup> The digital optical comparator that I used imaged the part with a camera and used software to analyze the image generated by the camera. I then updated the model's dimensions with those I obtained from the comparator (**Figure 4**). The final dimensions of the prism are shown in the engineering drawing of the prism (**Appendix I**).



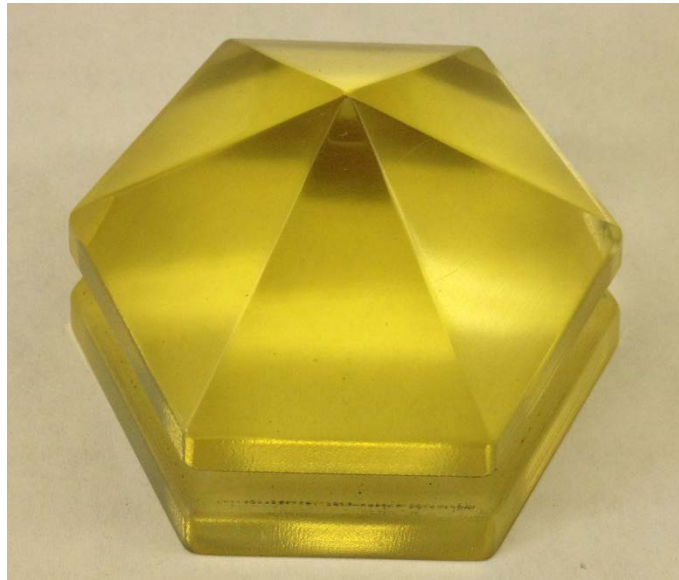
**Figure 4:** Isometric CAD rendering of the virtual model.

I enlisted the help of Dr. Richard Savage to determine the original prism's material. He utilized a handheld x-ray fluorescence (XRF) machine to analyze the prism's glass. The XRF results revealed a 4.5 weight percentage of lead but could not measure the composition percentage of lighter elements (most likely sodium, silicon, and oxygen). This is due to the fact that this handheld XRF tool does not employ a vacuum; therefore the x-rays emitted by these lighter elements were absorbed by the air molecules between the sample (the prism) and the detector and thereby not detected.



### 3.2 Dimensional Verification

The dimensions obtained through the use of the digital calipers and the optical comparator needed to be verified. The CAD model was printed on a rapid-prototyping machine out of a semitransparent acrylic material (**Figure 5**). This physical model of the virtual CAD model was then sent to the Sand Island lighthouse to be test fitted into the metal array. With word back from the lighthouse that the rapid-prototyped model did indeed fit into the metal array, I used the verified dimensions of the prism's CAD model as the dimensions of the mold's cavity (**Appendix II** and **Appendix IV**).

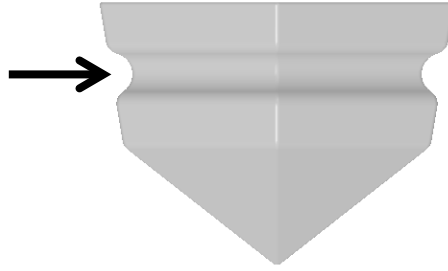


**Figure 5:** Acrylic physical model of the prism.

After verifying the model's dimensions, I created an engineering drawing of the prism (**Appendix I**). I sent this drawing to multiple different mold-making companies to get quotes for the cost of making a mold or of casting the actual prisms. The quotes I received were all surprisingly expensive – one company quoted \$650 for making a single mold, another company quoted \$600 per prism for up to 100 prisms and \$400 per prism for up to 500 prisms. These quotes were taken to the Piedras Blancas lighthouse staff board meeting to attempt to obtain funds; however, the staff board was unable to proffer such funds. Therefore I needed to create a mold here at Cal Poly.

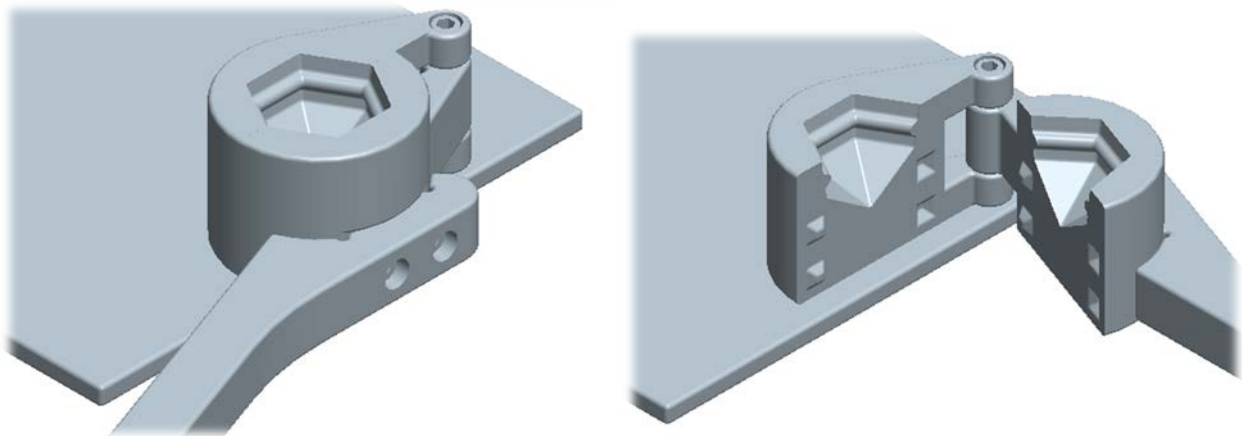
### 3.3 CAD Model of the Casting Mold

The ideal design of a mold for casting glass would be a single piece mold; the mold would be filled with molten glass, the glass would be allowed to solidify in the mold, and then the mold would be inverted and the part would simply fall out. However, due to the undercut feature (**Figure 6**) of this prism, the mold needed to split open to allow for removal of the solidified glass.



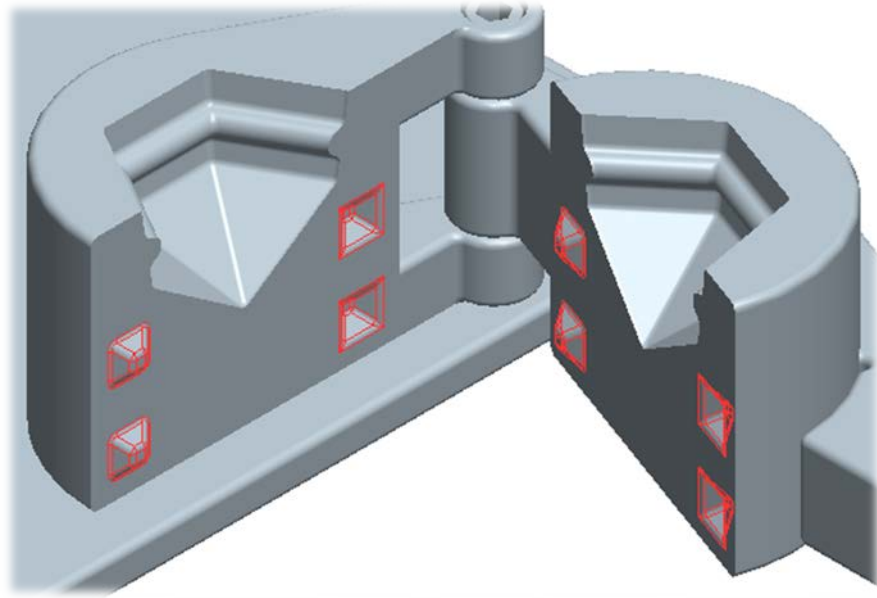
**Figure 6:** The concave feature of the prism indicated by the arrow prevented the mold from being a single piece.

I chose to follow a basic “kick-mold” design (**Figure 7**): the two mold halves were hinged together with one half bolted to a baseplate and the other half free to rotate about the hinge. The operator would stand on the baseplate with his left foot and hold the mold closed by pressing his right foot against a handle attached to the freely rotating mold half. The operator would then fill the mold with molten glass, allowing it to solidify completely within the mold, and then kick open the mold to release the solidified part.



**Figure 7:** The closed mold (left) and the open mold (right).

To align the two halves with respect to each other – to ensure that the two halves of the cavity were aligned – I incorporated pyramid shaped alignment protrusions and corresponding indentations on the adjoining faces of the two halves (**Figure 8**) (**Appendix III** and **Appendix V**). I designed the dimensions of the hinge to allow for some play so as to not interfere with the alignment provided by the pyramids and indentations.



**Figure 8:** The pyramids and corresponding indentations (highlighted red) keep the cavities of the two halves aligned.

With a basic design of the mold modeled in CAD software, I dimensioned the mold's cavity with respect to the verified dimensions of the rapid-prototyped prism. I designed the hinge to correspond to a purchasable shoulder bolt I found on McMaster Carr's online catalog. After completing the CAD model of the mold, I decided to rapid-prototype a physical model of the mold out of acrylonitrile butadiene styrene (ABS) (**Figure 9**).



**Figure 9:** The rapid-prototyped mold was used as a physical reference for creating CNC codes and for machining the mold.



### 3.4 Generating CNC Code

The CAD model I created of the mold was used to create G-codes for machining the actual mold. G-code is a programming language that controls the movement of the cutter of a CNC mill with respect to the material being machined. They define the speed of the spindle, the tool that should be in the spindle, the position of the material with respect to the spindle (X and Y position of the table and Z height of the spindle), and the feed rate at which to move the material.

I consider myself to be sufficiently experienced to create CAD models of the prism and the mold halves. However I have had no experience with creating G-codes. Therefore, I enlisted the help of a Manufacturing Engineering Junior, Sam Kaplan, to create the G-codes and machine the two halves of the mold. He utilized a program “Expert Machinist” (which is a sub-program of the Pro-Engineer software) to create the G-code program.

### 3.5 Choosing Mold Material

I was able to narrow the material selection down to a few possibilities for the mold material: bronze, graphite, or stainless steel. Bronze is a commonly used material for glass molds because it has a high thermal conductivity (which allows the molten glass to cool faster, thereby increasing production rates). Bronze is extraordinarily easily machined, and could produce excellent surface finishes with minimal post-milling processing. However, a solid block of bronze in the size that we needed for the mold would have been too expensive (\$199.33 plus shipping and handling for a 2” x 2.5” x 12” bar on McMaster Carr’s online catalog).

Before we ordered a bar of material for machining the mold, we were donated a block of graphite (**Figure 10**) by Eric Dandurand of Harmony Glassworks. This graphite block (approximately 3” x 5” x 12”) was large enough to machine the two halves of the mold. For a proof of concept, we decided to use the donated graphite. However, the brittleness of graphite presented a concern in terms of the mold’s design: the hinge features, if machined into the graphite, would likely have made the graphite too weak. Therefore, for our proof of concept mold, we decided to exclude the features that would weaken the graphite, such as the hinges and the external rounds. The exclusion of these features in no way affected the performance of the actual cavity of the mold.

Graphite has high temperature resistance that can withstand the molten temperature of glass (which is expected to be approximately 820°C – as determined by the temperature at which the viscosity is low enough to allow the glass to deform under its own weight<sup>7</sup>), a high thermal conductivity (which allows for faster production), and a low coefficient of thermal expansion (CTE) (**Table I**). The low CTE means that as the mold’s temperature is raised, the cavity’s dimensions change minimally; which therefore minimizes the variation in dimension of the cast prism. Because solid graphite is so soft (it is the same thing as pencil lead) and can be easily flaked away, graphite is easily machined. The ease of machining graphite allows for extremely smooth milled surfaces; which in turn eliminates the need for post-milling processing (polishing).

**Table I:** Comparison of thermal properties of bronze, graphite, and stainless steel.<sup>8</sup>

Material	Melting Temperature (°C)	CTE ( $10^{-6} \text{ K}^{-1}$ )	Thermal Conductivity ( $\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$ )
Bronze	947 – 1070	16.5 – 17.5	84 – 86
Graphite	3220 – 3420	0.4 – 0.7	113 – 163
Stainless Steel	1370 – 1450	13 – 20	12 – 24

Stainless steel has sufficient thermal properties (high temperature resistance, high thermal conductivity, and low CTE) but is not as optimal as graphite or bronze. Also, stainless steel is not as easily machined as graphite or bronze. However, the durability of stainless steel would allow for the hinges to safely be machined into the two halves without the chance of breaking.



**Figure 10:** The donated graphite block was milled down to two blocks (2" x 2.5" x 4.625"), each of which were milled into half of the mold.

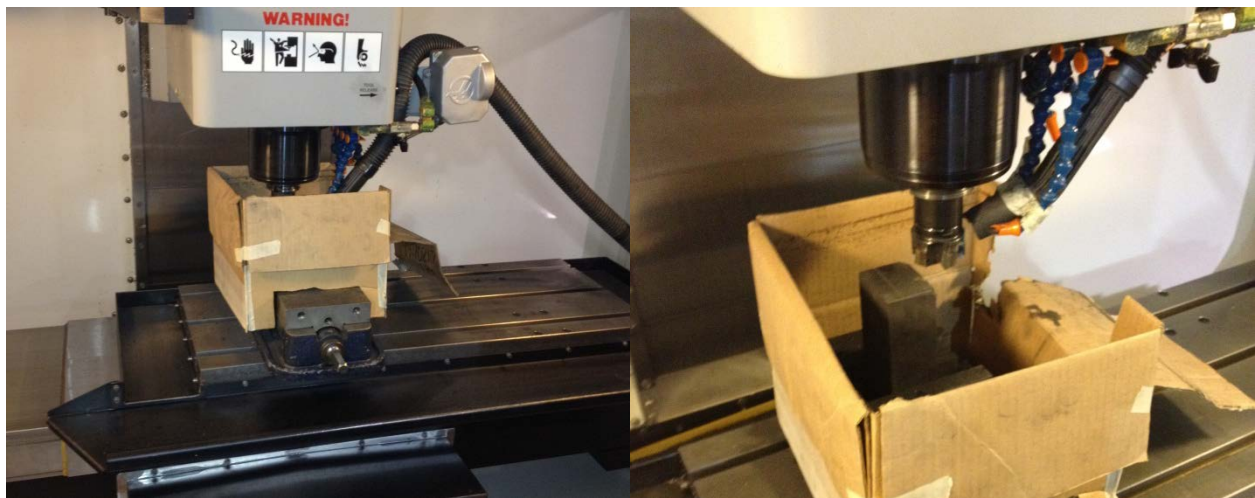
### 3.6 Milling the Mold Halves

The generated G-codes were uploaded to the Haas 3-axis CNC mill in Cal Poly's Industrial and Manufacturing Engineering lab. One of the blocks of graphite was placed into the vice of the mill and the coordinate system of the CNC mill was zeroed to the appropriate corner of the graphite block. The G-code program first utilized a 5/8" flat end mill bit to cut away the bulk of the material needed to be removed, then it switched to a 1/4" flat end mill bit to remove more material that could not be reached by the 5/8" mill bit (**Figure 11**). Finally, the program used a 1/8" ball end mill bit to define the actual surfaces of the mold's cavity and the registering pyramids and indentations.



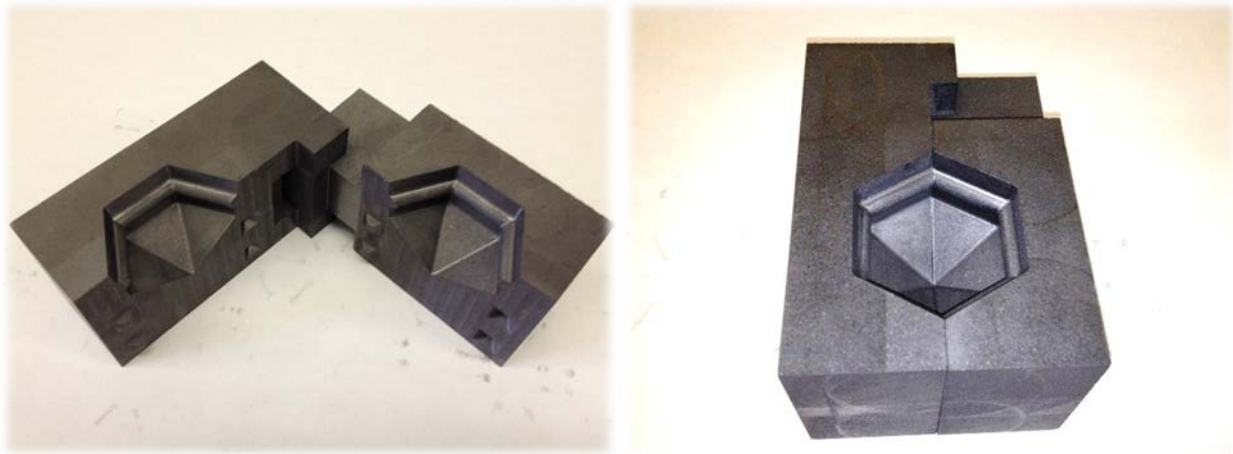
**Figure 11:** The graphite mold partially machined.

To prevent the graphite from making an enormous mess inside the mill, a cardboard box was cut to surround the graphite block and a vacuum's hose was fixed to the coolant outlets (**Figure 12**).



**Figure 12:** The coolant outlet hoses could be positioned close to the cutting bit, which allowed the vacuum's hose to be close to the source of the graphite shavings.

The decision to ignore (and not machine) the external, insignificant features allowed Sam Kaplan to complete machining the two halves in about 3 hours total. With the mold cavity and the registering pyramids and indentations machined (**Figure 13**) the mold could viably be used to cast glass.



**Figure 13:** The completed proof of concept mold, consisting of the two graphite halves.

### 3.7 Casting Borosilicate Glass

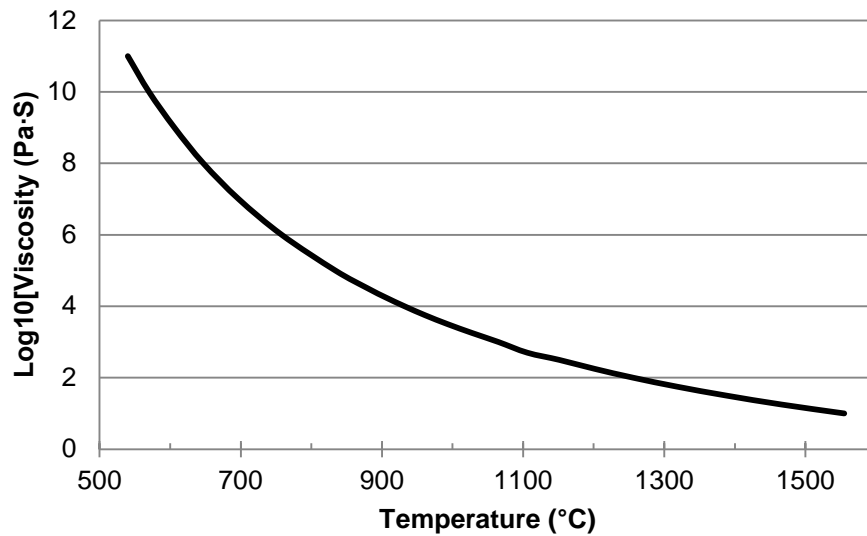
Utilizing my artistic glass working skills I decided to cast proof of concept prisms out of borosilicate glass. Borosilicate glass (commonly known as Pyrex) is used for artistic lampworking: the craft of melting solid glass rods (colored or clear) in a propane-oxygen torch and manipulating the molten glass to make small scale glass art. I have instructed craft classes in lampworking for the last three years of my college career and have thereby developed advanced skills in lampworking. These advanced skills allowed me to successfully create proof of concept prisms. It proved to be extremely convenient that I had these skills for working with borosilicate not only because was I able to create prisms using these skills, but also because borosilicate is a viable (if not optimal) material for these prisms.

Borosilicate glass has high clarity (high transmission percentage) and a high refractive index (transmitted light is spread to a wide angle) (**Table II**). Borosilicate is used for the production of chemistry glassware due to its extreme resistance to degradation (both physical and chemical): it can withstand corrosive environments (such as that of the salty sea air), ultraviolet radiation, and physical abrasion (high resistance to surface scratches) with negligible degradation. Additionally, Pyrex is known to have a low CTE (**Table II**); which is why it is used to make baking dishes that can endure rapid thermal shock without fracturing (e.g. moving a Pyrex dish from a hot oven to cool sink water). In regards to the prisms, borosilicate's low CTE will prevent the glass from drastically shrinking in size as it cools from molten temperature to room temperature.

**Table II:** Material properties of borosilicate glass.<sup>9</sup>

<b>CTE (<math>10^{-6} \text{ K}^{-1}</math>)</b>	3.2 – 3.3
<b>Index of Refraction</b>	1.46 – 1.48

To cast the proof of concept prisms, I used the facilities at Cal Poly's Craft Center (part of Associated Students, Inc.) and began by acquiring a 1 inch diameter, solid, clear rod of borosilicate. I introduced one end of this rod into a propane-oxygen torch's flame. Rotating the rod about its axis continuously, I heated the glass rod slowly at first to avoid creating a drastic stress concentration between the surface and the interior of the solid rod; which could potentially fracture the glass. Once I preheated the end of the rod I brought it closer to the torch's tip and into the hottest portion of the flame. As the glass on the end of the rod melted (**Figure 14**), the rotation of the rod, as well as the surface tension of the molten glass, kept the molten glass from dripping off the end of the rod. The molten glass formed a ball on the end of the rod and, as I continued to heat it, the molten glass gathered larger (**Figure 15**).



**Figure 14:** Graph of viscosity of borosilicate with respect to temperature.<sup>10</sup>



**Figure 15:** The glass gathered on the end of the rod glowed white hot.



Because the mold had no hinges, I used a C-clamp to press the two halves of the mold together. After I had gathered the correct amount of glass on the end of the rod (approximated by visual inspection), I held the rod vertical, with the molten portion on the bottom, and forced the molten glass into the mold (**Figure 16**).



**Figure 16:** The molten glass must be forced downward into the mold to fill all the details.

I then used a flat, graphite paddle to push glass into the top portion of the mold. After the glass had solidified inside the mold, I removed the C-clamp, opened the two halves, and removed the prism. However, the top face of the prism was still attached to the initial glass rod (**Figure 17**).



**Figure 17:** The cast glass is still attached to the initial rod.

To remove the prism from the rod, I used a tool called a “claw-grabber” (**Figure 18**) to hold onto the bottom of the prism and I heated the glass rod just above the top face of the prism. With that glass molten I was able to stretch it out (thereby decreasing its diameter) until the diameter was small enough to allow surface tension to cut the molten glass and separate the rod from the prism.



**Figure 18:** A six-wire claw-grabber firmly held the six facets of the prism.<sup>11</sup>

This method of flame cutting the prism off the rod left a significant amount of extra glass on the top face of the prism. To remove this extra glass, I heated the top face to molten without heating the other features of the prism and tweezed away the extra glass. I repeated this until sufficient glass had been removed. To flatten the top face I heated the entire top face to molten and pressed it on a flat graphite pad.

After completely shaping the prism, I placed the prism in a kiln to cool it from working temperature (560°C) to room temperature over a period of approximately 12 hours. This slow cooling was necessary to eliminate any stresses that could have developed if the surface cooled significantly faster than the interior.

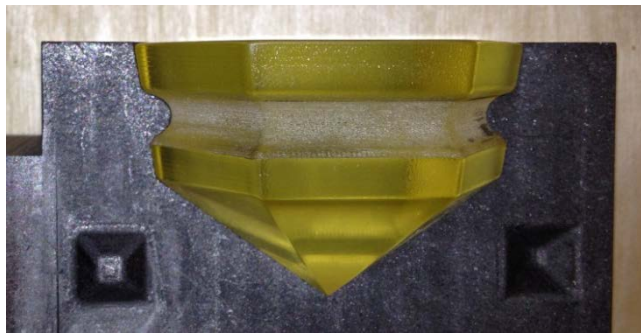
#### 4. Results

I have cast 4 prisms using the lampworking techniques stated previously. These 4 prisms all had excellent surface finishes and showed no evidence of any marks made by the parting line of the mold (**Figure 19**). Due to the fact that I had to approximate the size of the gather necessary to completely fill the mold, I consistently overfilled the mold. I had determined that it was possible to remove extra glass from the prisms' top surfaces but it would have been impossible (or at least impractical) to under-fill the mold and attempt to add additional glass to get the top surface to the correct height. Therefore, I consistently had to remove extra glass from the top surface.



**Figure 19:** The 4 prisms cast out of borosilicate next to the rapid-prototyped prism.

This process (done by hand and by eye) inherently created variation in the height of the prisms. The ideal height of the prisms would be the height at which the top surface of the prism is flush with the top surface of the mold (**Figure 20**). However, the top surfaces of the prisms I had produced were about 1/16" to 1/8" above the top surface of the mold (**Figure 21**).



**Figure 20:** The acrylic prism placed into one half of the mold to show the ideal height.



**Figure 21:** A glass prism placed into one half of the mold to show the achieved height.



## 5. Discussion

### 5.1 Leaded Glass

I was not surprised to find 4.5 weight percent lead in the original prism; leaded glass is commonly used for optics because it has high clarity (analogous to high brightness or a high transmission percentage) and a high refractive index (it disperses the light to a wide angle) (**Table III**). The addition of lead to silica glass decreases the glass transition temperature of the glass (**Table IV**), thereby making manufacturing easier.

**Table III:** Material properties of leaded glass.<sup>12</sup>

<b>CTE (<math>10^{-6} \text{ K}^{-1}</math>)</b>	9.7 – 10.1
<b>Index of Refraction</b>	1.52 – 1.54

**Table IV:** Comparison of glass transition temperatures of various glass compositions.<sup>13</sup>

<b>Material</b>	<b>Glass Transition Temperature (°C)</b>
<b>Leaded Silica Glass</b>	432 – 580
<b>Soda-Lime Silica Glass</b>	454 – 607
<b>Borosilicate Glass</b>	488 – 648

However, although leaded glass has these desirable optical properties, it also has poor resistance to surface scratches. The fact that the prisms' top faces are flush with the floor of the beacon room means that they are walked on repeatedly. The original prism's top surface was scratched and scuffed, which effectively decreases the amount of light that could possibly be transmitted. Additionally, I would not feel comfortable being exposed leaded glass at molten temperature. At this elevated temperature lead particles could potentially escape the glass, enter the surrounding air, and then be inhaled (which logically presents health concerns).

### 5.2 Imperfect Prisms

Although the additional height of the top surface of the prisms is not ideal, it is not extremely detrimental. This extra height could potentially capture more light from the beacon light; however, it also means that the top surface of the prism will not be perfectly flush with the beacon room's floor, which may create an uneven walking surface in the floor of the beacon room. There is also a greater chance of scratching the more exposed top surface of the prism.

Additionally, the claw-grabber tool used to maintain control of the prism as the initial rod is melted off tended to leave indentations in the glass where the end of the wires touched the glass (**Figure 22**). This could be minimized by waiting longer between removing the solidified part from the mold and placing the claw-grabber onto the prism (allowing it to more completely solidify). However, even when I did this,

the claw-grabber would inevitably leave indentations as the glass heated up while I was working on the top face.



**Figure 22:** Handling marks (circled in red) left by the ends of the wires of the claw-grabber.

### 5.3 Future Method for Casting Prisms

The lampworking methods used to create the proof of concept casts produced prisms that were slightly too tall and that had handling marks from the claw-grabber. I suggest that future casting methods should focus on minimizing the variation in height and eliminating the handling marks. One possibility is to cast these prisms by filling the mold with molten glass poured from a crucible (**Figure 23**).



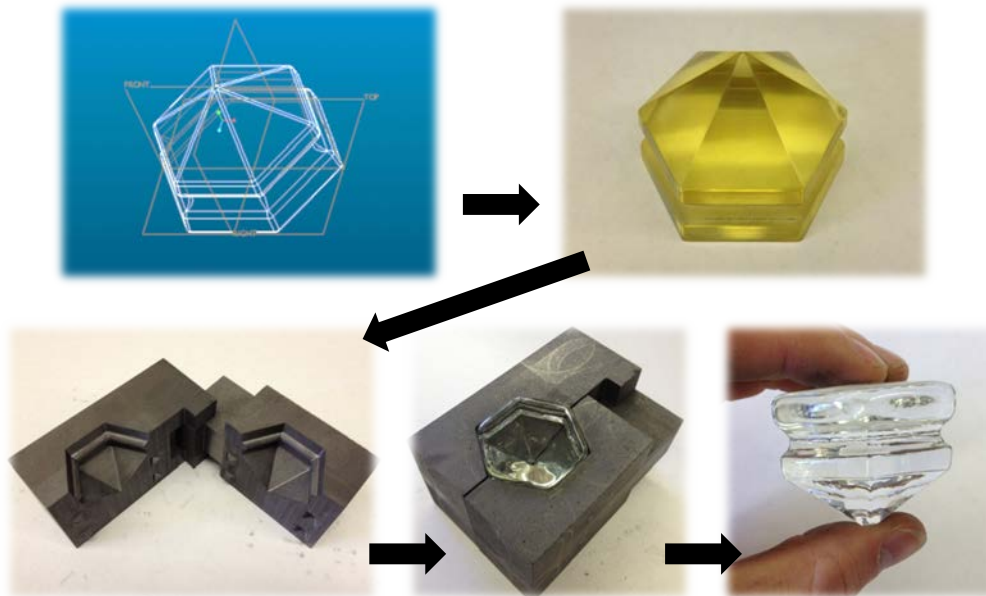
**Figure 23:** Pouring molten glass from a crucible requires full heat protection attire.<sup>14</sup>

This method would, after sufficient practice, allow the casting technician to more accurately gauge the amount of glass that is poured into the mold. The fact that glass would be poured into the mold from a crucible means that there is no solid glass rod from which the prism needs to be removed; thereby eliminating the need for removing the prism from the mold, attaching the claw-grabber, cutting the prism free from the initial rod, and flattening the top surface. Once the appropriate amount of glass has been poured into the mold, the glass poured into the mold would separate itself from the stream of glass coming from the crucible due to surface tension and ample superheat of the molten glass. Pouring the glass from a crucible effectively decreases the number of processing steps, eliminates the unnecessary handling marks, and allows the height of the prisms to be honed to more accurately resemble the height of the original prism.

In addition to eliminating the additional processing steps, production rates would be increased if the mold used was made of stainless steel. Unlike the graphite mold, the hinge features of a stainless steel mold would be able to withstand repeated opening and closing; and with all the features of the mold included in the machining process, the mold could be used as its design intended (as a kick-mold). Possible costs associated with this crucible method may include the cost of studio use (for a studio that contains a furnace in which to heat the crucible), an increased cost of manufacturing the mold (due to slower feed rates and therefore longer machining times), and a greater cost of energy for powering the furnace as compared to the energy required to power the small kiln I used to anneal the prisms in the Craft Center.

## 7. Summary

To fabricate replacement glass prisms, I first measured and modeled the original prism. I then verified the dimensions of the model by rapid-prototyping a physical model of the prism and test fitting that into the metal array at the lighthouse. From there I used the verified dimensions to create a CAD model of the casting mold. The model of the mold was used to create G-codes for machining the mold out of a viable material. After choosing graphite as the mold material, the G-codes were used to CNC mill the two halves of the mold. I brought the machined mold to the Craft Center; where I gathered molten glass on the end of a solid, borosilicate glass rod and filled the mold with the molten glass. I removed the solidified prism from the mold and melted the initial rod off the top face of the prism. After flattening the top face of the prism, I placed it into a kiln to slowly cool over a period of 12 hours. The intent of the project was to create glass prisms that matched (as closely as possible) the dimensions and shape of the original prism (**Figure 24**).



**Figure 24:** Depiction of the general steps taken to complete the project.

## **6. Conclusions**

The initial CAD model of the prism accurately represented the size and shape of original prism since a rapid prototyped prism did indeed fit properly into the metal array. The mold design allowed for easy manufacture and accurate alignment of the two mold halves. The mold material withstood the high temperature conditions of casting molten glass. Although the graphite mold was not able to accommodate the hinge, a stainless steel mold would be a viable replacement.

The prisms created as proof of concept prisms (those created at the Craft Center by lampworking methods) can be utilized as replacement prisms. They have clean, smooth surfaces with no evidence of a parting line. They are made of borosilicate; which has optimum optical and degradation properties for this specific application. The dimensions of the prism (aside from the overall height of the top surface) accurately represent the dimensions of the original prism and therefore will efficiently illuminate the maintenance room.

The suggested method for creating the prisms in the future will eliminate the problems associated with the proof of concept method. Casting glass prisms with a crucible will eliminate additional processing steps, thereby increasing productivity and eliminating unnecessary handling marks, and it will produce prisms with more accurately dimensioned top surfaces.

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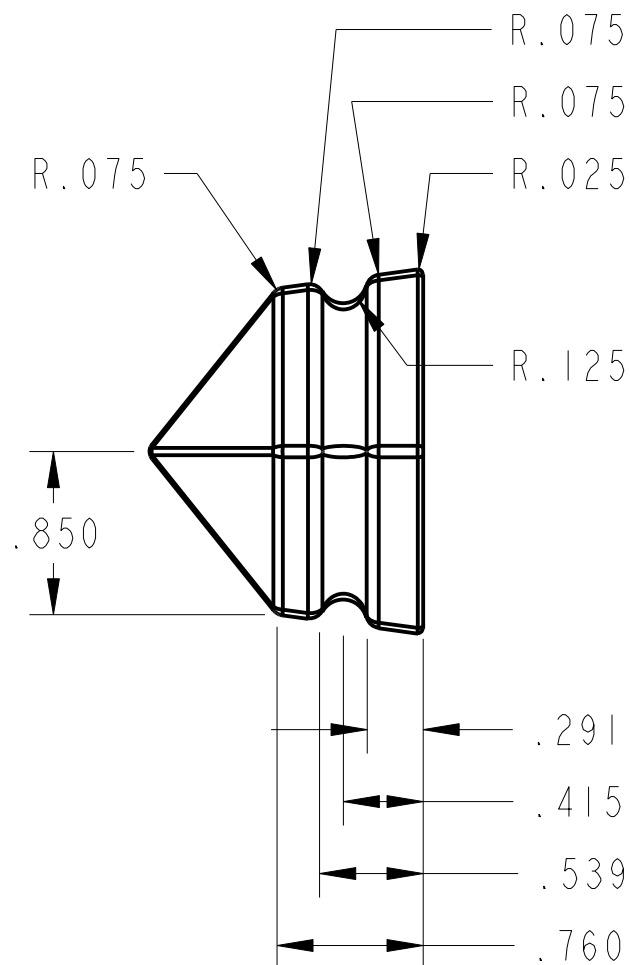
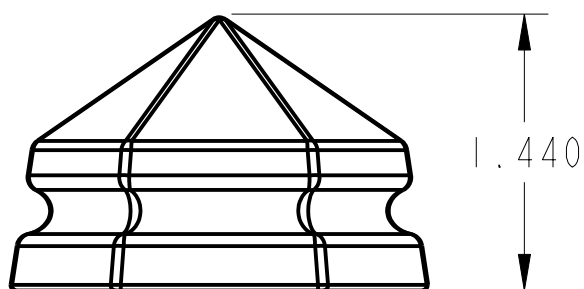
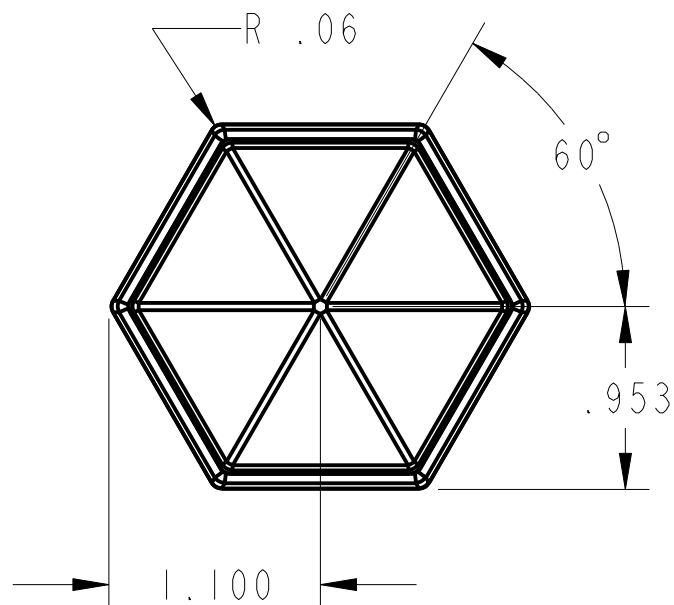
MODEL NAME

PRISM

TITLE

Drawing of Prism for Lighthouse

Appendix I



UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.001  
ANG +/- 1°

DRAWN BY  
Daniel Garcken

DATE  
27 Feb. 2012

CHECKED BY

DATE

APPROVED BY

DATE

TITLE

Drawing of Prism for Lighthouse

PROJECT

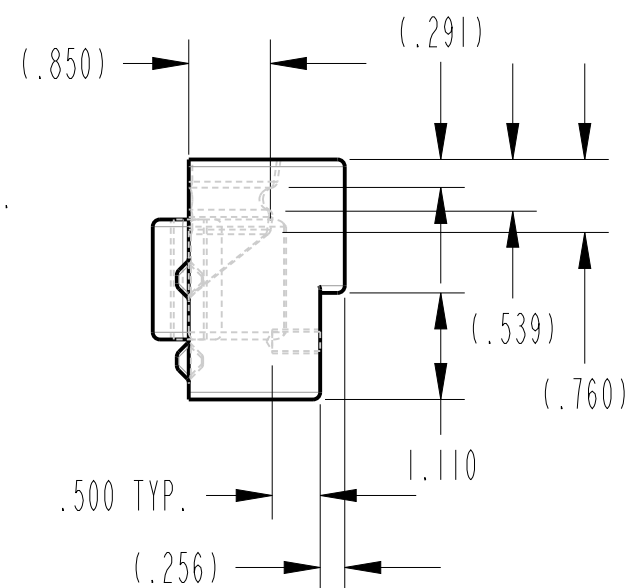
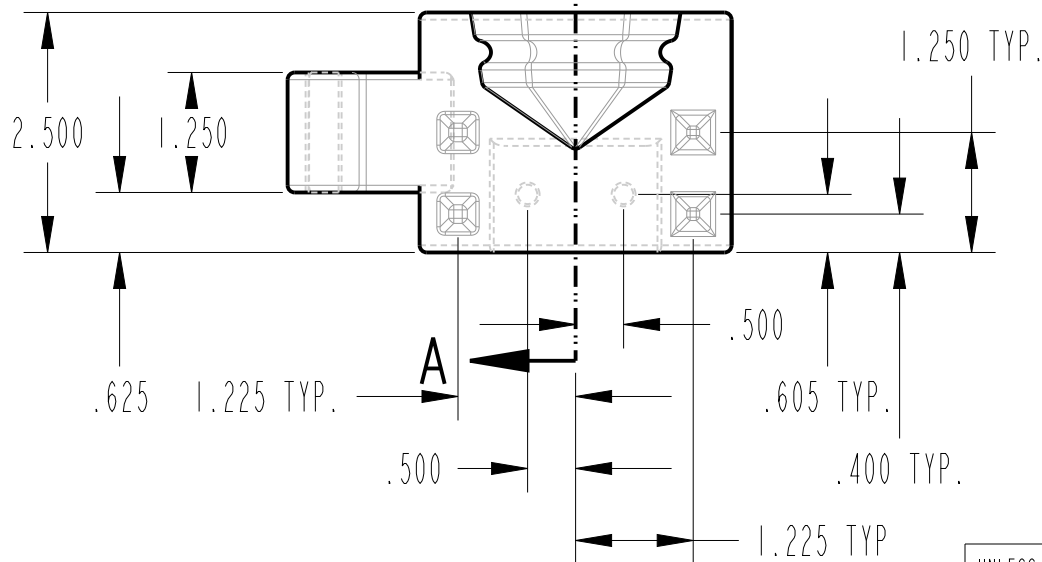
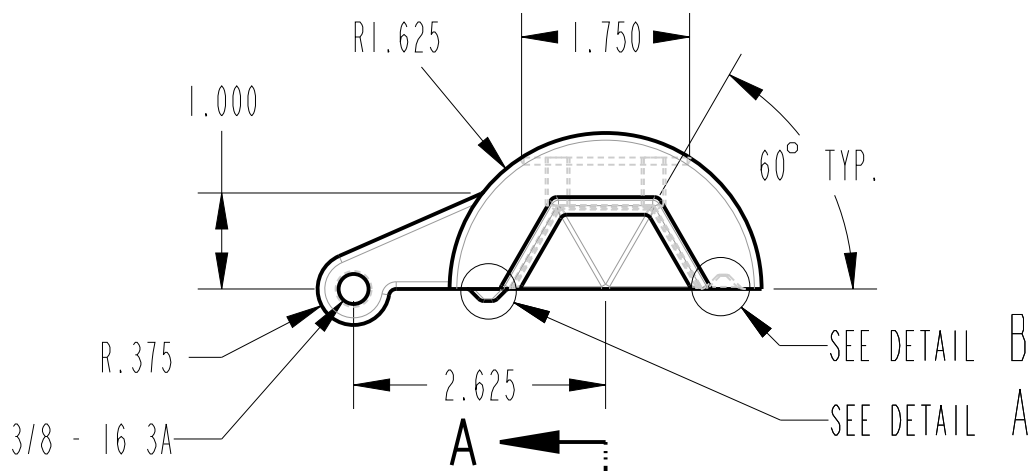
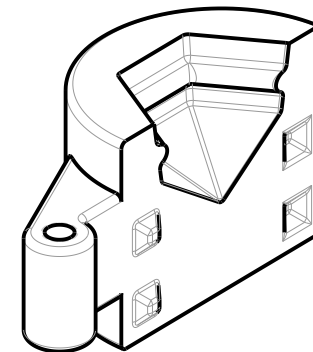
Senior Project

SHEET 1 OF 1

SCALE 1 : 1

MODEL NAME  
MOLD\_ATITLE  
Handle Side of Kick Mold

Appendix II

MATERIAL  
Bronze

UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.005  
ANG +/- 1°

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NOTE  
UNLESS OTHERWISE SPECIFIED  
R .075 ON ALL ROUNDED EDGES

TITLE

Handle Side of Kick Mold

PROJECT  
Kick Mold

DRAWING 1 OF 4

SHEET 1 OF 2

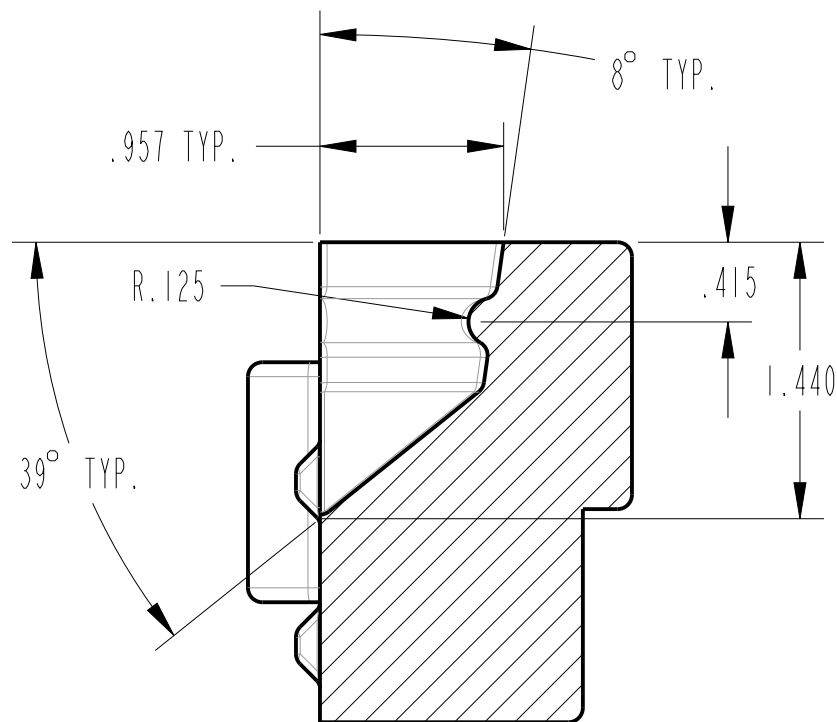
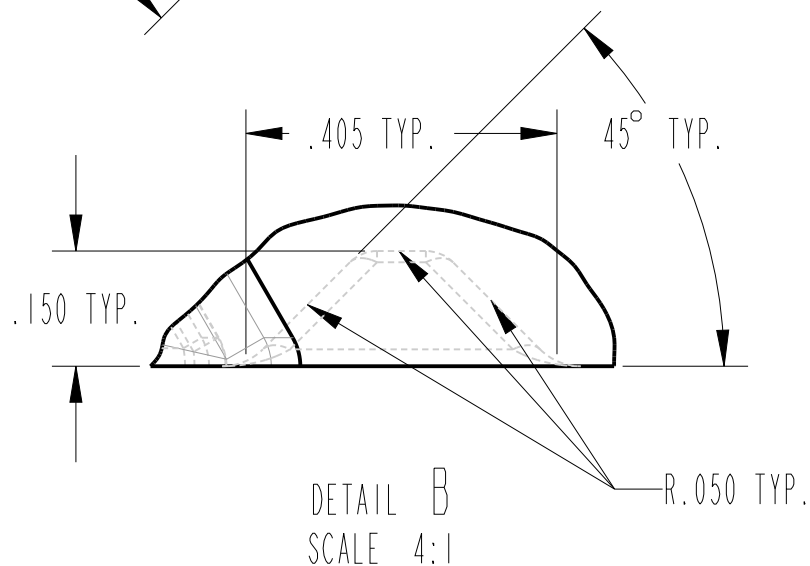
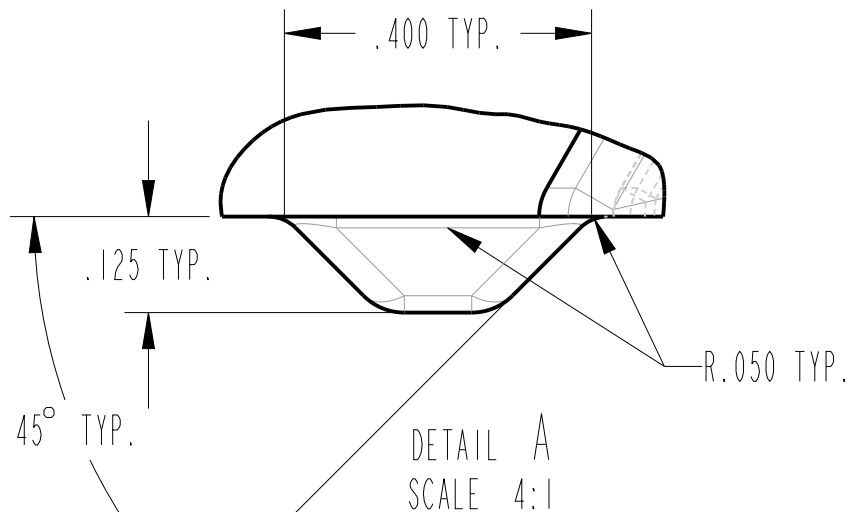
SCALE 1 : 2



MODEL NAME  
MOLD\_A

TITLE  
Handle Side of Kick Mold (Cont.)

Appendix III



SECTION A-A  
SCALE 1:1

MATERIAL  
Bronze

UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.005  
ANG +/- 1°

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NOTE  
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R .075 ON ALL ROUNDED EDGES

TITLE  
Handle Side of Kick Mold (Cont.)

PROJECT  
Kick Mold

DRAWING 1 OF 4

SHEET 2 OF 2

SCALE 1 : 1

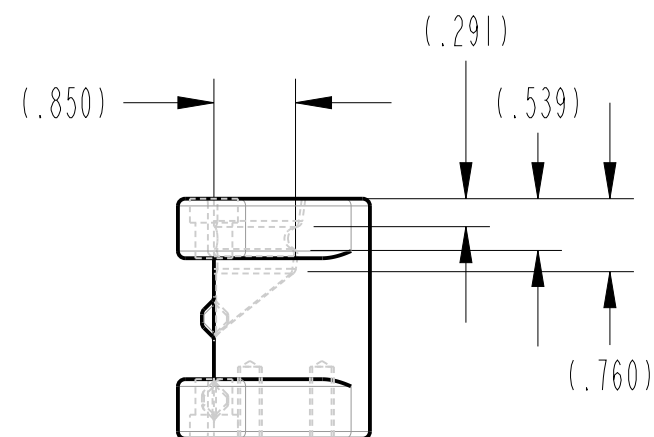
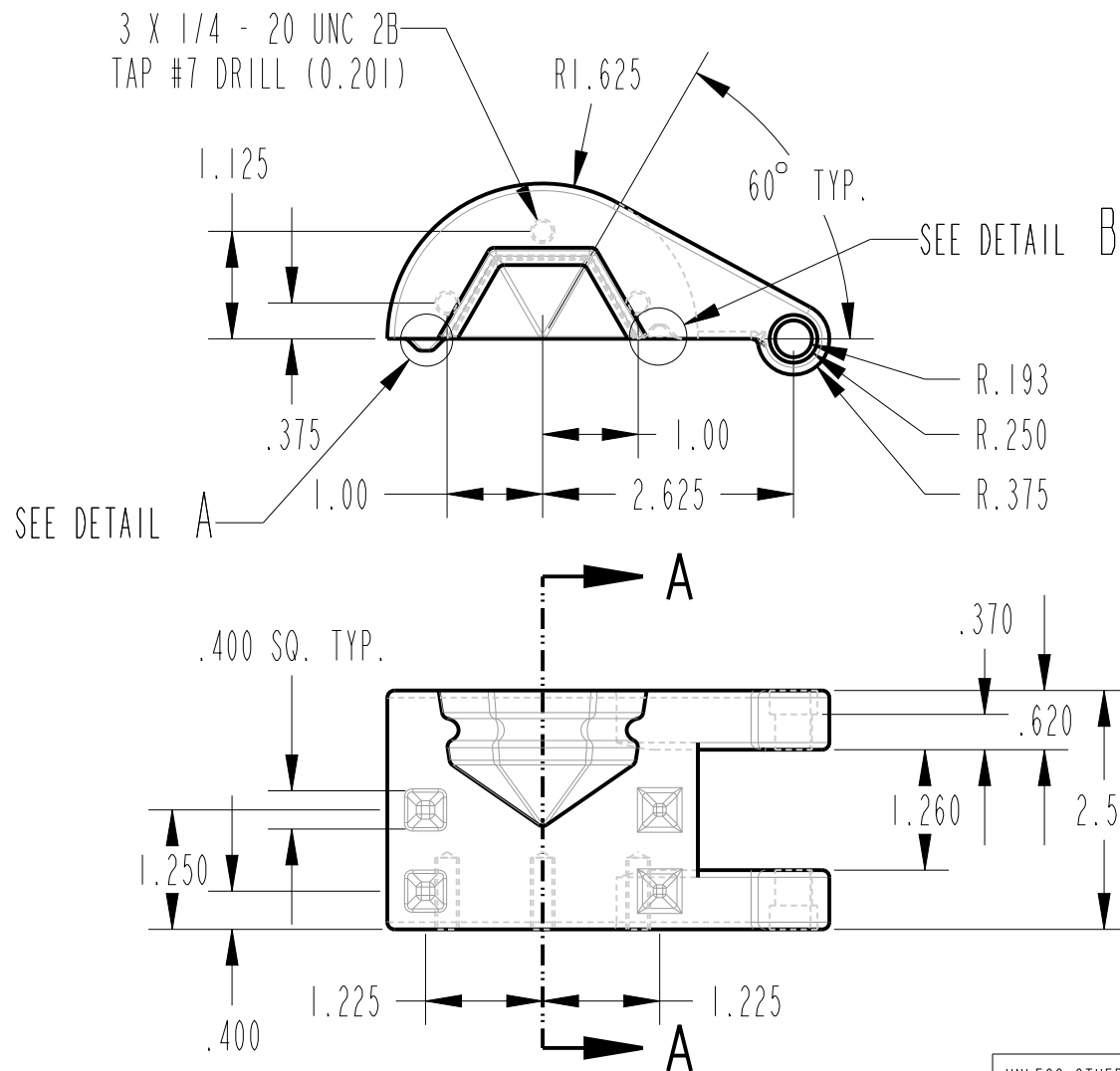
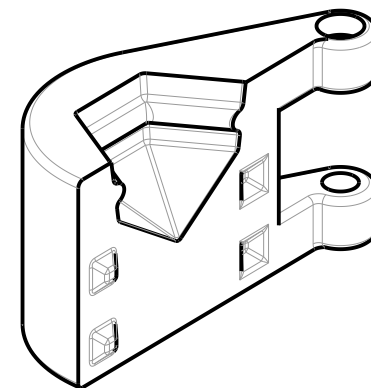
MODEL NAME

MOLD\_B

TITLE

Base Side of Kick Mold

Appendix IV



MATERIAL

Bronze

UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.005  
ANG +/- 1°

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NOTE

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TITLE

Base Side of Kick Mold

PROJECT

Kick Mold

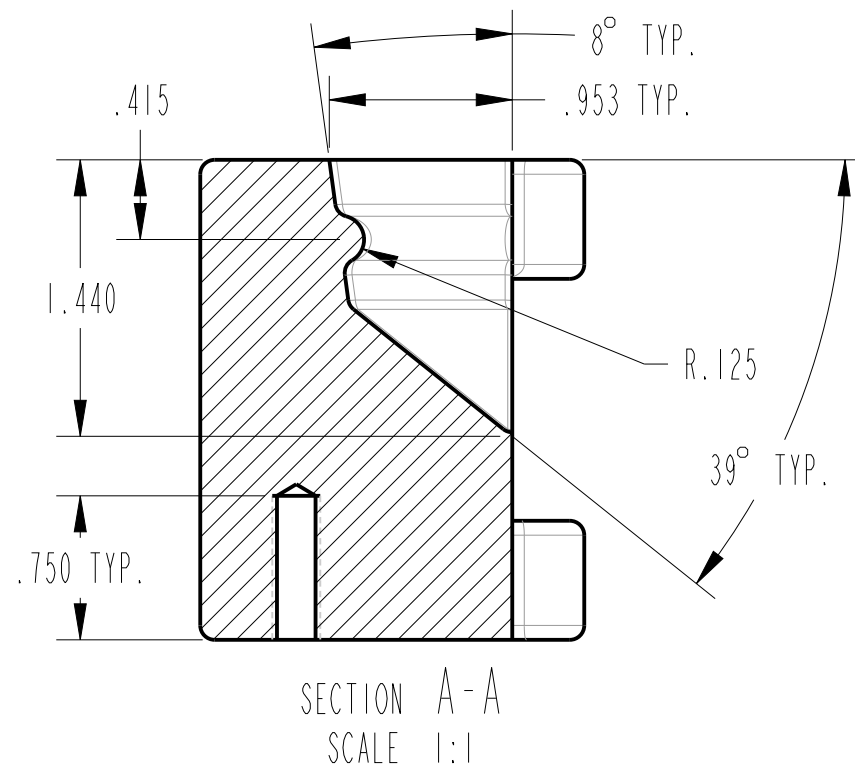
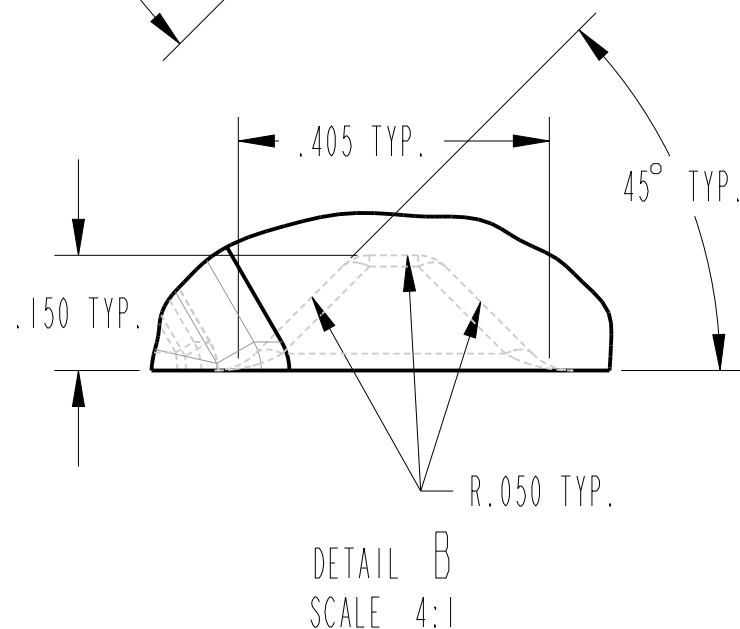
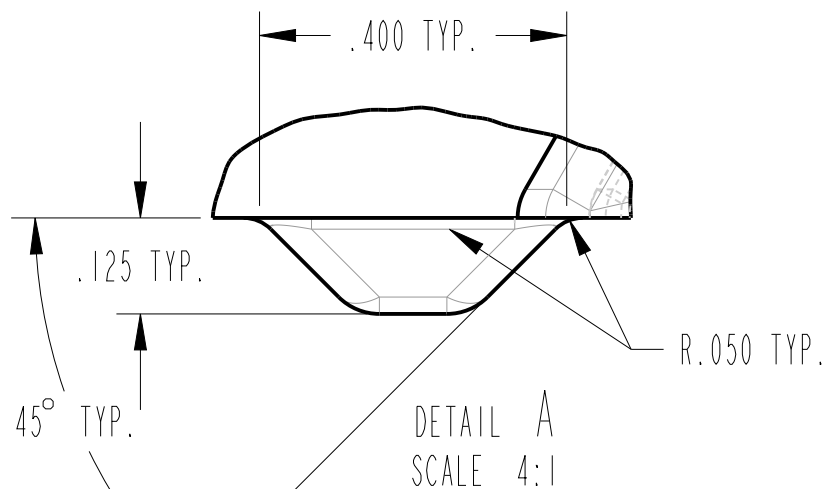
DRAWING 2 OF 4

SHEET 1 OF 2

SCALE 1 : 2

MODEL NAME  
MOLD\_BTITLE  
Base Side of Kick Mold (Cont.)

Appendix V

MATERIAL  
Bronze

UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.005  
ANG +/- 1°

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NOTE  
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R .075 ON ALL ROUNDED EDGES

TITLE  
Base Side of Kick Mold (Cont.)PROJECT  
Kick Mold

DRAWING 2 OF 4

SHEET 2 OF 2

SCALE 1 : 1

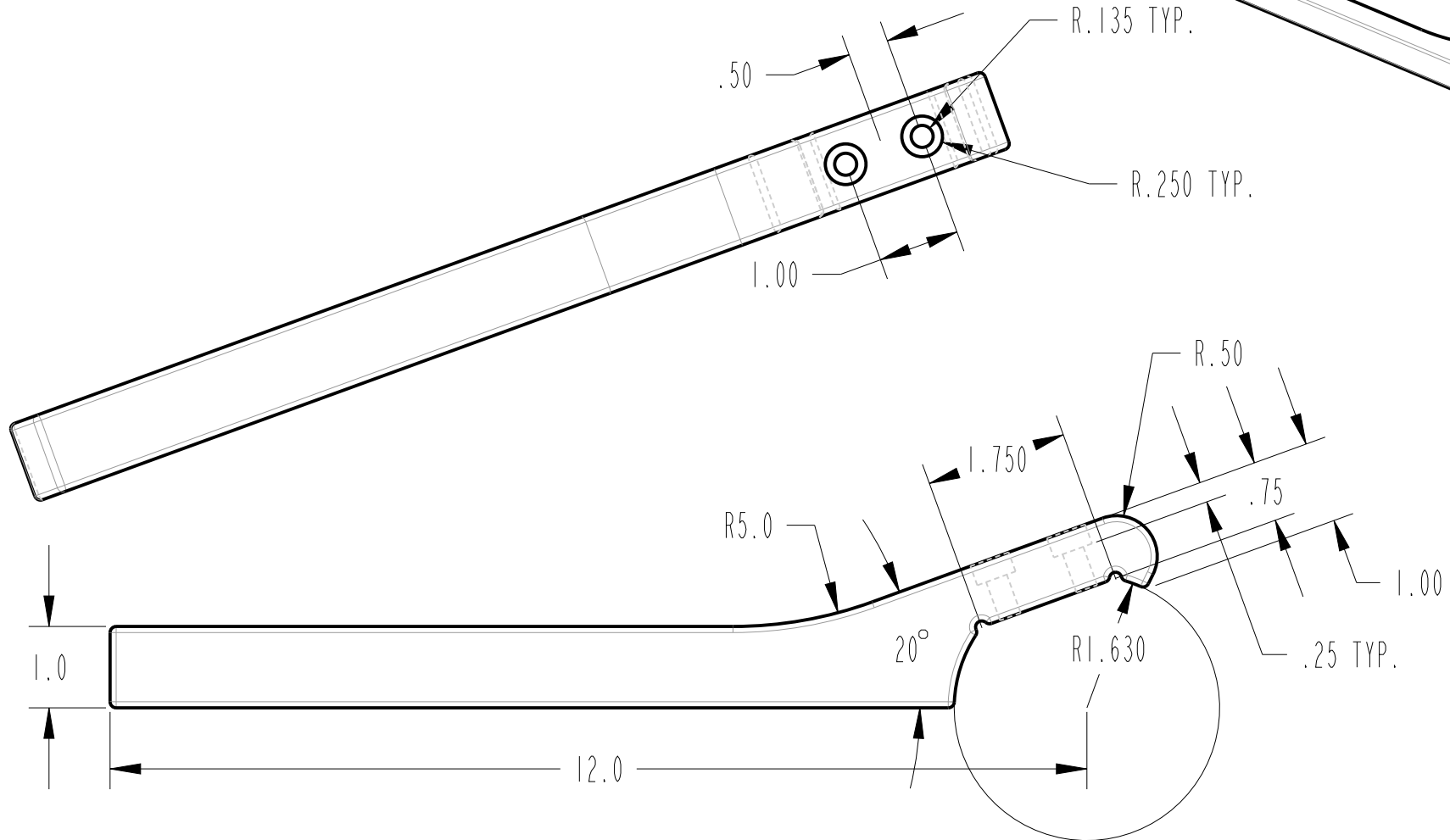
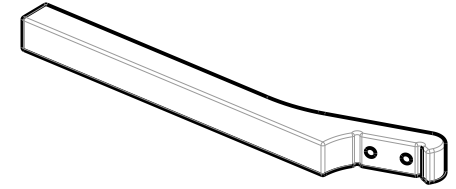
MODEL NAME

HANDLE

TITLE

Kick Mold Handle

Appendix VI



MATERIAL

Aluminum

UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.005  
ANG +/- 1°

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TITLE

Kick Mold Handle

PROJECT

Kick Mold

DRAWING 3 OF 4

SHEET 1 OF 1

SCALE 1 : 2

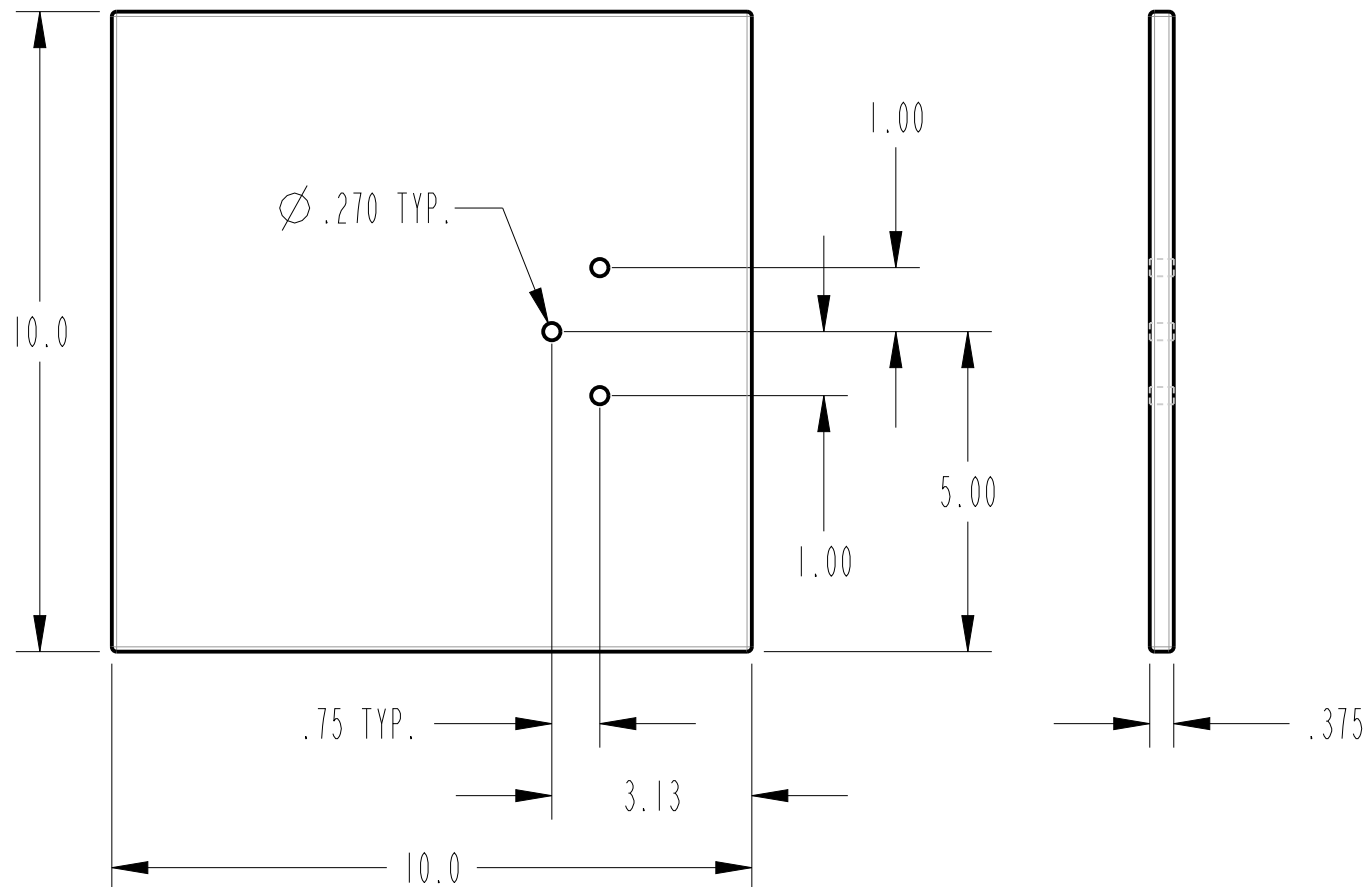
MODEL NAME

BASE

TITLE

Kick Mold Base

Appendix VII



MATERIAL

Aluminum

UNLESS OTHERWISE SPECIFIED ALL  
DIMENSIONS ARE IN INCHES.  
TOLERANCES ARE:  
X.X +/- 0.1  
X.XX +/- 0.01  
X.XXX +/- 0.005  
ANG +/- 1°

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NOTE  
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TITLE

Kick Mold Base

PROJECT

Kick Mold

DRAWING 4 OF 4

SHEET 1 OF 1

SCALE 1 : 3