Design and Preliminary Characterization of Thermally-actuated Pumps

Utilizing Marangoni and Leidenfrost Effects

by

Stephen Joseph Sedler

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering (Honors Associate)

Presented May 24, 2007
Commencement June 2007

AN ABSTRACT OF THE THESIS OF

Stephen Joseph Sedler for the degree of Honors Baccalaureate of Science in Mechanical Engineering presented on May 24, 2007. Title: Design and Preliminary Characterization of Thermally-actuated Pumps Utilizing Marangoni and Leidenfrost Effects

Abstract approved:

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Vinod Narayanan

Design and preliminarily characterization of two thermally-actuated pumps is presented in this thesis. The unique feature of both pumps is the presence of periodic asymmetrical structures on the channel walls. Two heat transfer effects are used with surface asymmetry to generate forces that drive the fluid in a preferential direction in these pumps. Specifically, a closed-channel pump utilizing the Leidenfrost effect on a ratchet-like asymmetrical topology and an open-channel pump utilizing the Marangoni effect on a ratchet-like asymmetric topology are investigated. The Leidenfrost pump design consists of a closed-channel with ratcheted sidewalls to propel the liquid. A key feature of the closed channel pump is a proposed concept for vapor removal. The vapor is extracted from the liquid channel to the surrounding atmosphere through separate variable-depth channels. The Marangoni pump design consists of an open-channel with a ratcheted bottom channel wall. Designs of the pump are debugged using proof-of-concept testing to yield final pump designs. These final designs are then characterized based on mass flow rate for varying temperature inputs at a fixed pressure differential across the pump. The Leidenfrost pump shows a large variation in mass flow rate for lower Leidenfrost surface temperatures and more consistent flow rates at the high Leidenfrost temperature transition. The Marangoni pump yields conflicting data that may be improved upon with a more sensitive setup.

Key Words: pumping, asymmetric topology, Leidenfrost, Marangoni

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APPROVED:

Mentor, representing Mechanical Engineering

Committee Member, representing Mechanical Engineering

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Stephen Joseph Sedler, Author

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CONTRIBUTION OF AUTHORS

Chapter 3 was written as a senior project group consisting of Andrew Brock, Christopher Iadanza, Mark Luckeroth, and Stephen Sedler. Design and testing of the Leidenfrost pump along with the writing in Chapters 4.1, 4.2, and 7.1 was completed by the senior project group as well. Design and testing of the Marangoni pump was completed by Myeong Chan Jo and Stephen Sedler.

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To Mom

and Dad and T and Austyn

who are most definitely cruzin'

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Design and Preliminary Characterization of Thermally-actuated Pumps Utilizing Marangoni and Leidenfrost Effects

1. INTRODUCTION

When it comes to pumps, the most utilized are mechanical pumps which use shaft power of an electric motor to displace a fluid. In contrast, the pump designs presented in this thesis attempt to utilize undesirable waste heat from a source to drive the fluid flow. These are called thermally-actuated pumps. Specifically, single-phase liquid and two-phase liquid-vapor pumping are studied here. These pumps presented utilize repeated asymmetry in pumping geometry to move fluid in a preferred direction.

Thermally-actuated pumps could be most readily pertinent to thermal management of high power devices. Currently some desktop computers use liquid cooling technology for the processor temperature regulation. These units require mechanical pumps that are powered by electrical motors and tend to be expensive, heavy, and noisy, while also containing moving parts that wear down. A thermally-actuated pump would eliminate the need for additional power input as well as moving parts. Thermally-actuated pumps also open up the possibility for the design of micro scale pumps which greatly reduce the weight and cost associated with thermal management technology.

The fluid-channel wall interface in the pump is the crucial feature of the proposed pump designs. One or more channel walls have an asymmetric topology which causes the fluid motion preferentially in one controllable direction creating a net flow of the liquid. This is in contrast to a flat fluid-channel wall which would have seemingly random flow, or a repeated symmetric surface which would only produce localized flow with no net fluid motion.

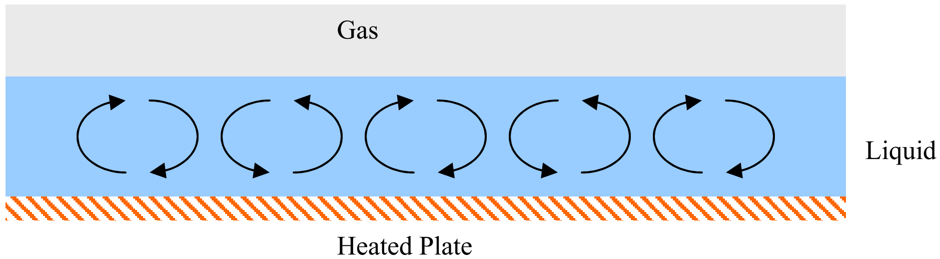
This thesis describes the design of a two-phase liquid-vapor pump that utilizes the Leidenfrost effect. Also discussed here is a single-phase liquid pump that drives fluid using surface tension gradients (Marangoni effect). Both pumps have asymmetric "ratchet-like" channel wall(s). Preliminary results of their performance are also reported.

The concepts on which the pumps will be based around are the Leidenfrost effect (film-boiling) and the Marangoni effect. The Leidenfrost effect occurs when a liquid is placed on a heated surface that is at a temperature significantly higher than the liquid saturation temperature. In this situation, the liquid floats on its own vapor cloud. When the liquid initially comes in contact with the heated surface, it quickly transforms part of the liquid into vapor. This vapor layer then inhibits the rapid heat transfer from the heated surface into the liquid while also lifting the liquid away from the heated surface. This concept can most easily be imagined in the kitchen. With a hot frying pan, a drop of water can be dropped into the frying pan and the water will hover around the frying pan, slowly boiling off. However, this concept is not limited to droplets hovering in a frying pan, as it is also possible to quickly poke wetted fingers in and out of a pot of molten lead without suffering any burns as shown by Walker [1].

The Marangoni effect occurs when a variation in surface tension is present between two liquids. This surface tension variation causes the higher surface tension liquid to pull on the lower surface tension liquid to produce a motion within the fluid. Ways of obtaining differing surface tensions to utilize the Marangoni effect include varying temperatures of the same liquid (since surface tension is a function of a liquid's temperature) or placing different miscible liquids with differing surface tensions in contact with each other. With the variance-in-temperature-method of changing the surface tension, the surface tension can continually be both increased and decreased as the temperature is decreased and increased, respectively. With the differing-liquids-method of creating a gradient, once the liquid mixture concentration is constant throughout, the motion ceases until another surface tension liquid is introduced.

When a liquid is heated on a flat surface, the warmer liquid near the heated surface will be driven upward to the liquid gas interface and cool down as the distance to the heated surface increases. Correspondingly, portions of cooler liquid will be driven downward and heat up as it approaches the heated surface [2]. Liquid motion is created, as shown in Fig. 1a, as the higher temperature (lower surface tension) liquid is pulled toward the lower temperature (higher surface tension) liquid. This can ultimately deflect the surface layer such that the downward motion liquid regions have larger liquid layer thicknesses than the upward driven liquid regions, as shown in Fig. 1b.

a



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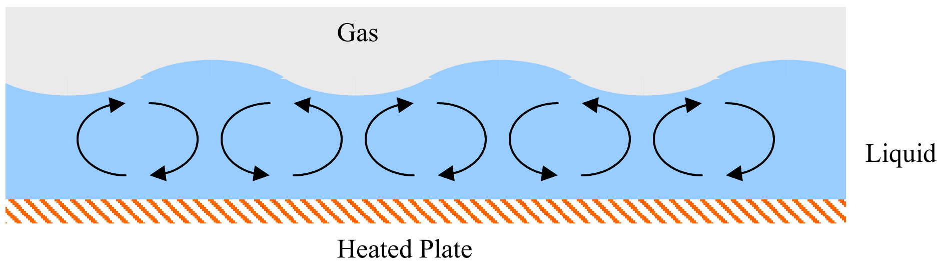

Figure 1: Diagram showing (a) circular fluid movement driven by variations in surface tension and (b) the resulting liquid deflection.

2. OBJECTIVES

The overall objective of this thesis is to design and perform a preliminary characterization of a pump that utilizes the Leidenfrost effect and a pump that utilizes the Marangoni effect. In both pumps, the method in which fluid flow is created is from the input of heat, rather than utilizing mechanical power. The performance of a liquid pump is typically characterized by the pressure differential across which it can pump fluid and flow rate that it is able to create.

2.1. Leidenfrost Pump

The goal of this part of the project is to use the self-propelled Leidenfrost droplet effect [3] to design a closed-channel liquid pump. This will include the design and testing of multiple pump concepts where the challenge is to enclose the fluid within the four pump channel walls while directing the superheated vapor produced such that it does not disrupt the pump performance. The pump should be capable of producing a continuous flow of liquid and be conducive to accurately measuring key characteristics of pump performance through global experiments.

2.2. Marangoni Pump

The goal of this section is to observe whether liquid in contact with a heated asymmetric surface could also create pumping of a liquid. This pumping could be expected due to the Marangoni effect. This observation is to be done through design and preliminary experiments of an open-channel pump. The design should also incorporate the ability to close the channel for future test cases. The broader goal is to test a closed channel pump that contains the fluid. However, in such a closed channel pump, natural convection (Bernardic convection) is expected to cause the driving force.

3. LITERATURE REVIEW

Reviewed in this section are only non-traditional methods of producing fluid motion. The concepts discussed in this section are not exhaustive of all possible methods of producing fluid motion, but are rather a disparate selection of methods which utilize different phenomena to produce fluid motion.

3.1. Self-Propelled Leidenfrost Droplets

Leidenfrost droplets, also known as film-boiling droplets, occur when a liquid is placed on a surface that is at a temperature significantly higher than the boiling point of the liquid. In this situation the droplet hovers above the surface on a film of its own superheated vapor. When this occurs on a relatively flat surface, the droplet will react to outside forces with little resistance causing sporadic movements as seen in Fig. 2a. However, when this occurs on a surface with a regular and asymmetric treaded pattern, the droplet will propel itself consistently across the surface perpendicular to the tread as seen in Fig. 2b.

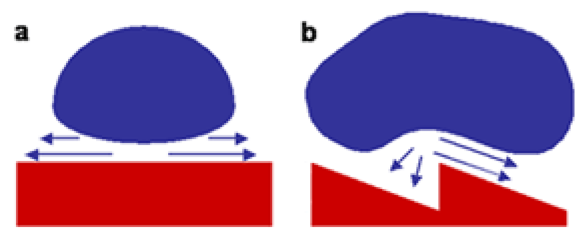

Figure 2: Cartoon drawing showing (a) a liquid droplet hovering on a layer of vapor above a heated flat surface and (b) a liquid droplet hovering on a vapor layer above a ratcheted surface where the vapor would drag the droplet to the right along the long side of the ratchet while the vapor on the short side of the ratchet is expelled in and out of the page. Image from Prof. Linke. [4]

Little is known about the cause of this phenomenon; the leading theory is that it is caused by the flow of the superheated vapor film around the saw-tooth-like or "ratchet" surface. This vapor flow is believed to exert a viscous force on the droplet with a bias to one side of each tread tooth creating acceleration in that direction. Droplet acceleration on the order of 1 m/s^2 and sustained droplet speeds of 5 cm/s have been observed [3].

3.2. Pumping Using Marangoni Effect

The Marangoni effect describes the phenomenon observed when liquids with different surface tensions come in contact with each other. The liquid with the higher surface tension pulls more strongly on the liquid with the lower surface tension, and creates an external flow. Alexeev et al. [5] have been able to produce localized fluid motion on symmetric surfaces due to the Marangoni effect and is shown in Fig. 3. Stroock et al. [6] expanded past the symmetric surfaces and utilized the Marangoni effect to produce

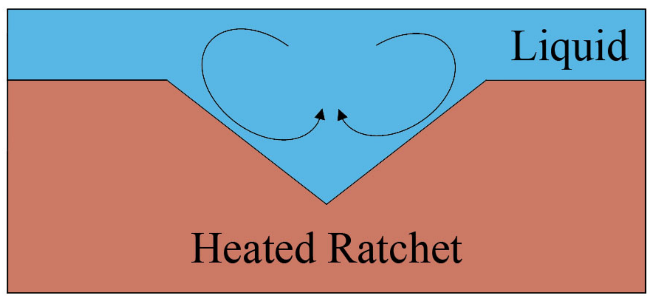

Figure 3: Diagram showing the direction of localized fluid motion on a heated symmetric ratchet.

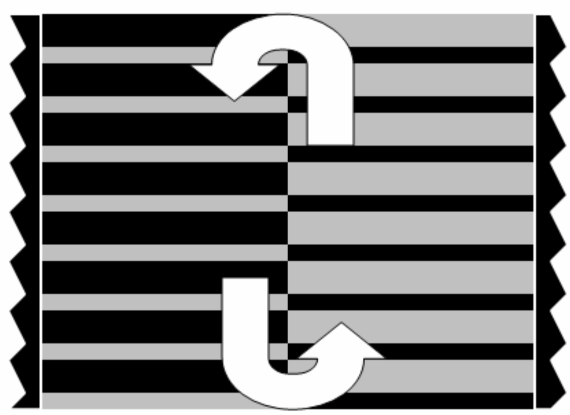

Figure 4: Liquid motion seen by Stroock et al. in open-channel, closed-loop system.

open-channel, closed-loop fluid flows of up to 2 mm/min on asymmetric topologies of 30-60-90 degree triangles with groove heights of 1.3 mm and fluid heights of up to 3 mm as shown in Fig. 4. Also shown was that the rate and direction of fluid flow was dependent on the thickness of the layer of fluid and the temperature difference between the ratcheted surface and the ambient air.

3.3. Electro-osmotic Pumps

An electro-osmotic pump works on the premise that fluid flows in the presence of an electric field. When a fluid is within a microchannel with charged walls, it will correspondingly create a layer of oppositely charged ions at the channel wall. Once an electric field is imposed along the length of the channel, flow of the outer layer near the wall begins toward the region of opposite polarity. This outer flow then causes the inner bulk of the fluid to flow through viscous forces [7]. Such a pump utilizes electrical power to drive the fluid. For such a pump to work, the size of the pump needs to be very small since the inner bulk of fluid is propelled by viscous forces. Scaling the pump to larger sizes would not work as the back pressure from the outflow would overcome any pumping action that could be obtained. Finally, it is important in this type of pump that the walls of the channel be charged. Since electrical (and hence thermal) insulating materials hold charges well, heat transfer from the pump walls to the fluid within the pump would be severely restricted, thereby defeating one of the primary desires in this project of utilizing waste heat to drive the pumps.

3.4. Ferro Fluid

Research in Germany [8] has led to the development of a method of pumping a magnetic fluid, or ferro fluid, without use of any moving parts. This method consists of colloidal suspensions of magnetic particles within a circular duct. The duct is wrapped with two sets of electrical coils in different orientations. Each set of coils is stimulated by an alternating current with a phase difference of 90 degrees. The relative orientation between the two sets of coils results in a rotating magnetic field that moves the magnetic fluid. An interesting attribute that was observed in experimentation was a change in flow direction when the difference in phase was changed from +90 degrees to -90 degrees. This method was originally tested on a duct of approximately 100 mm in diameter, but it is believed that this method should work for micro channel applications with a high degree of control over flow direction and velocity [8]. This method of pumping requires an external power source to energize the magnetic coils and the use of a ferro fluid.

3.5. Membrane Pumps

Membrane pumps are another method to move small amounts of various liquids, including water. In a membrane pump, the pumping action is created by the deflection of membranes. There are many different types of membrane pumps; they can be activated by different means such as electrostatic, electromagnetic, or photo-thermally [9]. The electromagnetic pump uses membranes with small amounts of metallic material embedded in them. The introduction of electromagnetic forces causes the membrane to deflect, which moves the fluid. Membrane pumps have been utilized to propel liquid through microchannels. A disadvantage to the membrane pumps is that they require moving parts that wear down and often have complicated valve systems to transport the liquid.

4. TEST SECTIONS AND EXPERIMENTAL FACILITIES

4.1. Prototype Leidenfrost Pump

4.1.1. Concept

Prof. Linke's group at the University of Oregon have observed droplet/slug pumping in an open channel with a flat bottom and ratcheted side walls [3]. It is important to note that only the vapor between the ratchet face and the liquid produces the liquid motion as shown in Fig. 2b. The droplet reacts with the ratchet surface causing vapor flows in two directions. The forward direction vapor drags the liquid along while the rest is ejected out the sides. The challenge is in removing the vapor from the channel since it expands to approximately 1000 times its liquid volume during vaporization. It is necessary to remove the vapor produced as it can quickly fill the channel and inhibit liquid flow through the channel. In a closed channel, the rest of the vapor cannot get ejected from the sides (i.e. along the treads) hence the need for vapor routing. The proposed quad-mini-vapor-channel design (see Fig. 5) uses the same general fluid flow setup of flat bottom with ratcheted sidewalls, but with alterations to remove the vapor

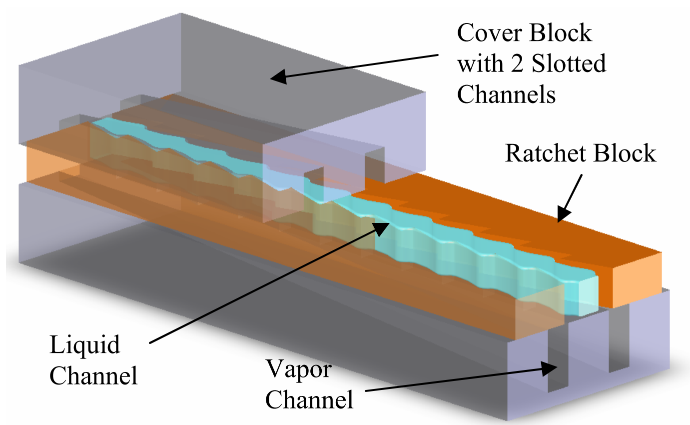

Figure 5: Prototype Leidenfrost design showing the general geometry with varying cross section vapor channels.

created. This design focuses on the ejection of the vapor created by inducing a vapor channel pressure differential through an increase in vapor channel cross-sectional area along the length of the ratchets. The theory behind the droplet pumping is that the liquid is pulled along through the channel by the viscous forces of the vapor. Since the pump must be a closed channel pump, it is also this back flow and side flow of vapor that could cause opposing forces of large magnitude on the liquid that could overcome the vapor drag force if only a lid is placed on the channel; backflow of liquid has been seen in laboratory experiments performed by our group as a result of poor vapor management. To allow the vapor to escape from the liquid pumping channel, vapor channels were created in the base and lid sections of the liquid channel. The vapor channels lie above and below the base of the ratchets to allow for the vapor to flow along the long side of the ratchet as seen in Fig. 6, all the while dragging the liquid along, and then out into the vapor channel.

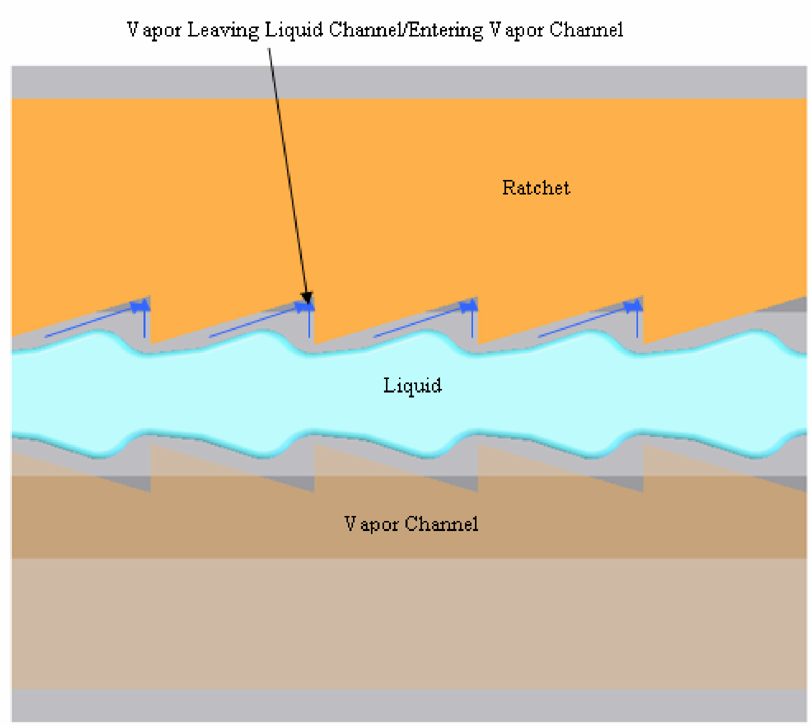

Figure 6: Diagram showing the vapor path from liquid to vapor channels.

The vapor that is created that flows along the short side of the ratchet flows directly into the vapor channel, thus removing the vapor that opposes the overall net flow of the liquid.

Once the vapor has been removed from the liquid channel and is in one of the vapor channels, the focus is on removing the vapor from the vapor channels. To create this flow of vapor in the channels, the depth of the channels increases along the length of the channel, from a small depth at the inlet end to a larger depth at the outlet end. As fluid moves along the length of the channel, the cross-sectional area of the vapor channel increases. By having this increase in cross-sectional area, there is a decrease in flow resistance in the axial direction from inlet to outlet compared with a constant depth channel, thus creating a flow from the small area of the channel to the larger area. Also, by having the flow in the vapor channel in the same direction as the flow in the liquid channel, the momentum of the vapor can be utilized to drive liquid flow rather than impeding its motion by a reversal in vapor flow. Since the flow of the liquid is created by this vapor flow, it is important not to impede the vapor flow along the ratchets. By utilizing this unidirectional flow in all of the channels, it may be possible to create higher speed and more efficient fluid flows in all of the channels.

4.1.2. Preliminary Test Section for Proof of Principle Studies

The test section used in the preliminary experiments consisted of two 100 mm (4 in) long aluminum blocks with two grooves cut into the blocks at an angle of

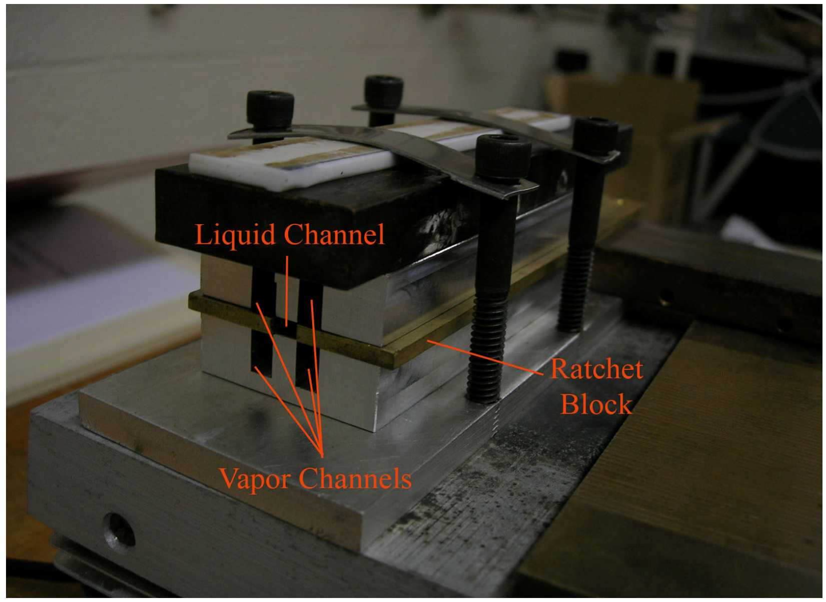

Figure 7: Picture of Leidenfrost pump preliminary test section showing the quad-mini-vapor-channel setup.

approximately 5 degrees for the length of the blocks. The spacing between the grooves in each block was approximately 5 mm. The width of each of the grooves were approximately 6.4 mm (0.25 in). The ratchet blocks were placed between the aluminum blocks with the ratchet positioned to allow for vapor to escape from the liquid channel near the base of the ratchet into the vapor channels as shown in Fig. 7.

4.1.3. Observations From Proof of Principle Studies

In testing the quad-mini-vapor-channel preliminary design, some useful observations were made. The initial setup used a quad-vapor-channel design as shown in Fig. 7. This setup only allowed for a fixed liquid channel width of approximately 5 mm when utilizing all of the channels. After aligning the ratchets with the channels as best possible and clamping the components together, the setup was heated and water was introduced into the channel using a chemical squirt bottle. Steam could be seen coming from the vapor channels. Small amounts of water (tiny droplets) however, were also seen sliding down the bottom vapor channels. These little drops were able to make it into the vapor channel due to the slight misalignment between the channels and ratchets (see Fig. 6). Estimating the position of the ratchet by visual inspection with respect to the vapor channel was the only way to fix the components together in this test. To overcome this issue in future designs, the use of dowel pins for the alignment was noted.

To eliminate the seepage of water into the vapor channels, the setup was modified into a dual-mini-vapor-channel setup by removing the two bottom vapor channels as seen in Fig. 8. Observed in this setup was that water was reluctant to flow into the closed channel from the open channel in which the water was placed. This resistance to flow into the closed channel occurred at the interface between the two aluminum pieces that were heating the brass ratchet. This resistance to water flow into the channel could have been due to the width of the liquid channel being too large. Since it was seen in open channel testing that it was not until the liquid channel width was reduced to

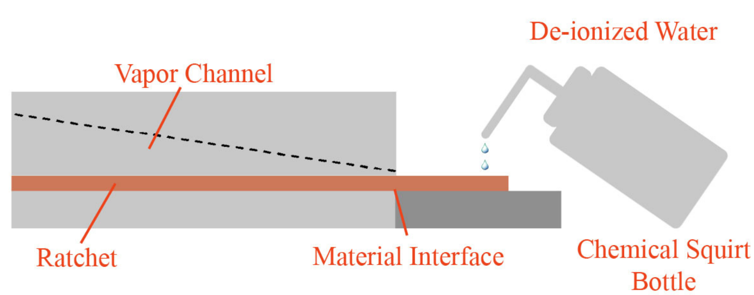

Figure 8: Cartoon showing the dual-mini-vapor-channel setup.

approximately 3 mm that the water began to flow freely, the approximately 5 mm liquid channel width that was used in the dual vapor channel design could have been too wide to propel the water into the closed channel. This may have been the result of having too high of a droplet mass to liquid-ratchet surface area ratio.

With the test setup that was being used, the only way in which a smaller channel width could be used and still allow testing of the vapor channel idea was to align the ratchets to create a solo mini vapor channel arrangement. In doing this, the channel width was minimized to approximately 3 mm with one ratchet along the ceiling/vapor channel edge and the other ratchet allowing for no vapor channel escape. This arrangement proved to be beneficial as the water no longer resisted flowing into the closed channel from the open channel.

From this proof of principle testing, it became apparent that the dual-mini-vapor-channel concept would be able to be utilized within a final design. Also gathered from this testing was the knowledge that a liquid channel width of approximately 3 mm would need to be used in order for liquid propulsion to occur.

4.2. Final Leidenfrost Pump Design

4.2.1. Pump

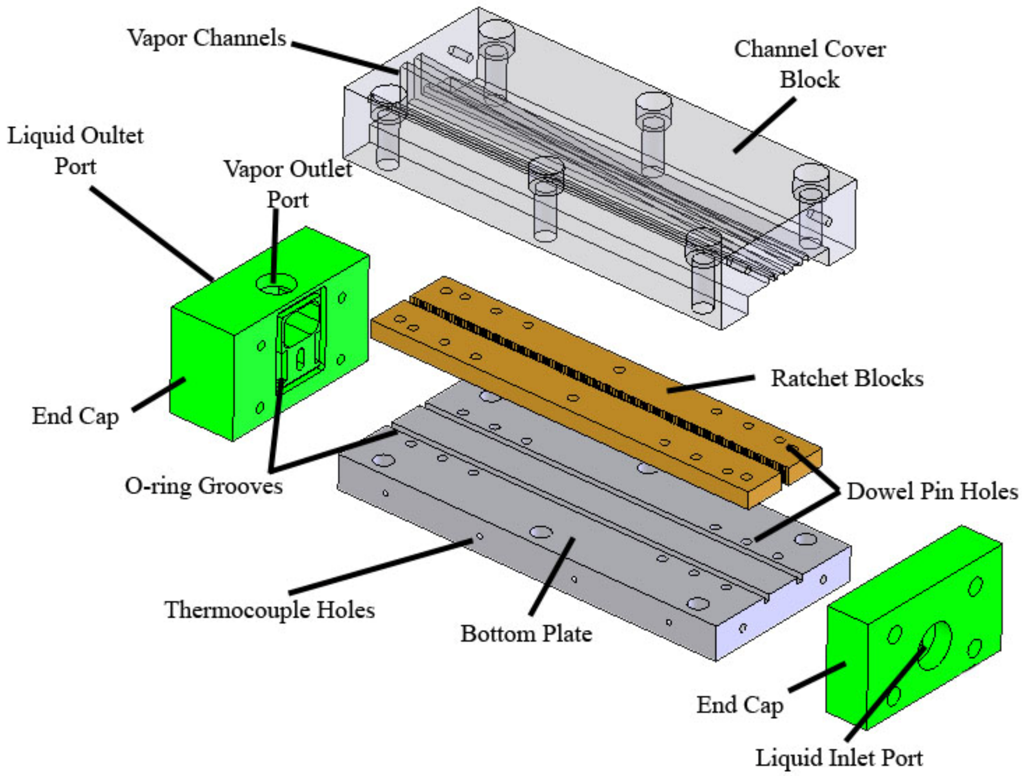

Figure 9: Exploded section showing the pump components of the Leidenfrost pump.

Figure 9 shows an exploded view of the pump test section. The final design utilized the dual-mini-vapor-channel on top of the liquid channel. This allowed for vapor to escape to the vapor channels while allowing the liquid to remain in the liquid channel. The liquid channel width was approximately 3 mm, since the testing showed this width allowed for pumping of water to occur, and its length was 152 mm (6 in) and height 6.4 mm (0.25 in) as this was the length of the existing ratchet blocks. The ratchet height was 0.3 mm (0.013 in) with periods of

2 mm (0.08 in). Dowel pins were included in the design to allow for altering liquid channel widths and also for use in alignment of the liquid and vapor channels (see Fig. 6).

The slotted channel cover block was placed on top of the ratchet blocks to create a liquid channel. Two vapor channels, oriented parallel to the liquid channel, had a width of 3.2 mm (0.125 in) and a taper of 5 degrees running from the inlet end cap to the outlet end cap. On the outlet end of the pump, the vapor channels connected to the outlet end cap vapor port which was threaded to allow a fitting to be connected if desired. The vapor was released to the surroundings, but the capability to capture the vapor was included for future testing.

The liquid channel in the end caps were of comparable size to the liquid channel in the length of the pump. The width of the end cap liquid channels was 3.2 mm (0.125 in) and the height was 7.9 mm (0.312 in). The liquid channel height in the end caps was larger than in the pump in order to remove the rounded end cap channel corners from the direct path of the pump's liquid channel. On each end cap, the inlet and outlet liquid ports were threaded to allow a barbed fitting to be attached so the liquid could travel through the pump and into two reservoirs on either side. On the outlet end cap, a thread conversion adapter was attached onto which the barbed fitting attached.

Thermocouple holes were evenly spaced along the length of the bottom plate 6.4 mm (0.25 in) beneath the top surface of the bottom plate. The holes terminated at a depth of 31.8 mm (1.25 in), directly beneath the center line of the liquid channel. It was at these locations that the thermocouple (K-type) readings that represent the surface temperature of the ratchet pump were recorded.

Also included in the design were o-ring grooves in the slotted channel cover block, bottom plate, and both end caps. These were included to create a seal to contain the liquid in the test section. The o-ring grooves ended up not being used as the high temperatures involved would not allow the liquid water to escape without it first being vaporized, where the vapor would then take the path of least resistance out through the vapor channels.

4.2.2. Heater Block

A heater block was also designed on which the pump assembly was mounted as seen in Fig. 10. This heater block utilized two 1000 W cartridge

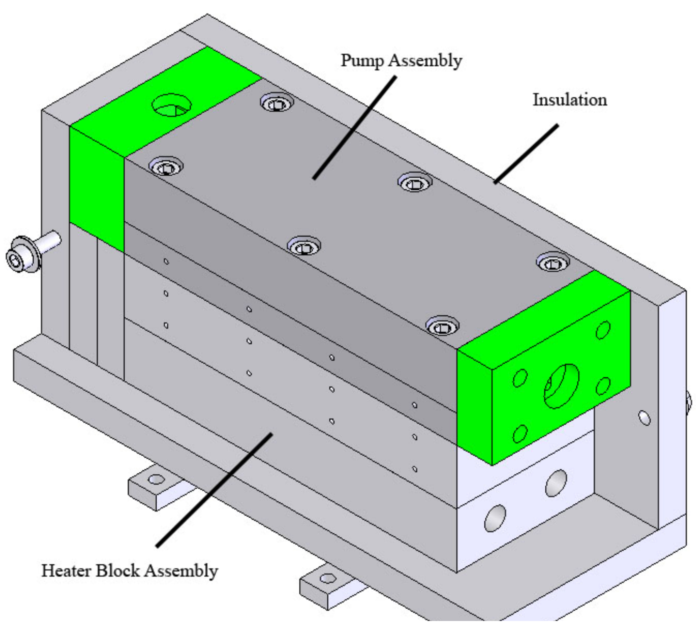

Figure 10: Pump assembly affixed to the top of the heater block assembly.

heaters (Fast Heat CH40371US 120V) as heat sources which were placed in close tolerance holes 12.7 mm (0.5 in) beneath the top of the heater block surface as shown in Fig. 11. The heater block was included to sufficiently heat the pump section to the high temperatures needed in order for the Leidenfrost effect to take place. The 38.1 mm (1.5 in) height of the heater block assembly above the cartridge heater holes was chosen so as to allow one-dimensional conduction to occur above the two-dimensional heat input from the cartridge heaters. The heater block assembly also contained a thermocouple hole array along the length of the pump and at various heights to allow the heat flux and surface temperature to be determined at any given time at several axial locations along the test section. The vertical spacing between thermocouples was 12.7 mm (0.5 in) so as to allow a measurable temperature difference to occur between the spacing. If the spacing had been too small, the error in the thermocouple readings would significantly

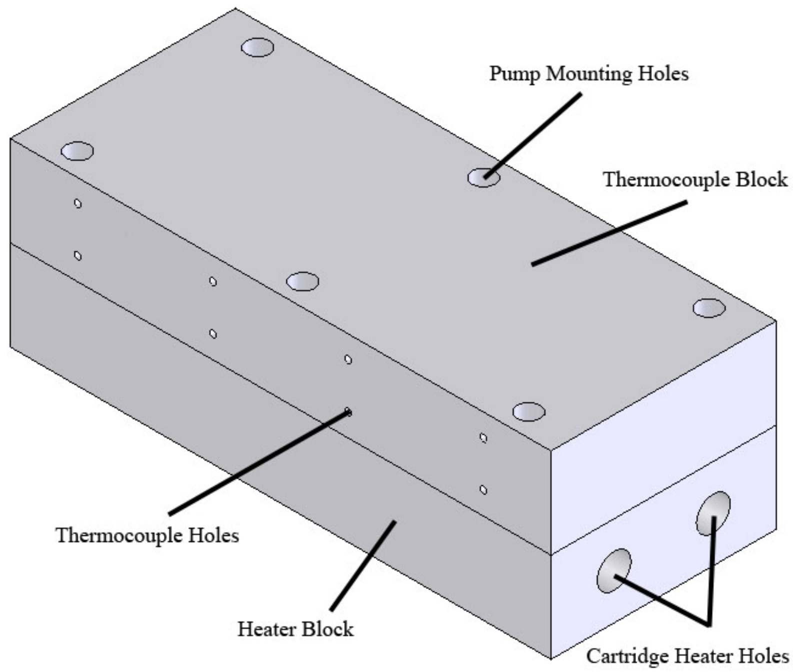

Figure 11: Leidenfrost Pump Heater Block Assembly

affect the calculated heat flux. Local heat flux was not measured in this work as the more critical parameter of interest was the surface temperature.

4.2.3. Test Reservoirs

The fluid was contained in two reservoirs on both ends of the pump as seen in Fig. 12. These reservoirs consisted of two beakers with barbed tube fittings attached to them. The reservoirs were connected to the pump using Teflon tubes of 10.2 mm (0.4 in) inner diameter that ran for a length of 100 mm (4 in). The

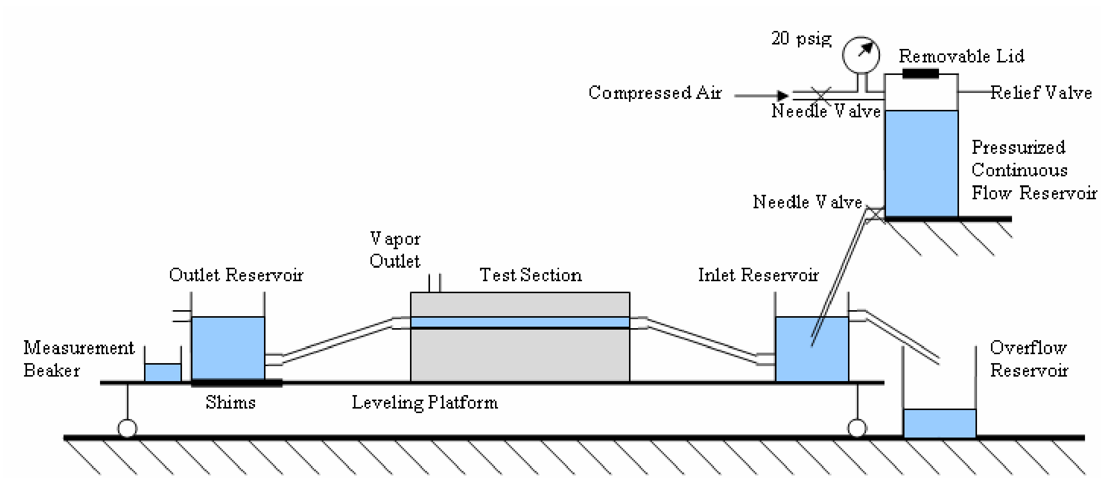

Figure 12: Diagram showing the test setup for the Leidenfrost pump.

height of the liquid in these reservoirs was at the same level as the top of the fluid channel initially, although the reservoirs could be raised or lowered with shims as specified by the test plan to create a pressure differential across the pump.

Fluid was supplied to the inlet reservoir through a 12 L (3 gal) pressurized continuous flow reservoir that was held at a steady pressure of 140 kPa (20 psi) with the use of the building's compressed air. A needle valve controlled the flow rate of de-ionized water that was continually supplied to the inlet reservoir from the pressurized continuous flow reservoir. The test section and inlet and outlet reservoirs were placed on a leveling platform. The thermocouple readings were taken with a rotary switch (Omega OSW3-20) and a handheld readout (Tektronix DTM920). The entire temperature measurement unit was calibrated as a whole using NIST traceable RTD.

Detailed part drawings and bill of materials of the Leidenfrost pump are provided in Appendix A.

4.3. Marangoni Pump Designs

4.3.1. Preliminary Design

The first conceptual design shown in Fig. 13, looked to utilize the Marangoni effect to drive fluid flow. An external insulation layer would surround an internal insulation layer. Multiple insulation layers were included to help in directing all the heat input upward through the test section. Inside the internal insulation, an

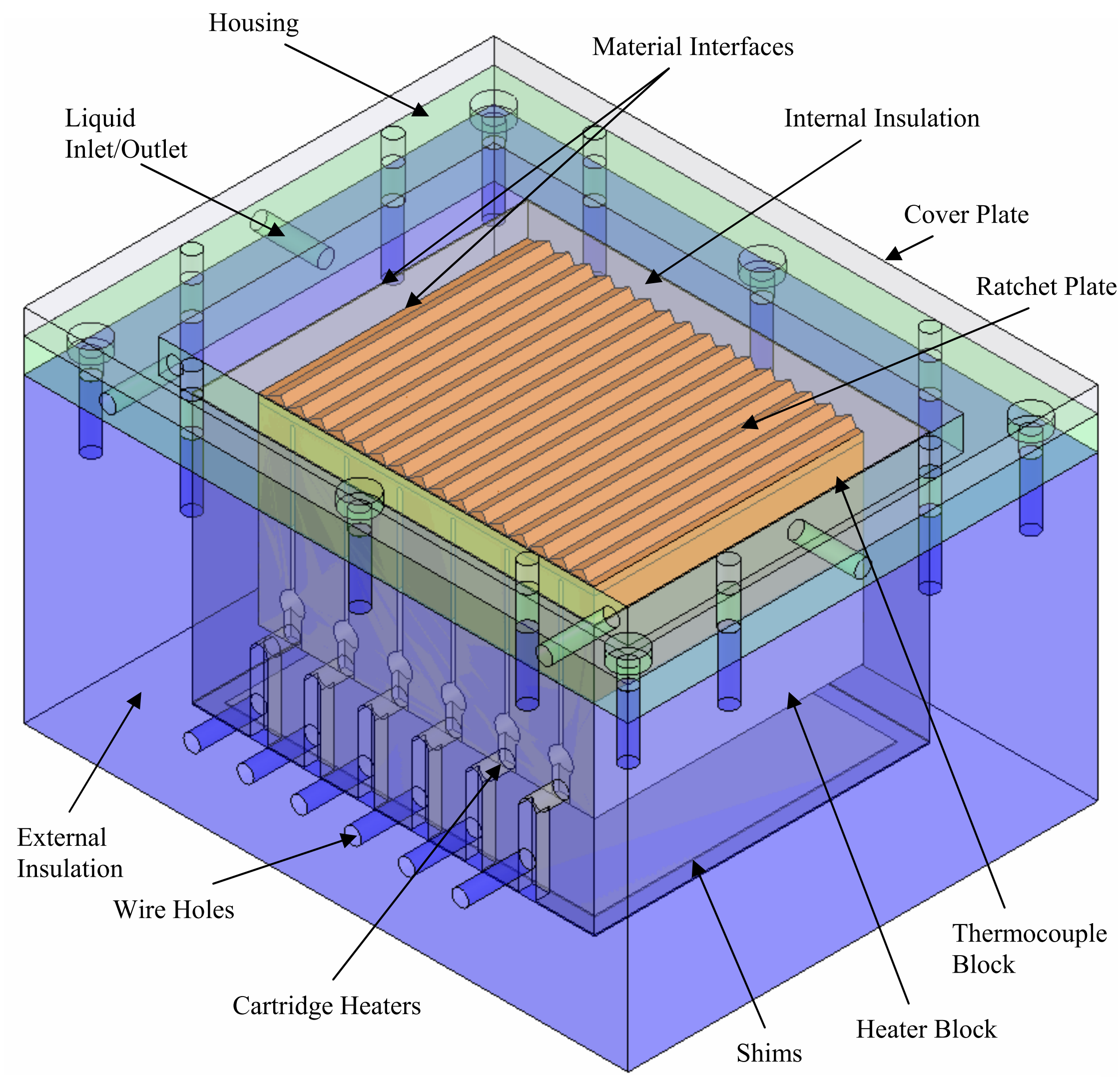

Figure 13: Preliminary Marangoni pump conceptual design.

aluminum heater block would be placed. Inside the heater block would be six cartridge heaters to input heat into the system. Above this heater block would be a thermocouple block which would contain an array of thermocouples to allow for a heat flux to be calculated. Above the thermocouple block would be the ratchet plate with the asymmetrical topology. A housing that surrounds the ratchet plate would be used to contain the fluid. An inlet and outlet port were located in the housing.

This design also included the ability to add a cover plate over the housing. To change the thickness of the layer of liquid on the ratchet plate, shims would need to be added between the two insulation layers. The result would have been an increase in the level of the heater block, thermocouple block, and ratchet plate, which would yield a smaller thickness between the ratchet plate and cover plate.

Some of the drawbacks of this design became apparent when running through a simulation of the testing process within SolidWorks™. The amount of disassembly and reassembly that would be needed to simply change the height of the fluid layer in the closed setup was impractical since the shims would need to be added between the layers of insulation, within the insulation core. The lack of o-rings and the inclusion of material interfaces (see Fig. 13) within the fluid channel was another drawback to the design. With the material interfaces within the channel, this design would have allowed fluid to leak between the insulation layers and eventually out of the test section through the wire holes.

4.3.2. Prototype Design

The first prototype was altered significantly from the first computerized design. As can be seen in Fig. 14, the outer layer of insulation was removed, the method of altering the closed-channel fluid layer thickness changed, the material interfaces were removed from within the channel, and o-rings were added to contain the fluid within the channel.

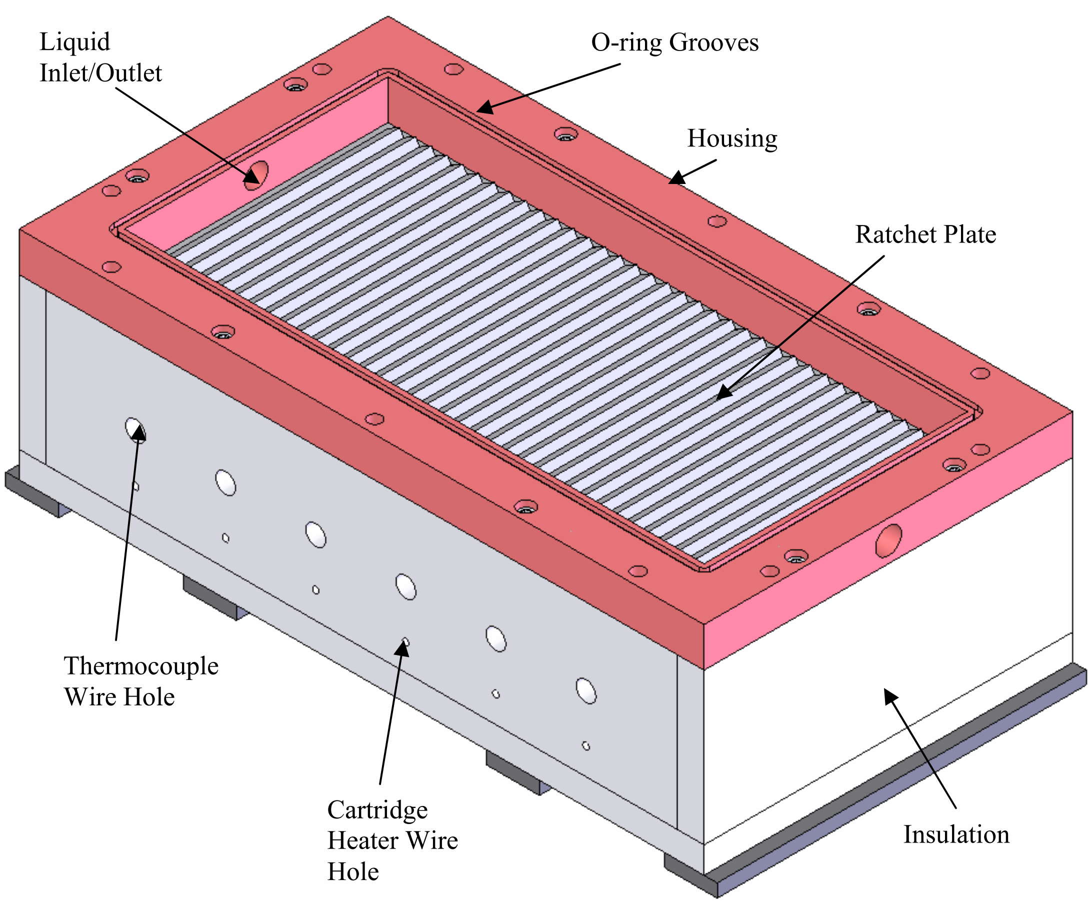

Figure 14: Diagram showing the prototype design.

The method of creating liquid flow was similar to the previous design. The test section was still heated by cartridge heaters within a heater block. The thermocouple block was also present to allow for temperatures to be measured and heat fluxes calculated at six equally-spaced axial locations.

In order to ease the assembly and manufacturing, the five-sided outer layer of insulation was removed and the inner layer of insulation was changed into single sided pieces instead of one “box” of insulation. This allowed for a simpler assembly with respect to component handling, as well as allowed for larger tolerances on the insulation component as it did not have to fit with the metal components exactly.

The previous issues of potential fluid leakage from the channel were addressed with the addition of o-rings and the removal of the material interface from within the channel. The insulation-ratchet plate interface was moved from inside the channel to beneath the housing on the outside of the o-ring grooves. This was done by expanding the size of the ratchet plate to allow the housing to compress on the metal ratchet plate on which the fluid is located, rather than on the insulation.

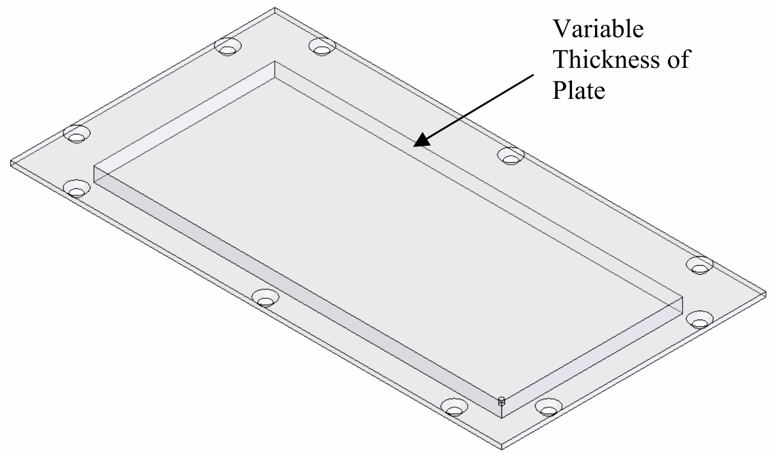

Figure 15: Cover plate showing the ability to change liquid layer thickness in the channel.

To address the issue of excess disassembly and reassembly needed to change the closed-channel fluid layer thickness in the previous design, the use of shims was discarded and instead multiple cover plates were created. The multiple cover plates ranged from a flat piece that bolted flush with the top of the housing to a cover plate that dropped down into the channel and decreased the fluid thickness layer to a fourth as seen in Fig. 15.

A few issues arose from this design during the preliminary testing stage. First pin-hole cracks developed from the heating and bolt tightening of the fiberglass housing. This allowed liquid to penetrate the cracks in the housing and leak to the outer walls. Another issue identified was that the grooves cut in the housing for the o-rings were slightly larger than they needed to be and thus did not allow for enough compression to seal the channel completely. The third issue identified was that the flow restriction using a single inlet and single outlet channel may have been large enough to attenuate the pumping generated by the Marangoni effect.

4.4. Final Marangoni Pump Design

4.4.1. Pump

The final design utilized a ratchet plate with a 30-60-90 degree repeated ratchet similar to the geometry used in the experiments by Stroock et al.[6]. In this design, the ratchet pattern has a height of 3.3 mm (0.13 in) in comparison to the ratchet height used by Stroock et al. [6] of 1.3 mm. The size of the ratchets in relation to the rest of the pump can be seen in Fig. 16.

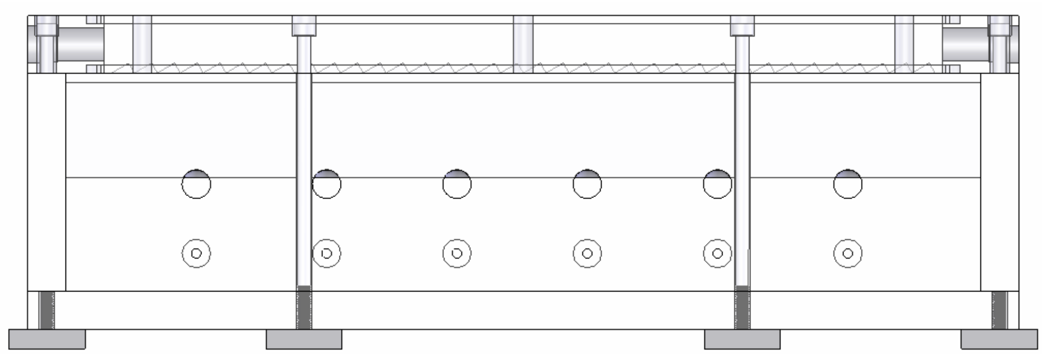

Figure 16: Drawing showing the complete pump test section.

To address the issues from the prototype of the leakage through pin-hole cracks in the fiberglass housing, the housing material was changed from a fiberglass laminate to a lexan plastic. This removed the material layer separation problem seen in the fiberglass by choosing a material that did not have layers. The laxan housing allowed for testing at comparable surface temperatures while increasing the durability of the housing.

The next issue of o-ring fit was addressed by slightly increasing the o-ring groove size while also using a thicker o-ring. This allowed for more compressibility in the o-ring to produce a tighter constriction for leakage to occur.

The final issue of flow constriction was addressed by altering the housing to have three liquid input and three liquid output ports. This addition can be seen in Fig. 17 and shows the amount of flow constriction reduction from the prototype design with only one inlet and one outlet.

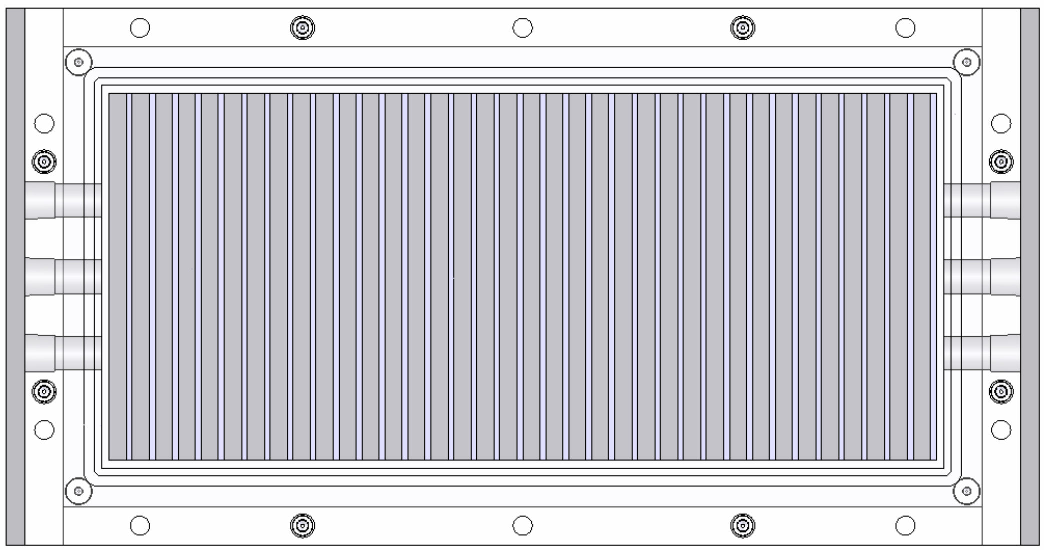

Figure 17: Open channel drawing showing the increase in input and output ports and relative size of ratchets.

4.4.2. Heater Block

In order to heat the fluid in the channel, a heating block was fixed to the base of the system. Six evenly spaced holes in the block allowed for the six cartridge heaters to slide into the close tolerance holes. Attached to the top of the heating block was the thermocouple block. This block, as seen in Fig. 18, allowed for the temperatures to be measured at different heights within the block. Thermocouple readings along with known spacing would allow for a heat flux into the fluid to be calculated.

The 57.2 mm (2.25 in) height of the heater block assembly above the cartridge heater holes was chosen so as to allow one-dimensional conduction to occur above the two-dimensional heat input from the cartridge heaters. With the one-dimensional assumption, a heat flux could be calculated from the thermocouple readings. The heater block assembly also contained a thermocouple hole array along the length of the pump and at various heights to allow the heat flux and surface temperature to be determined at any given time. The vertical spacing between thermocouples was 10.2 mm (0.4 in) so as to allow a measurable temperature difference to occur between the spacing. If the spacing had been too small, the error in the thermocouple readings would significantly affect the calculated heat flux. Heat flux values did not end up being calculated as the measured temperatures did not allow for correct heat flux calculations, and thus the focus was turned to the top plane of thermocouple readings.

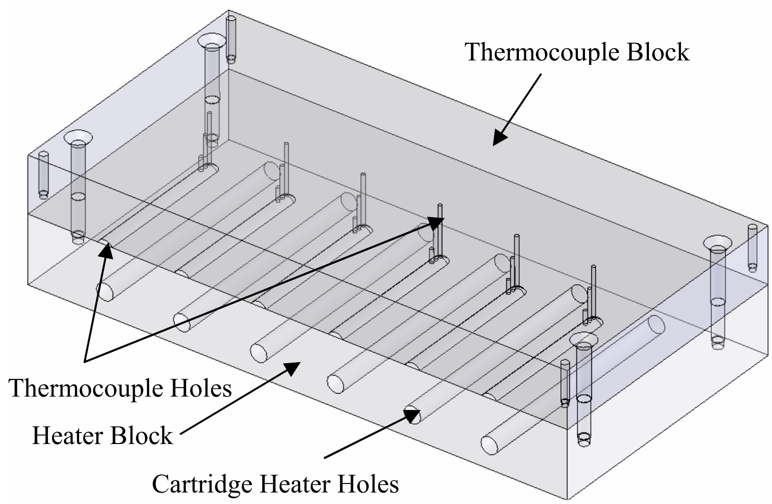

Figure 18: Marangoni Pump Heater Block Assembly

The cartridge heaters were heated by supplying them with a steady AC voltage which could be varied with a variac. The current and voltage supplied to the array of cartridge heaters was observed with a set of multimeters to consistently supply the heaters with the same power. Extra insulation was added so an average heat flux could be determined from the power supplied to the heaters and the known surface area of the channel. Also there would be heat loss to the surroundings that needed to be accounted in order to determine the actual average heat flux. Since surface temperature was of greater interest, these heat losses were not estimated.

The thermocouple (K-type) readings to determine the temperature were obtained using LabVIEW™ and a data acquisition card.

4.4.3. Test Reservoirs

The inlet and outlet reservoirs both consisted of plastic beakers that had 4 holes drilled into each of them, with 3 holes near the bottom and one hole near the top. In each hole was a barbed fitting to which tubes from the test section were connected.

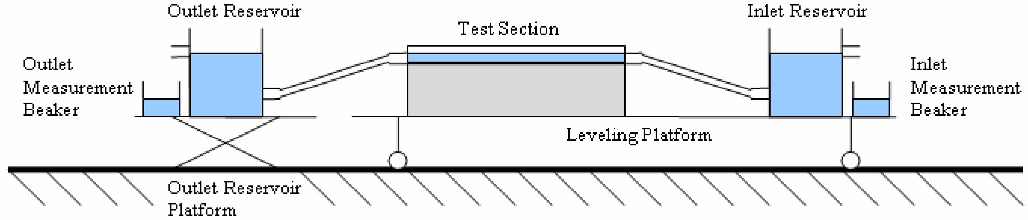

Figure 19: Schematic showing Setup 1 of the Marangoni pump experiments.

Multiple measurement arrangements were used in attempting to determine the direction of flow and the mass flow rate. Setup 1 seen in Fig. 19 shows the component arrangement first tested. In this setup, measurements of liquid overflow were taken both the inlet side and the outlet side to determine the direction of flow in the system.

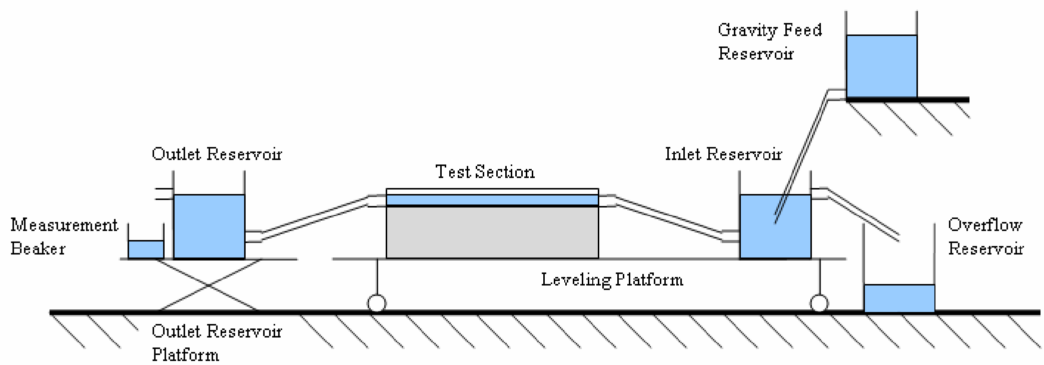

Figure 20: Schematic showing Setup 2 of the Marangoni pump experiments.

In Setup 2 shown schematically in Fig. 20, the arrangement was altered to allow for a continuous fluid input into the inlet reservoir so as to maintain a constant fluid level in the inlet reservoir. The amount of pumping that occurred would then be measured by the amount of liquid that overflowed out of the outlet reservoir.

Detailed part drawings and bill of materials of the Marangoni pump are provided in Appendix B.

5. TEST PROCEDURE & DATA REDUCTION

5.1. Leidenfrost Pump

5.1.1. Cleaning Procedure

To clean the ratchet block, bottom plate and slotted top, the components were each polished with a fine metal polishing cream (All Metal Polishing Creme, Maas International, Inc.). Excess polishing cream residue was then wiped from the components. Each component was then rinsed with acetone and scrubbed with a toothbrush. The rinse and scrub procedure was then repeated a second time. The component was then rinsed with de-ionized water. This rinse-scrub-rinse-scrub-rinse procedure was then repeated with isopropyl alcohol, methanol, and ethanol. The components were then dried with kimwipes (Kimtech Science) and pressurized air.

5.1.2. Testing & Data Reduction Procedure

To assemble the pump and setup for testing (see Fig. 9 for reference), the dowel pins were placed in their corresponding holes and the ratchets on their corresponding dowel pins, making sure to orient the ratchets in the same desired direction. The slotted top was placed above the ratchets and bottom plate in the desired position and bolted down with 6 cap screws. The two end caps were then attached to their corresponding ends by 4 cap screws each. The thread conversion adapter and pipe fittings were then screwed into the end caps. The calcium silicate insulation was then placed around the pump. The reservoirs were then attached to the pipe fittings using Teflon tubing and the setup was leveled using a leveling platform. Cups were then placed beneath and around the fittings so they could be filled with ice later. The inlet reservoir was then continuously filled at a constant rate with de-ionized water and an overflow drain allowed for a constant water level to be maintained within this reservoir. The test section and the outlet reservoir were allowed to fill with water until the outlet reservoir drain began to overflow. Shims were then placed beneath the outlet reservoir until the water stopped dripping from the overflow port. The continuous water input into the inlet reservoir was turned off and sufficient water was removed from both reservoirs to allow the water level to drop below the bottom of the liquid channel. The cups were then filled with ice to surround the fittings. This ice was added to prevent nucleate boiling from occurring in the fittings. Ice was added as needed to maintain the ice surrounding of the fittings and water was removed from the cups throughout the experiment.

To begin the experiment, the variac connected to the two cartridge heaters was turned on. Thermocouple readings from the bottom plate were observed. Once the desired surface temperature was attained, the continuous water flow was turned back on, maintaining the same water level as had been present when placing the shims beneath the outlet reservoir. Once the inlet and outlet reservoirs were filled to their designated levels and water had begun to flow from the outlet reservoir overflow port, the measurement beaker was placed beneath the overflow port and the stopwatch was started. When 12 minutes had elapsed, the recorded thermocouple readings of the bottom plate were averaged to determine the bottom plate temperature. Water was collected in the measurement beaker for 25 minutes. The amount of water that had overflowed into the measurement beaker was then determined with a scale (Scientech SA120) and recorded. The recorded mass was then divided by the measurement time interval to determine the time-averaged mass flow rate.

5.2. Marangoni Pump

5.2.1. Cleaning Procedure

To clean the ratchet plate, a fine metal polishing cream was scrubbed over the entire top surface of the ratchet plate. The remaining residue was wiped clean from the surface. The ratchet plate was then rinsed and wiped with isopropyl alcohol and then rinsed with de-ionized water. The ratchet plate was then wiped dry with kimwipes.

5.2.2. Setup 1 Testing Procedure

To assemble the pump and setup for Setup 1 experiments, the bottom and top surfaces of the thermblock were painted with thermally conductive grease and the ratchet plate was bolted to the thermblock with four screws. A viton o-ring was placed in the o-ring groove along the bottom side of the housing to prevent leakage and the housing was bolted down with eight cap screws. The reservoirs were then connected to the housing with six tubes and cork insulating blocks were placed around the sides of the test section. Silicon oil (SIL 180, Thermo Electron Corporation) was then supplied to the inlet and outlet reservoirs. The apparatus was leveled by adjusting the leveling platform until the measured fluid height was consistent throughout the whole of the channel. The height of the outlet reservoir platform was adjusted until a drip rate from the outlet reservoir overflow tube matched that of the inlet reservoir overflow tube. The test section was then left alone until the dripping from the inlet and outlet reservoir overflows ceased. The height of the fluid in the channel was measured with a ruler and recorded. The measurement beakers were then cleaned and placed on the digital scale and their masses were recorded.

To begin the heated testing, the variac connected to the six cartridge heaters was turned on. The surface temperature of the ratchet plate was observed with thermocouples in the thermblock. Once the surface temperature of the ratchet plate reached steady state, the hour-long test initiated by placing the measurement beakers beneath the reservoir overflow tubes and starting the stopwatch. At one hour, the measurement beakers were removed and weighed. The thermocouple temperature readings and the power input were recorded as well.

5.2.3. Setup 2 Testing Procedure

To assemble the pump and setup for Setup 2 experiment, the bottom and top surfaces of the thermblock were painted with thermally conductive grease and the ratchet plate was bolted to the thermblock with four screws. A viton o-ring was placed in the o-ring groove along the bottom side of the housing to prevent leakage and the housing was bolted down with eight cap screws. The reservoirs were then connected to the housing with six tubes and cork insulating blocks were placed around the sides of the test section. Silicon oil (SIL 180, Thermo Electron Corporation) was then supplied to the inlet, outlet, and continuous flow reservoirs. The apparatus was leveled by adjusting the leveling platform until the measured fluid height was consistent throughout the whole of the channel. The height of the inlet reservoir was adjusted until a consistent stream of oil flowed out of the inlet reservoir overflow tube. The level of the inlet reservoir was chosen so as to maintain a constant fluid level in the inlet reservoir. The height of outlet reservoir platform was adjusted until a consistent drip was achieved from the outlet reservoir overflow tube. The height of the fluid in the channel was measured and recorded. The measurement beaker was cleaned then placed on the digital scale and the ‘zero’ state was set on the scale. The inlet reservoir overflow fluid in the overflow beaker was replaced to the continuous flow reservoir. The measurement beaker was placed beneath the outlet reservoir overflow tube and the stopwatch was started. At the 38 minute mark on the stopwatch, the fluid from the overflow beaker was replaced into the continuous flow reservoir. At one hour, the measurement beaker was removed and weighed. The mass was recorded as the first steady overflow mass. The hour-long steady overflow mass was repeated until a similar mass was achieved from one test to the next.

To begin the heated testing, the variac connected to the 6 cartridge heaters was turned on. The surface temperature of the ratchet plate was observed with thermocouples in the thermblock. The oil from the measurement beaker and overflow beaker was replaced into the continuous flow reservoir as needed so as to not allow the continuous flow reservoir to run dry. Once the surface temperature of the ratchet plate reached steady state, the hour-long test was repeated twice. At the end of the first and second hour-long tests, the oil masses in the measurement beaker were determined and labeled the first and second heated overflow mass, respectively. The thermocouple temperature readings and the power input were recorded as well.

The system was then turned off, the oil was removed from the system, and the test section was allowed to cool over night. The next day, the housing was removed and the ratchet plate was rotates 180 degrees. The test section was then assembled in the same manner as the day before and the testing was repeated.

5.2.4. Data Reduction Procedure

The sign (positive and negative) designating the direction of flow is assigned in relation to the ratchet plate. The direction was assigned according to Fig. 21.

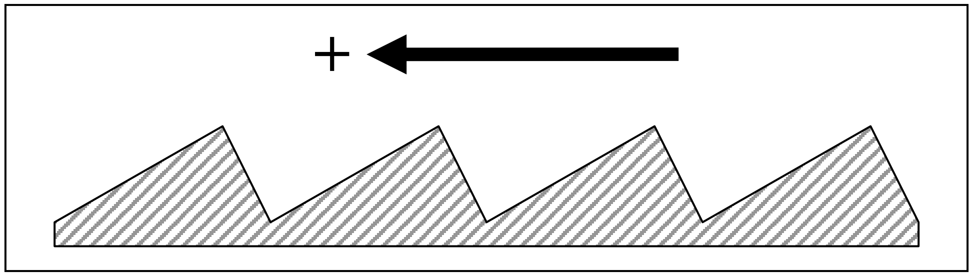

Figure 21: Cross section of ratchet plate designating the positive direction of fluid travel.

The steady unheated overflow mass was then subtracted from the heated overflow mass to yield the Marangoni driven flow mass in relation to the ratchet orientation. For the 180 degrees ratchet plate orientation, the steady overflow mass was subtracted from the heated overflow mass to yield the Marangoni driven flow mass in relation to the reversed ratchet orientation.

6. RESULTS & DISCUSSION

6.1. Leidenfrost Pump

6.1.1. Qualitative Discussion

During the testing, sporadic pumping of the liquid was observed. The liquid would exit from the pump in bursts rather than in a continuous flow as one would expect from a traditional pump. The vapor port also contained a fine mist of water that would be rapidly ejected into the surrounding air. These burst of water mist and the popping sounds were reduced by the addition of ice to the cups surrounding the barbed fittings.

The reservoir system was designed to be easily adjustable (with the use of plastic tubing) and measurable (with the use of shims) to change the pressure head seen across the pump from inlet to outlet. However, during testing it was observed that surface tension forces acting on the liquid at the inlet and outlet overflow spouts introduced flow unsteadiness as the water would resist overflowing until enough liquid accumulated.

In addition to inlet and outlet flow unsteadiness, it was observed that as the working fluid entered and exited the pump, it would encounter a section of channel that was at boiling temperature but below the Leidenfrost regime. At these locations the droplets would come into contact with the surface and rapid boiling would result. This was generally caused in sections of channel outside of the pump where there was no access to the vapor channel. This caused sporadic flows resulting in scattered flow rate data. Better data were obtained in final testing by cooling the channel sections directly outside of the pump inlet and outlet with ice. This was done to force the region of the channel where the surface temperature (compared to Leidenfrost) was lower than the Leidenfrost temperature in which nucleate boiling occurs into the pump rather than in the barbed fittings. This gave the vapor produced from the nucleate boiling access to the vapor channels in order to allow it to freely escape from the system.

6.1.2. Quantitative Discussion

Data obtained from the Leidenfrost Pump experiments can be seen in Table 1.

Table 1: Leidenfrost Pump Results

Avg. Temp. (°C)	Time (min)	Mass (g)	Mass Flow Rate (g/min)	Uncertainty: Time (min)	Uncertainty: Mass (g)	Uncertainty: Mass Flow Rate (g/min) (%)		Average Liquid Velocity (cm/s)
289	25	100.64	4.03	0.03	0.01	0.005	(0.13%)	0.35
294	25	56.67	2.27	0.03	0.01	0.003	(0.13%)	0.20
301	25	145.45	5.82	0.03	0.01	0.008	(0.13%)	0.51
302	25	160.56	6.42	0.03	0.01	0.009	(0.13%)	0.56
310	25	116.13	4.65	0.03	0.01	0.006	(0.13%)	0.41
330	25	44.75	1.79	0.03	0.01	0.002	(0.14%)	0.16
333	25	31.99	1.28	0.03	0.01	0.002	(0.14%)	0.11
335	25	41.36	1.65	0.03	0.01	0.002	(0.14%)	0.15

Figure 22 shows the mass flow rate versus the average bottom plate temperature.

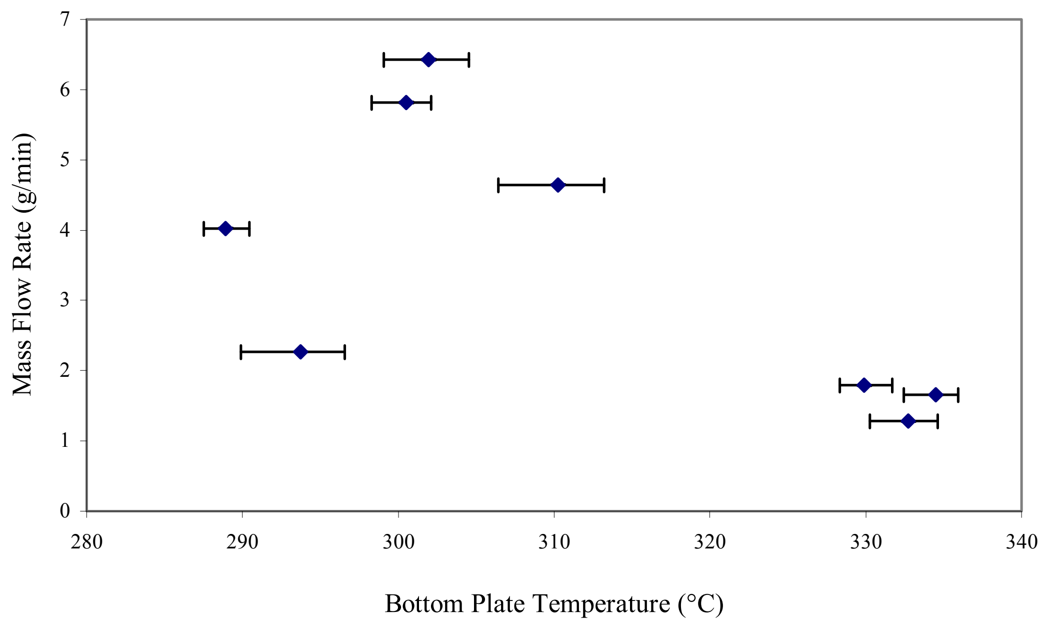

Figure 22: Leidenfrost pump flow rate versus temperature plot

The results show a general trend of an increase in the mass flow rate to approximately 6 g/min at a bottom plate temperature of approximately 300°C. With a continued increase in temperature, the mass flow rate decreases to lower levels. Observation is that sporadic flow rates occur at lower surface temperatures and then a seemingly more repeatable mass flow rate occurs at a surface temperature of approximately 330°C. This is consistent with observations by Linke et al. [3] for droplet flows on a ratchet surface. According to Linke et al. [3], the temperature of the ratchet surface needed to be higher than approximately 330°C in order to exit the low-temperature Leidenfrost regime where they observed "strong fluctuations in droplet trajectory," and entered the high-temperature regime. Linke et al. [3] reported lower droplet accelerations in this high-temperature regime, however this acceleration was more consistent. The data shows a range of mass flow rate for temperatures below 330°C but display a cluster of similar mass flow rates above 330°C.

Average liquid velocity data calculated from the measured mass output divided by the product of the water density at STP and cross-sectional area of the liquid channel. This yielded average liquid velocity rates of up to 0.56 cm/s. This number can be roughly compared to the Linke et al. [3] open-channel droplet velocities of up to 5 cm/s. The variation between these velocities may in large part be due to the spurts of liquid that flowed from the closed-channel pump. While the Linke et al. [3] value was measured on images of individual drops in an open-channel, the closed-channel pump had to contain a liquid that not only ran the length of the pump, but was also connected to water within each reservoir. Surface tension forces may have been a factor in slowing the liquid pumping in the channel. Better vapor management in the form of an open-channel versus a closed channel may also have been a reason for differences in velocities obtained. Another factor that could increase the variation is that some of the water collected over the 25 minute measurement interval may have evaporated, thus decreasing the apparent average velocity.

6.2. Marangoni Pump

Data obtained from Setup 1 can be seen in Table 2.

Table 2: Marangoni Setup 1 Test Results

Avg. Temp. (°C)	Time (min)	Ratchet Direction from Inlet to Outlet	Layer Thickness (in)	Positive Mass (g)	Negative Mass (g)	Positive Flow Rate (g/min)	Negative Flow Rate (g/min)	Total Mass (g)	Net Mass (g)
83	60	+	0.5	1.519	3.782	0.025	0.063	5.302	-2.263
97	60	+	0.5	2.632	7.101	0.044	0.118	9.733	-4.469
95	60	-	0.5	9.108	0.337	0.152	0.006	9.445	8.771
84	60	+	0.75	1.372	10.755	0.023	0.179	12.127	-9.383
98	60	+	0.75	1.615	11.130	0.027	0.186	12.745	-9.515
95	60	-	0.75	3.278	1.801	0.055	0.030	5.079	1.478

Uncertainty: Time (min)	Uncertainty: Positive Mass (g)	Uncertainty: Negative Mass (g)	Uncertainty: Positive Flow Rate	Uncertainty: Negative Flow Rate
0.03	0.001	0.001	0.09%	0.06%
0.03	0.001	0.001	0.07%	0.06%
0.03	0.001	0.001	0.06%	0.30%
0.03	0.001	0.001	0.09%	0.06%
0.03	0.001	0.001	0.08%	0.06%
0.03	0.001	0.001	0.06%	0.08%

Data obtained from Setup 2 with zero initial outlet reservoir overflow can be seen in Table 3.

Table 3: Marangoni Setup 2 With No Initial Room Temperature Overflow Test Results

Temp. (°C)	Time (min)	Ratchet Direction from Inlet to Outlet	Layer Thickness (in)	Mass (g)	Flow Rate (g/min)
94	60	+	0.531	0	0
98	60	-	0.531	0	0

Data obtained from Setup 2 with an initial outlet reservoir overflow can be seen in Table 4.

Table 4: Marangoni Setup 2 With Initial Room Temperature Overflow Test Results

Temp. (°C)	Time (min)	Uncer-tainty: Time (min)	Ratchet Direc-tion from Inlet to Outlet	Layer Thick-ness (in)	Mass (g)	Uncer-tainty: Mass (g)	Mass Flow Rate (g/min)	Uncer-tainty: Mass Flow Rate	Net Mass Flow Rate (g/min)	Percentage of Original Mass
Room	60	0.03	-	0.56	10.052	0.001	0.168	0.06%		
Room	60	0.03	-	0.56	8.383	0.001	0.140	0.06%		
Room	60	0.03	-	0.56	5.822	0.001	0.097	0.06%		
Room	60	0.03	-	0.56	5.292	0.001	0.088	0.06%		
102	60	0.03	-	0.56	1.271	0.001	0.021	0.10%	-0.067	24%
104	60	0.03	-	0.56	0.786	0.001	0.013	0.14%	-0.075	15%
Room	60	0.03	+	0.56	22.720	0.001	0.379	0.06%		
Room	60	0.03	+	0.56	22.841	0.001	0.381	0.06%		
104	60	0.03	+	0.56	14.295	0.001	0.238	0.06%	-0.142	63%
104	60	0.03	+	0.56	0.688	0.001	0.012	0.16%	-0.369	3%

6.2.1. Discussion

The results seen in Table 2 do not show a consistent direction of liquid travel. In the run at 97°C, the net direction of liquid travel is in the negative direction from the outlet end to the inlet end. Reversing the ratchet plate and running the experiment again at 95°C resulted in a net direction of liquid travel in the positive direction from the outlet end to the inlet end. Running the experiment again with a thicker fluid layer resulted in similar contradictory fluid direction results.

These contradictory results may have been the result of the sensitivity in leveling the apparatus. In the setup of these tests, the process of leveling involved adjusting the level of the outlet reservoir platform until the same drip rate was achieved out both reservoir overflow ports. When a matching drip rate was thought to have been obtained from both overflow ports, the inlet and outlet was assumed to be on a level plane.

Also present in the results was the evidence that the liquid level needed to be constantly replenished. Between experimental runs, the liquid was replenished to the channel so as to return the liquid layer thickness to the same height as had been present in the previous run. This however raised the question of when to start the stopwatch to begin the data collection. This question may have caused the results to vary in total mass output between re-runs of the experiment without turning the experiment off and starting again.

Since the results showed that the direction of liquid flow was not consistent with respect to the ratchet plate geometry and overall directions and magnitudes of mass flow rate between similar runs, Setup 2 (see Fig. 20) was introduced. This setup added the gravity feed reservoir to maintain a constant liquid level in the inlet reservoir. In the first runs of this setup, whose results are shown in Table 3, the outlet reservoir platform was adjusted upward just until dripping from the outlet reservoir overflow port ceased. This was done to put the liquid right on edge before it would overflow into the measurement beaker. This was done under the assumption that once the pump was turned on, the liquid would drop into the measurement beaker with a change in fluid level in the outlet reservoir due to pumping. The results showed otherwise with no flow in either ratchet plate orientation.

Having no overflow with both ratchet plate orientations led to the assumption that the pressure head needed to raise the liquid level was not possible using the Marangoni pump. In order to overcome this, the configuration of Setup 2 was altered to let a continuous drip of liquid overflow from the outlet reservoir overflow port, at room temperature, to ensure that there was no pressure head in the outlet reservoir overflow port that the liquid needed to overcome when heated. This "room temperature" condition was measured to allow a flow rate difference to be seen when compared to the heated condition. As can be seen in Table 4, the hour-long mass measurements for both ratchet plate orientations resulted in less overflow for the heated cases than for the room temperature cases. This again adds to the contradictory results within the same setup with only the ratchet plate orientation as the difference.

In relating these results to the results of Stroock et al. [6], a comparison cannot be achieved. Stroock et al. [6] were able to achieve flow velocities of approximately 1 mm/s in an open, recirculating channel (see Fig. 4). With the recirculating channel used by Stroock et al. [6], there was no involvement of reservoirs and leveling of multiple components. This difference may have been a large reason as to why liquid flow was seen by Stroock et al. [6], yet was not achieved in the setups discussed here. The ability to reach the sensitivities needed to repeatedly measure a liquid flow was not present.

7. CONCLUSIONS & RECOMMENDATIONS

7.1. Leidenfrost Pump Recommendations

Since ice was used to cool the inlet and outlet sections of the channel, it would be beneficial to redesign the inlet and outlet to control the vapor produced in these sections of the pump. Doing this would allow for the elimination of the ice, and would also improve the consistency of the results by eliminating the localized pressure spikes in the channel through vapor extraction.

Another improvement to the measurement capabilities of the setup would be to redesign the reservoirs to create a more sensitive metering system. The inlet reservoir should be designed to allow for the input flow rate to the pump to be measured. This would give additional insight on its effects on the pumping performance and can be accomplished in the same manner that is used to measure flow rate at the exit reservoir. In addition to this, the rate at which fluid is being supplied to the inlet reservoir should be more consistent and quantifiable. This could be accomplished by using a syringe pump.

7.2. Marangoni Pump Recommendations

Some next steps in investigating the Marangoni pump would be to further increase the sensitivity of the test facility. With the current setup, the gravity feed continuous flow reservoir does provide a constant flow, but not one that is steady enough for the sensitivity of the output measurement. It was observed that the overflow rate from the outlet reservoir varied from approximately 8 seconds/drop before the continuous flow reservoir replenishment to approximately 2 seconds/drop after the replenishment. While the liquid level in the inlet reservoir during this change in output rates did not appear to change, it obviously did result in a minute change that could not be easily seen and thus resulted in altering mass flow rates. To overcome this obstacle, a syringe pump should be used instead of the continuous flow reservoir to precisely control the rate and amount of liquid input.

Another step that may be taken to improve upon the setup would be to make more precise measurement reservoirs. One characteristic of the new reservoirs that may be an improvement over the current ones would be to reduce the amount of fluid that they could hold. This would result in a more defined fluid level in the system, and would also reduce the amount of liquid in the system that is not being heated by the pump.

One other improvement to the setup would be to use a different material for the housing that would be capable of withstanding higher temperatures. This would allow for a larger range of temperatures to be explored, which may produce higher mass flow rates through increased surface tension gradients.

7.3. Final Words

This project worked to design and characterize pumps utilizing asymmetric surfaces and heat inputs to drive fluid flow. These non-traditional pumps resulted in mixed results. The Leidenfrost design yielded results which gave a general trend of pump output over varying temperatures, but also had its limitations in setup measurability and vapor management that allowed sporadic pumping to occur. The Marangoni design went through setup iterations to improve upon the measurability and repeatability of the results. The Marangoni setup and test procedure will need to be refined based on the recommendations until a repeatable measurement can be obtained to show performance.

8. BIBLIOGRAPHY

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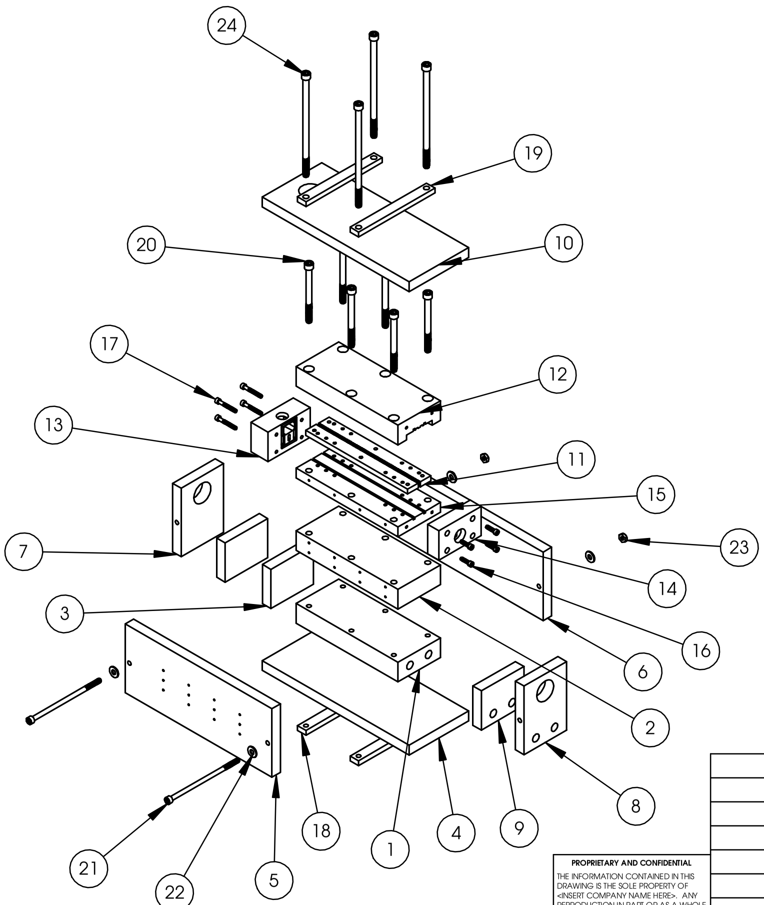
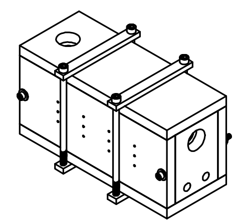
9. APPENDICES

9.1. APPENDIX A: LEIDENFROST PUMP PART DRAWINGS



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	heatblock	2.5x6x1 6061 Al	1
2	thermblock	2.5x6x1 6061 Al	1
3	insFill	2.5x2x0.5 CaSi	2
4	insBot	3.5x8.65x0.5 CaSi	1
5	insFront	3.5x8.65x0.5 CaSi	1
6	insBack	3.5x8.65x0.5 CaSi	1
7	insOut	2.5x3.5x0.5 CaSi	1
8	insIn	2.5x3.5x0.5 CaSi	1
9	insInSpace	2.5x2x0.5 CaSi	2
10	insTop	3.5x8.65x0.5 CaSi	1
11	ratchet	Ratchet	2
12	slotted_top	2.5x6x1	1
13	end_fitting_1	1.5x1x2.5 6061 Al	1
14	end_fitting_2	1.5x0.65x2.5 6061 Al	1
15	bottom_plate	2.5x6x0.5 6061 Al	1
16	90128A148	Cap Screw #6-32, 1/2" Lg.	4
17	92196A153	Cap Screw #6-32, 1" Lg.	4
18	botStand	0.5x4.5x0.25 6061 Al	2
19	topStand	0.5x4.5x0.25 6061 Al	2
20	91251A553	Cap Screw 1/4"-20, 2-3/4" Lg.	6
21	92196A286	Cap Screw # 10-32, 4" Lg.	2
22	91090A103	Washer, 13/64" Id., 0.5"Od.	4
23	90730A015	Hex Nut, # 10-32, 1/8" H.	2
24	91251A090	Cap Screw 1/4"-20, 5" Lg.	4
25	3618K753	1000W, 120V Cartridge Heater	2



PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Pump Assembly

SIZE B | DWG. NO. Assem2 | REV
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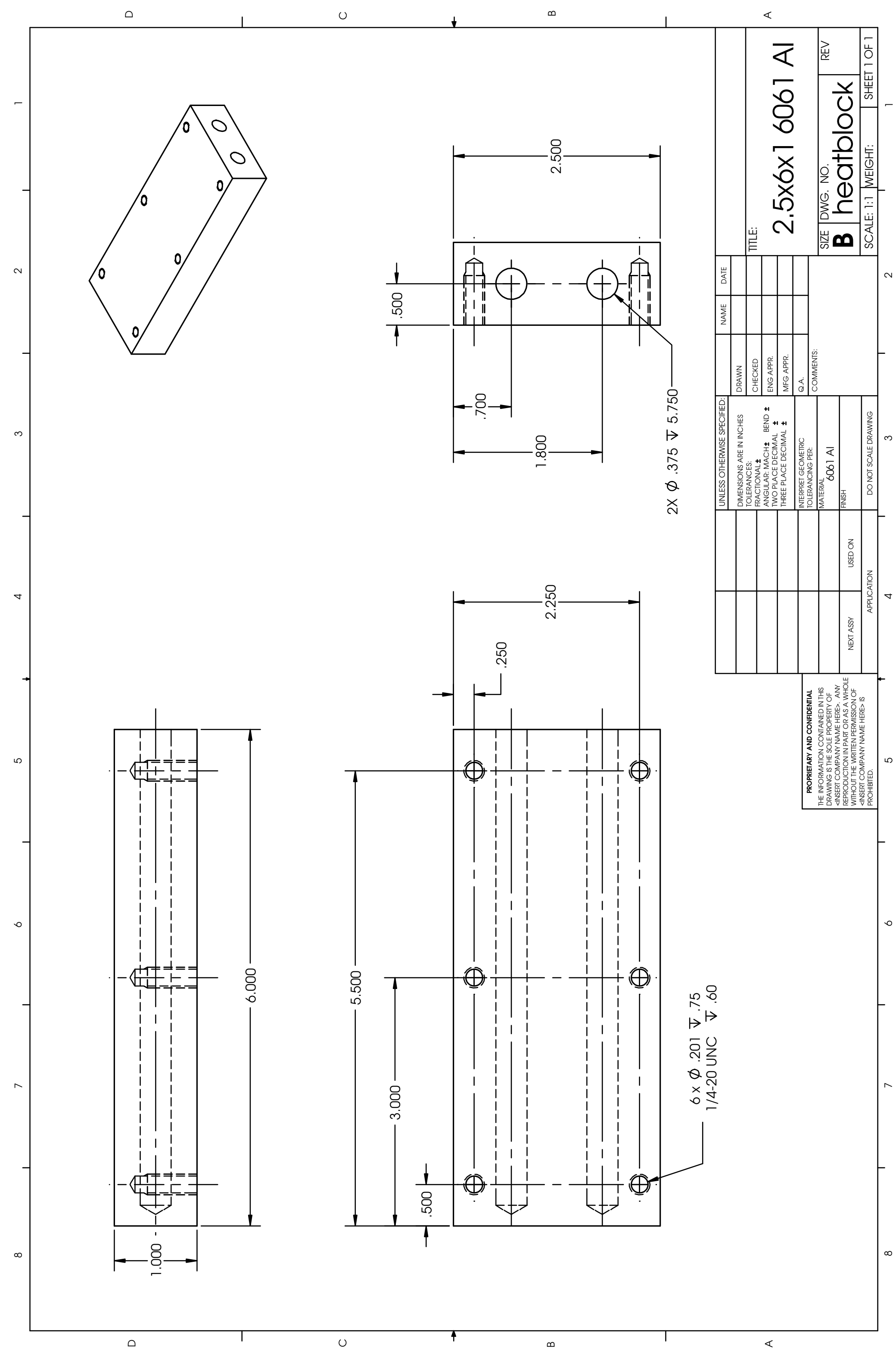
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1.000
6 x ⌀ .201 ↧ .75
1/4-20 UNC ↧ .60
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ANGULAR: MACH ± BEND ±
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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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FINISH
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NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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B
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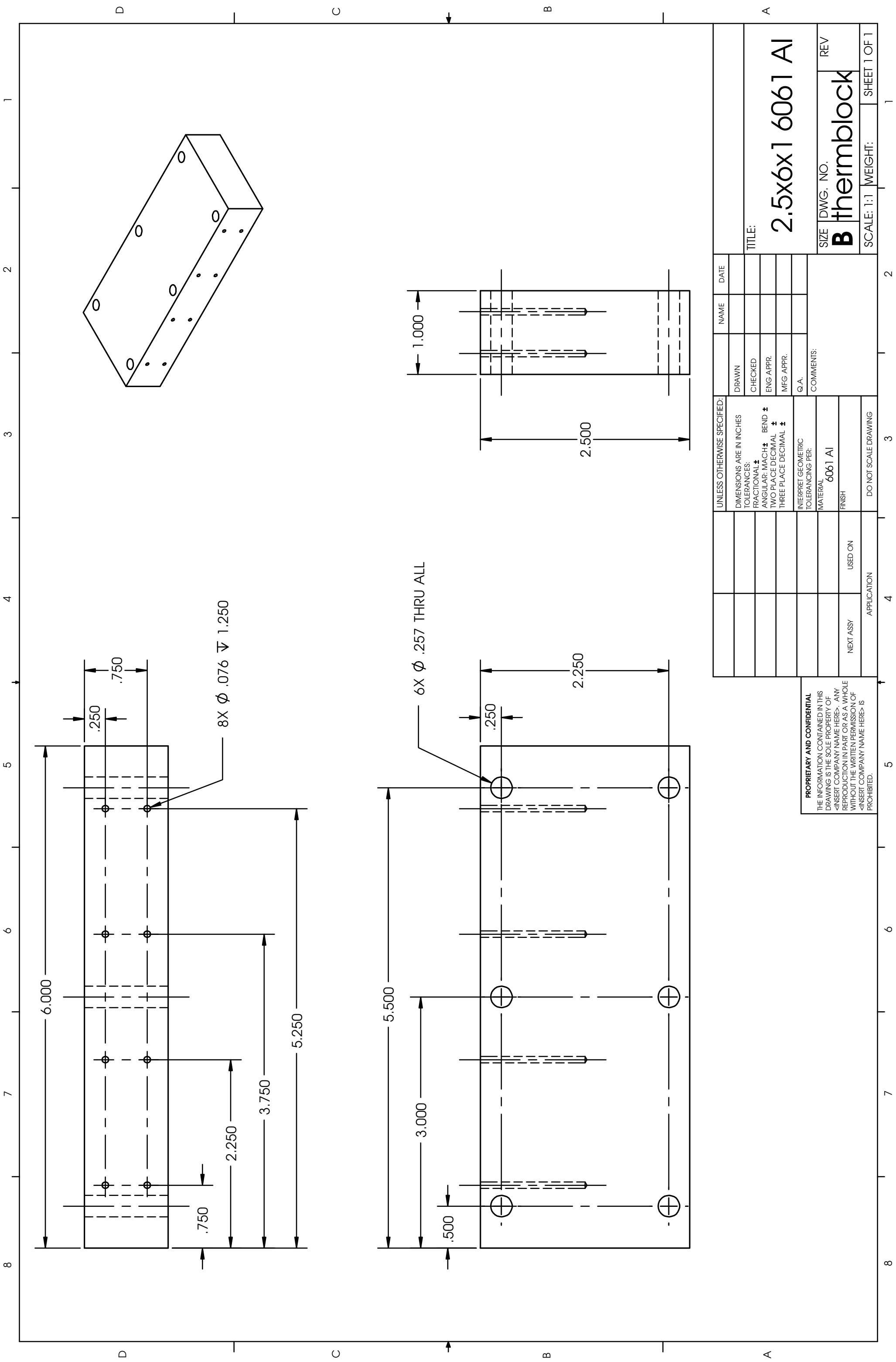
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL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.250
5.500
3.000
.500
1.000
2.500
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THREE PLACE DECIMAL ±
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MFG APPR.
Q.A.
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DATE
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SHEET 1 OF 1
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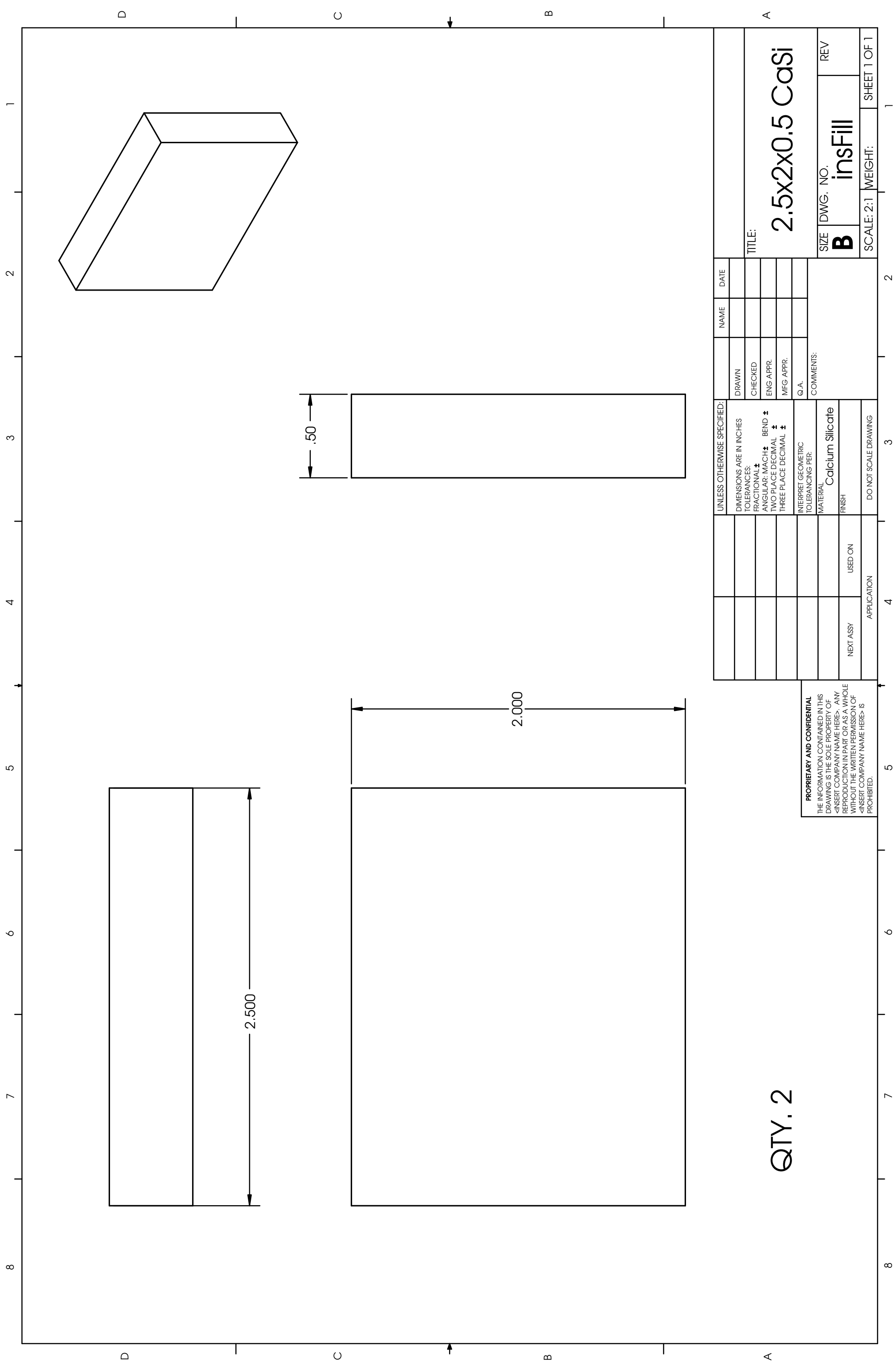

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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
2.5x2x0.5 CaSi
SIZE
B
DWG. NO.
insFill
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
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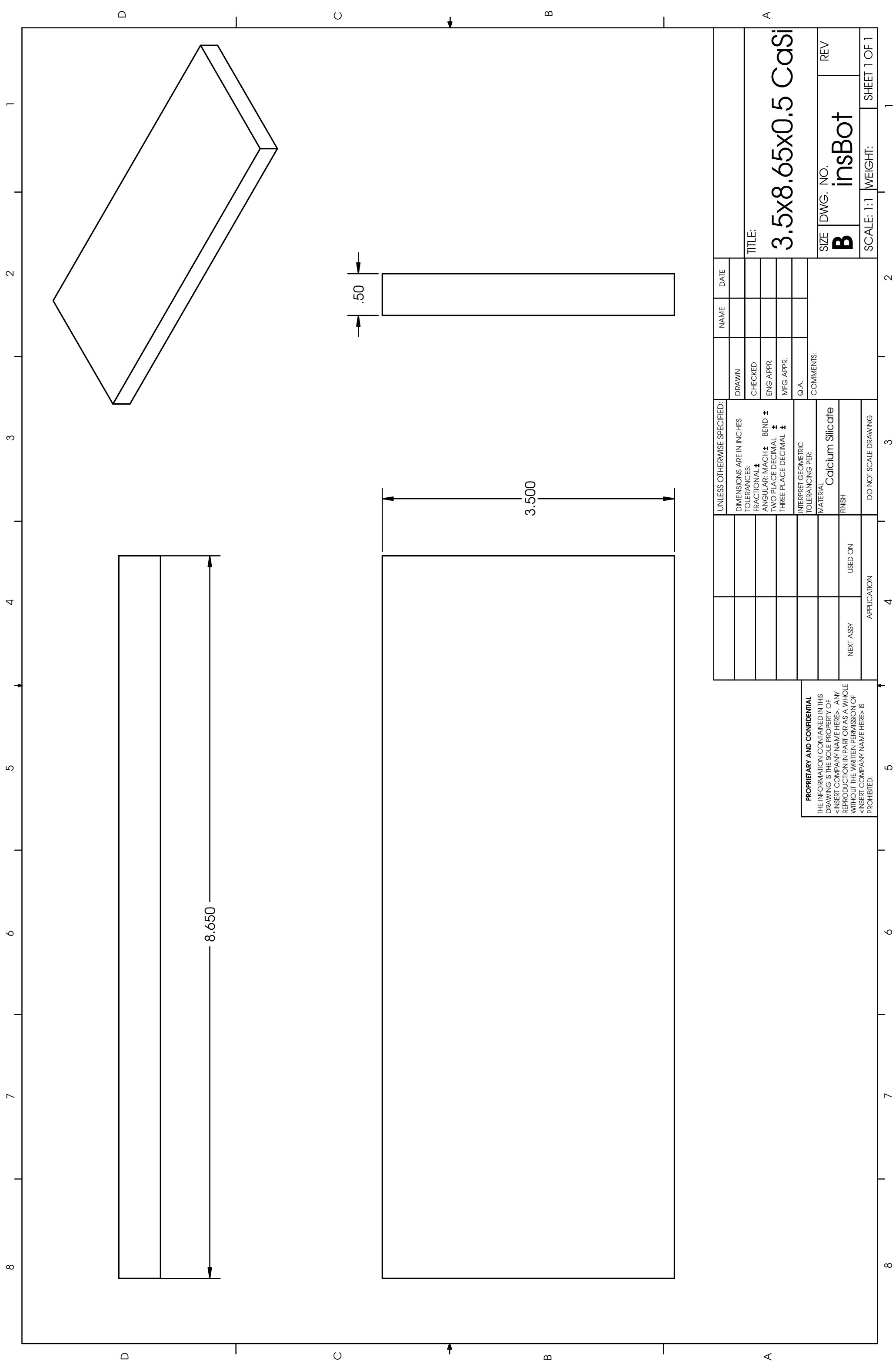

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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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FINISH
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NEXT ASSY
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DRAWN
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ENG APPR.
MFG APPR.
Q.A.
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DATE
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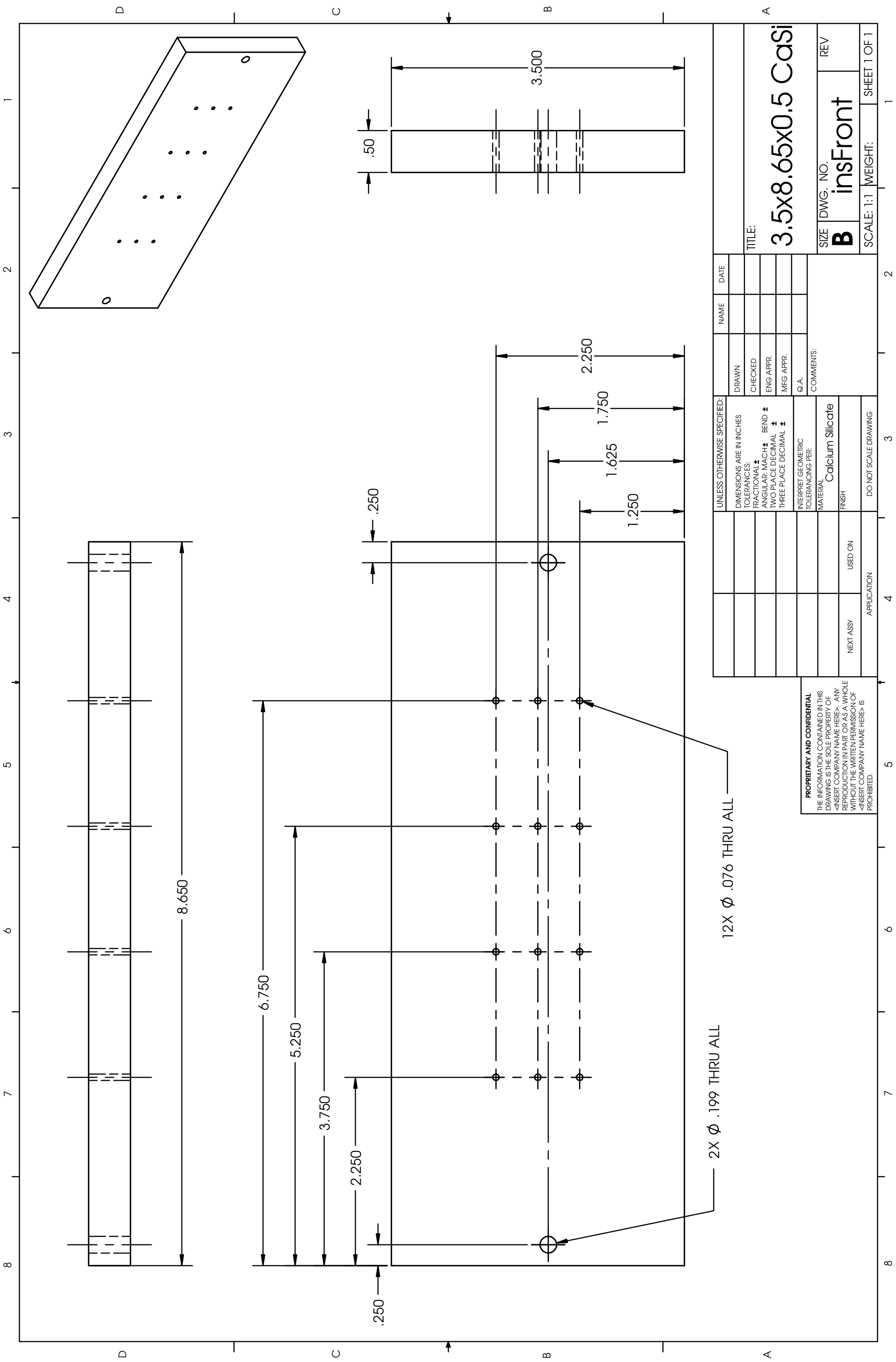
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12X Ø .076 THRU ALL
2X Ø .199 THRU ALL
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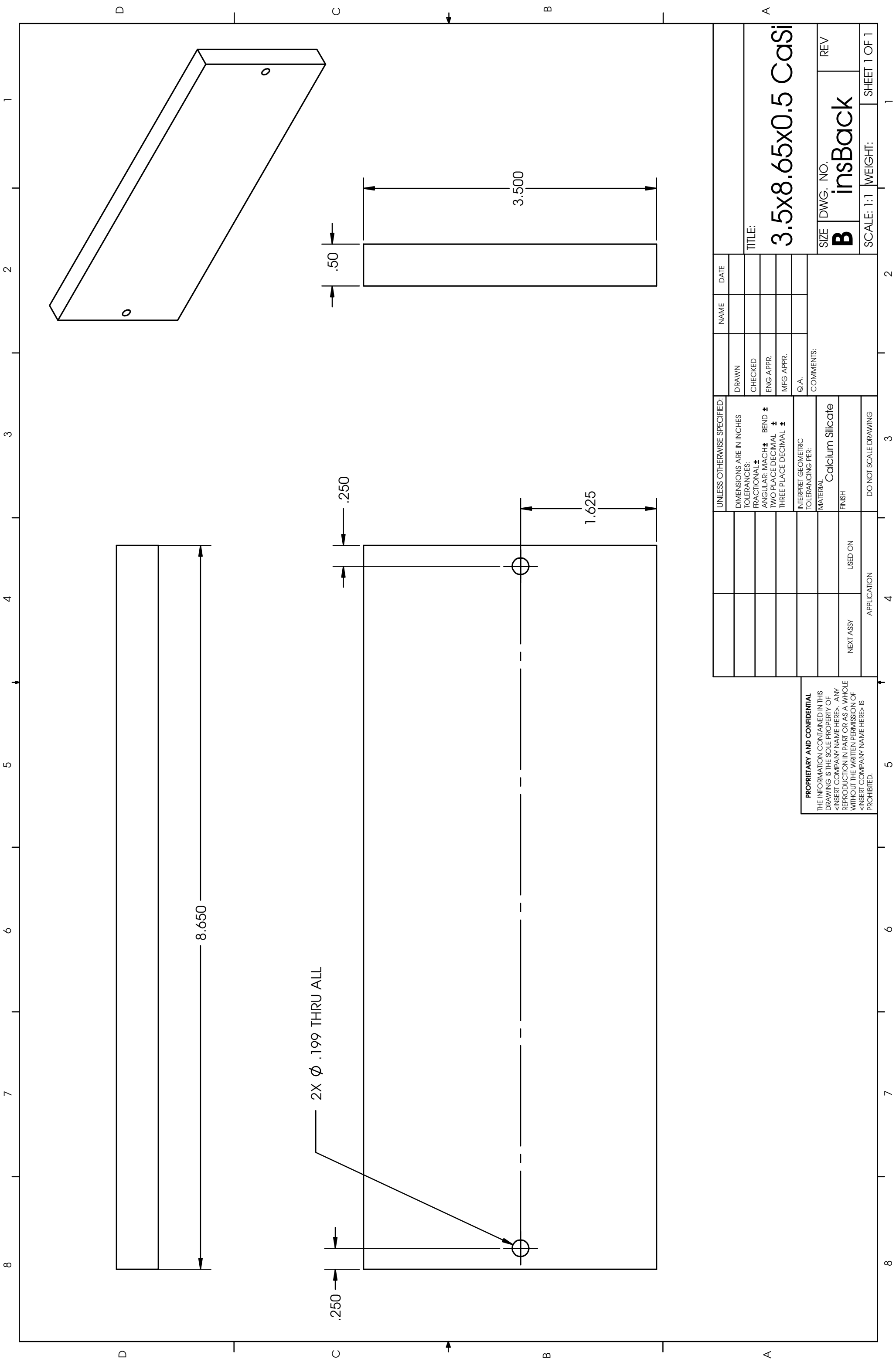
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WEIGHT:
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THREE PLACE DECIMAL ±
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COMMENTS:
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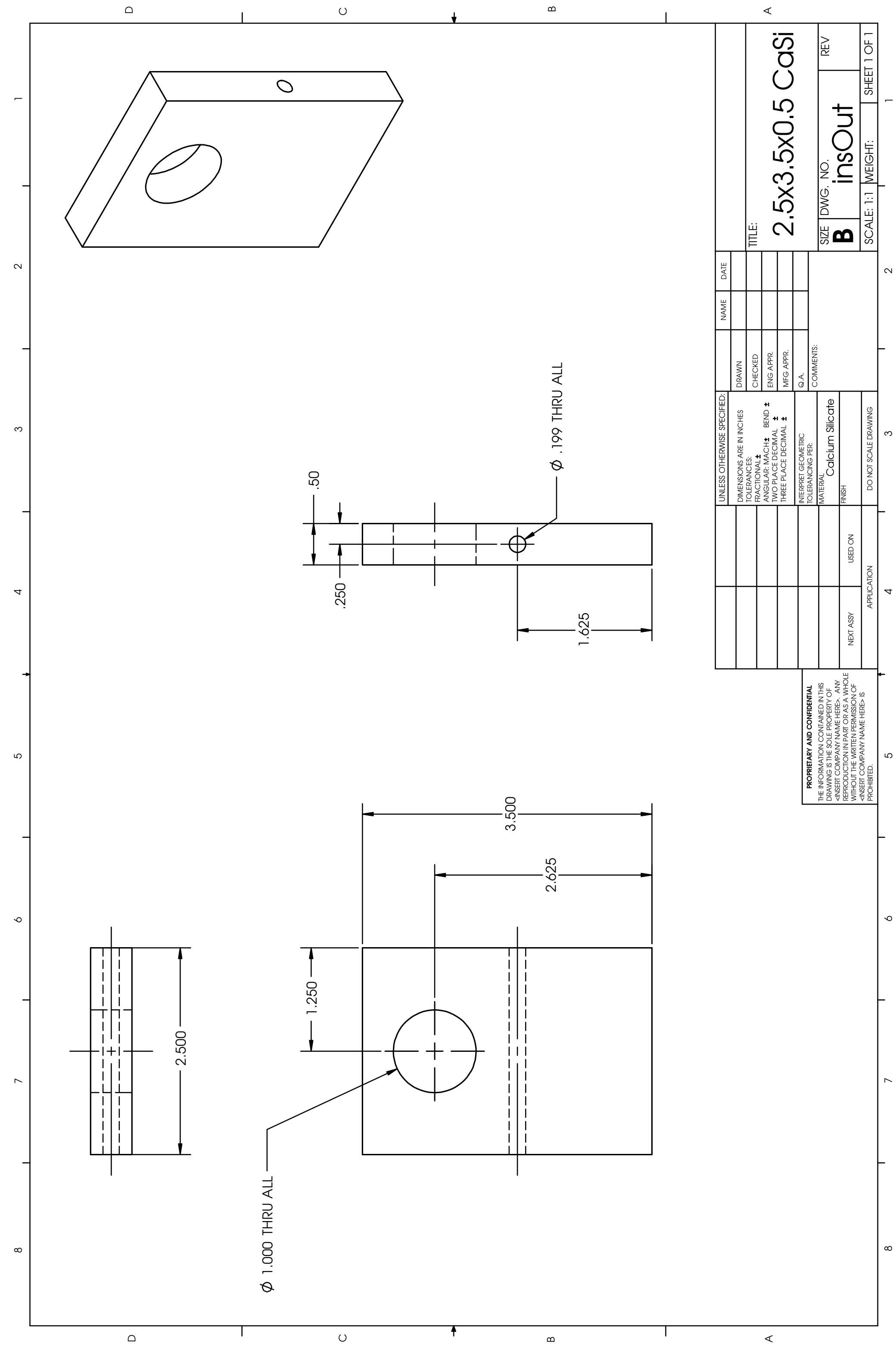

Ø 1.000 THRU ALL
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1.250
2.625
3.500
.250
.50
1.625
Ø .199 THRU ALL
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
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insOut
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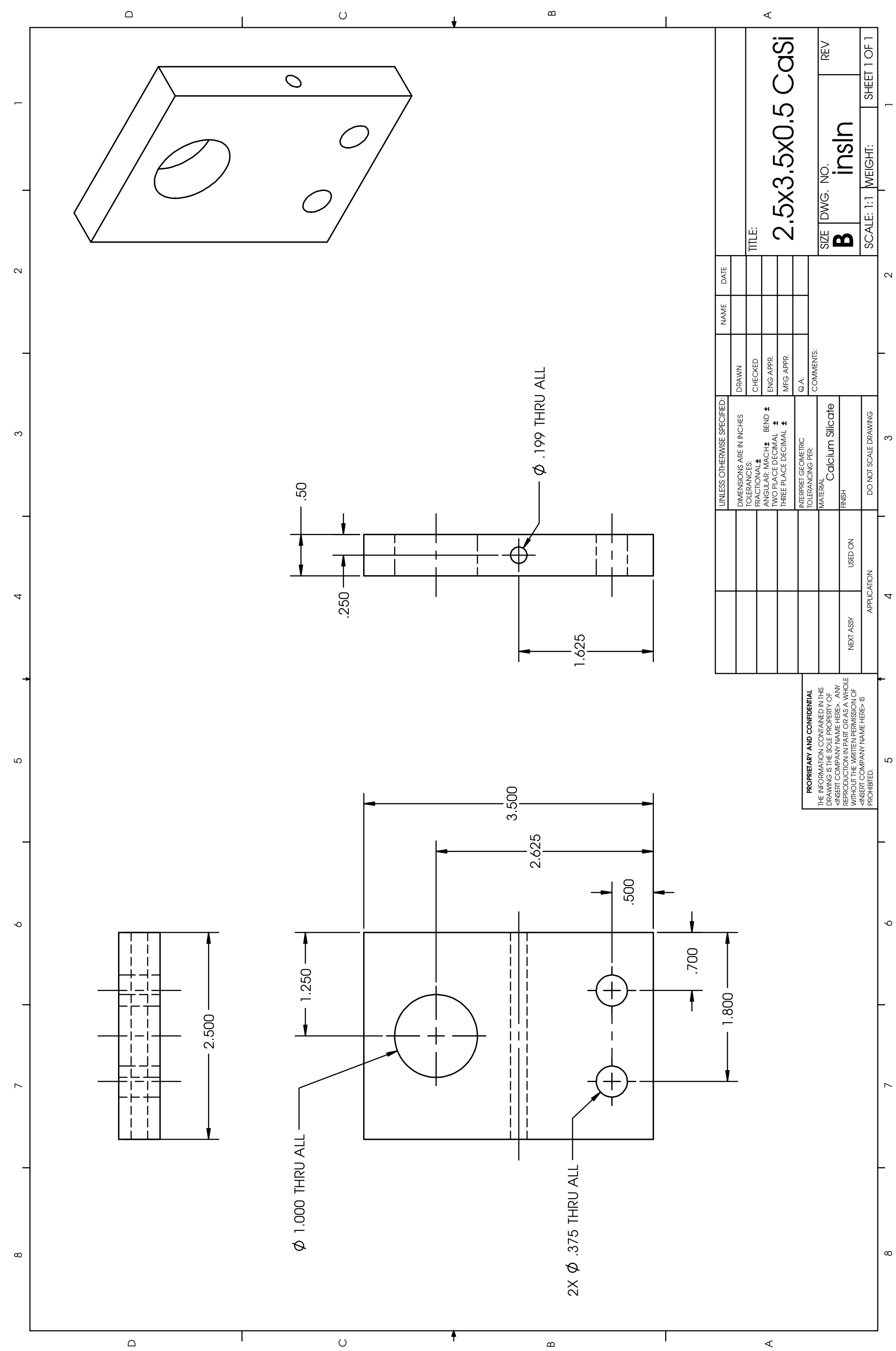

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THREE PLACE DECIMAL ±
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MATERIAL
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FINISH
DO NOT SCALE DRAWING
DRAWN
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ENG APPR.
MFG APPR.
Q.A.
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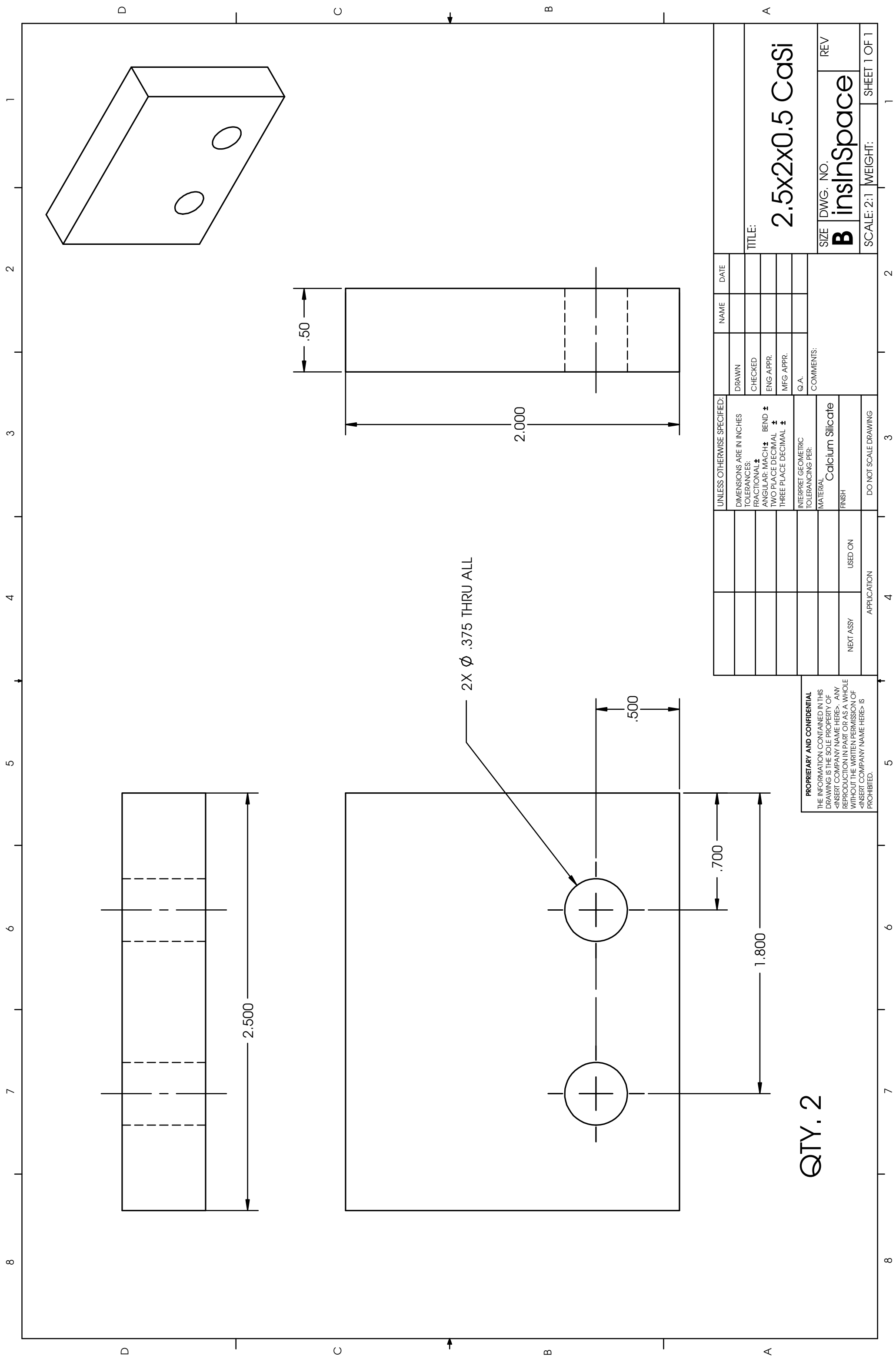
Ø 1.000 THRU ALL
2X Ø .375 THRU ALL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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
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ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
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DATE
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B
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REV
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WEIGHT:
SHEET 1 OF 1
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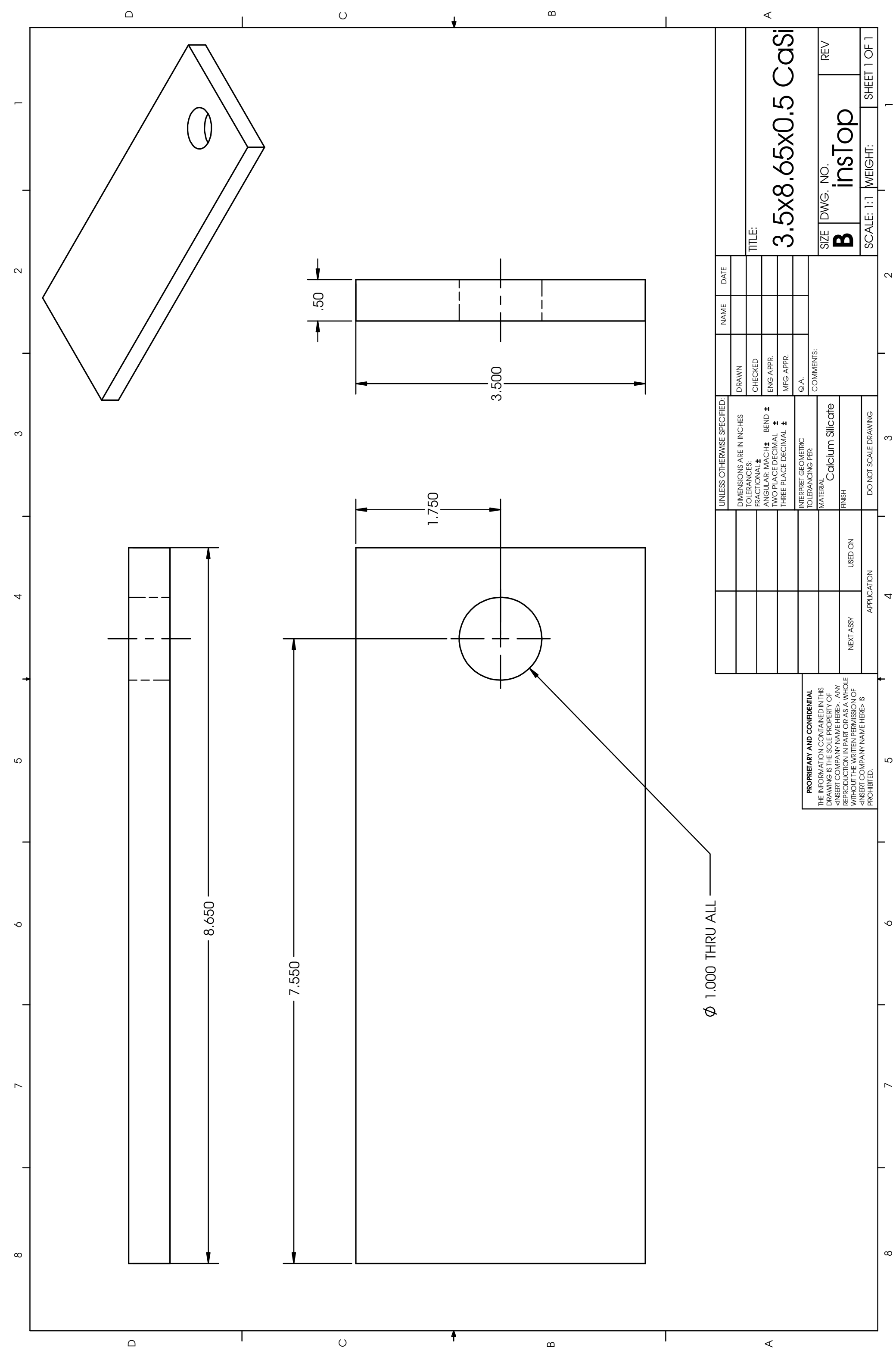

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3.500
1.750
8.650
7.550
Ø 1.000 THRU ALL
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
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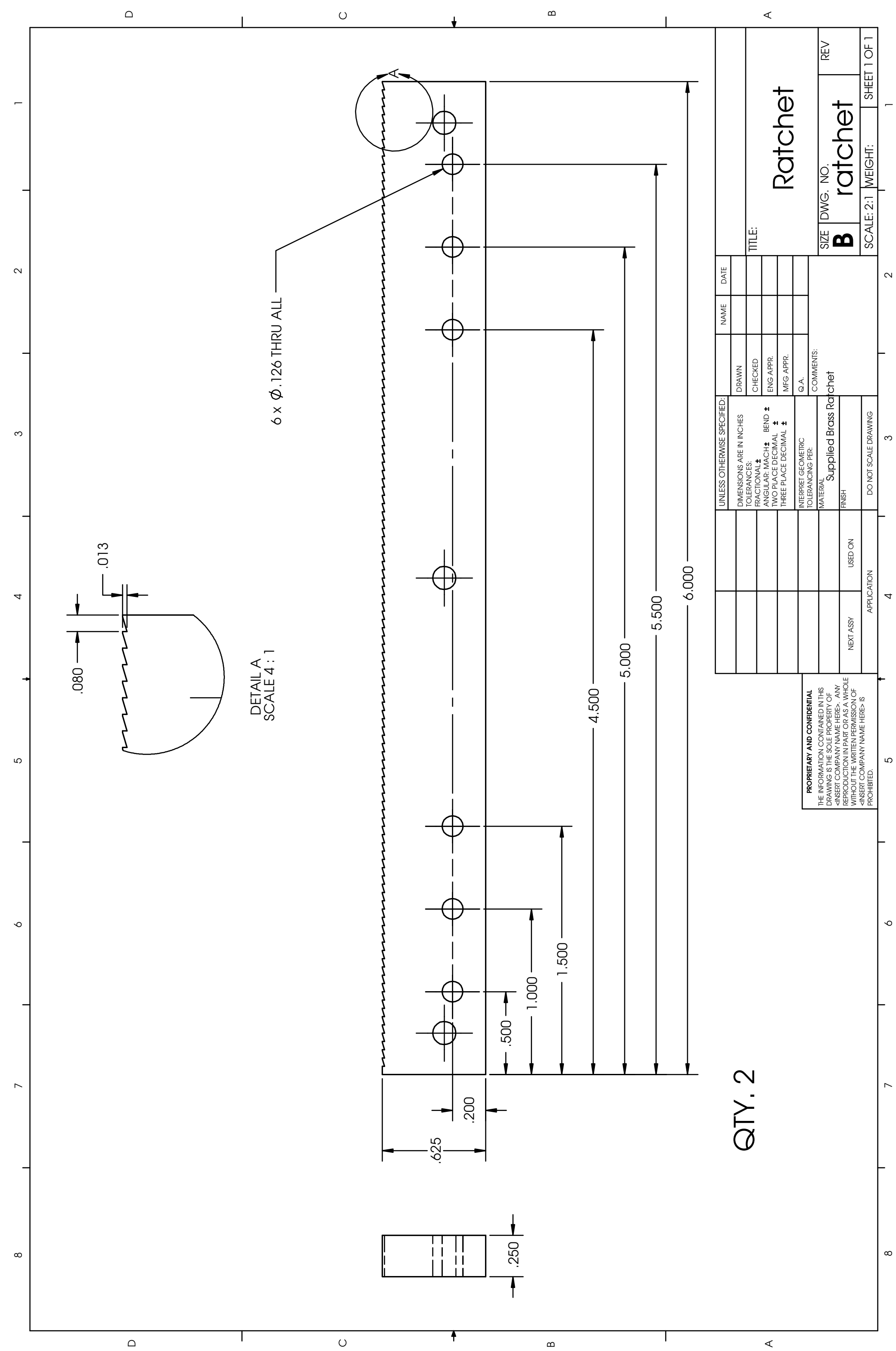
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL



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ratchet
REV
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QTY. 2
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DETAIL A
SCALE 4 : 1
A
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.080
.500
1.000
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4.500
5.000
5.500
6.000
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.625
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ANGULAR: MACH ± BEND ±
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THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Supplied Brass Ratchet
FINISH
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MFG APPR.
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COMMENTS:
NAME
DATE
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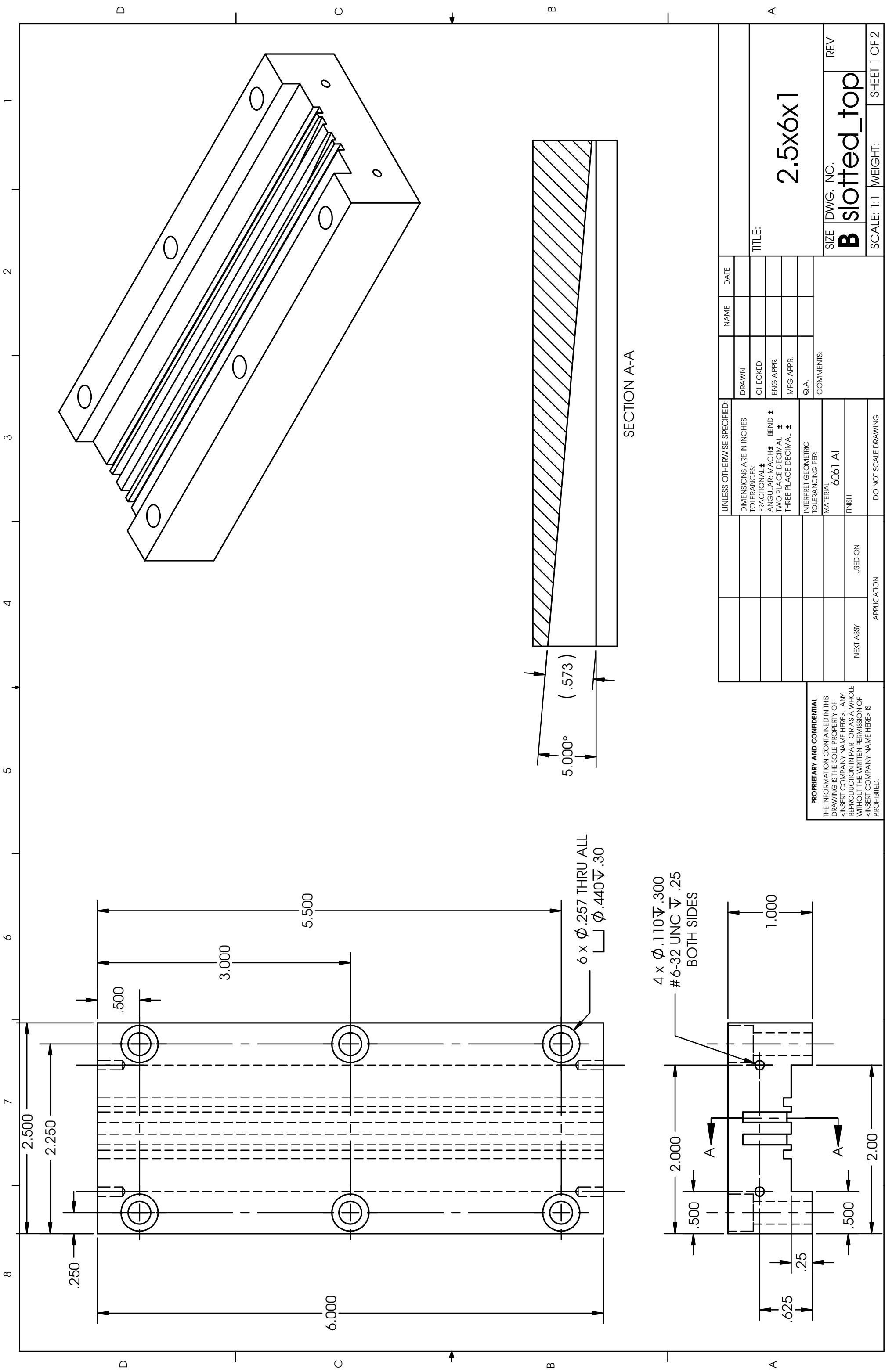

SECTION A-A
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(.573)
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⌴ ⌀.440 ↧ .30
4 x ⌀.110 ↧ .300
#6-32 UNC ↧ .25
BOTH SIDES
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3.000
.500
2.500
2.250
.250
6.000
1.000
2.000
2.00
.500
.500
.25
.625
A
A
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PROPRIETARY AND CONFIDENTIAL
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B
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REV
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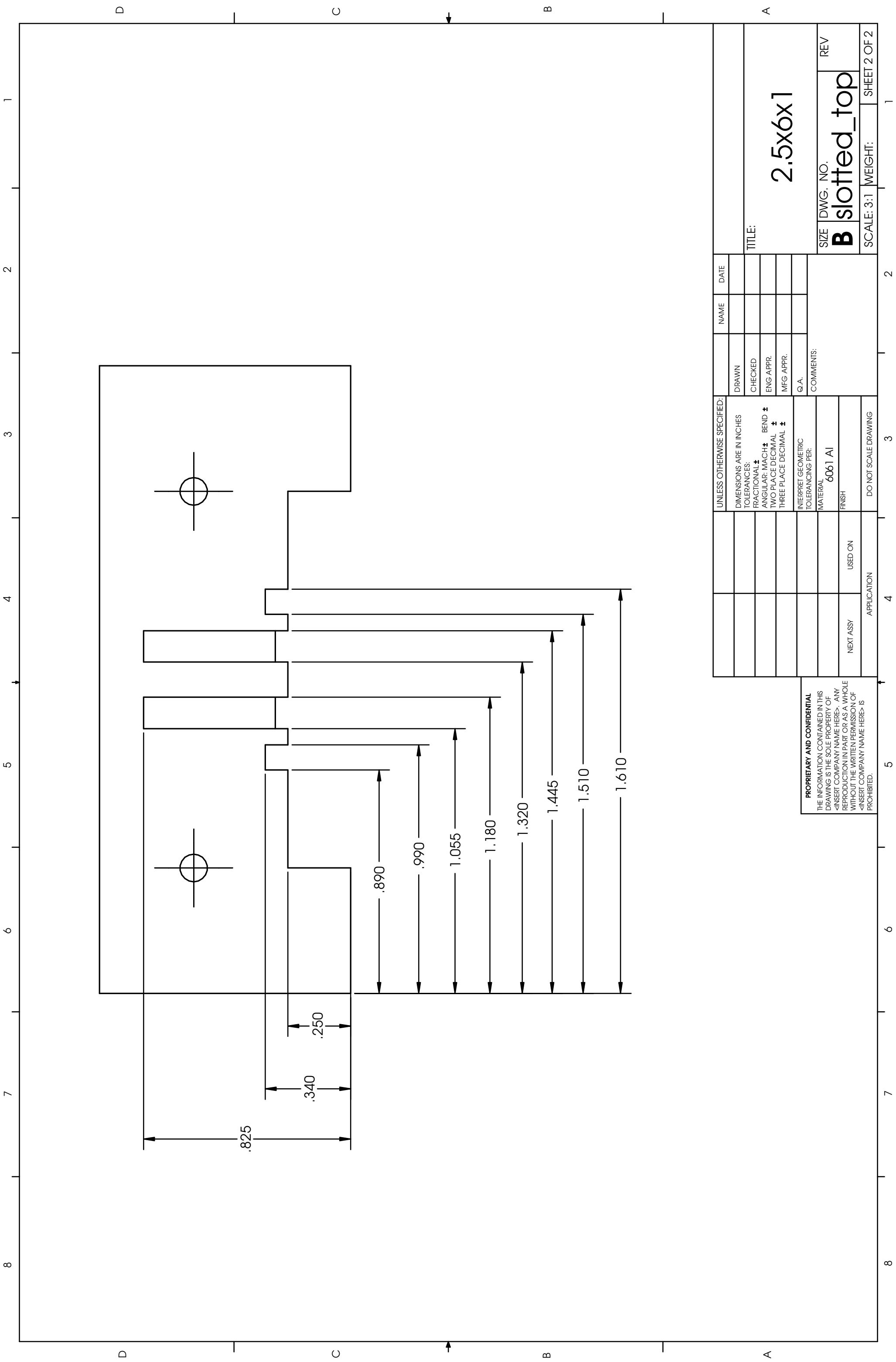
WEIGHT:
SHEET 1 OF 2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UNLESS OTHERWISE SPECIFIED:
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TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
NEXT ASSY
USED ON
APPLICATION
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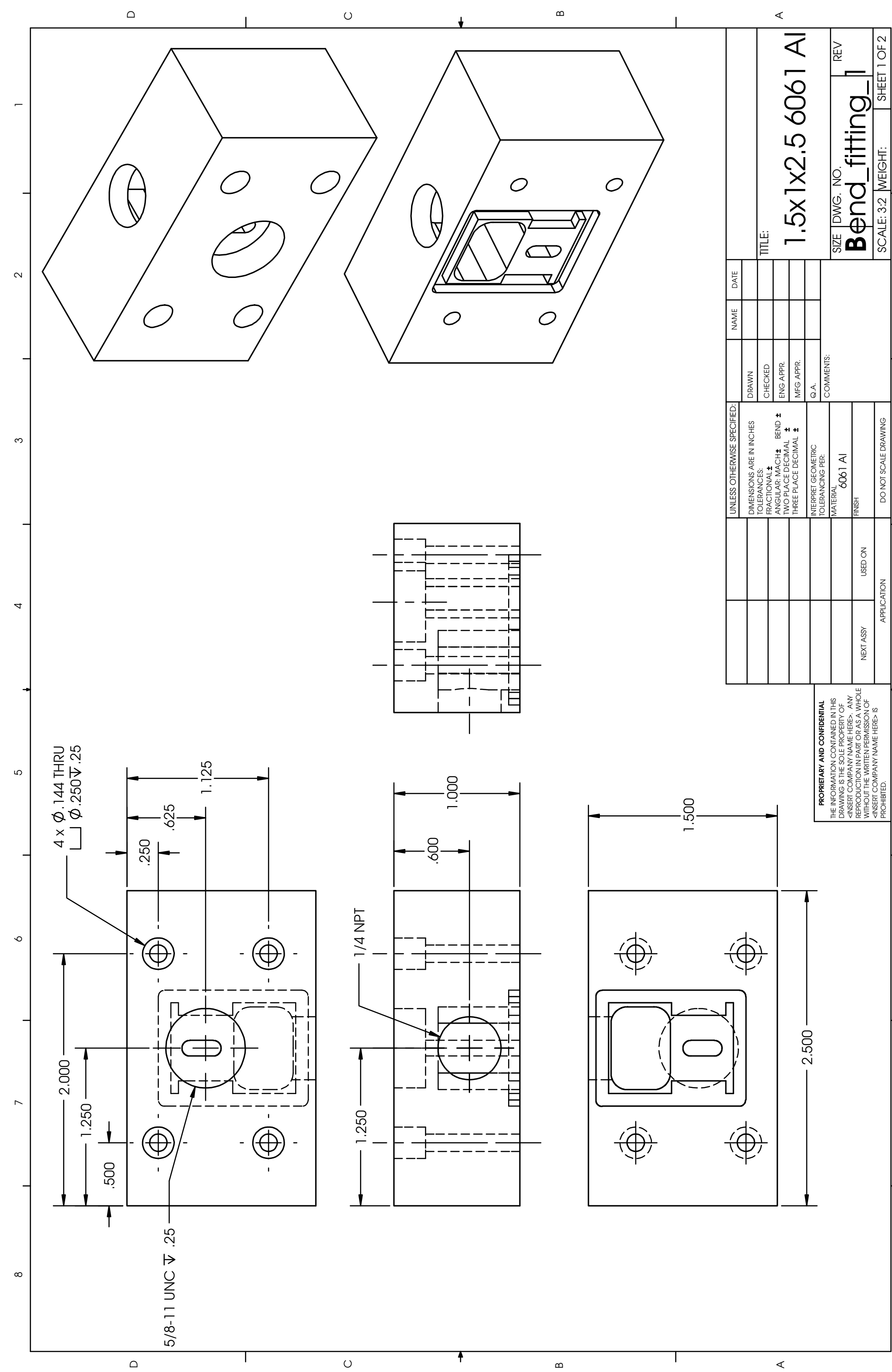
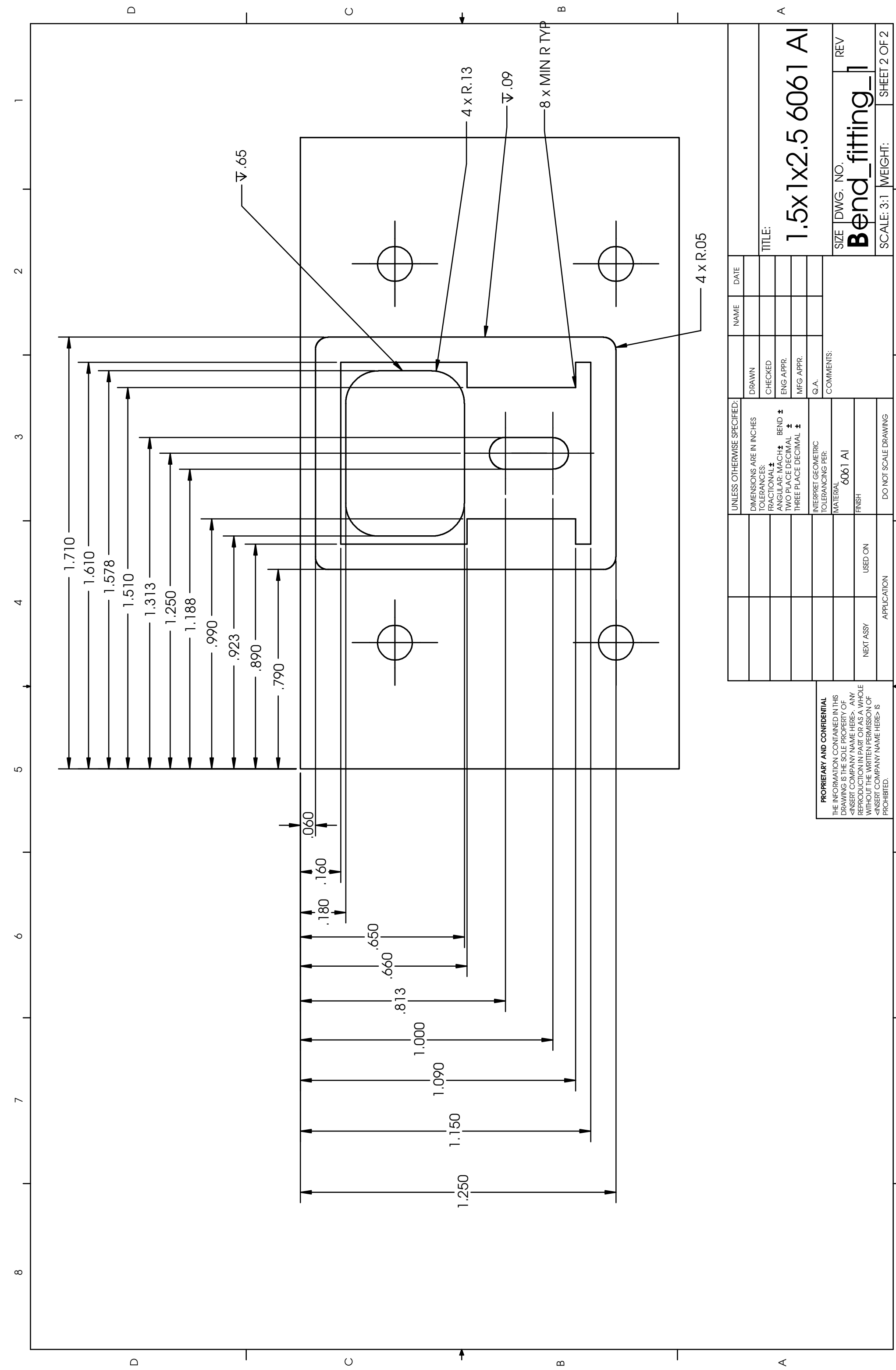


1.5x1x2.5 6061 Al
Bend_fitting_1
SIZE B
DWG. NO.
REV
SCALE: 3:2
WEIGHT:
SHEET 1 OF 2
TITLE:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PROPRIETARY AND CONFIDENTIAL
4 x Ø.144 THRU
Ø.250 ↧ .25
5/8-11 UNC ↧ .25
1/4 NPT
.250
.625
1.125
.600
1.000
1.500
2.000
1.250
.500
2.500



⌴.65
4 x R.13
⌴.09
8 x MIN R TYP
4 x R.05
1.710
1.610
1.578
1.510
1.313
1.250
1.188
.990
.923
.890
.790
.060
.160
.180
.650
.660
.813
1.000
1.090
1.150
1.250
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
1.5x1x2.5 6061 Al
SIZE
B
DWG. NO.
Bend_fitting_1
REV
SCALE: 3:1
WEIGHT:
SHEET 2 OF 2
PROPRIETARY AND CONFIDENTIAL
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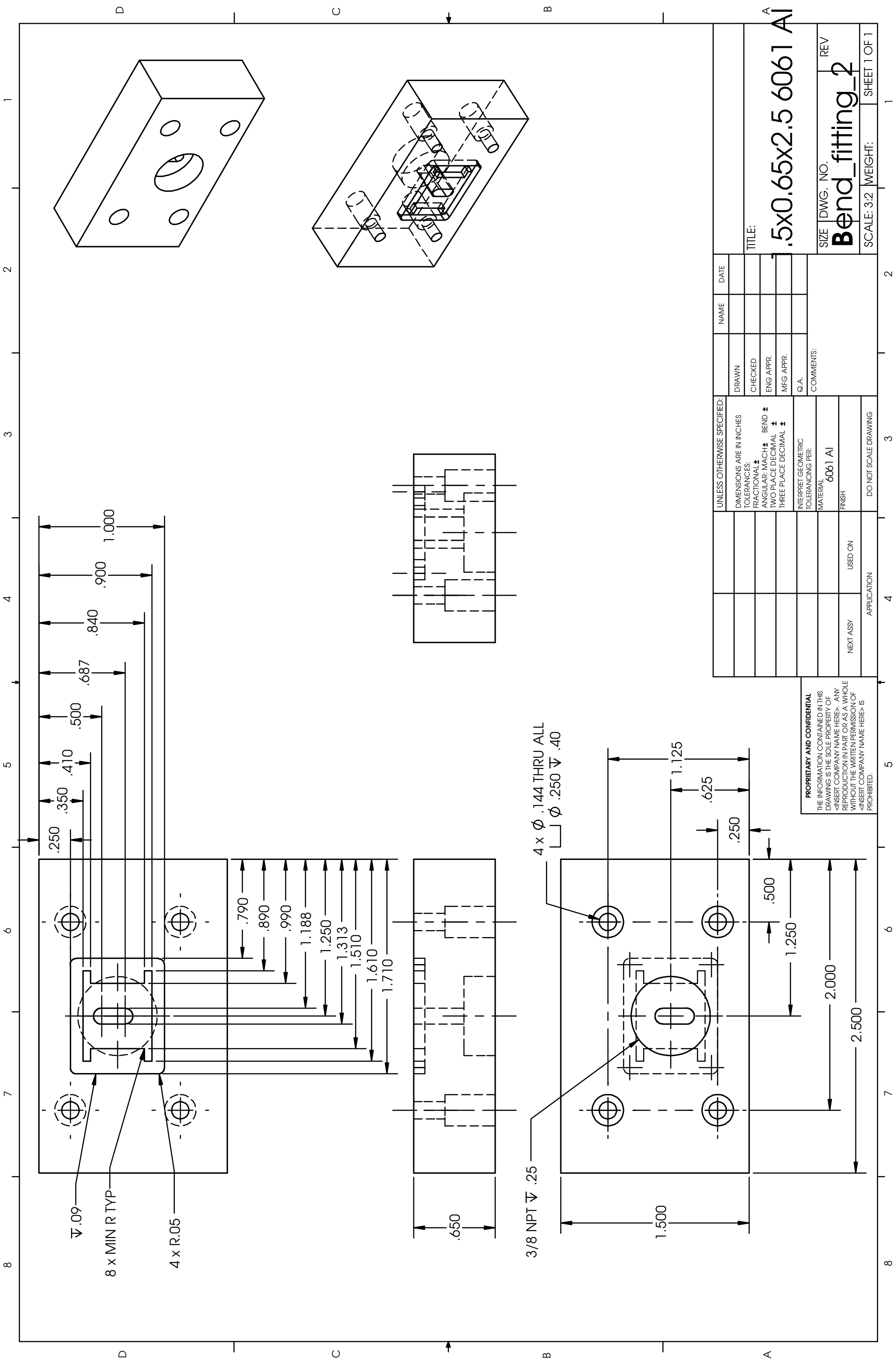

TITLE:
1.5x0.65x2.5 6061 Al
SIZE
DWG. NO.
B
Bend_fitting_2
REV
SCALE: 3:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PROPRIETARY AND CONFIDENTIAL
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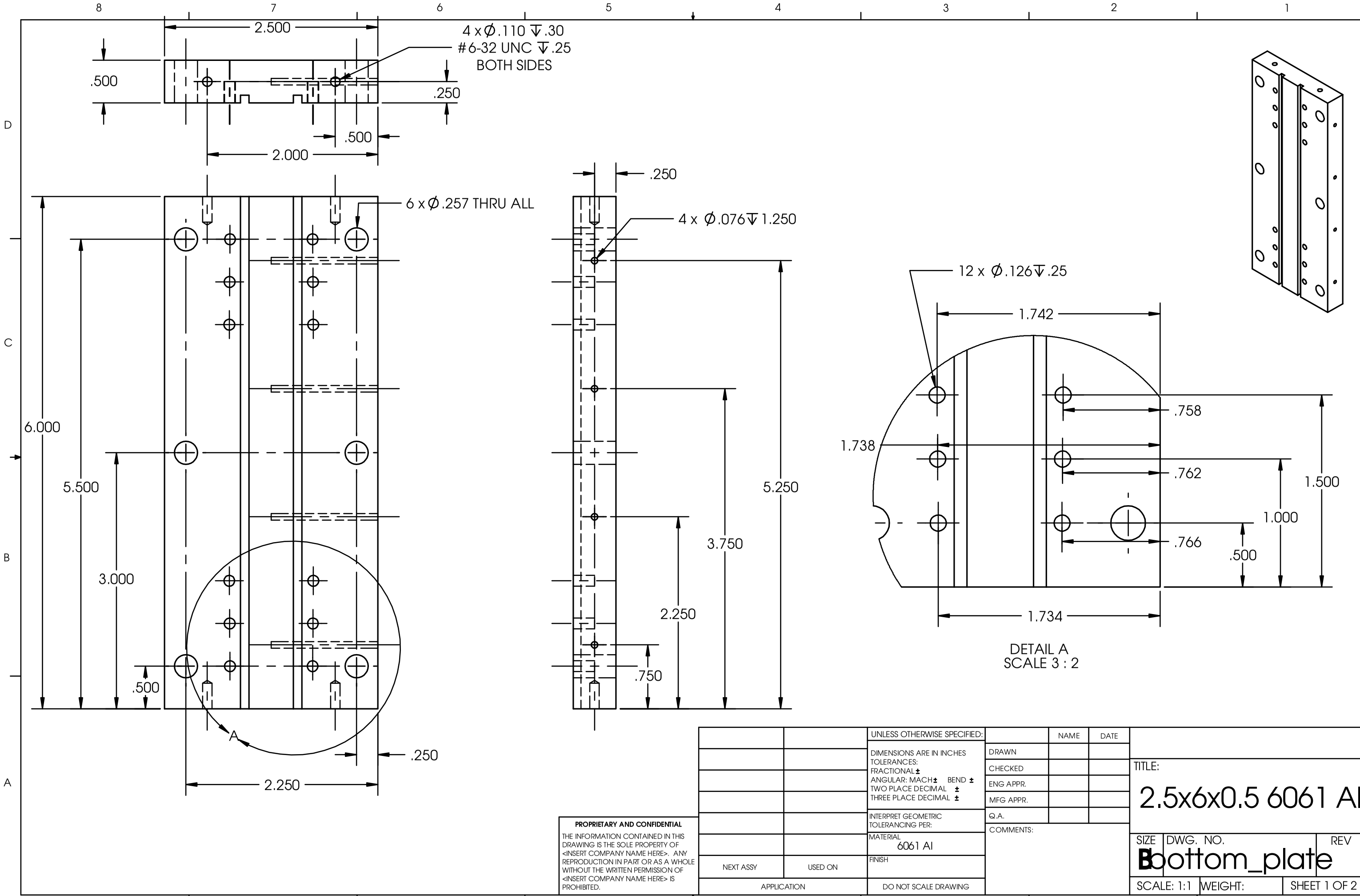
4 x ⌀ .144 THRU ALL
⌴ ⌀ .250 ↧ .40
3/8 NPT ↧ .25
↧ .09
8 x MIN R TYP
4 x R.05
.250
.350
.410
.500
.687
.840
.900
1.000
.790
.890
.990
1.188
1.250
1.313
1.510
1.610
1.710
.650
1.500
1.125
.625
.500
2.000
2.500


4 x Ø.110 ↧.30
#6-32 UNC ↧.25
BOTH SIDES
2.500
.500
.250
.500
2.000
6 x Ø.257 THRU ALL
6.000
5.500
3.000
.500
.250
2.250
A
.250
4 x Ø.076↧1.250
5.250
3.750
2.250
.750
12 x Ø.126↧.25
1.742
1.738
.758
.762
.766
1.500
1.000
.500
1.734
DETAIL A
SCALE 3 : 2
PROPRIETARY AND CONFIDENTIAL
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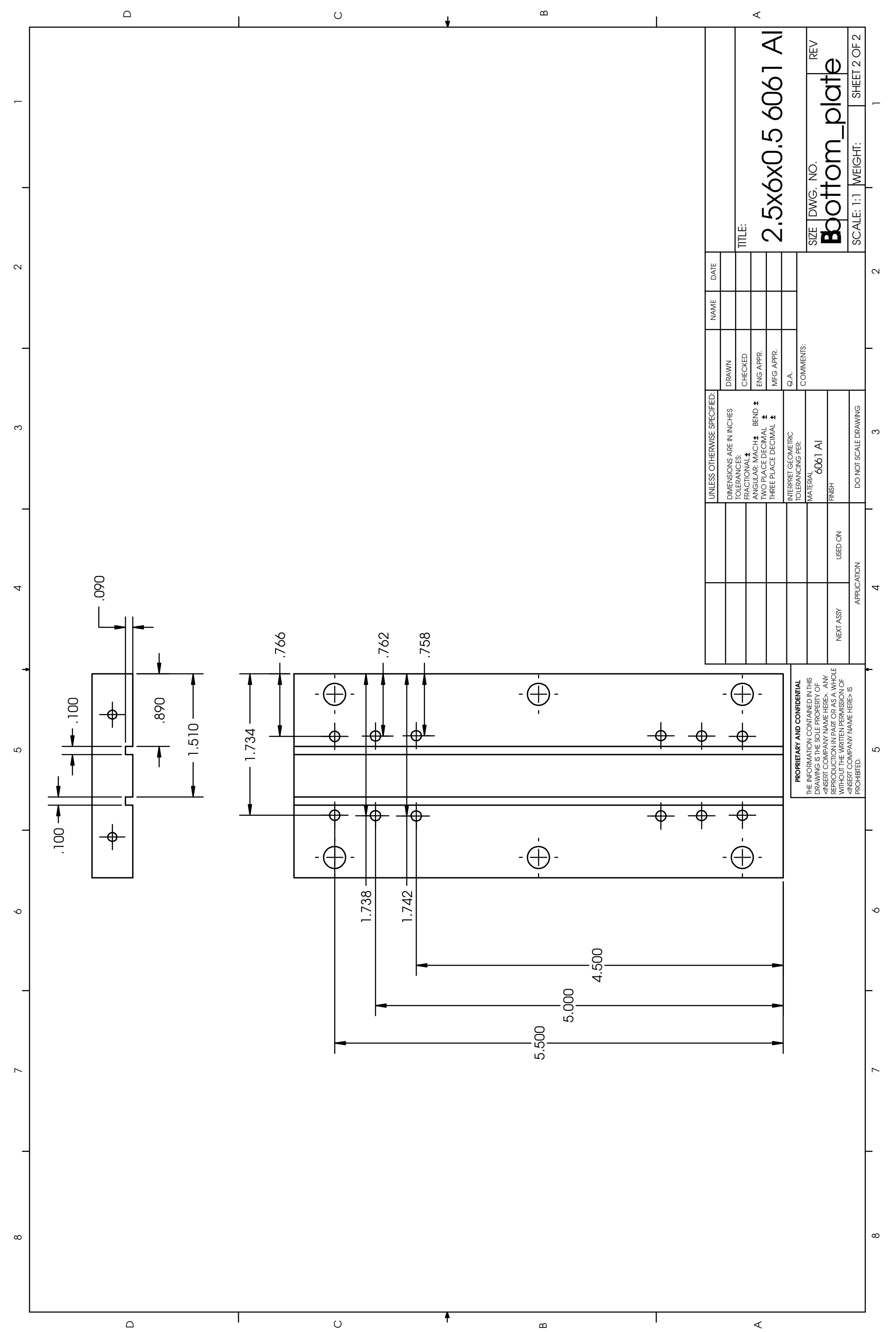
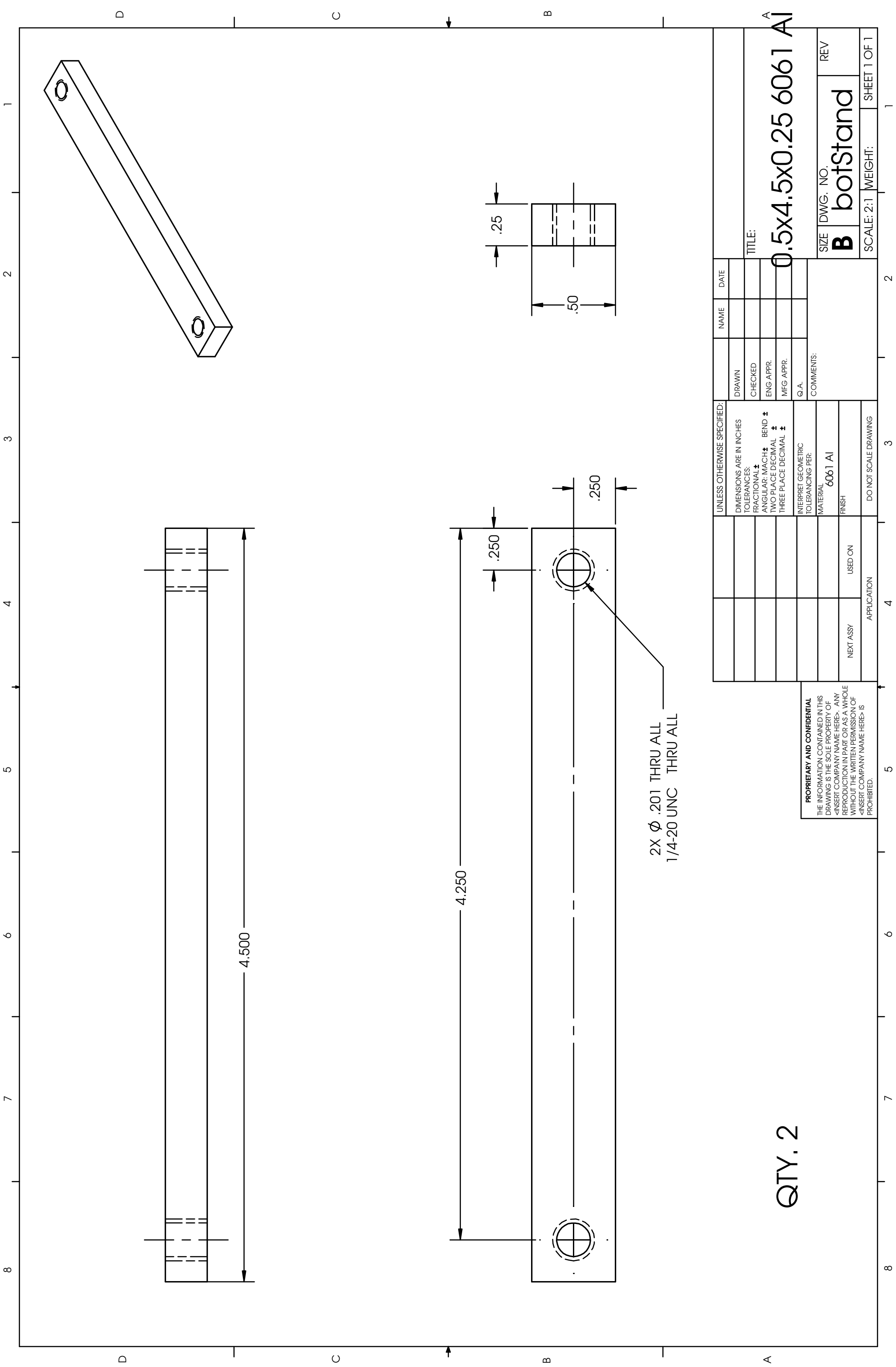
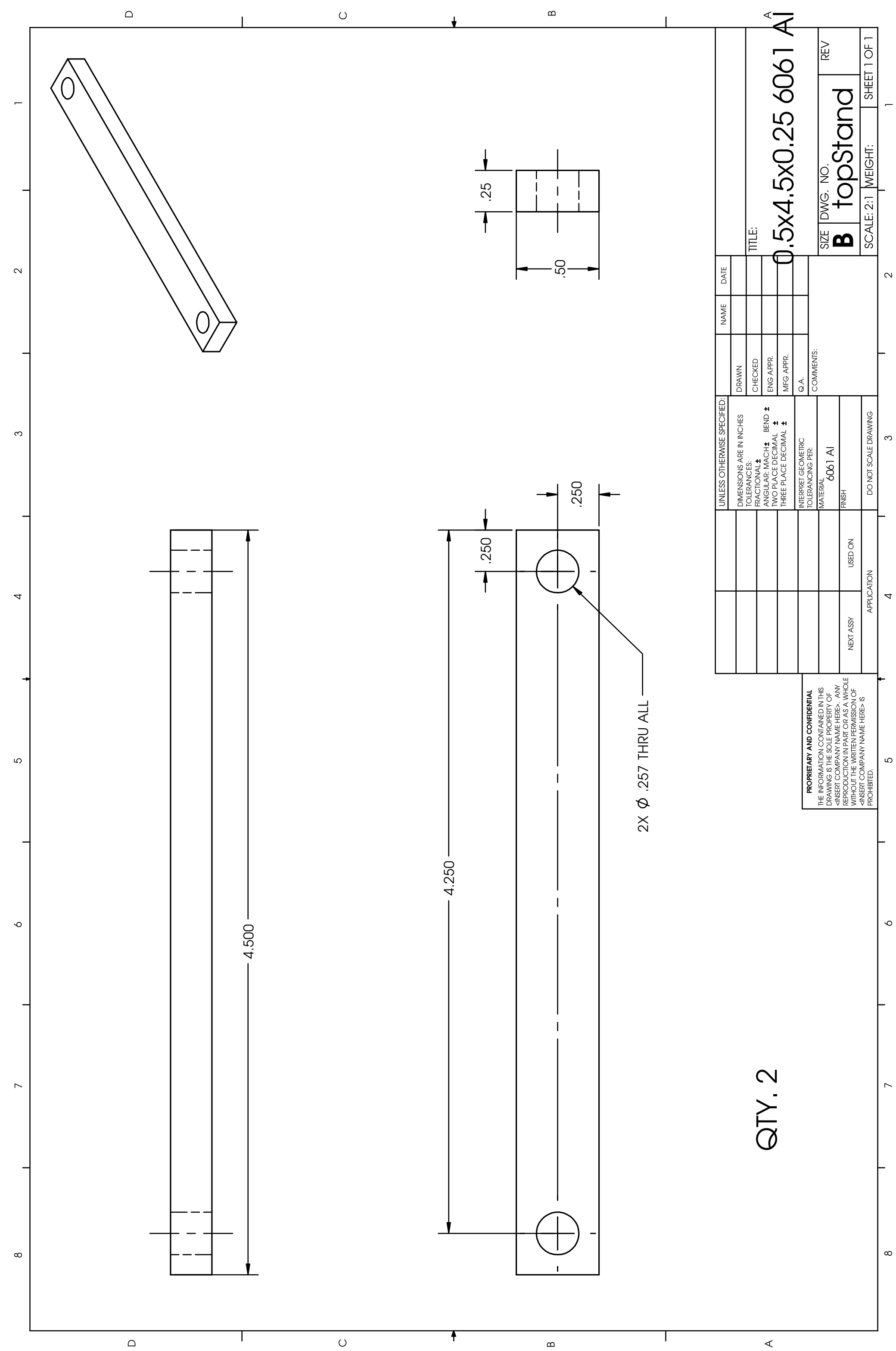
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
2.5x6x0.5 6061 Al
SIZE
B
DWG. NO.
bottom_plate
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 2



TITLE:
2.5x6x0.5 6061 Al
SIZE
B
DWG. NO.
Bottom_plate
REV
SCALE: 1:1
WEIGHT:
SHEET 2 OF 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
.090
.100
.890
1.510
.100
1.734
.766
.762
.758
1.738
1.742
4.500
5.000
5.500



.25
.50
4.500
4.250
.250
.250
2X Ø .201 THRU ALL
1/4-20 UNC THRU ALL
QTY. 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
0.5x4.5x0.25 6061 Al
SIZE
B
DWG. NO.
botStand
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


QTY. 2
4.500
4.250
.250
.250
.25
.50
2X ⌀ .257 THRU ALL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
0.5x4.5x0.25 6061 Al
SIZE
B
DWG. NO.
topStand
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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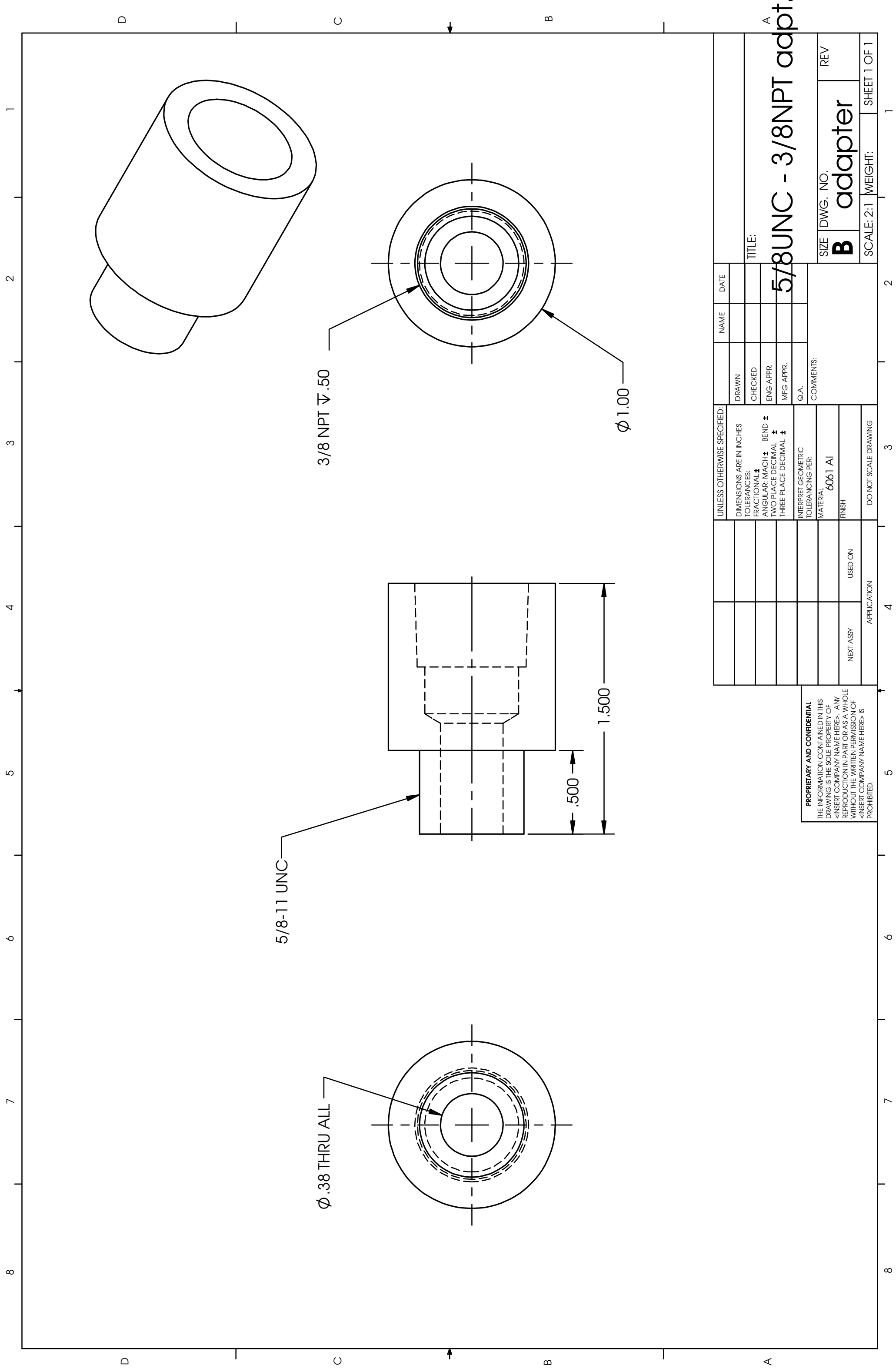

3/8 NPT ↧ .50
Ø1.00
5/8-11 UNC
.500
1.500
Ø.38 THRU ALL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 Al
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
5/8UNC - 3/8NPT adpt.
SIZE
B
DWG. NO.
adapter
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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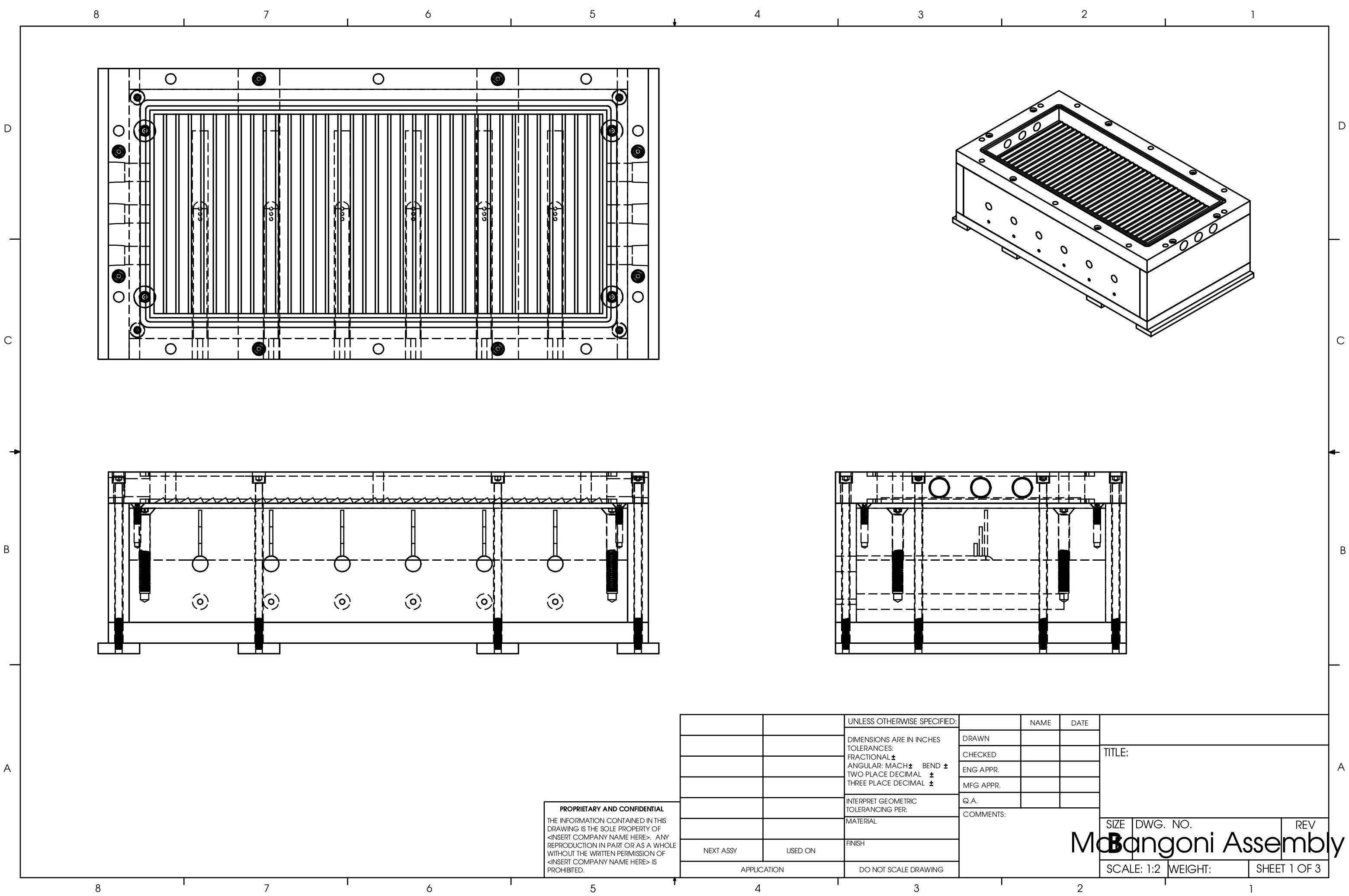
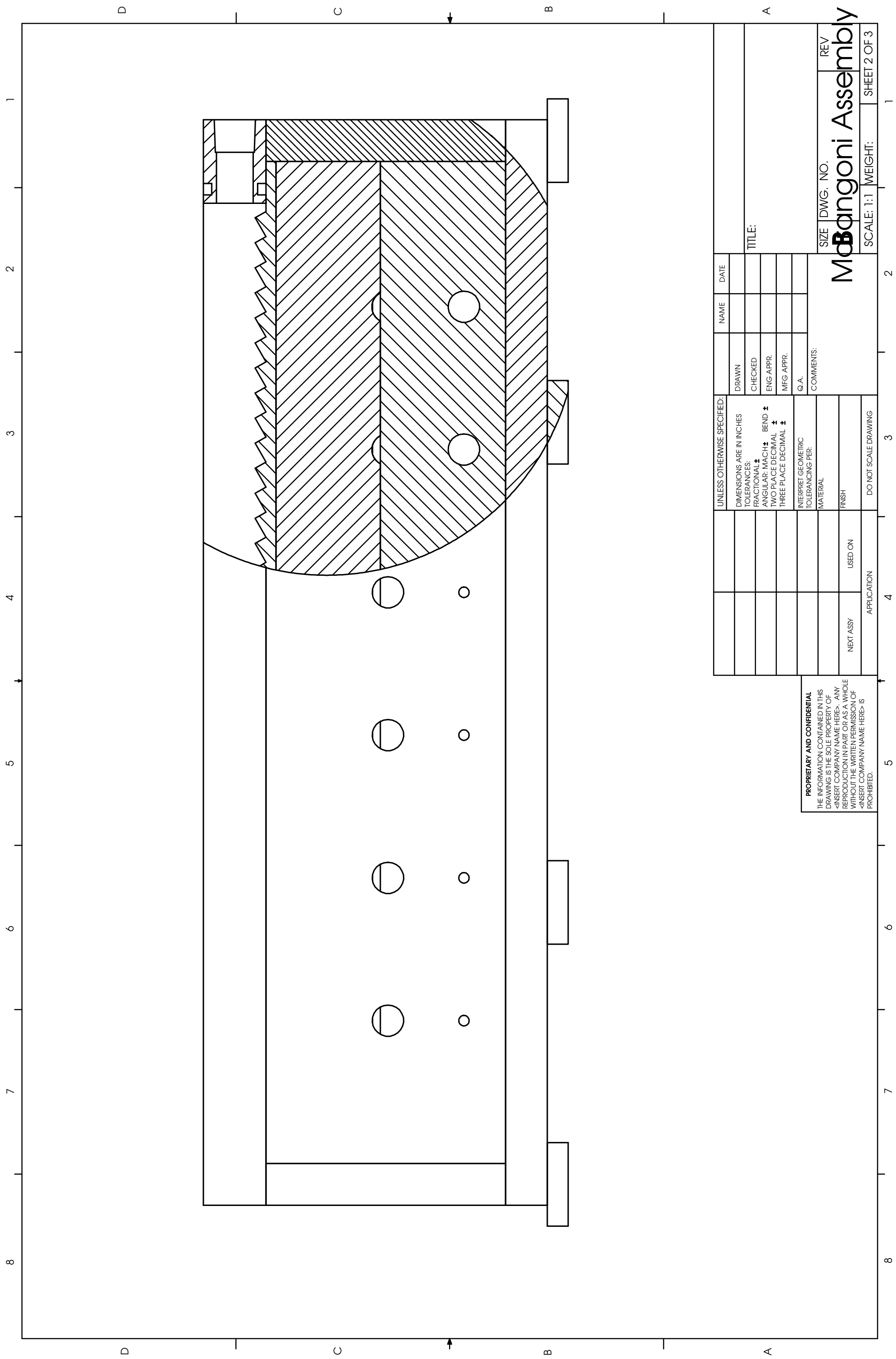
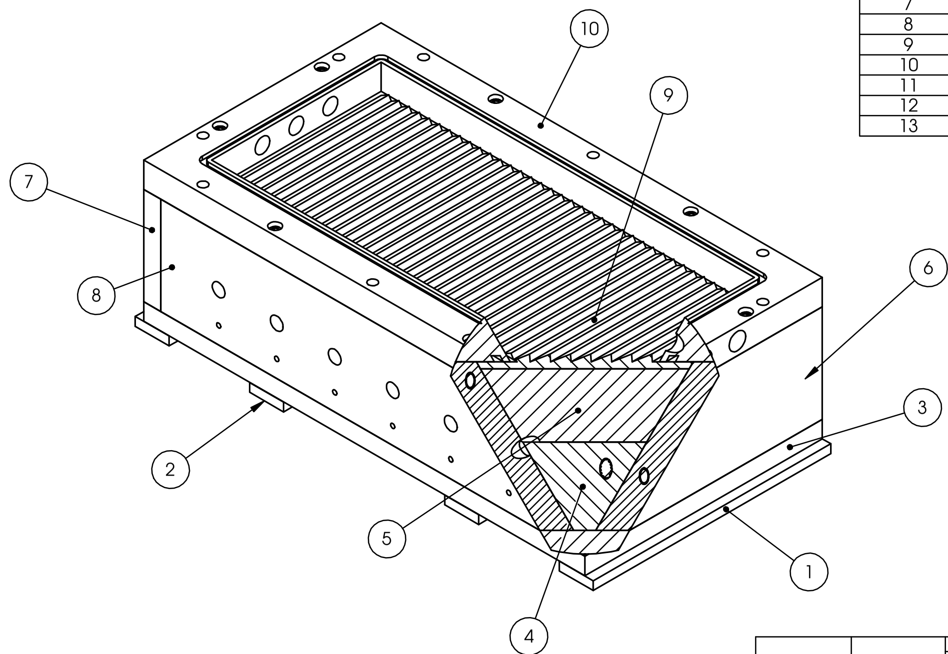
9.2. APPENDIX B: MARANGONI PUMP PART DRAWINGS


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
B
Marangoni Assembly
SCALE: 1:2
WEIGHT:
SHEET 1 OF 3
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.


Marangoni Assembly
SIZE B
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 2 OF 3
TITLE:
UNLESS OTHERWISE SPECIFIED:
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	crossSupportEnds		2
2	crossSupportMid		2
3	bottomins		1
4	HeatingBlock		1
5	ThermBlock		1
6	rearins		1
7	sideins		2
8	frontins		1
9	RatchetedTestBlock		1
10	Housing		1
11	91253A194		4
12	91253A550		4
13	92196A213		8

PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY | USED ON | APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

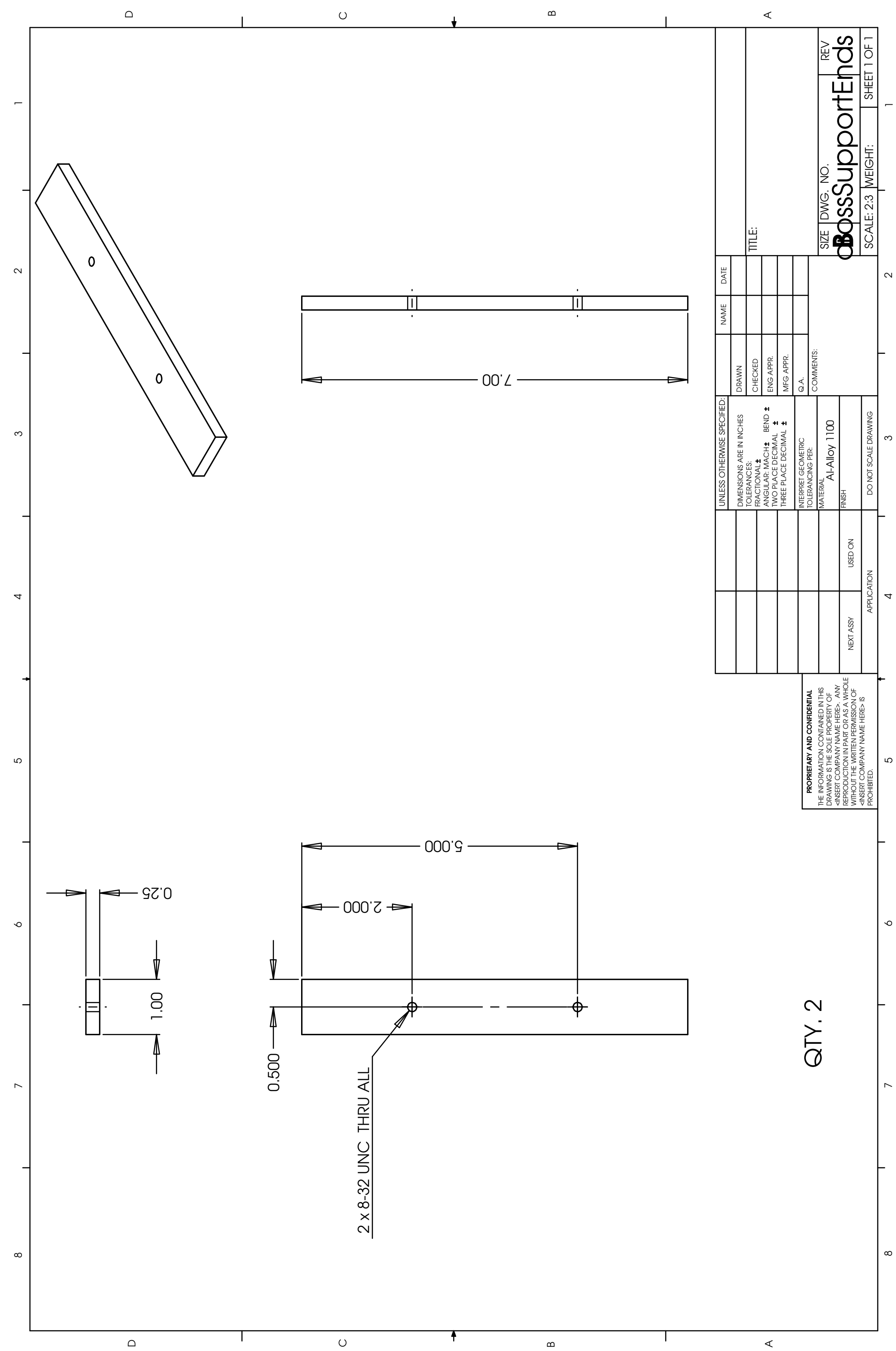
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B | DWG. NO. Marangoni Assembly | REV

SCALE: 1:2 | WEIGHT: | SHEET 3 OF 3


7.00
5.000
2.000
0.25
1.00
0.500
2 x 8-32 UNC THRU ALL
QTY. 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Al-Alloy 1100
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
DWG. NO.
REV
BossSupportEnds
SCALE: 2:3
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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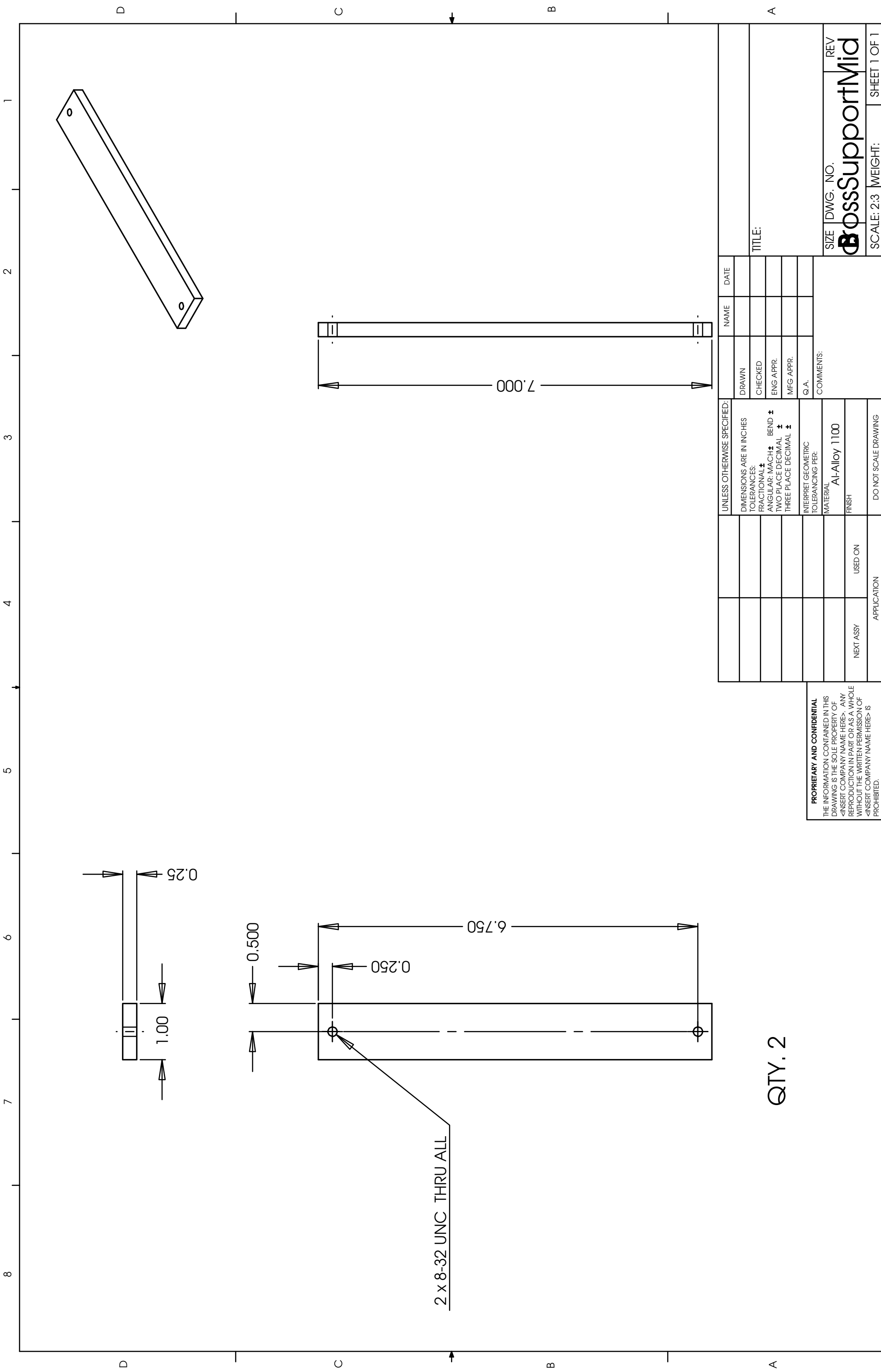
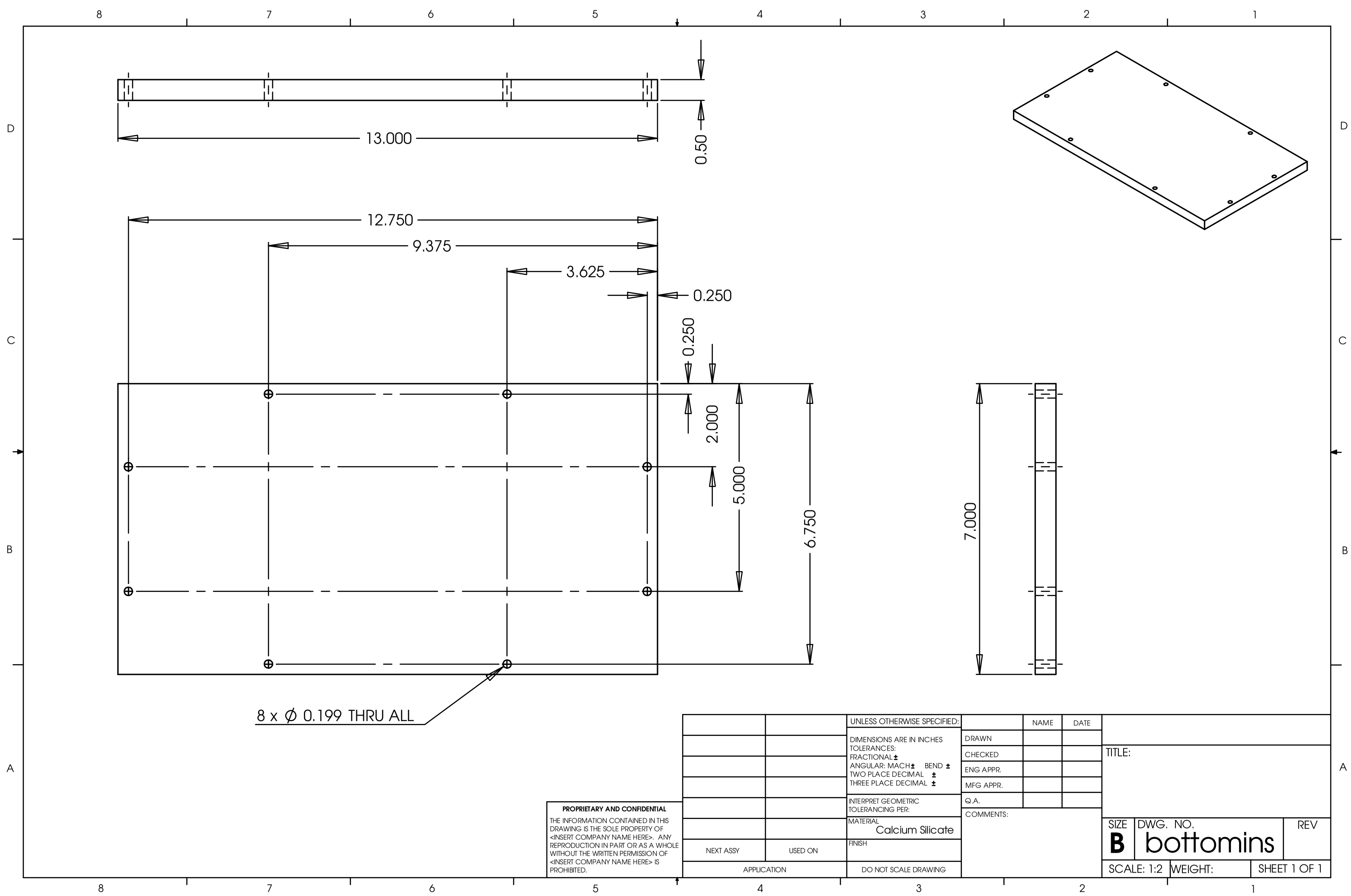

7.000
0.25
6.750
0.500
0.250
1.00
2 x 8-32 UNC THRU ALL
QTY. 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Al-Alloy 1100
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
DWG. NO.
REV
B
CrossSupportMid
SCALE: 2:3
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


13.000
0.50
12.750
9.375
3.625
0.250
0.250
2.000
5.000
6.750
7.000
8 x Ø 0.199 THRU ALL
PROPRIETARY AND CONFIDENTIAL
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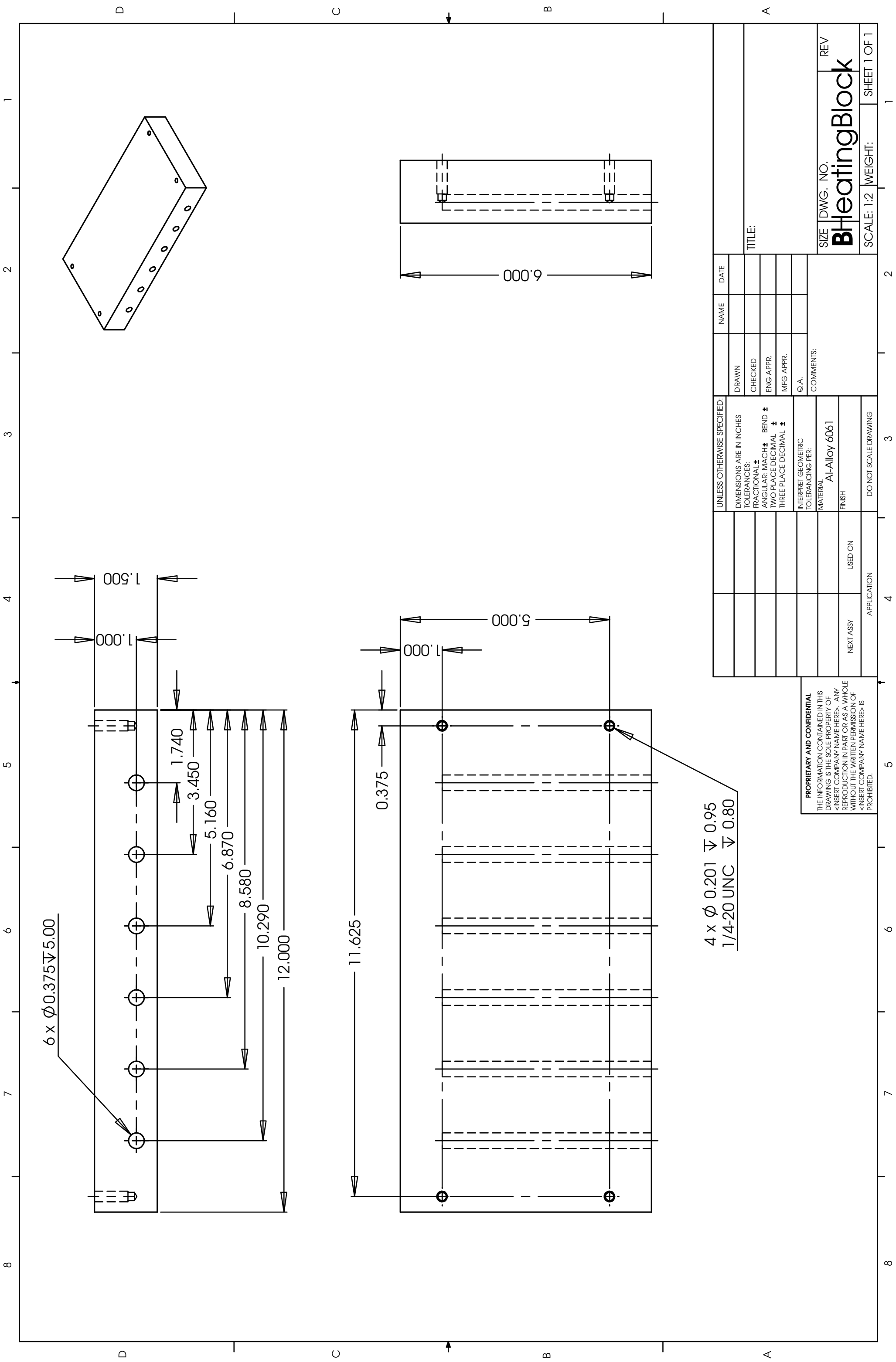
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
B
DWG. NO.
bottomins
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


6.000
1.500
1.000
5.000
1.000
1.740
3.450
5.160
6.870
8.580
10.290
12.000
11.625
0.375
6 x Ø0.375 ↧5.00
4 x Ø 0.201 ↧ 0.95
1/4-20 UNC ↧ 0.80
PROPRIETARY AND CONFIDENTIAL
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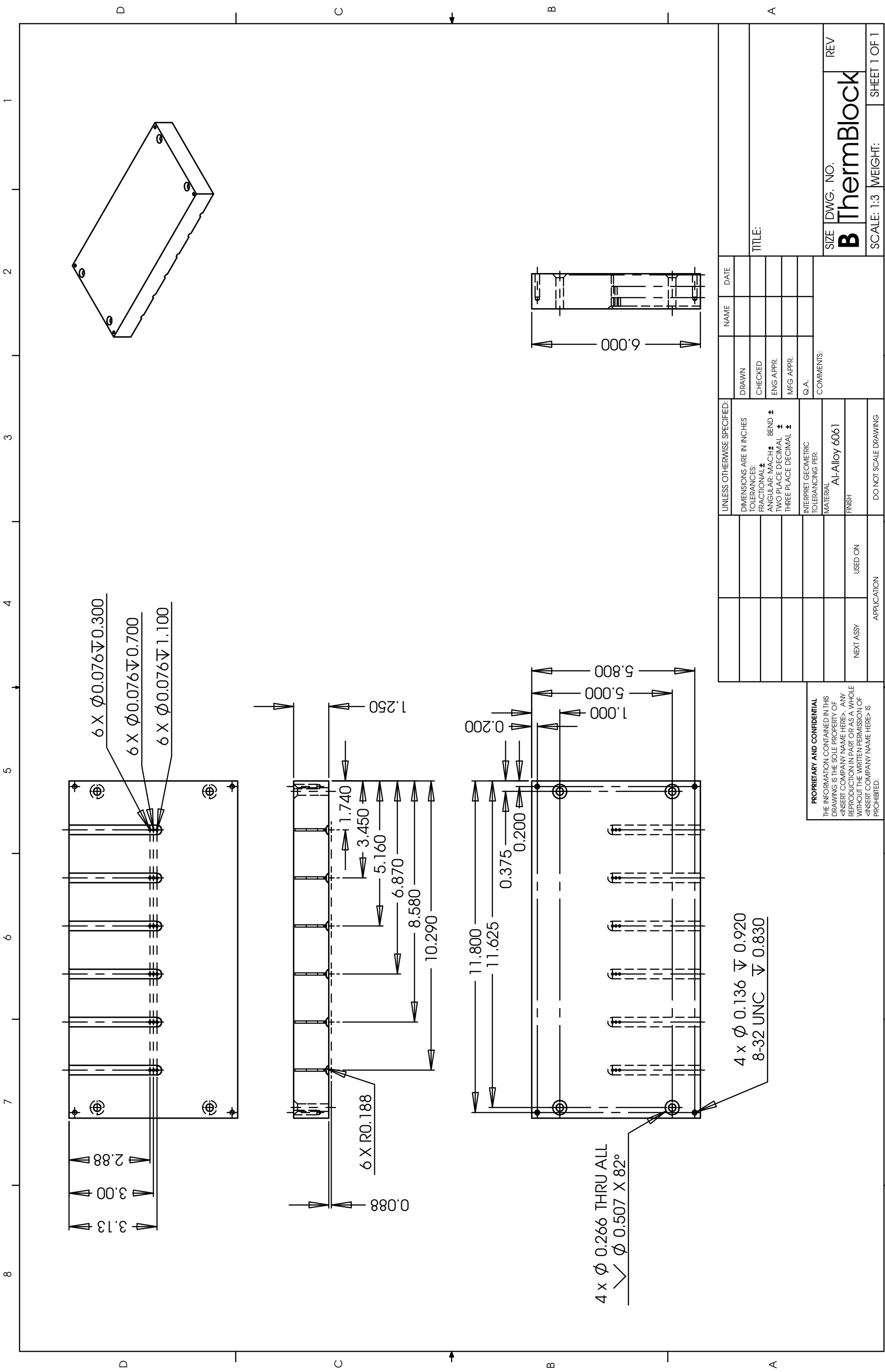
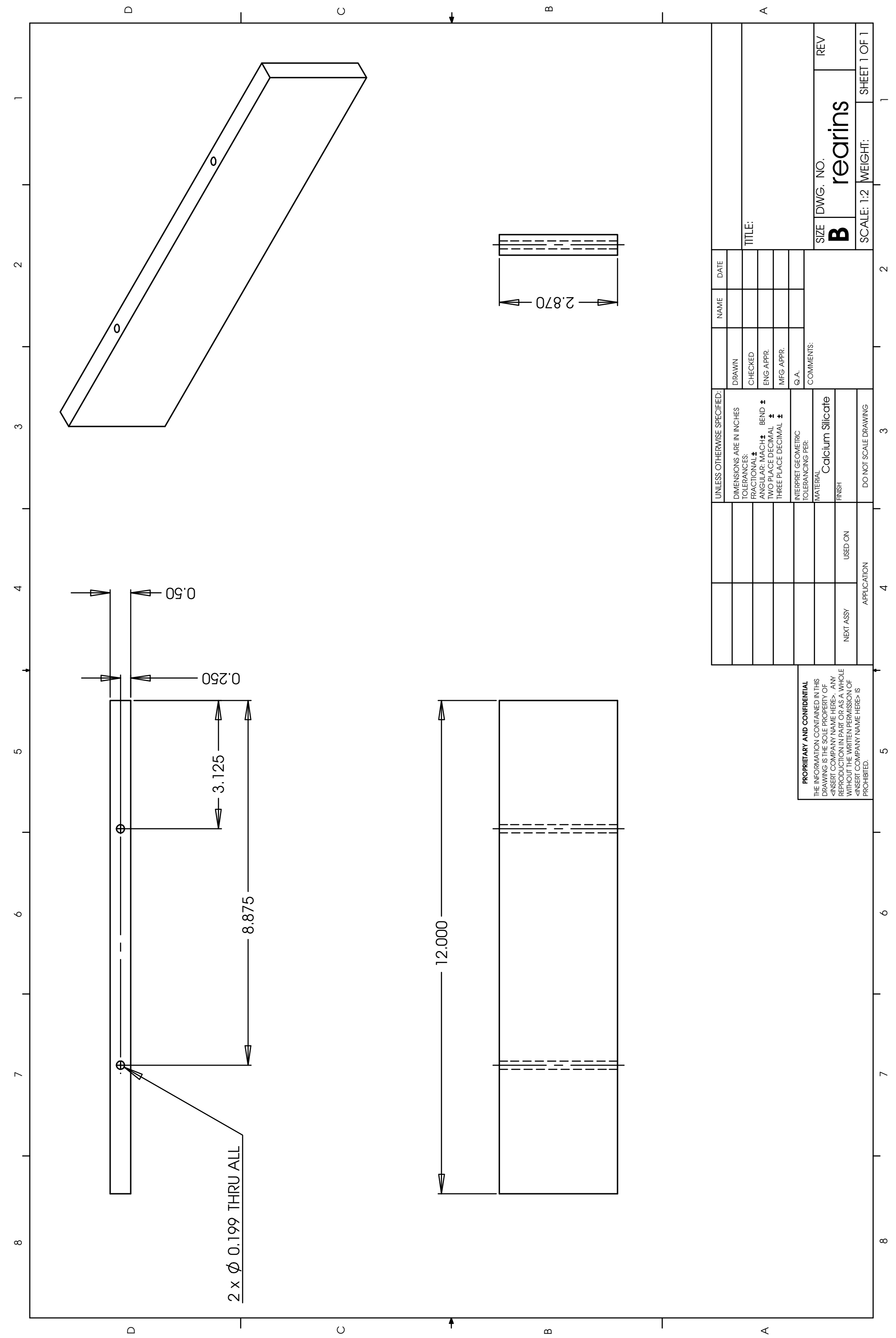
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Al-Alloy 6061
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
DWG. NO.
REV
B
HeatingBlock
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1



6 X Ø0.076↧0.300
6 X Ø0.076↧0.700
6 X Ø0.076↧1.100
1.250
0.200
1.000
5.000
5.800
6.000
1.740
3.450
5.160
6.870
8.580
10.290
11.800
11.625
0.375
0.200
6 X R0.188
0.088
2.88
3.00
3.13
4 x Ø 0.136 ↧ 0.920
8-32 UNC ↧ 0.830
4 x Ø 0.266 THRU ALL
⌵ Ø 0.507 X 82°
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Al-Alloy 6061
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
DWG. NO.
REV
B
ThermBlock
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL


0.50
0.250
3.125
8.875
2 x Ø 0.199 THRU ALL
12.000
2.870
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
B
DWG. NO.
rearins
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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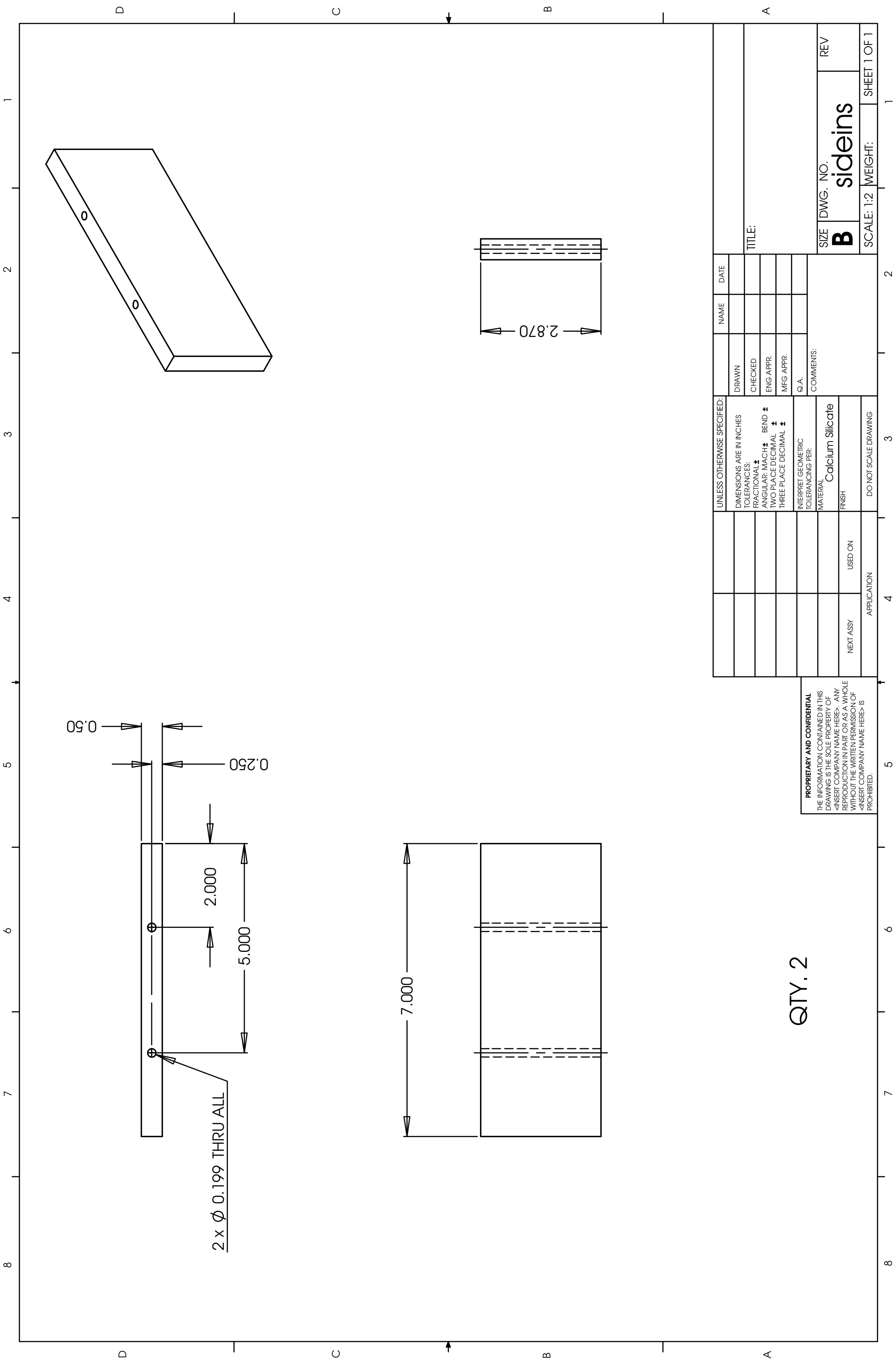

2.870
0.50
0.250
2.000
5.000
7.000
2 x Ø 0.199 THRU ALL
QTY. 2
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
B
DWG. NO.
sideins
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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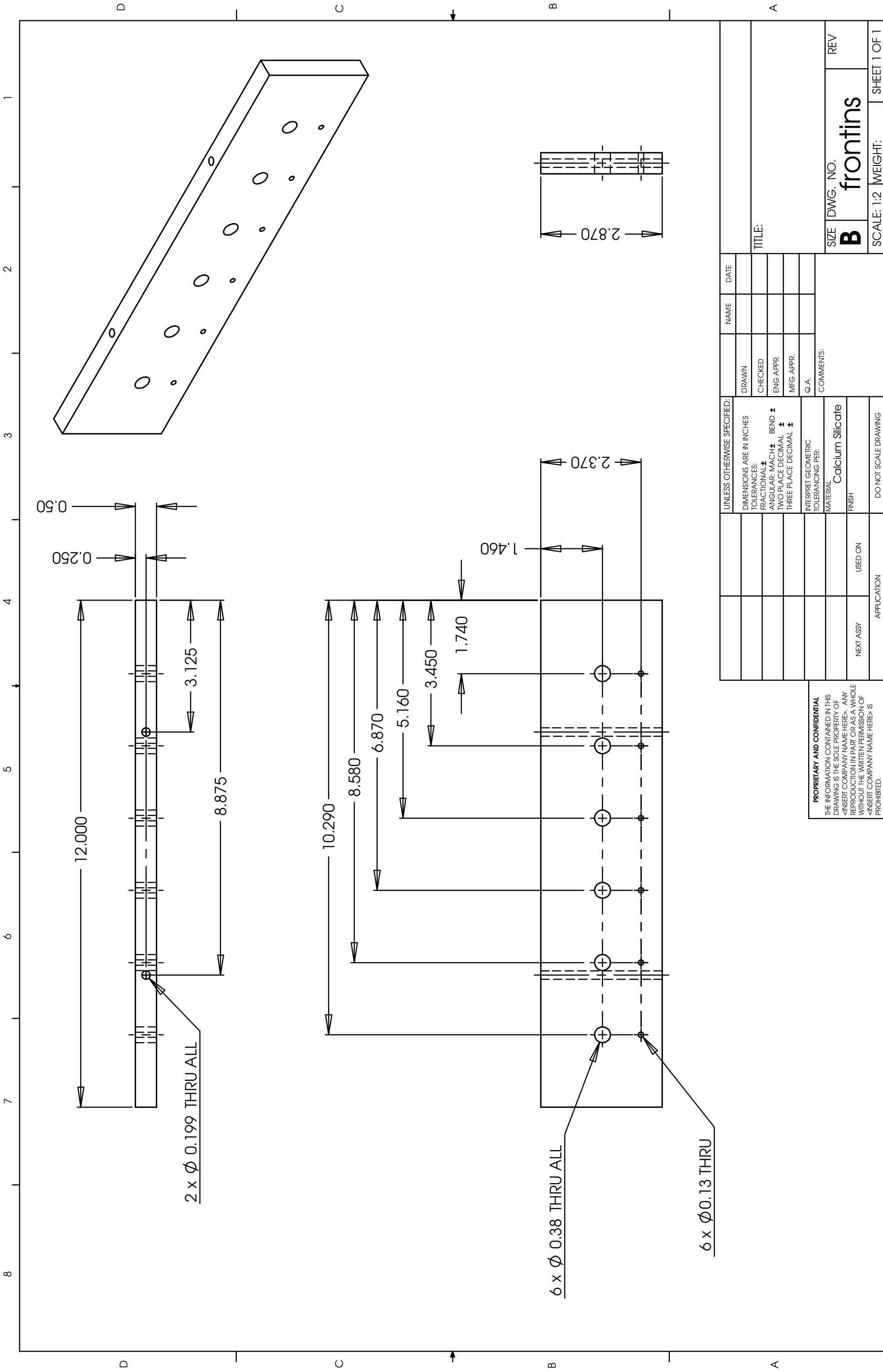

12.000
3.125
8.875
0.50
0.250
2 x Ø 0.199 THRU ALL
10.290
8.580
6.870
5.160
3.450
1.740
1.460
2.370
2.870
6 x Ø 0.38 THRU ALL
6 x Ø0.13 THRU
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Calcium Silicate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
B
DWG. NO.
frontins
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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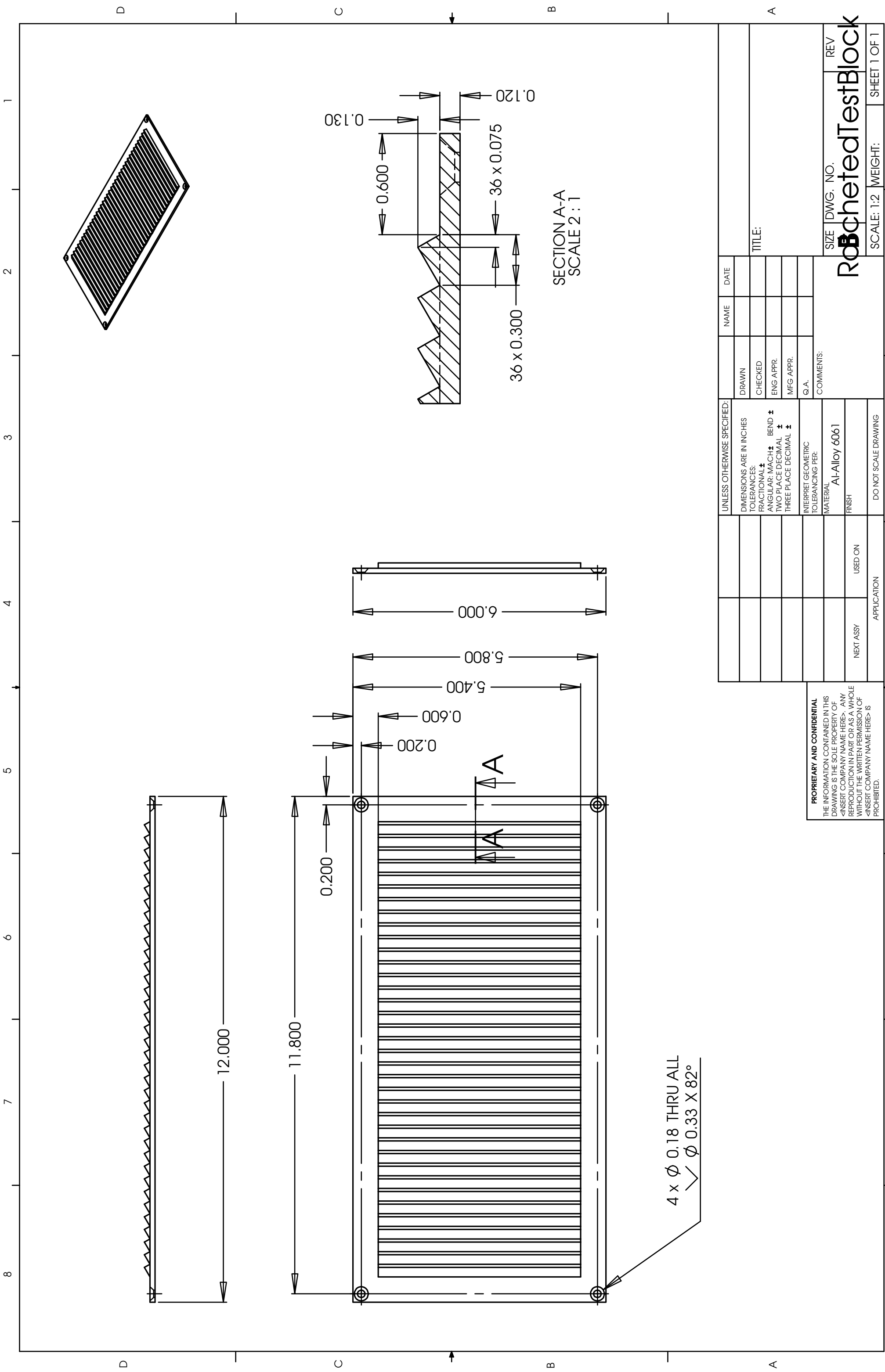
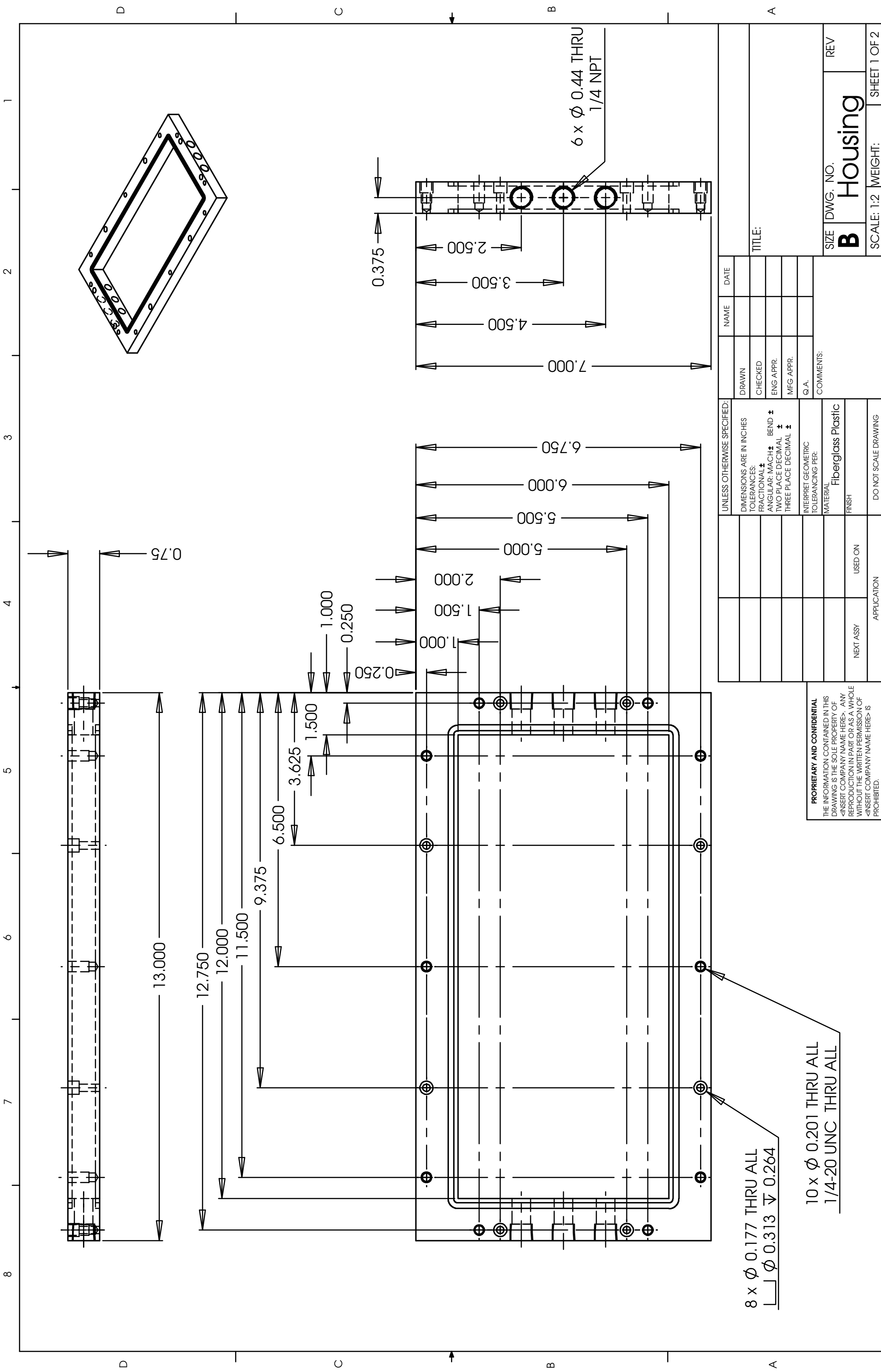


12.000
11.800
0.200
0.200
0.600
5.400
5.800
6.000
4 x Ø 0.18 THRU ALL
Ø 0.33 X 82°
0.130
0.120
0.600
36 x 0.075
36 x 0.300
SECTION A-A
SCALE 2 : 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL
Al-Alloy 6061
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
TITLE:
SIZE
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


6 x Ø 0.44 THRU
1/4 NPT
0.375
2.500
3.500
4.500
7.000
6.750
6.000
5.500
5.000
2.000
1.500
1.000
0.250
1.000
0.250
0.75
1.500
3.625
6.500
9.375
11.500
12.000
12.750
13.000
10 x Ø 0.201 THRU ALL
1/4-20 UNC THRU ALL
8 x Ø 0.177 THRU ALL
⌴ Ø 0.313 ↧ 0.264
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Fiberglass Plastic
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
B
DWG. NO.
Housing
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 2
PROPRIETARY AND CONFIDENTIAL
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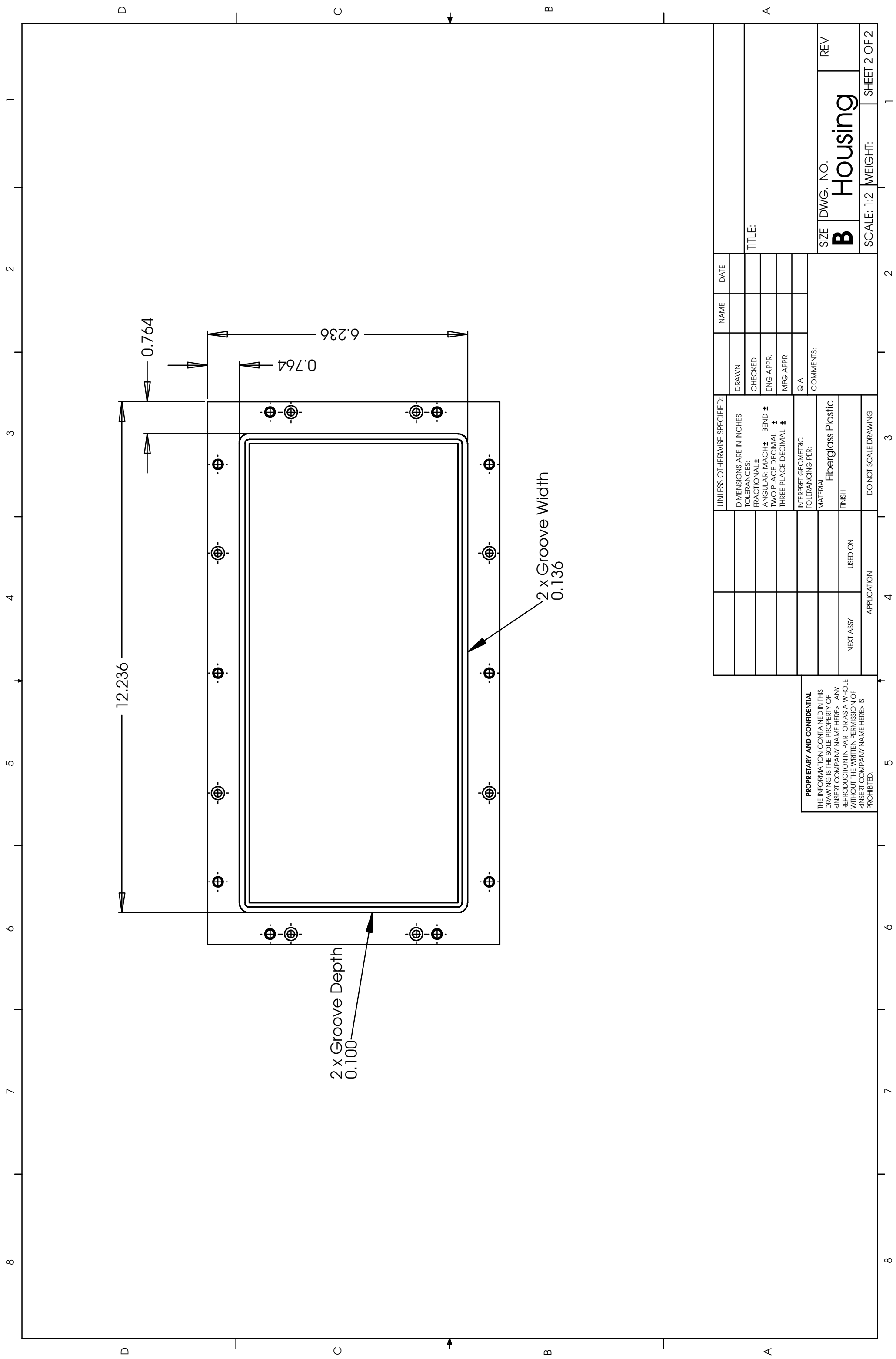

0.764
6.236
0.764
12.236
2 x Groove Width
0.136
2 x Groove Depth
0.100
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Fiberglass Plastic
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
B
DWG. NO.
Housing
REV
SCALE: 1:2
WEIGHT:
SHEET 2 OF 2
PROPRIETARY AND CONFIDENTIAL
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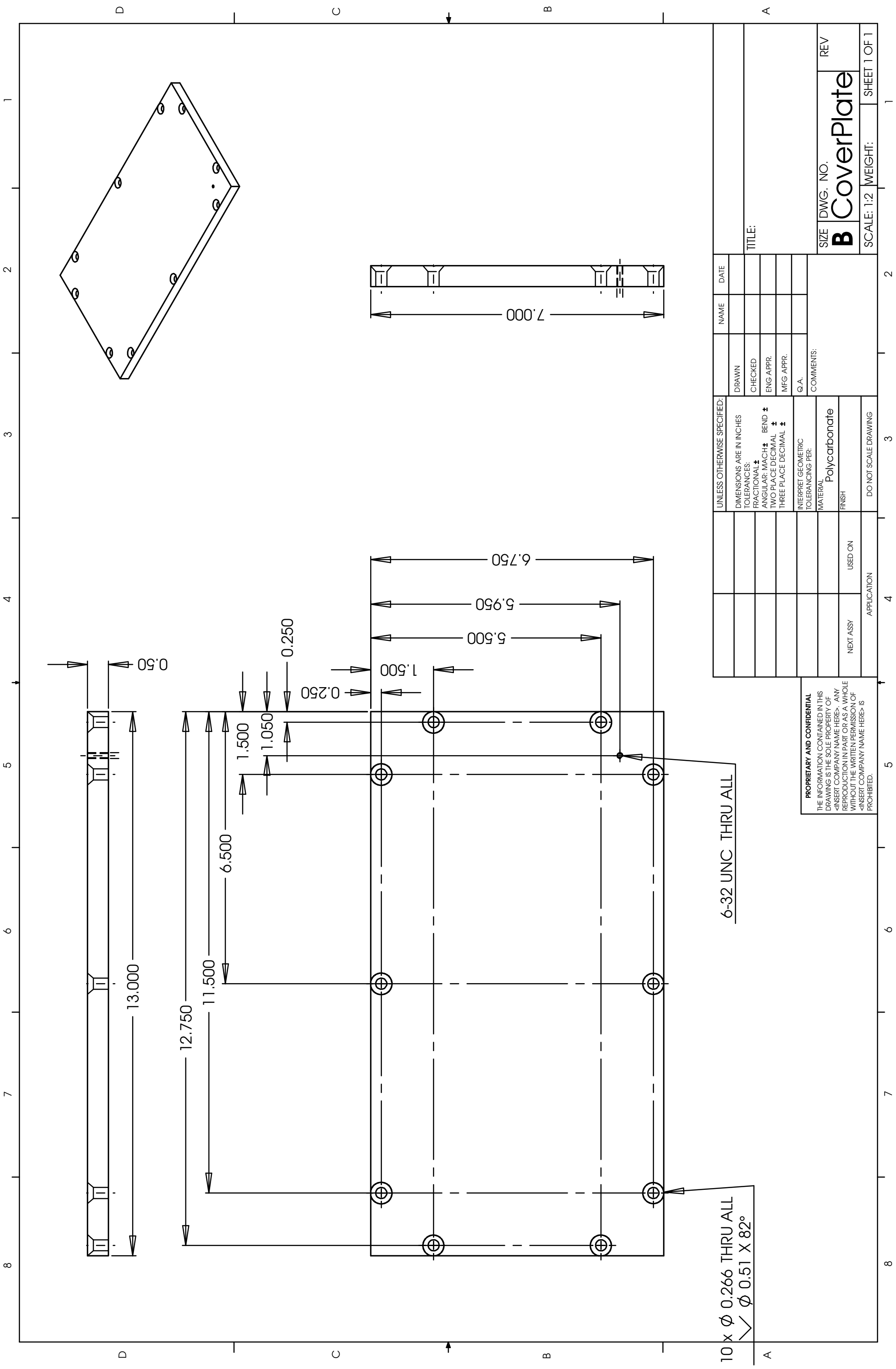
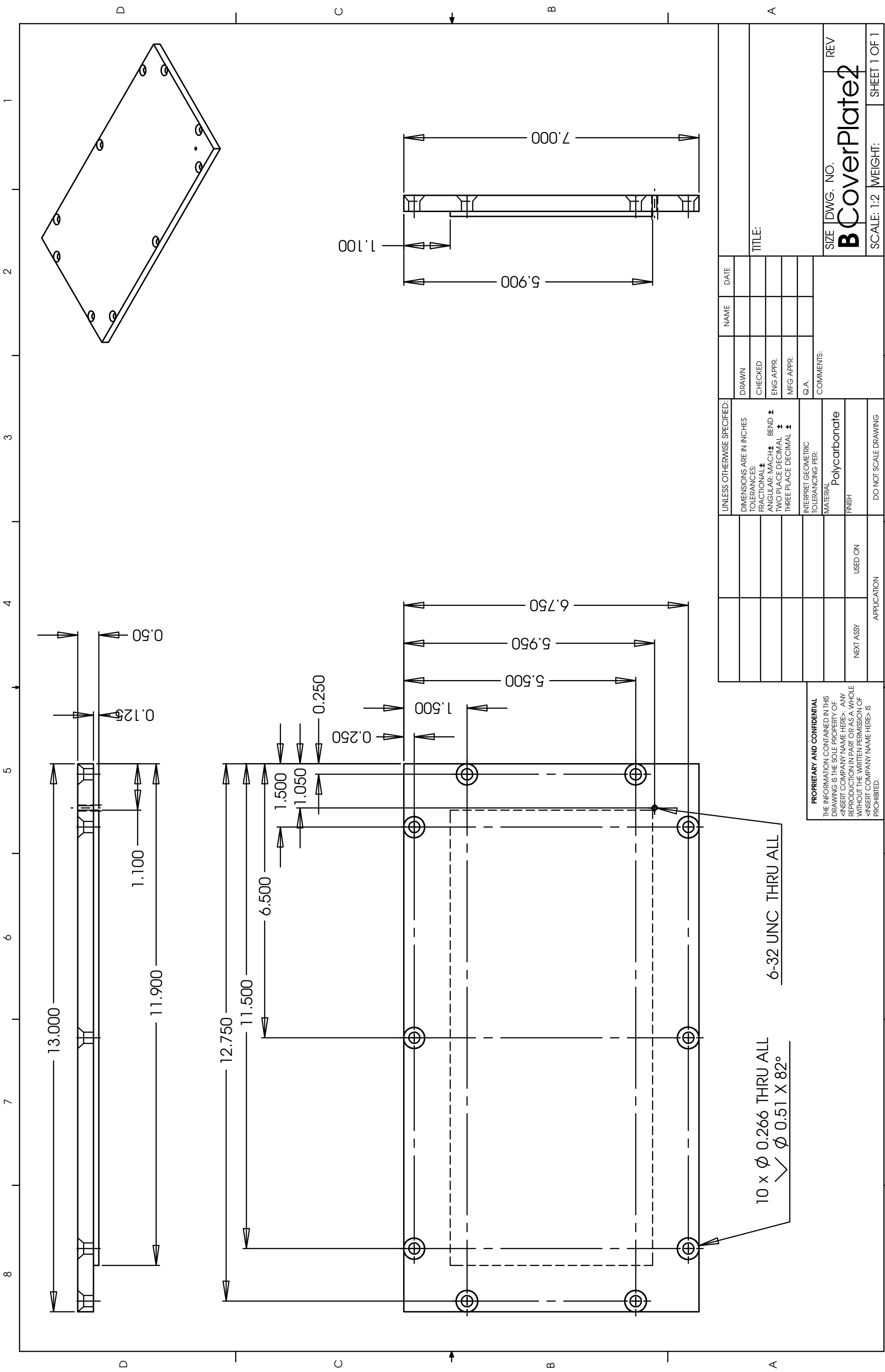


CoverPlate
Polycarbonate
SIZE B
DWG. NO.
REV
TITLE:
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
PROPRIETARY AND CONFIDENTIAL
DO NOT SCALE DRAWING
6-32 UNC THRU ALL
10 x Ø 0.266 THRU ALL
Ø 0.51 X 82°
7.000
6.750
5.950
5.500
1.500
0.250
0.50
13.000
12.750
11.500
6.500
1.500
1.050
0.250



7.000
1.100
5.900
6.750
5.950
5.500
0.50
0.125
1.500
0.250
0.250
13.000
11.900
1.100
12.750
11.500
6.500
1.500
1.050
6-32 UNC THRU ALL
10 x Ø 0.266 THRU ALL
⌵ Ø 0.51 X 82°
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Polycarbonate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
B
DWG. NO.
CoverPlate2
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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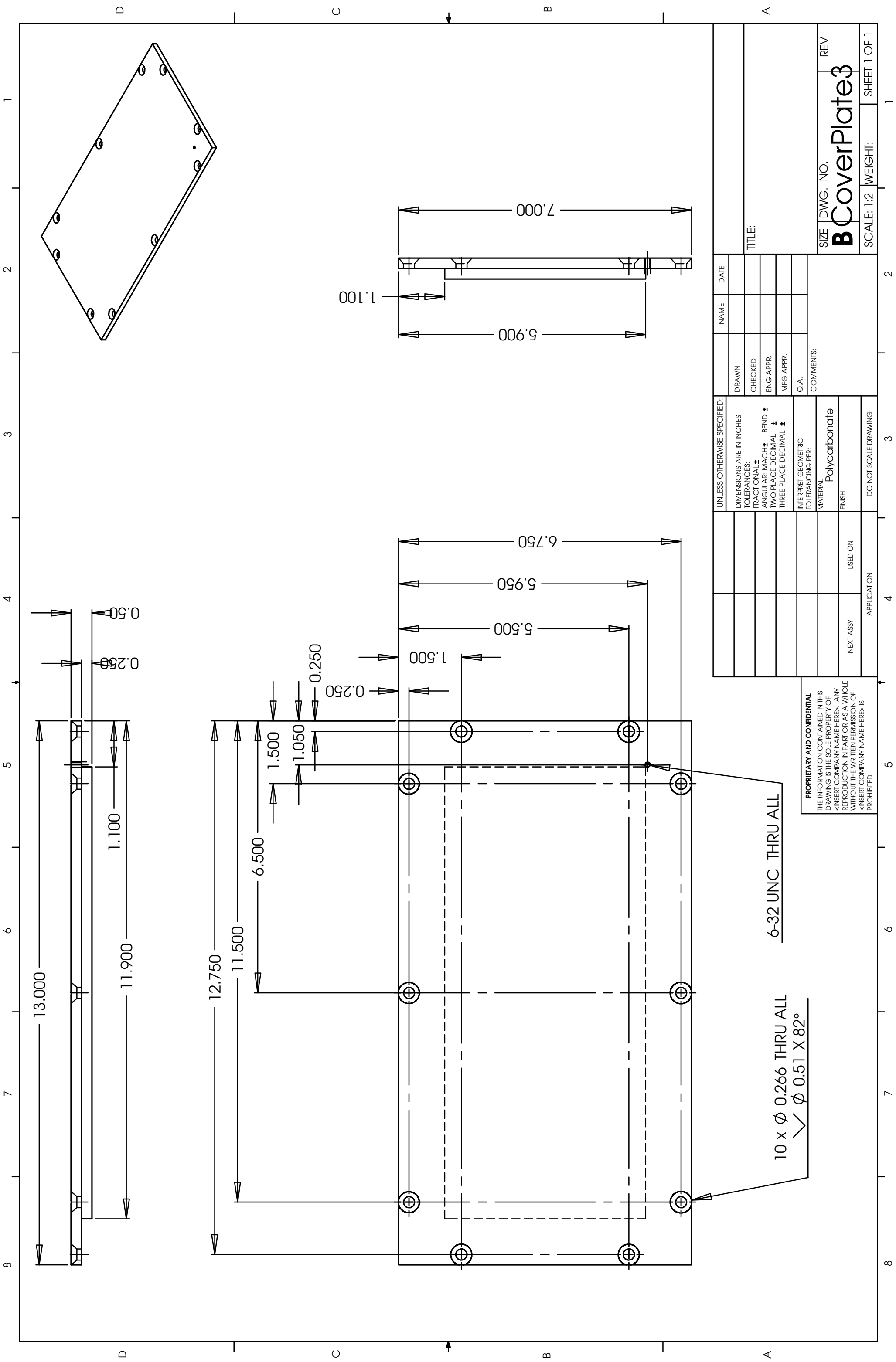
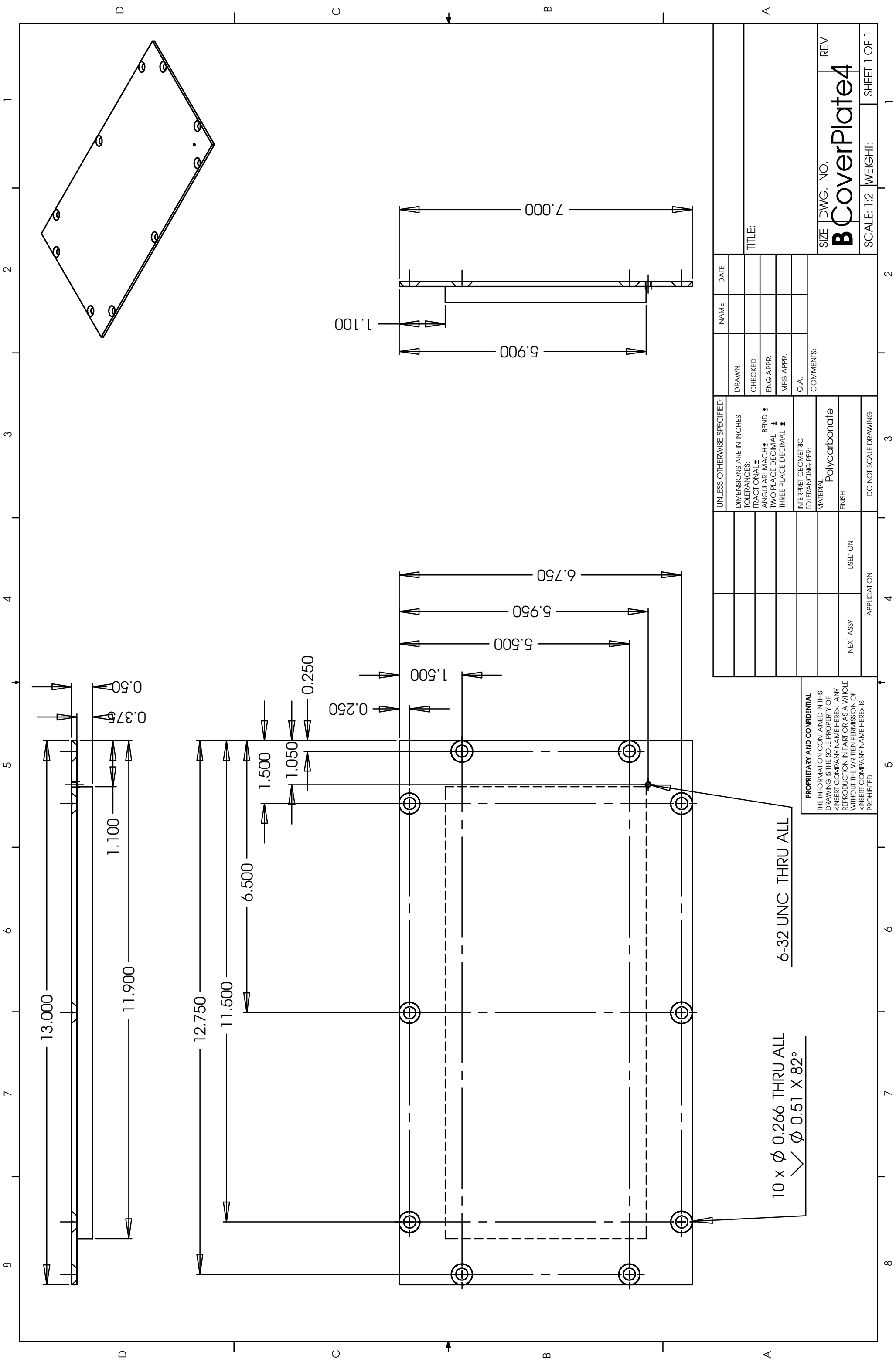


UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Polycarbonate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE:
SIZE
DWG. NO.
REV
B
CoverPlate3
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
10 x ⌀ 0.266 THRU ALL
⌵ ⌀ 0.51 X 82°
6-32 UNC THRU ALL
7.000
5.900
1.100
6.750
5.950
5.500
1.500
0.250
0.250
0.50
13.000
11.900
1.100
12.750
11.500
6.500
1.500
1.050


CoverPlate4
SIZE
B
DWG. NO.
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
TITLE:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Polycarbonate
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
PROPRIETARY AND CONFIDENTIAL
10 x Ø 0.266 THRU ALL
Ø 0.51 X 82°
6-32 UNC THRU ALL
13.000
11.900
1.100
0.50
0.375
12.750
11.500
6.500
1.500
1.050
0.250
0.250
1.500
5.500
5.950
6.750
5.900
1.100
7.000