Final Design for Fluidic Lens to be used in Opthalmic Correction
Randall Marks

Purpose:
To design a variable focal length phoropter capable of continuous correction of refractive error within a reasonable range.

Requirements:

1. **System Performance Requirements**
   - 1.1. Lens must fit in front of the human eye
     - 1.1.1. Should be located at the front focal point of the eye.
     - 1.1.2. Horizontally, edge of the lens must be less than 1" from the center of curvature to fit in front of the eye.
   - 1.2. Lens must be capable of producing Zernike terms Z[2,0], Z[2,-2], and Z[2,2] independently.
     - 1.2.1. Lens must be capable of producing ±3 diopters of astigmatism in any direction.
     - 1.2.2. Lens must be capable of producing ±5 diopters of power.
     - 1.2.3. Lens must be capable of repeatably and consistently producing changes of less than 0.25 diopter of astigmatism and power.
   - 1.3. Lens must have a 6-32 x 1/8" screw hole for mounting in the test equipment.
   - 1.4. Individual lens cells must be individually testable.
   - 1.5. Combination of alignment and lens error must produce less than 0.30 microns RMS error with a 6mm diameter at maximum operating deflection on axis to be unnoticeable to the human eye within a safe margin.
   - 1.6. Design should incorporate prior design technology to better predict performance and expedite fabrication
   - 1.7. Lens stack should be no thicker than 2 cm, and, to improve field performance, should be as thin as possible.
2. **Lens Construction Requirements (from prior design preference)**
   - 2.1. Must have a 0.5mm hole in the structure for injecting fluid into the lens cell.
   - 2.2. Must have a 0.5mm hole in the structure for bleeding off excess gas pockets.
   - 2.3. PDMS membranes are to be used for lens surfaces, which require power.
     - 2.3.1. The membrane front surface must be formed against a 2" diameter, 0.25 wave glass flat, and must be flat to gravity within 0.25°.
   - 2.4. The lenses are to be filled with deionized water.
   - 2.5. Each membrane must be aligned with a minimal amount of tension in all planar directions from the center.

Design Concept:
A fluidic lens can be used to generate refractive correction. The lens is two fluids of different indexes separated by a transparent, elastic membrane. In order to achieve a large index difference, liquids are used in the confined chamber, and air is generally used outside the membrane. Since liquids are, to a large extent, incompressible, and the membrane is much more compliant than its chamber, the increase in fluid volume in the chamber is entirely accommodated for by the fluidic membrane: it will bow outward, and the change in volume underneath it is equal to the change in volume in the chamber. Depending on the thickness and tension preload of the membrane, this will produce a pressure inside the chamber. This pressure is the force that forces the membrane shape to be approximately parabolic with a circular restraint, producing an approximately “spherical” lens. If the restraint is rectangular, it separates the curvature in two directions, which is the equivalent of having a spherical curvature plus a cylindrical curvature. This cylindrical curvature produces astigmatism in the wavefront.

The basic design is shown in Figure 1. It is a lens with 3 variable elements with power. They are stacked in series to provide variable, controlled correction. In order to produce astigmatism with a fluidic lens, a residual spherical term is also produced. This can be corrected with a variable spherical lens, which can also add a variable amount of spherical correction. To produce all angles of astigmatism without rotating the astigmatic lens, a second lens must be inserted at 45° from the original. These three lenses allow for all amounts of astigmatic and defocus refractive error to be corrected within the dynamic range of the device.

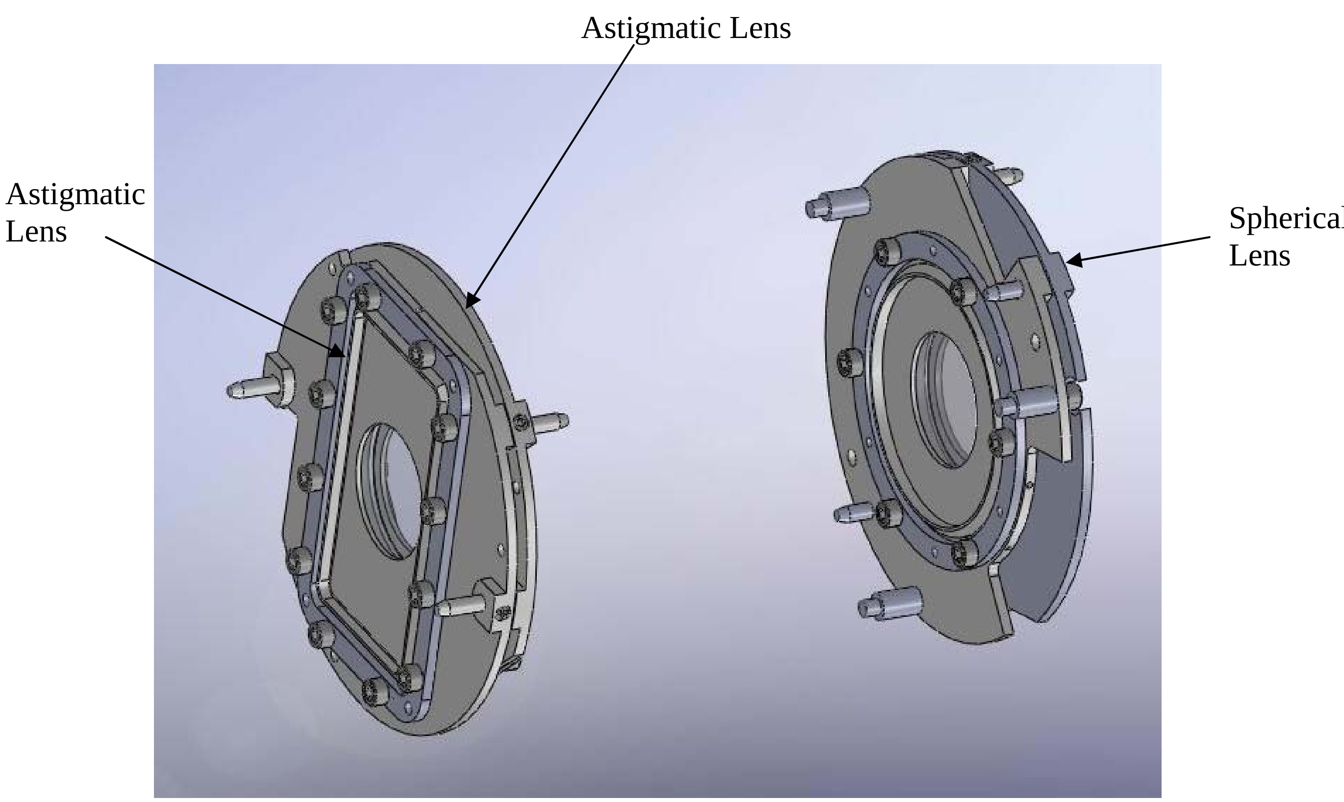


Figure 1: Image of Astigmatic and Spherical Lenses
(Note: Membranes not shown)

It was decided that 3D of astigmatism and 5D of power would be acceptable correction for most patients, and that those with higher errors, especially in the spherical correction, could be corrected by adding an offset lens with higher amounts of power and/or astigmatism. Since the fluidic lenses produce an approximately parabolic wavefront, this additional lens at higher powers is necessary to avoid field effects, and is not strictly a limit of the dynamic range of the fluidic lens. Since the astigmatic lens produces approximately as much residual power as it does astigmatism, the spherical fluidic lens must have an increased dynamic range of 8D.

Each lens is controlled with a separate fluid volume. Since the curvatures are approximately parabolic, the power produced is controlled by the aperture area, and is independent of whether both optical surfaces of the lens are membranes, or one is a membrane and the other a rigid, flat piece of glass. Since each additional membrane adds errors associated with aligning the membrane, it was decided that each lens should only have one variable surface. Furthermore, since both astigmatic lenses need to be oriented to each other, they were attached at their glass interface. Because the surface is approximately parabolic, this orientation does not add significant spherical aberration on the second lens. Spacers then separate these two lenses from the circular lens. Since restraints on the distance a lens can be placed in front of the eye are constant, it was decided that the flat glass surface should be placed closest to the eye. A goal is to place an expected mean power at approximately 17mm from the eye, which is the approximate front focal plane. Since the astigmatism power is likely to be much less than the power from the spherical surface, this surface should be approximately 17mm from the eye. However, the design of this structure is not part of this project, but just that there must simply be room to do so.

Another integral part of this project is the alignment jig used to assemble the lens together. In order to avoid the problem of having some slack on the membrane after it is assembled, which would cause it to fail at low powers, the membrane must be placed under a tension that is symmetric with the desired shape of the lens. This means that the spherical lens must have circularly symmetric tension, and the astigmatism must have tension that is symmetric about both the horizontal and vertical axis. In order to achieve tension, the membrane is held in place, and a flange from the lens is inserted into a retainer. This flange stretches the membrane. When the retainer is then clamped down on the membrane to hold it in place, some tension still remains, though the Poisson effect reduces it. If the retainer and the flange are not centered to each other, this tension becomes non-uniform, and some static amount of astigmatism is formed. The astigmatism lens does not really suffer from this because the most probable misalignments do not affect the symmetry, since astigmatism is desirable. Therefore, an alignment jig must be made to keep these errors as small as possible given the cost requirements in order to improve the quality of the lenses. See Figure 2 for images of the alignment jig, which will be discussed in more detail later.

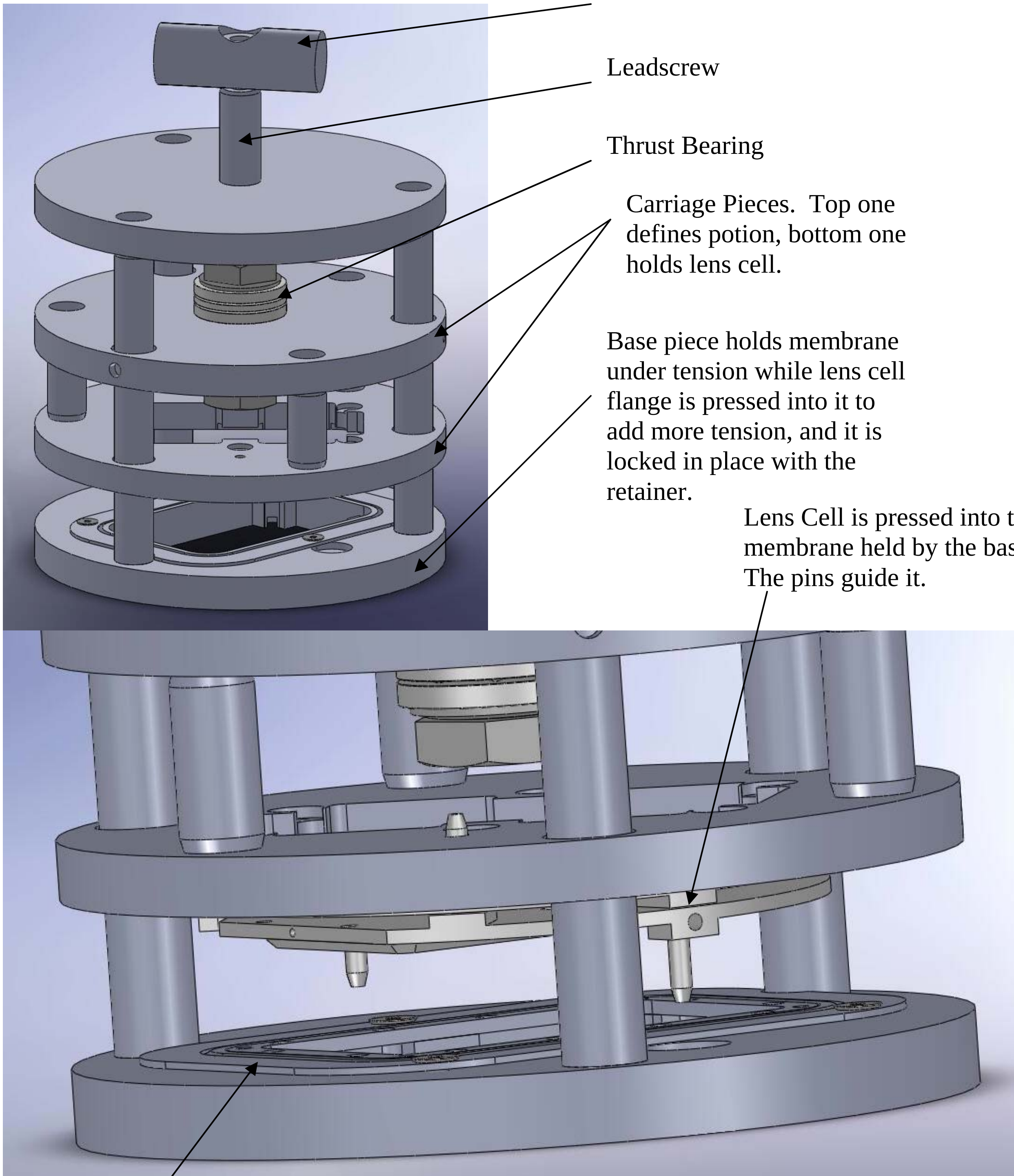


Figure 2: Alignment Jig

The final part of the design is the mold for the PDMS membranes. Due to the fact that they each require approximately 5 hours to mix and cure at 65°C, it is best to manufacture them all at once. Therefore, a 3 chambered mold was designed, with a 3 point contact with its base. It uses three springs wrapped around the screws attaching the two plates together such that the springs can be individually compressed to level the device as long as the springs remain in compression. See Figure 3 below for an image of this jig system. A circular level is used to assure that the top surface is flat to gravity. As long as the other surfaces are held to within 0.25° of this plane, it meets spec.

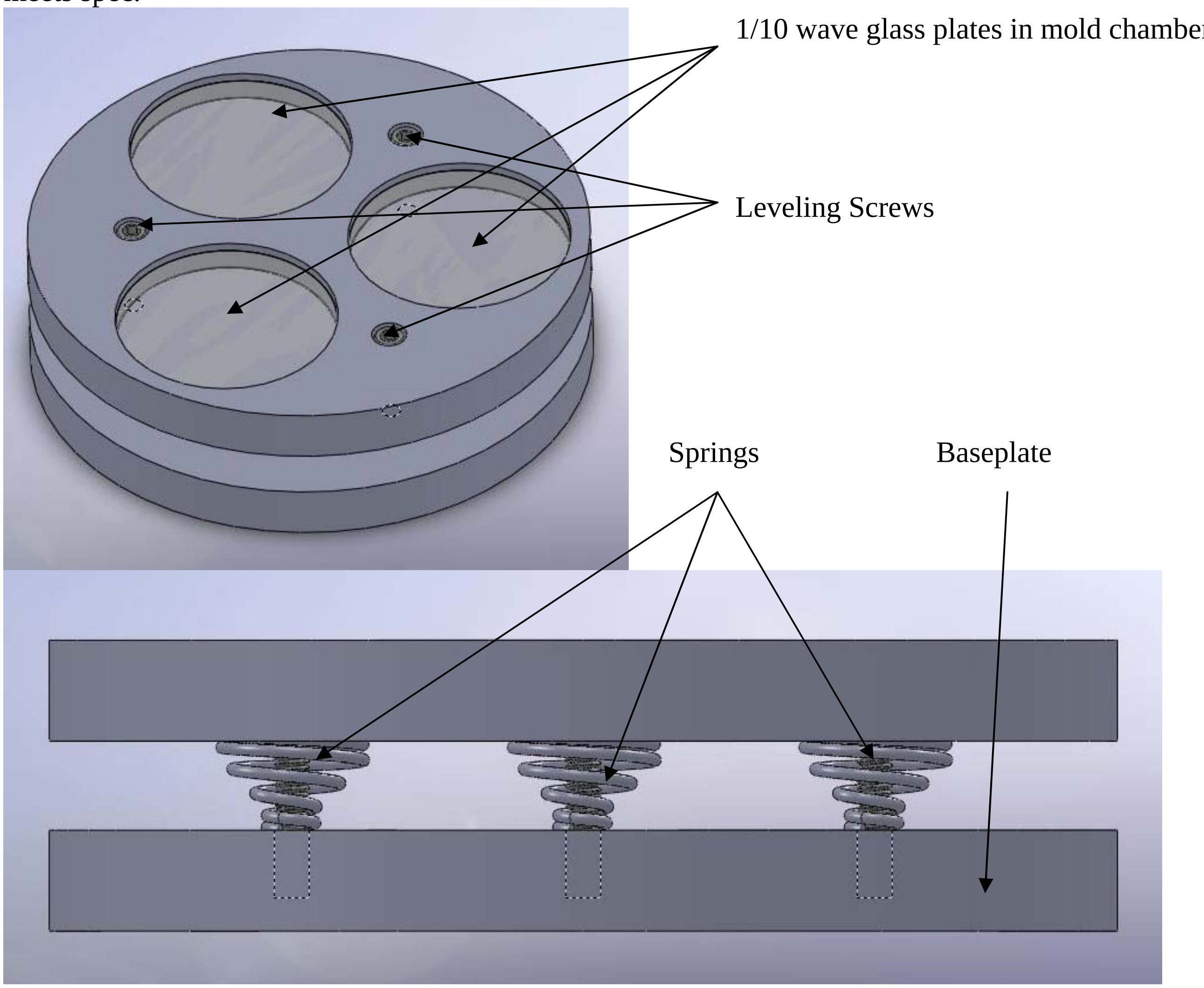


Figure 3: 3-Chamber Mold

Design Details

Much of the design process for this project was rather nebulous. What matters most is the cost of the parts and that they work, so extravagant mechanical requirements could not be used. Furthermore, it is unknown how much the tensioners really need to be aligned. The only real experience in the matter is mine, with doing it by hand, using the clearance holes in the tensioner to align it, but this never really worked well for the circular lens, but worked extremely well for the astigmatic lens. This could have been because the circular lens flange was too large for the retainer, and it could be due to the flange and retainer not being centered to each other when the tension was applied. This new design corrects both of these problems by increasing the clearance between the flange and the retainer as well as by improving the alignment process with the alignment jig.

In order to improve the alignment process, alignment pins are used. They pass through both the lens chamber and the base, which holds the retainer. This makes the error stack up between the two parts to be two times mechanical tolerance of the holes for the pins plus the clearance required on the fit of the retainer to the base. It would be nice to use alignment pins directly from the retainer to the part, however, this is not possible because it is a bad idea to pierce the membrane prior to the tension being applied: the stretching of the membrane could cause it to irreparably tear. Using .002" tolerances and .001" clearances, the pins can be located to .005" within the part. Since there is a bit of slop with the retainer, the whole thing can be engaged without a membrane in place, and the retainer can be aligned to the exact fit of the lens when they are pressed together. This should improve the quality of the alignment, but it is presently unknown how accurate I can make it. The loose system should be within ±200 microns, and it can possibly be improved by moving the retainer around some.

Another source of error could be the uniformity of the force used to apply the tension. Since this system is being driven by a leadscrew, and operating on the pins as bearings, it should have a very uniform force profile as they are pressed together. This should be a vast improvement over prior methods in which the force was added by hand, and the slack was taken up with screws bolted on.

Since the pins are meant to constrain the physical position of the parts, the other components must not: the posts that separate the carriage and the base from each other and the other holes for the pins in the base of the carriage, which are only meant to accommodate the pins going into them, but are not meant to constrain the position of the lens. Therefore, all of these sections where a cylinder enters a hole are left loose enough so as not to over constrain them, but tight enough such that they do not allow too much motion and would add too much difficulty to be able to drive the system reliably and repeatably.

Evaluation of Adherence to Design Requirements:

1. System Performance Requirements

1.1. Lens must fit in front of the human eye

1.1.1. Should be located at the front focal point of the eye.

1 cm is left for clearance to the eye from the spherical surface membrane. This should be adequate.

1.1.2. Horizontally, edge of the lens must be less than 1” from the center of curvature to fit in front of the eye.

Lens is 1.75” in diameter and is centered about the eye.

1.2. Lens must be capable of producing Zernike terms Z[2,0], Z[2,-2], and Z[2,2] independently.

1.2.1. Lens must be capable of producing ±3 diopters of astigmatism in any direction.

1.2.2. Lens must be capable of producing ±5 diopters of power.

1.2.3. Lens must be capable of repeatably and consistently producing changes of less than 0.25 diopter of astigmatism and power.

Using prior design technology, these values have been readily observed. The stack of three lenses together meets this requirement from a Zemax analysis using real surface curvatures.

1.3. Lens must have a #6-32 x 1/8” screw hole for mounting in the test equipment.

The mounting bracket, which is placed on top of the alignment pins, uses a #6-32 screw hole to mount to other assemblies.

1.4. Individual lens cells must be individually testable.

This requirement was slightly violated: the astigmatism lenses are not easily tested alone: one must be empty to test the other one completely alone, but it is still possible. The circular lens is easily tested alone.

1.5. Combination of alignment and lens error must produce less than 0.30 microns RMS error with a 6mm diameter at maximum operating deflection on axis to be unnoticeable to the human eye within a safe margin.

With the improved alignment techniques, there should be less error from alignment, but even if it is the same, it is still less than 0.30 microns RMS with the three lenses stacked together. Furthermore, the Zemax analysis on the tilt and decenter of the lenses shows that these are non-issues, with tolerances well beyond 1° with less than an additional 0.07 microns RMS, which is freely obtainable in this system.

1.6. Design should incorporate prior design technology to better predict performance and expedite fabrication

The rectangular aperture is identical to prior models. Since the circular aperture was much simpler, it was extended a bit to reduce its errors, which are associated with the ratio of the aperture size to the usable area in the lens.

1.7. Lens stack should be no thicker than 2 cm, and, to improve field performance, should be as thin as possible.

Lens stack is less than 12mm in thickness, easily meeting this requirement.

2. Lens Construction Requirements (from prior design preference)

2.1. Must have a 0.5mm hole in the structure for injecting fluid into the lens cell.

These holes were placed in both lenses, and a cutout was made to them to allow for the bit to reach far enough inside.

2.2 Must have a 0.5mm hole in the structure for bleeding off excess gas pockets.
These holes were placed in both lenses, and a cutout was made to them to allow for the bit to reach far enough inside. In the astigmatic lens, this hole was placed in a corner to make it easier to collect the bubbles on top of it.

2.3 PDMS membranes are to be used for lens surfaces, which require power.

2.3.1 The membrane front surface must be formed against a 2” diameter, 0.25 wave glass flat, and must be flat to gravity within 0.25°.
The new mold incorporates three of these glass plates, and is leveled using a circular level and the adjustment screws. The glass plates are each 1/10th wave glass plates to improve the surface quality beyond question.

2.4 The lenses are to be filled with deionized water.

2.5 Each membrane must be aligned with a minimal amount of tension in all planar directions from the center.
Tensioner design from previous lenses has been shown to do this adequately.

Preliminary Fabrication Plan

Parts fab/suppliers

1. All machined parts will be machined by the University Research Instrumentation Center at the University of Arizona
2. All custom glass pieces will be ground locally. A supplier has not yet been selected.
3. All non-custom glass plates will come from Edmund Optics, and are readily available for order on their website.
4. All non-custom mechanical and fluidic parts such as fasteners and syringes will be purchased from McMaster-Carr.
5. Sylgard 184 will be purchased from Dow-Corning for the PDMS. It comes in significantly large supplies such that quantity will not be an issue. Possibly a supplier of theirs will be necessary to find small enough quantities.

Assembly and Membrane Fabrication Procedure

See Appendix 1 for assembly and fabrication procedures below:

1. 3 Chamber Mold.
2. Membrane Fabrication
3. Membrane-Free Lens Cells
4. astig base assy
5. Lens Alignment Assembly astig
6. Phoropter Lens Assembly.

See Appendix 2 for Machined Part Drawings.

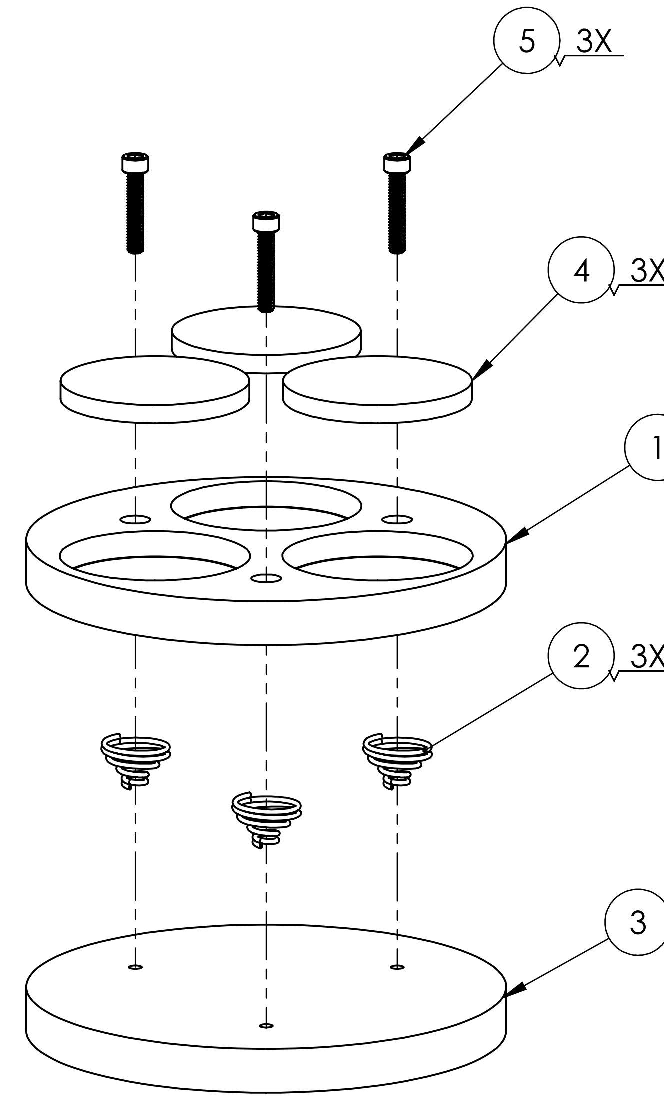
Preliminary System Test Plan

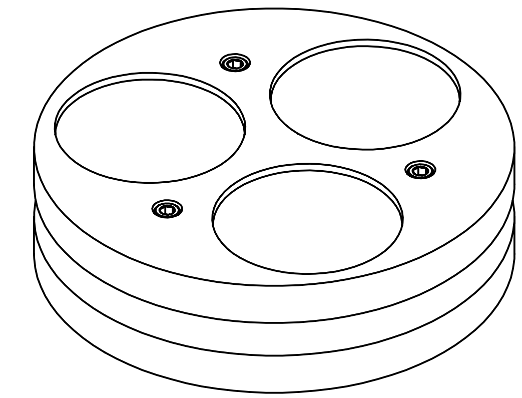
Lens will be tested using a Shack Hartmann wavefront sensor. It will be attached to the sensor with the 6-32 threaded hole, or some other adaptation/rework of the mounting bracket. Another student will be designing this testing structure as well as the wavefront sensor.

Appendix 1: Assembly Drawings

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	3 pc mold chamber		1
2	16920K210		3
3	3 chamber Mold base		1
4	50mm Glass Plate		3
5	92196A198		3

1. Prepare 5 ml of PDMS using a 10:1 ratio, and mix thoroughly.
2. Pre-heat an oven to 65°C for use for 4 hours.
3. Insert 3X Item 5 into Item 1 as shown.
4. One at a time, place Item 2 over end of Item 5, thread 3 turns into Item 3. Perform 3X total as shown.
5. Set assembly onto a bench and level with the large circular level.
6. Place 1 ml of PDMS into the bottom of each chamber in Item 1.
7. Tilt assembly around until the PDMS covers the bottom surface of the chamber. If more fluid is necessary, add more.
8. Place in vacuum chamber and apply vacuum to remove bubbles.
9. Carefully place each Item 4 into a chamber in Item 1 and leave there for 5 minutes.
10. Place small, plastic level on each glass surface after assuring that Item 1 is level.
11. Carefully press on each glass plate to level it out as much as possible.
12. Iterate steps 10 through 11 until the plates come out as level as possible.
13. Place assembly into oven at 65°C.
14. Level the top of the assembly again inside the oven.
15. Leave in oven for 4 hours.
16. Remove from oven and remove excess PDMS from the edges around each plate.





NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
SEE BOM
FINISH
NONE
DO NOT SCALE DRAWING

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

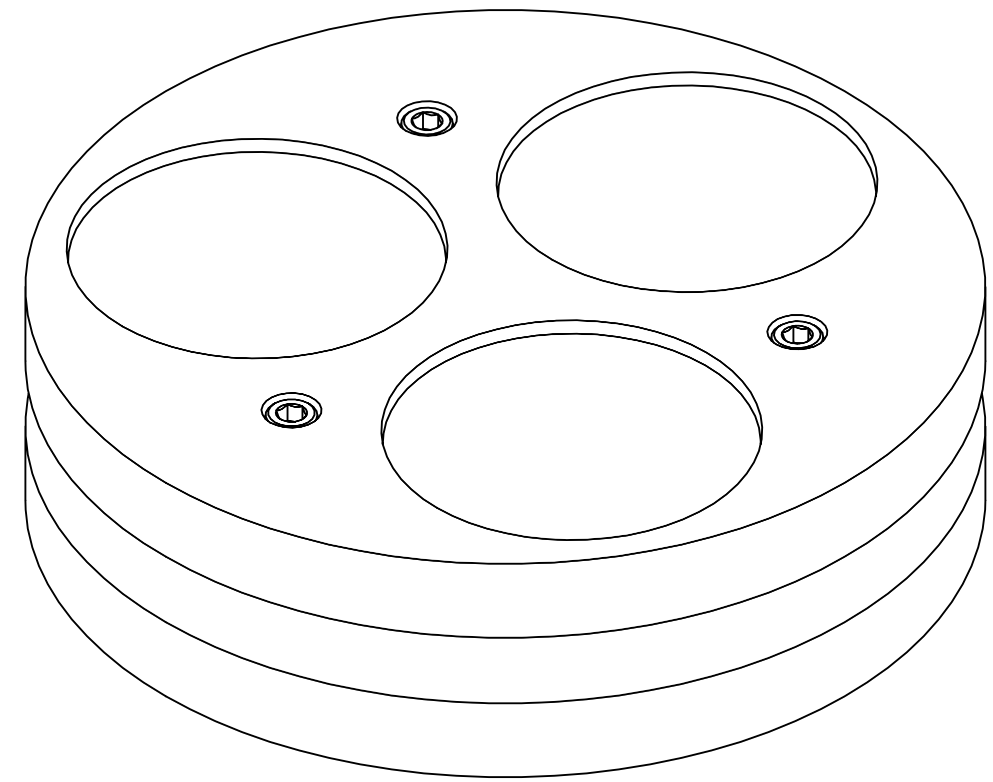
COMMENTS:

TITLE:

SIZE DWG. NO. REV
3BChamber Mold

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

1. Prepare 5 ml of PDMS using a 10:1 ratio, and mix thoroughly.
2. Pre-heat an oven to 65°C for use for 4 hours.
3. Pour 1 ml of PDMS into each chamber in the 3 chamber assembly shown to the right.
4. Tilt until PDMS evenly covers the surface of each glass plate.
5. Place into vacuum chamber and level using the three screws and the large circular level.
6. Apply vacuum until no bubbles are present.
7. Remove from vacuum chamber and place in oven.
8. Level again using the three screws and the large circular level.
9. Leave in the oven for 4 hours.
10. Remove assembly from the oven.
11. Use nylon tipped tweezers to bunch up the membrane around the edges of each cell, and gradually apply force underneath each membrane to separate from the glass. Place in a clean Petri dish for storage with the side formed on the glass plate facing upwards.



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 3 Chamber Mold

FINISH: NONE

DO NOT SCALE DRAWING

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

COMMENTS:

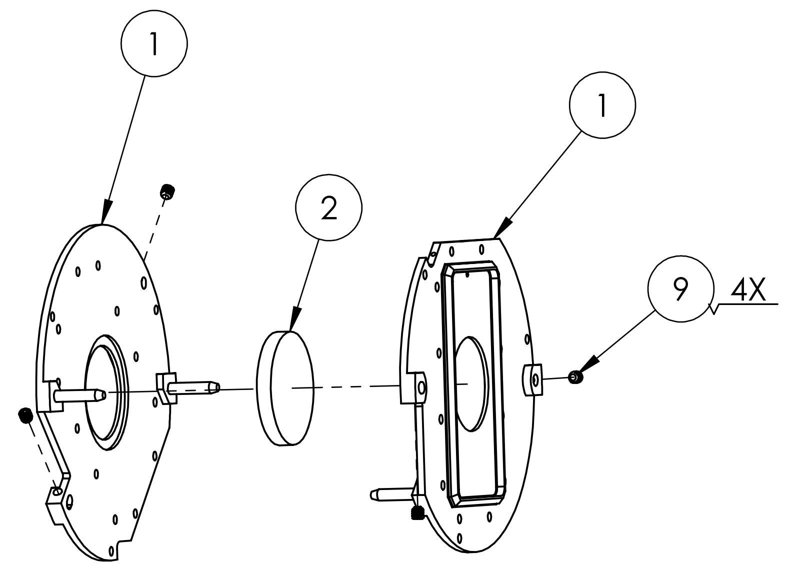
TITLE:

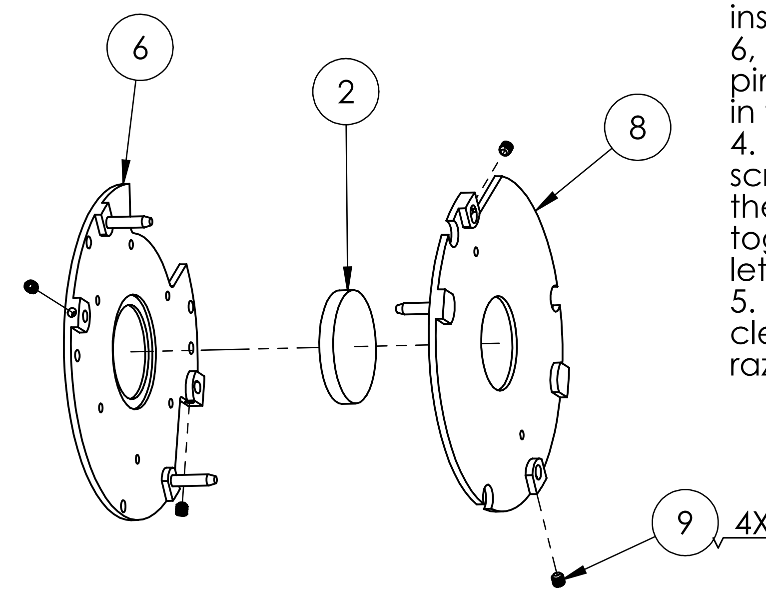
SIZE: B | DWG. NO.: Membrane Fabrication | REV

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Ret Insert 3 second		2
2	Glass Plate		2
6	Ret Insert 2 second circ		1
8	El Phoropter Ret Circ Glass		1
9	92311A050		8

1. Prepare 5 mL of PDMS in a 10:1 ratio.
2. Place a small amount on the outer corner of the inset in which the glass plate is going to be placed in both Item 1's.
3. Flip them so that their pins are facing each other, place Item 2 inside one of Item 1, and press the three pieces together, allowing the pins to enter the respective holes in the other part.
4. Press firmly together and use set screws, item 9 to tighten down on the pins to hold the pieces together. Place in the oven and let bake for 4 hours.
5. Remove from the oven, and clean up excess PDMS with a razorblade.





1. Prepare 5 mL of PDMS in a 10:1 ratio.
2. Place a small amount on the outer corner of the inset in which the glass plate is going to be placed in both Item 6 and Item 8.
3. Flip them so that their pins are facing each other, place Item 2 inside Item 6, and press the Items 6, 2, and 8 together, allowing the pins to enter the respective holes in the other part.
4. Press firmly together and use set screws, item 9 to tighten down on the pins to hold the pieces together. Place in the oven and let bake for 4 hours.
5. Remove from the oven, and clean up excess PDMS with a razorblade.

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
SEE BOM

FINISH
NONE

DO NOT SCALE DRAWING

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COMMENTS:

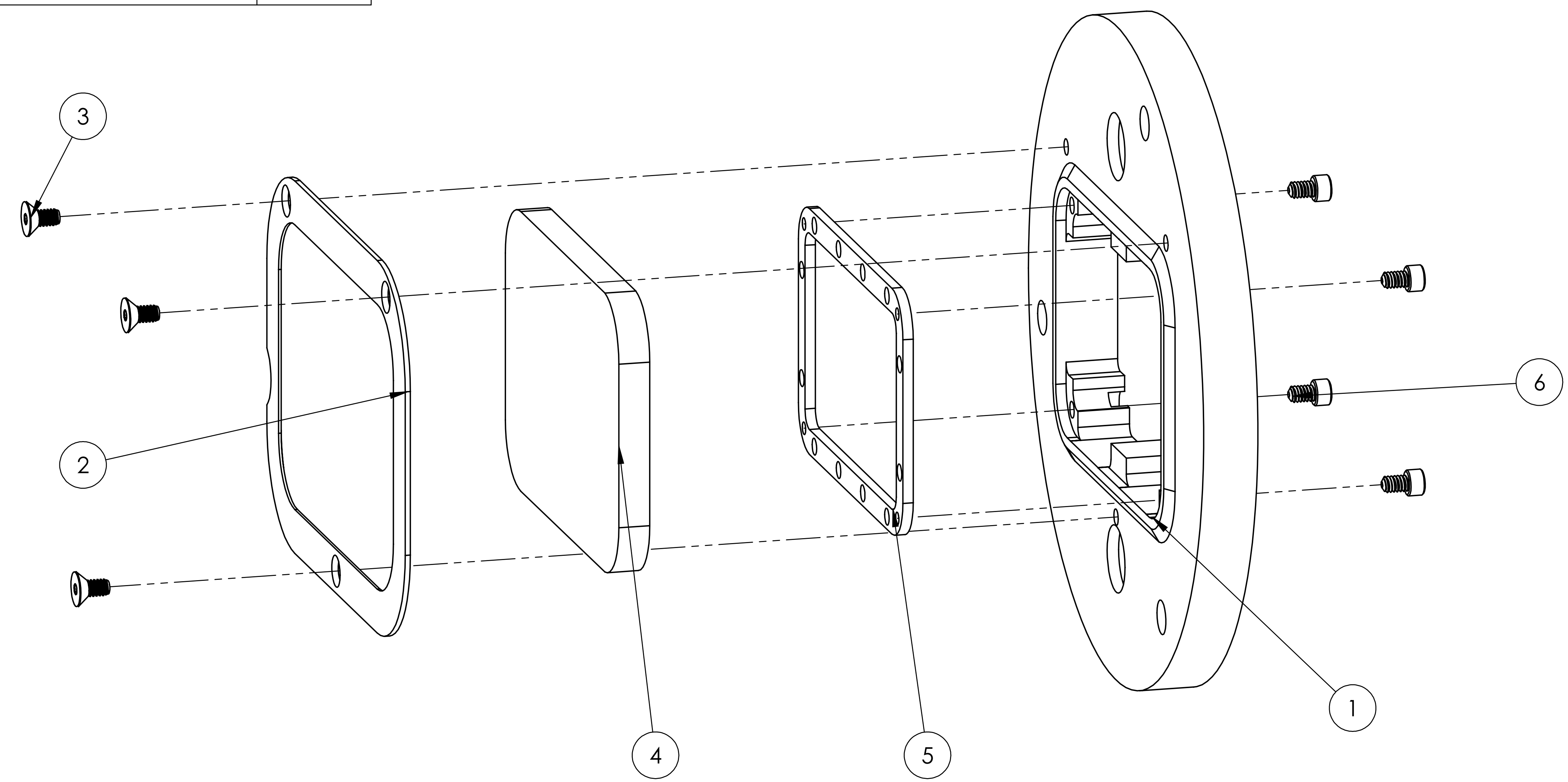
TITLE:

SIZE B DWG. NO. Membrane-Free Lens Cell REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Phor Align base astig		1
2	Astig Membrane Stretch Retainer		1
3	92210A010		3
4	Base Glass Plate Astig		1
5	Phoropter Membrane Retainer 2		1
6	92196A051		5

1. Bolt Item 5 to Item 1 using 4X Item 6
2. Attach membrane (not shown) to surface of Item 4 with the side formed on the glass facing item 1. Center the membrane on the glass.
3. Press Item 4 into Item 1 such that the glass is as symmetrically placed as possible.
4. Place Item 2 over item 4 and press it into the metal. Attach to Item 1 using 3X Item 3.
5. Tighten the 3X item 3 until strong resistance is felt.
6. Remove Item 4 with nylon tweezers to separate from the membrane.



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APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
SEE BOM

FINISH
NONE

DO NOT SCALE DRAWING

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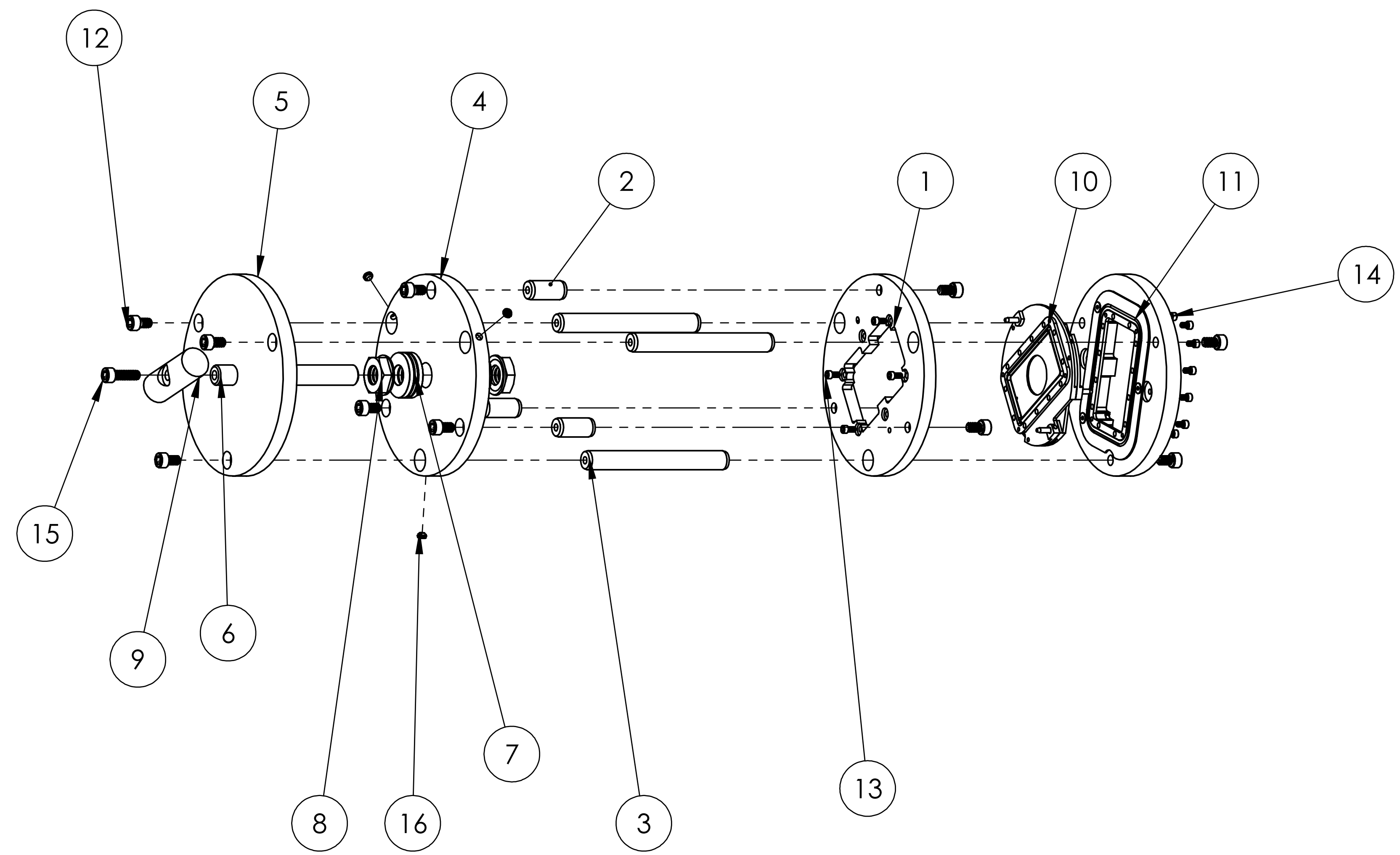
COMMENTS:

TITLE:

SIZE B | DWG. NO. Astig base assy | REV

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

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Phor Align base		1
2	Small Post		3
3	Small Post		3
4	Phor Align Top		1
5	Phor Align Base Top		1
6	Leadscrew		1
7	6655K33		2
8	95170A390		2
9	Leadscrew grip		1
10	Astig Lens Assy		1
11	astig base assy		1
12	92196A105		12
13	92196A052		4
14	92196A051		13
15	92196A108		1
16	92311A101		3



1. The word "Attach" means to thread the screws in until they loosly touch, but no further.
2. Thread Item 5 onto Item 6 such that it is approximately 0.25" from the end with the 4-40 thread.
3. Attach Item 9 to Item 6 using Item 15 and tighten.
4. Thread Item 8 up through Item 6 and slide Item 7 up to it.
5. Slide Item 4 up to Item 7, slide an Item 7 after it, and thread on an Item 8. Thighten both item 8 into each other at once, leaving less than 0.1" after the last nut.
6. Slide 3X Item 3 up through Item 4 and bolt to item 5 using 3X Item 12.
7. Loosly thread in 3X Item 16 into the side of Item 4, leaving room for the 3X Item 3 to slide.
8. Attach 3X Item 2 to Item 4 with 3X Item 12.
9. Slide Item 1 over 3X Item 3 and attach to 3X Item 2 using 3X Item 12.
10. Attach Item 10 to Item 1 using 4X Item 13, and tighten, allowing the pins to slide up into item 1.
11. Attach Item 11 to 3X Item 3 using 3X Item 12.
12. Align all pieces by eye, rotate Item 9 until the pins in Item 10 reach Item 11 slot and hole. Once they clear the entrance, bolt all previously "Attached" pieces together. Be careful not to allow the flange on part to to touch the membrane in Part 11.
13. Submerge Item 11 into deionized water such that it is below the surface by at least 5mm.
14. Press Item 10 into Item 11 by rotating Item 9. Once it is tight, use 3X Item 16 to keep it there.
15. Flip the assembly over, and use a pin to poke holes in the membrane from behind, using the holes for the retainer screws.
16. Run the retainer screws through the membrane and bolt to Item 10.
17. Remove retainer screws from back side of Item 11, which came from that assembly. There are four of them in the corners of the astigmatism retainer.
18. Unbolt 4X Item 13 from teh back of item 1, which releases Item 10 with membrane attached.
19. The same basic procedure is used for the circular version.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: SEE BOM

FINISH: NONE

DO NOT SCALE DRAWING

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COMMENTS:

TITLE:

Alignment fixture assembly de

SIZE: B

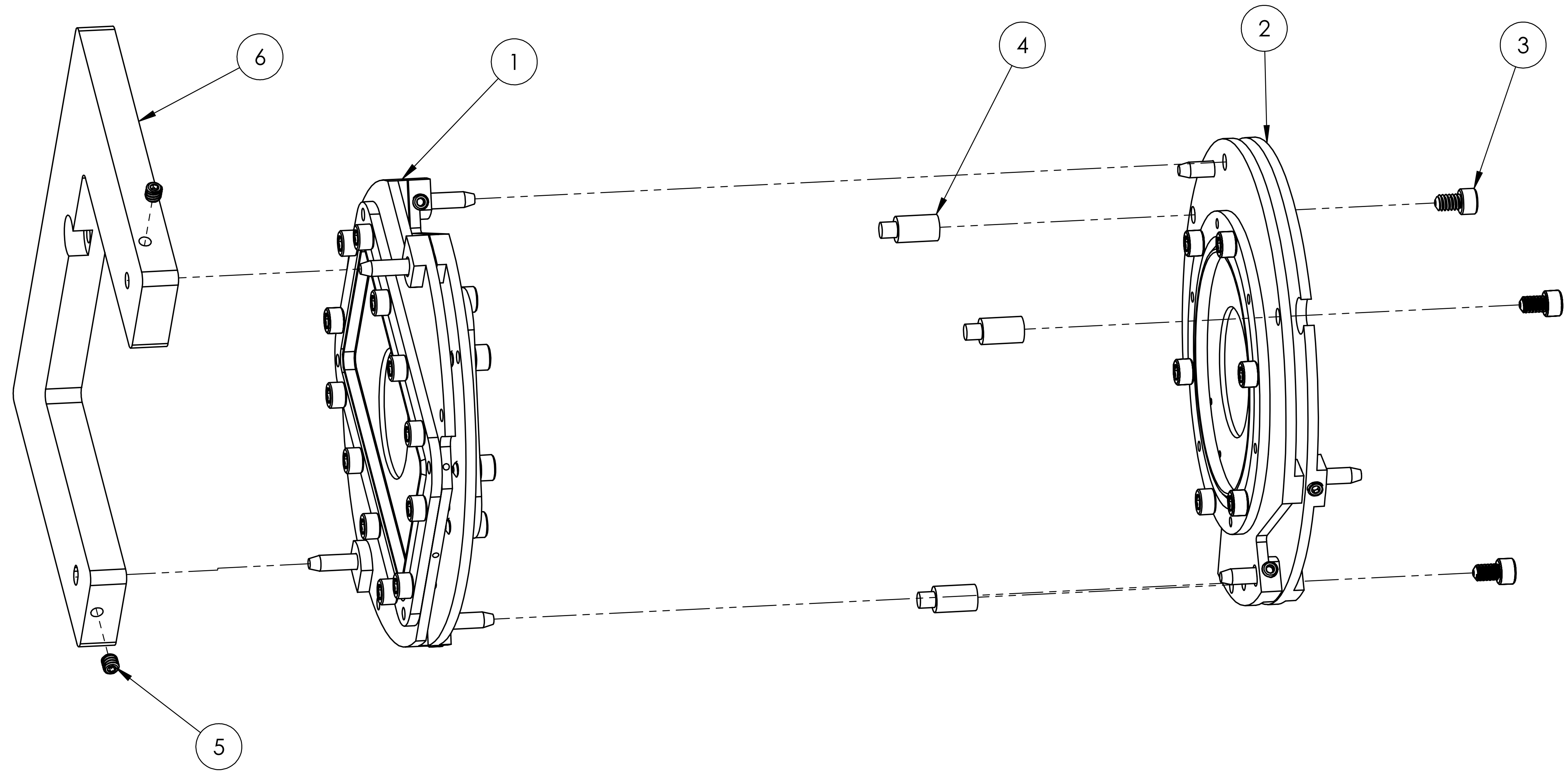
DWG. NO.: Lens Alignment Assembly ast

REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Astigmatic Fluidic Lens		1
2	Spherical Fluidic Lens		1
3	92196A051		3
4	EL Circ Spacer		3
5	92311A050		2
6	Phor External Mount		1

1. Bolt 3X Item 4 to Item1.
2. Rest Item 2 #0-80 clearance holes over the threads of the 3X Item 4, and bolt to them using 3X Item 3.
3. Slide Item 6 over the pins in Item 1, and bolt to it using 2X Item 5 as shown.



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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
See BOM

FINISH
NONE

DO NOT SCALE DRAWING

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

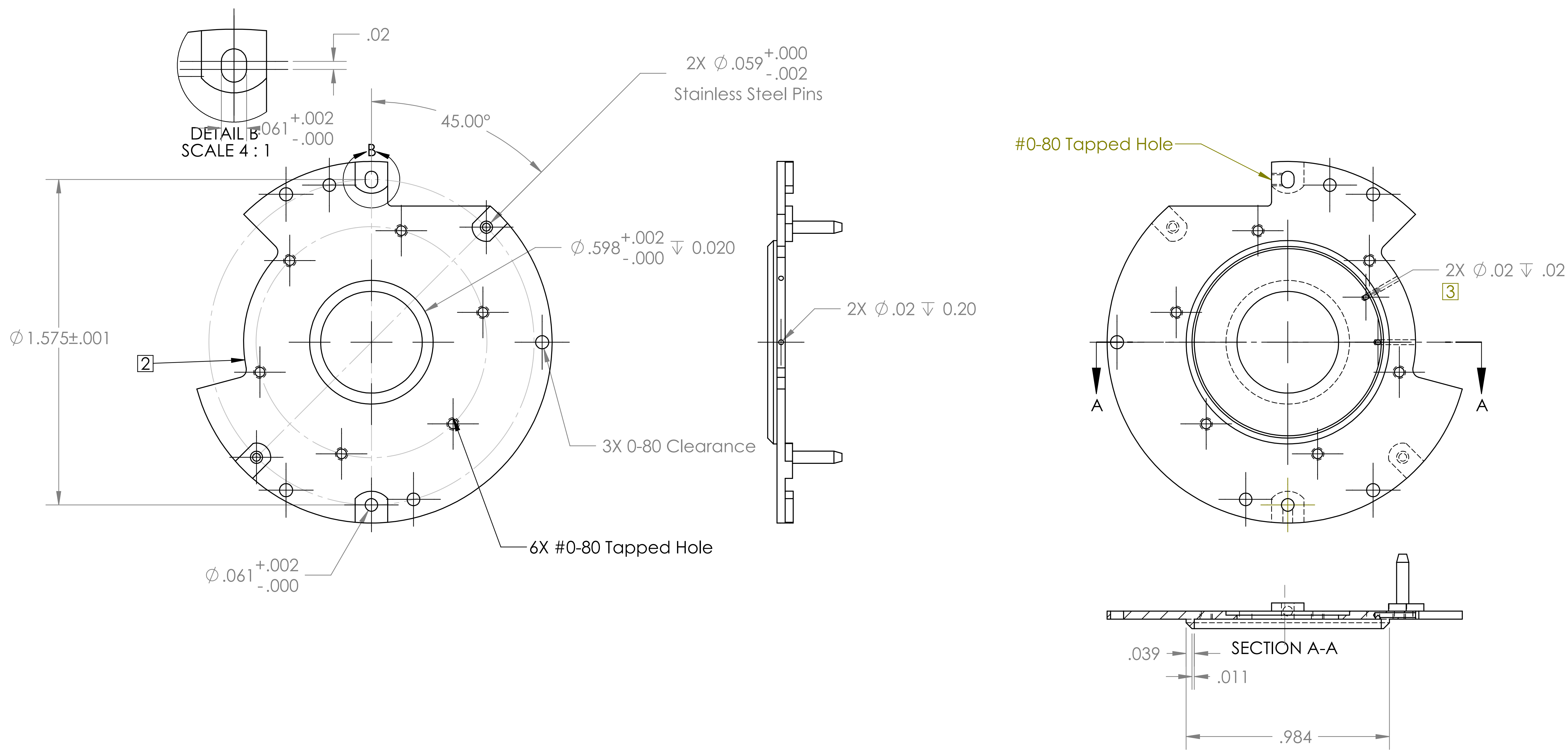
COMMENTS:

TITLE:

SIZE B | DWG. NO. Phoropter Lens Assembly | REV

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

Appendix 2: Machine Part Drawings



1. All dimensions not explicitly shown can be assumed to be .01 inches.
2. This section is designed to allow for access to the .02 hole locations to assure that the depth does not exceed 0.2. If this section must be widened to fit the tool into the area, it can be.
3. These two holes must match up with the two holes bored into the thickness of the material such that they must be able to transfer fluid.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: T6061 ALUMINUM

FINISH: BLACK ANODIZE

DO NOT SCALE DRAWING

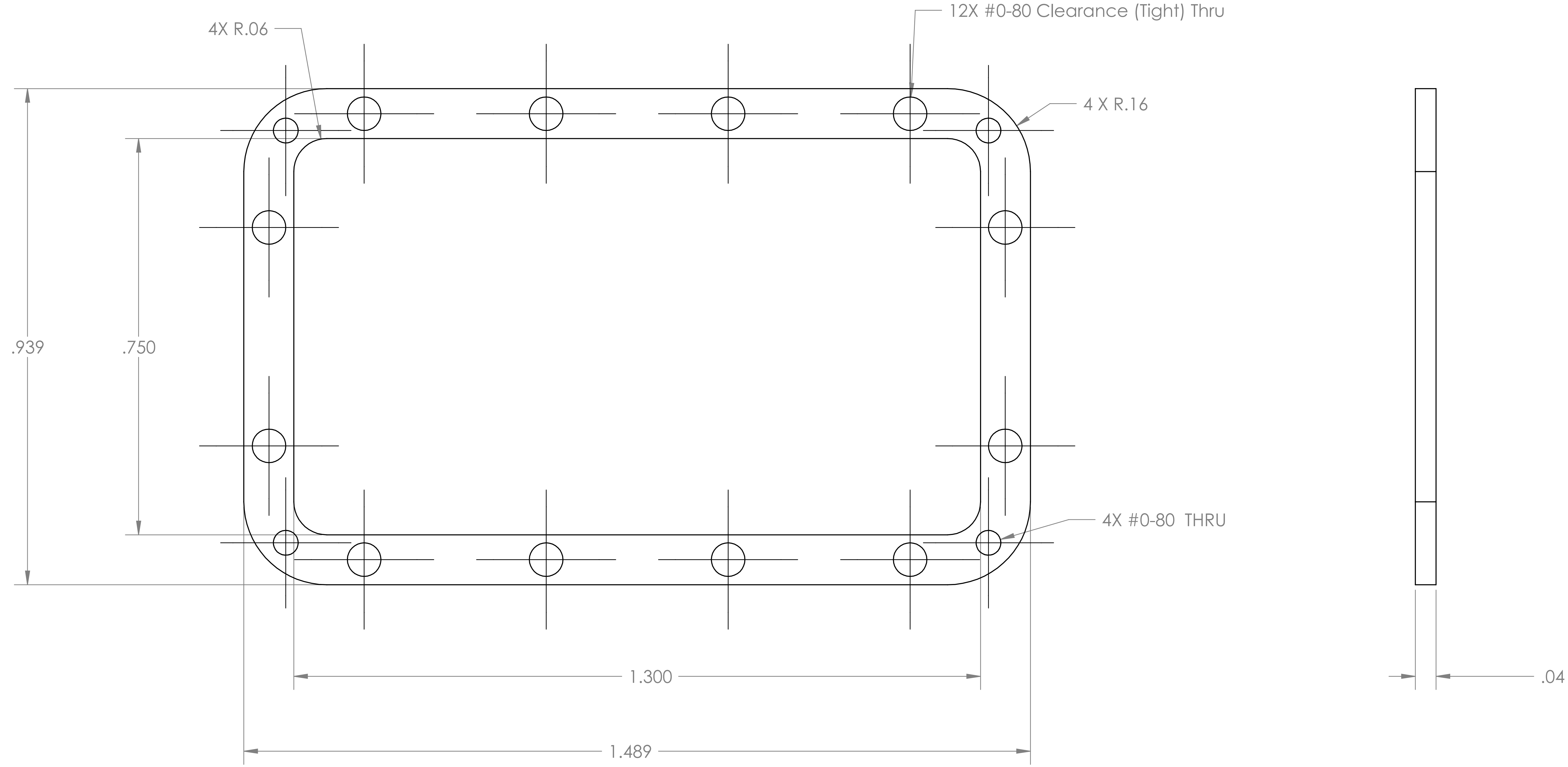
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE: B | DWG. NO.: Ret Insert 2 second circ | REV

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



1. All dimensions not explicitly shown can be assumed to be .01 inches.

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

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

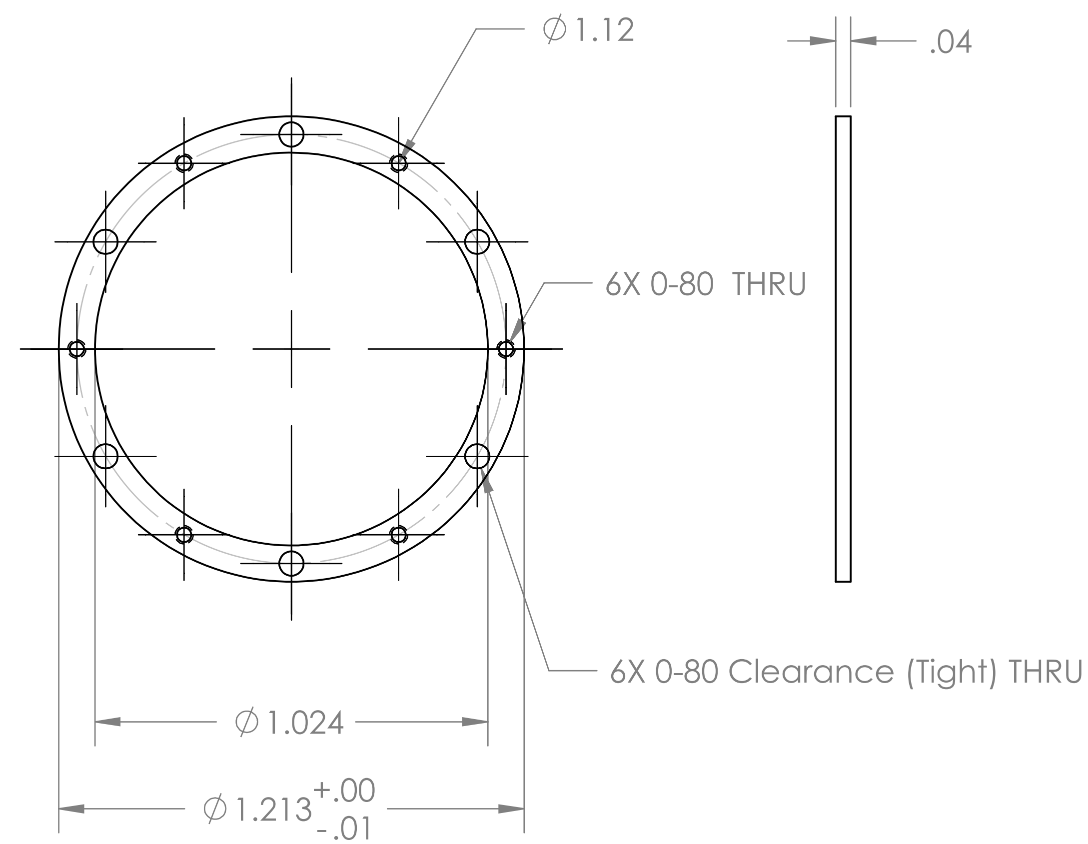
COMMENTS:

TITLE:

SIZE B | DWG. NO. | REV

Phoropter Membrane Retainer

SCALE: 5:1 | WEIGHT: | SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

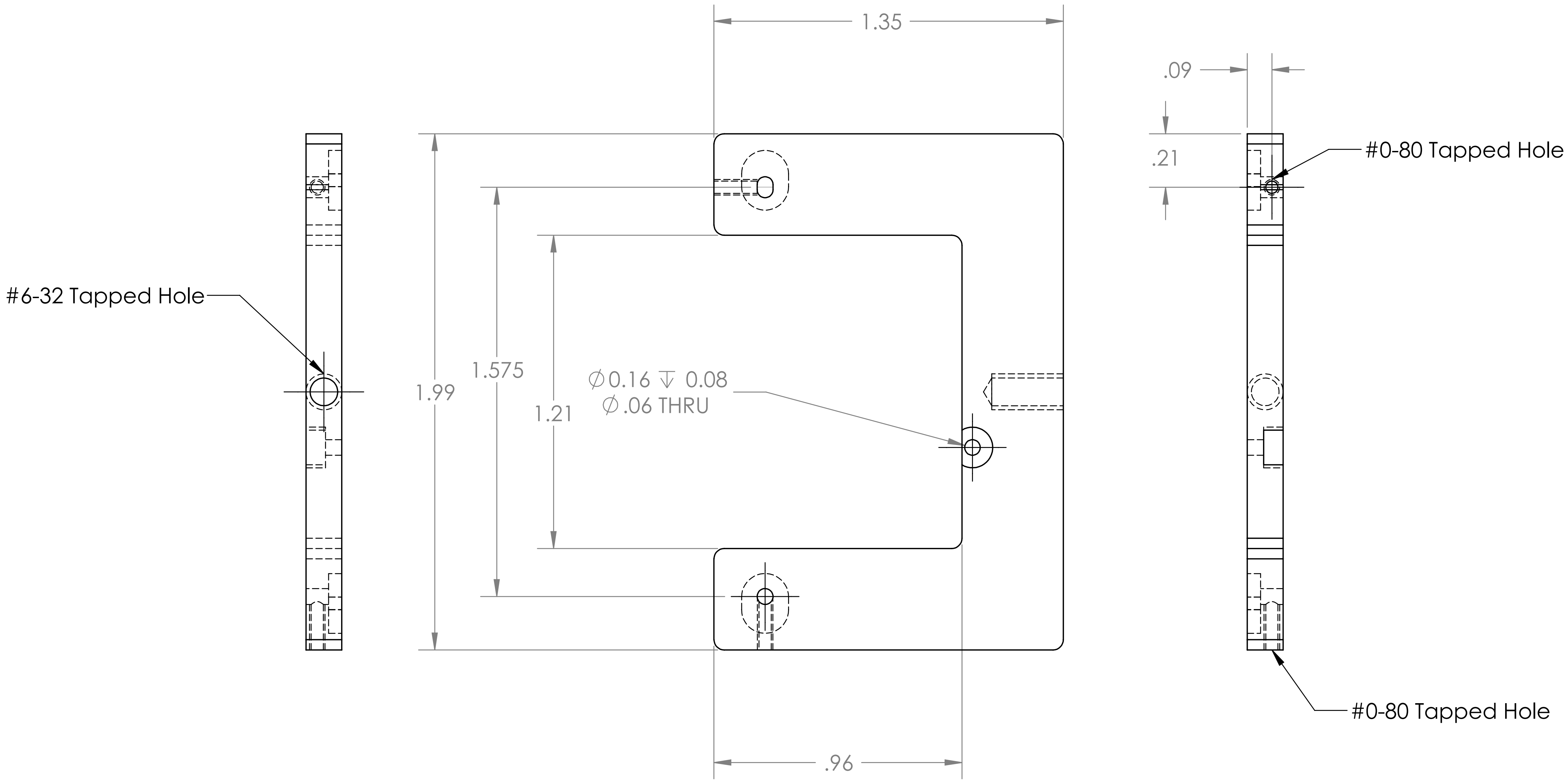
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B DWG. NO. Phoropter Memb Ret Circ 2 REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

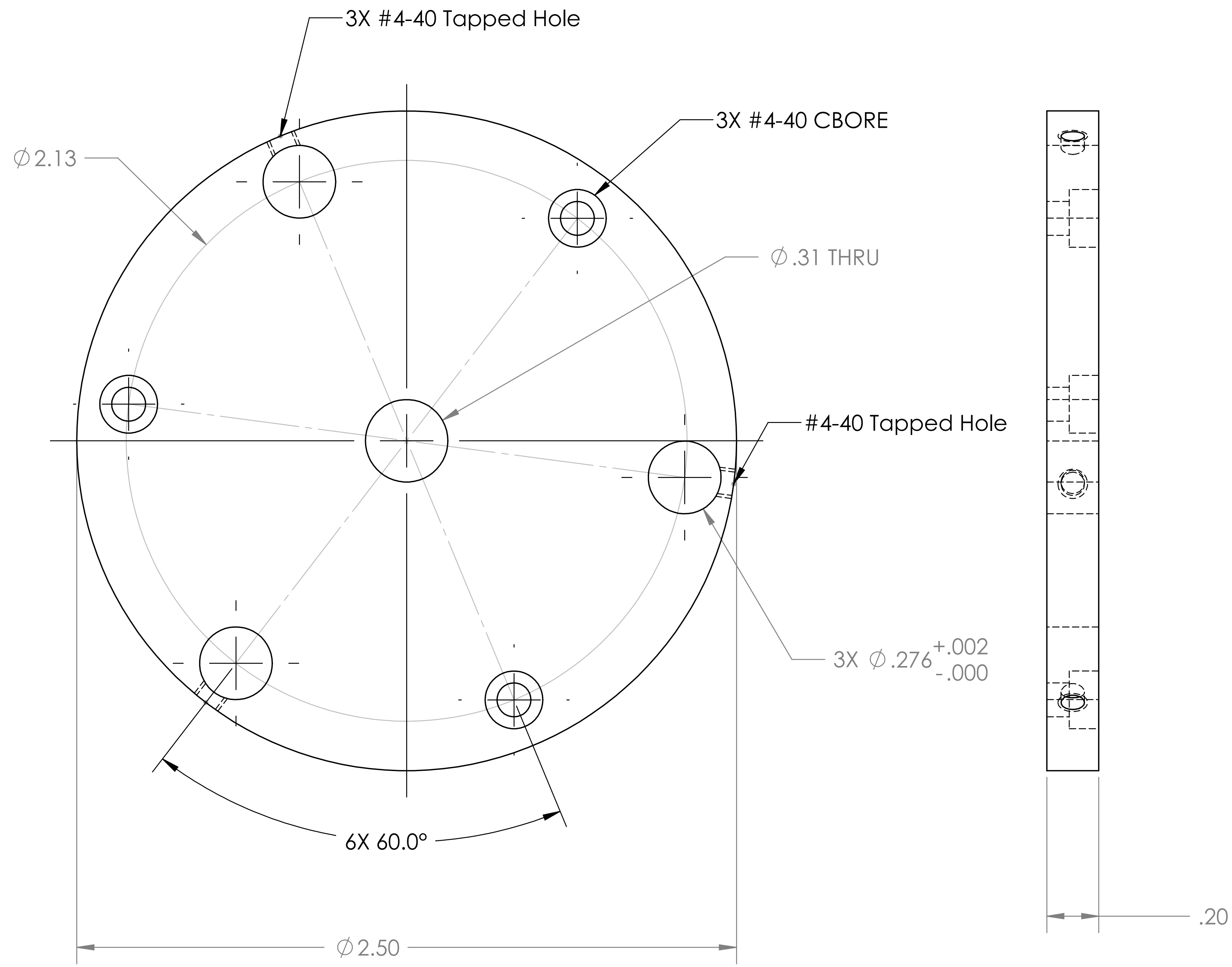
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B DWG. NO. Ph[illegible]r External Mount REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

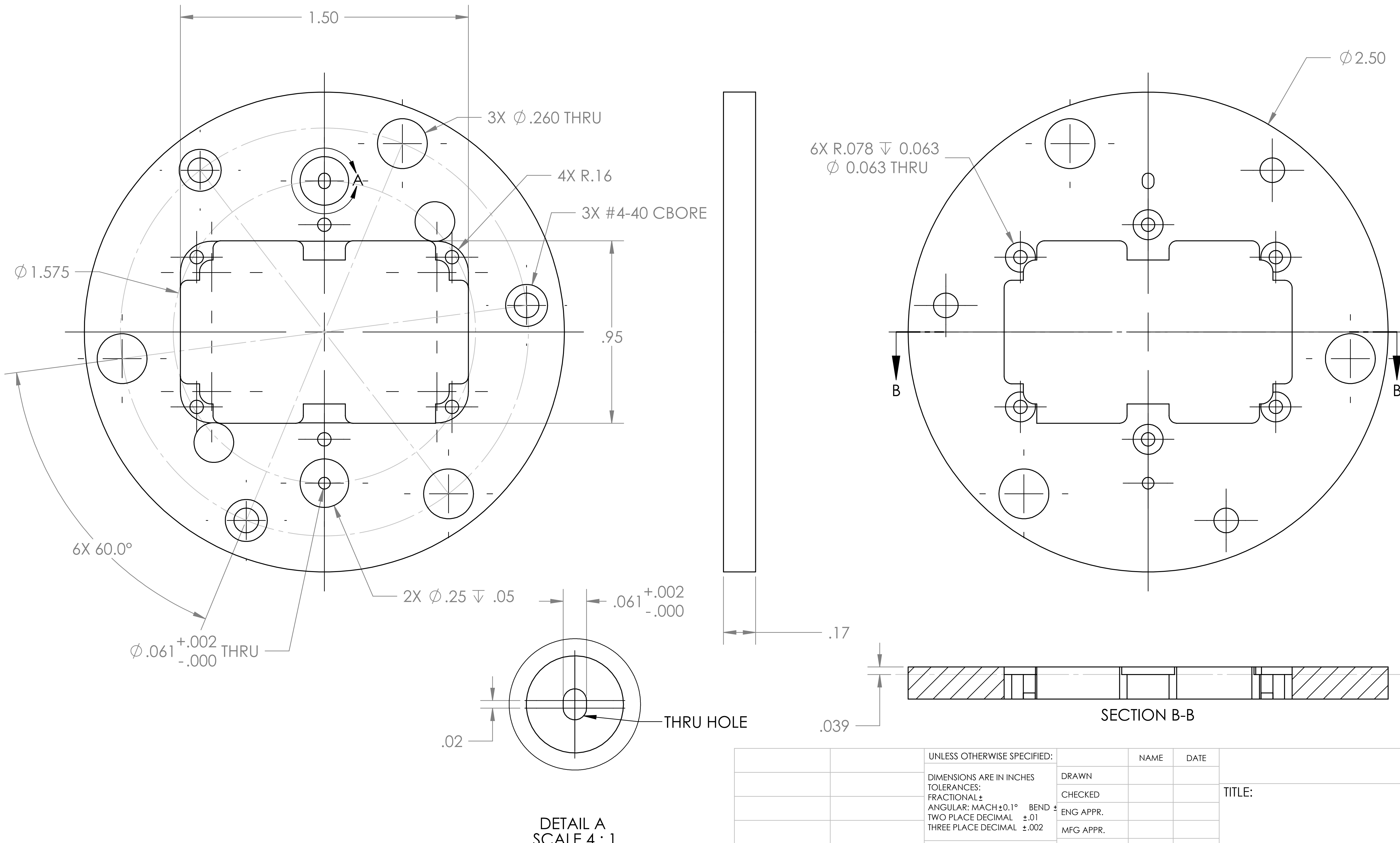
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B DWG. NO. Phor Align Top REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
T6061 ALUMINUM

FINISH
BLACK ANODIZE

DO NOT SCALE DRAWING

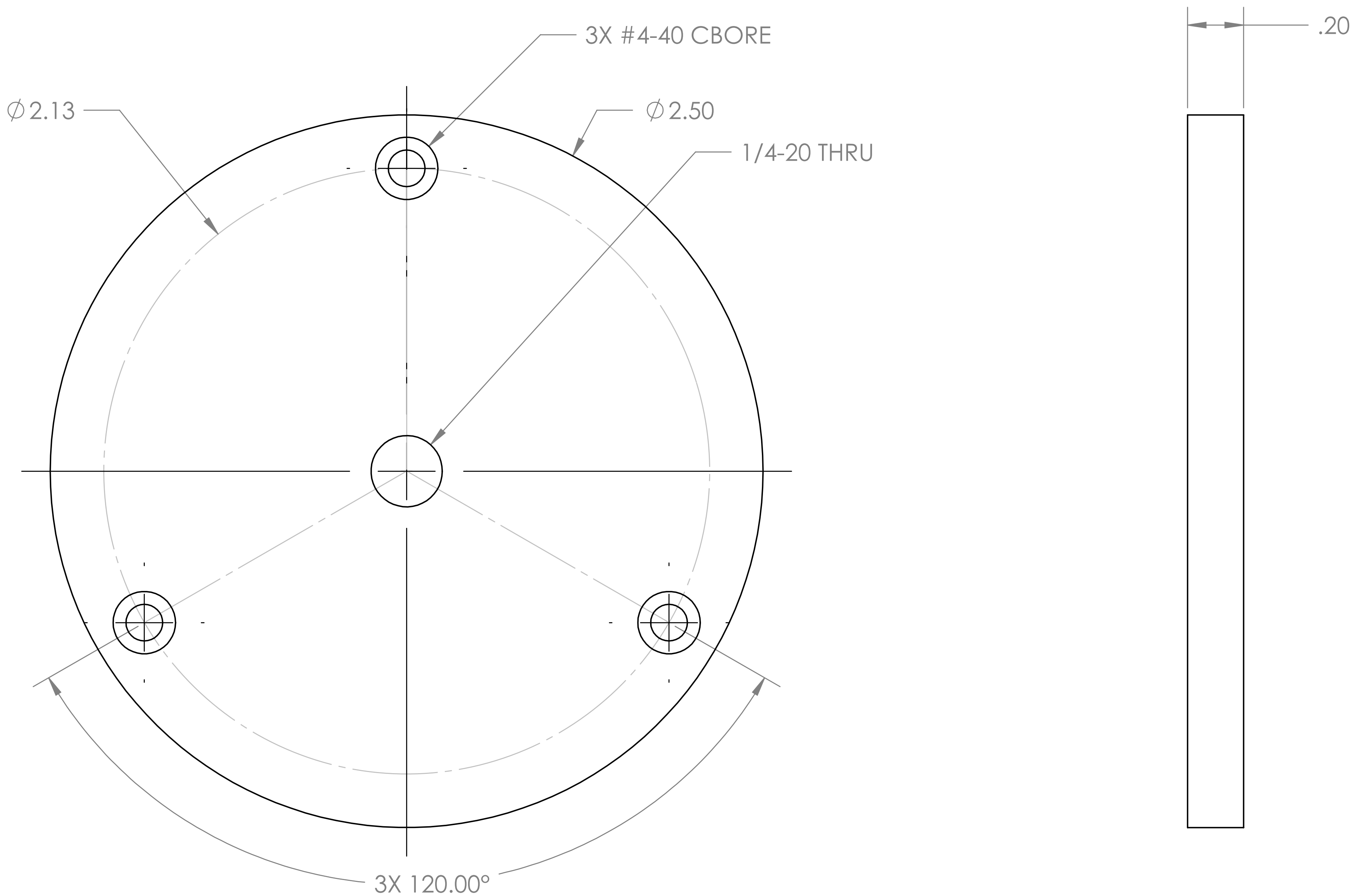
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE: B | DWG. NO.: hor Align base | REV

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



1. All dimensions not explicitly shown can be assumed to be .01 inches.

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: T6061 ALUMINUM

FINISH: BLACK ANODIZE

DO NOT SCALE DRAWING

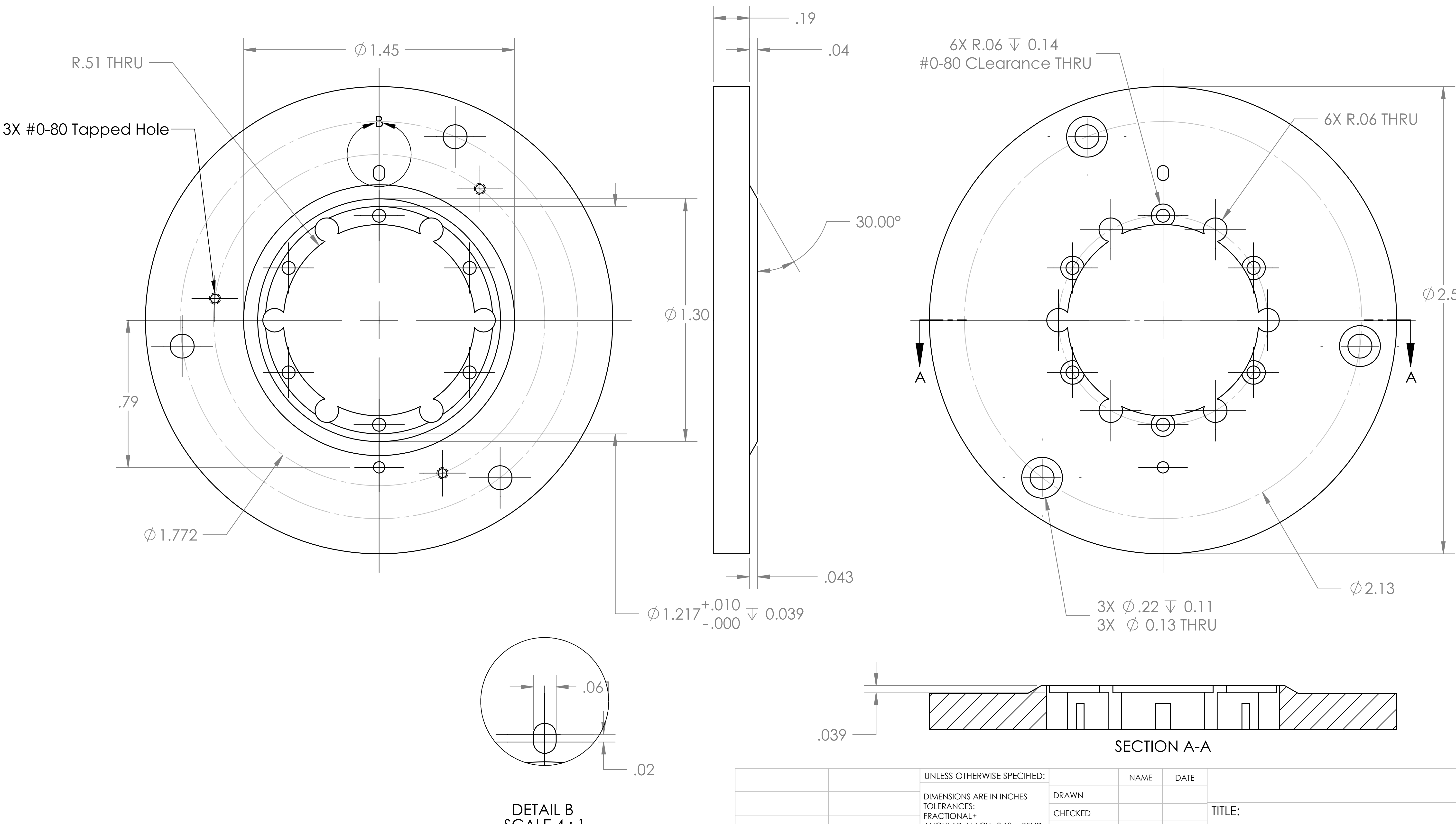
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
B	Ph[illegible]or Align Base Top	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL T6061 ALUMINUM
FINISH BLACK ANODIZE
DO NOT SCALE DRAWING

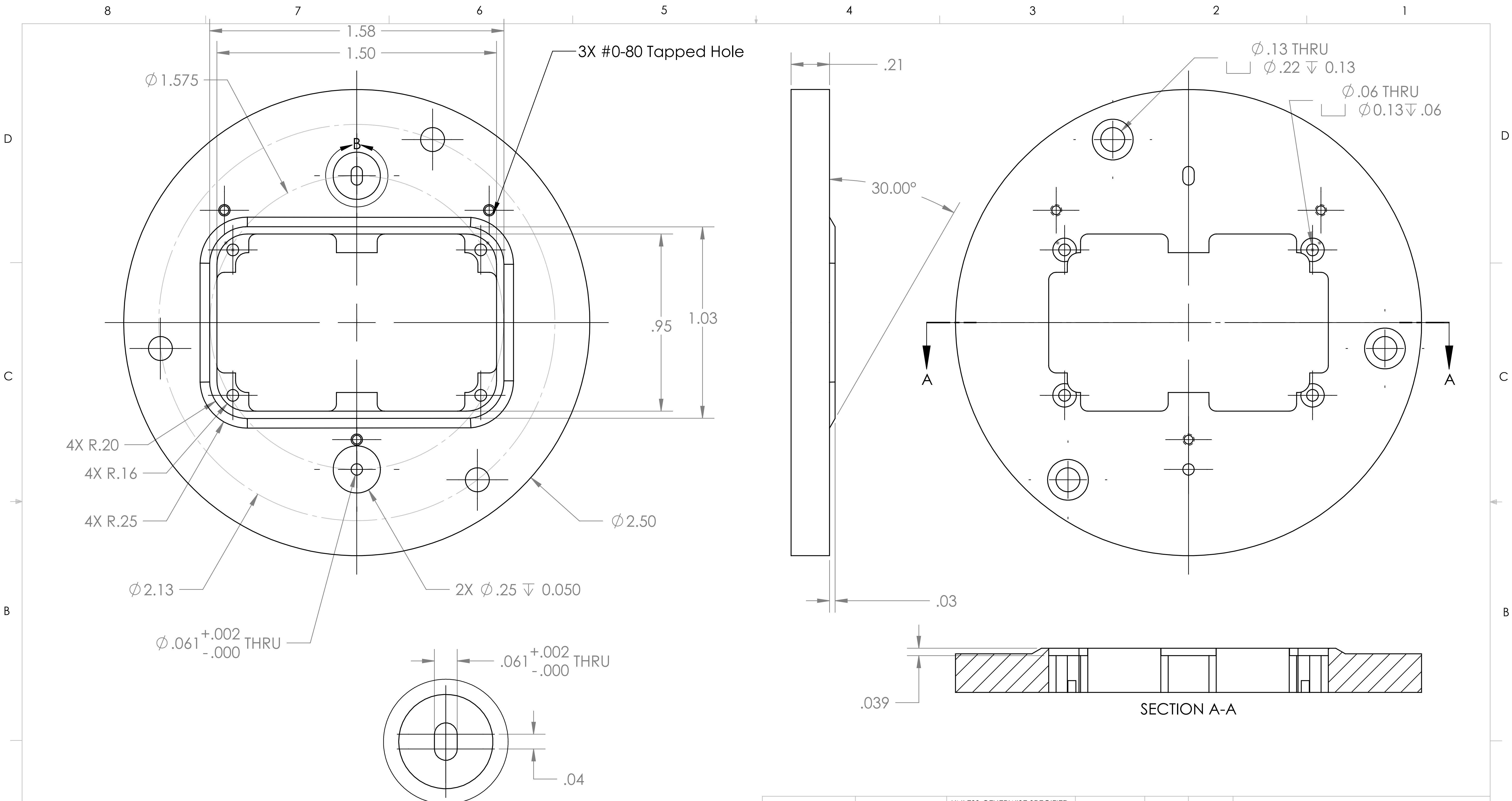
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B | DWG. NO. Phbr Align base circ | REV

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



DETAIL B
SCALE 4 : 1

1. All dimensions not explicitly shown can be assumed to be .01 inches.

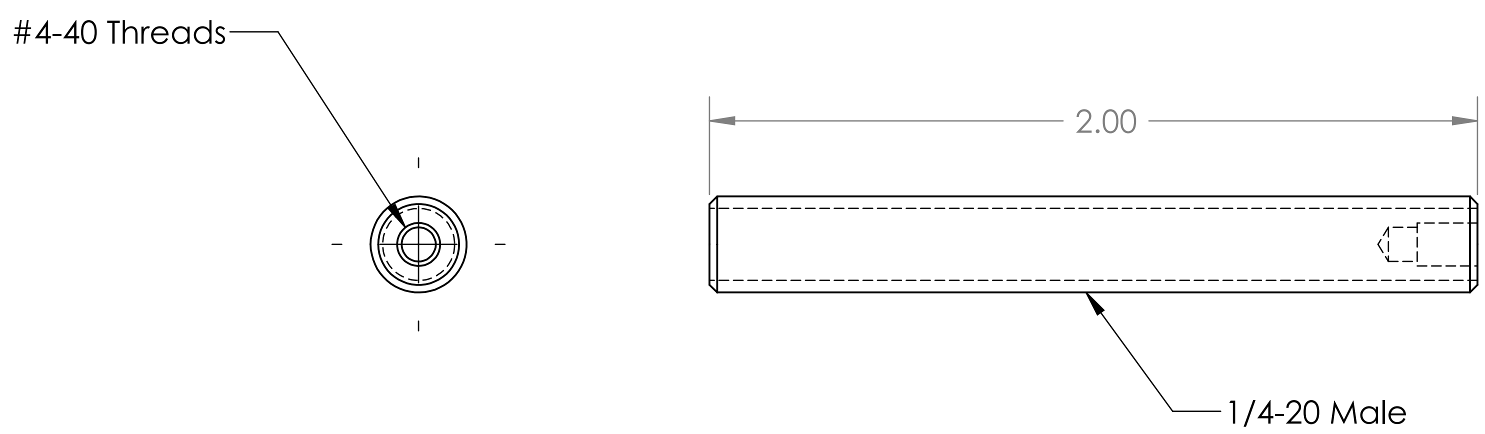
UNLESS OTHERWISE SPECIFIED:	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ±0.1° BEND ± TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.002	
INTERPRET GEOMETRIC TOLERANCING PER:	
MATERIAL	T6061 ALUMINUM
FINISH	BLACK ANODIZE
NEXT ASSY	USED ON
APPLICATION	DO NOT SCALE DRAWING

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

TITLE:

SIZE	DWG. NO.	REV
B	Phor Align base astig	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Stainless Steel

FINISH: None

DO NOT SCALE DRAWING

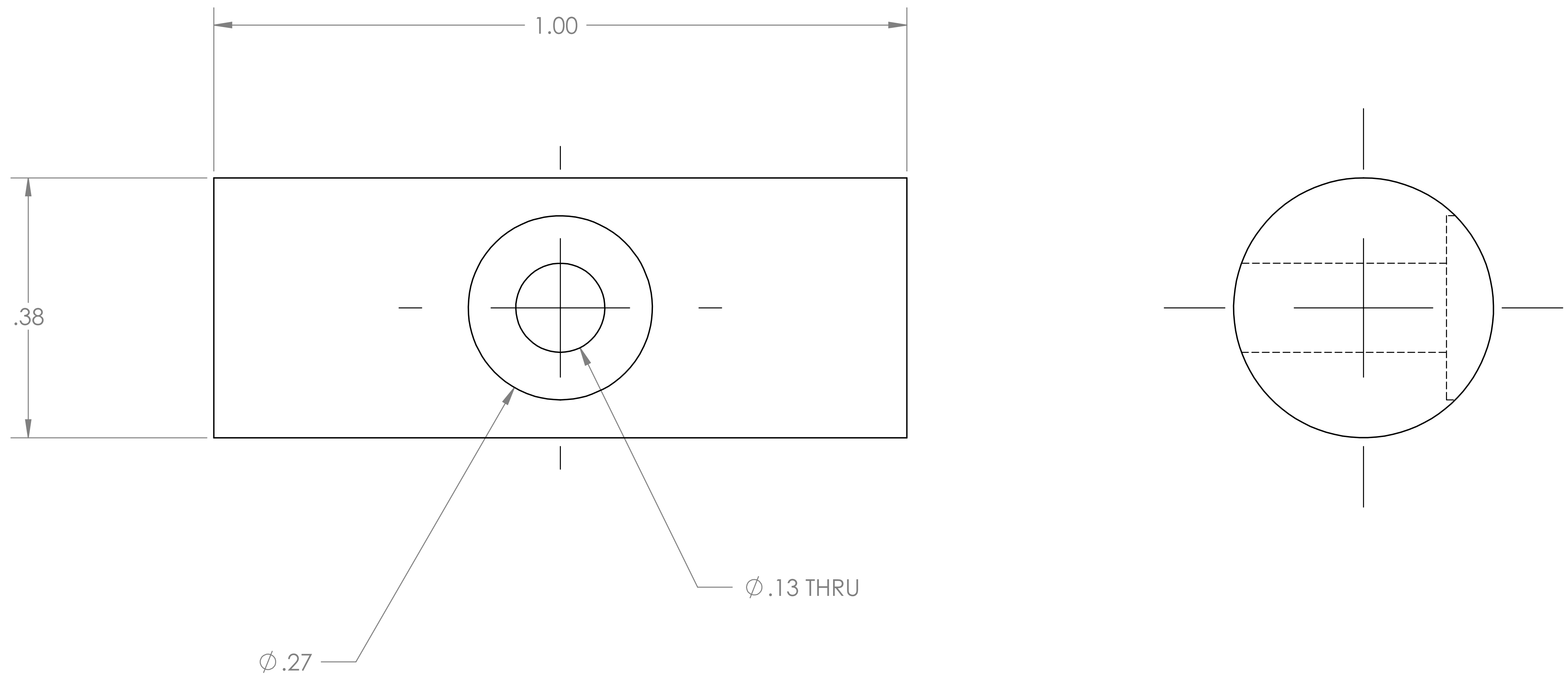
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
B	Leadscrew	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. This part only needs a #4-40 clearance hole and acts as a handle to rotate the leadscrew part.

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

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

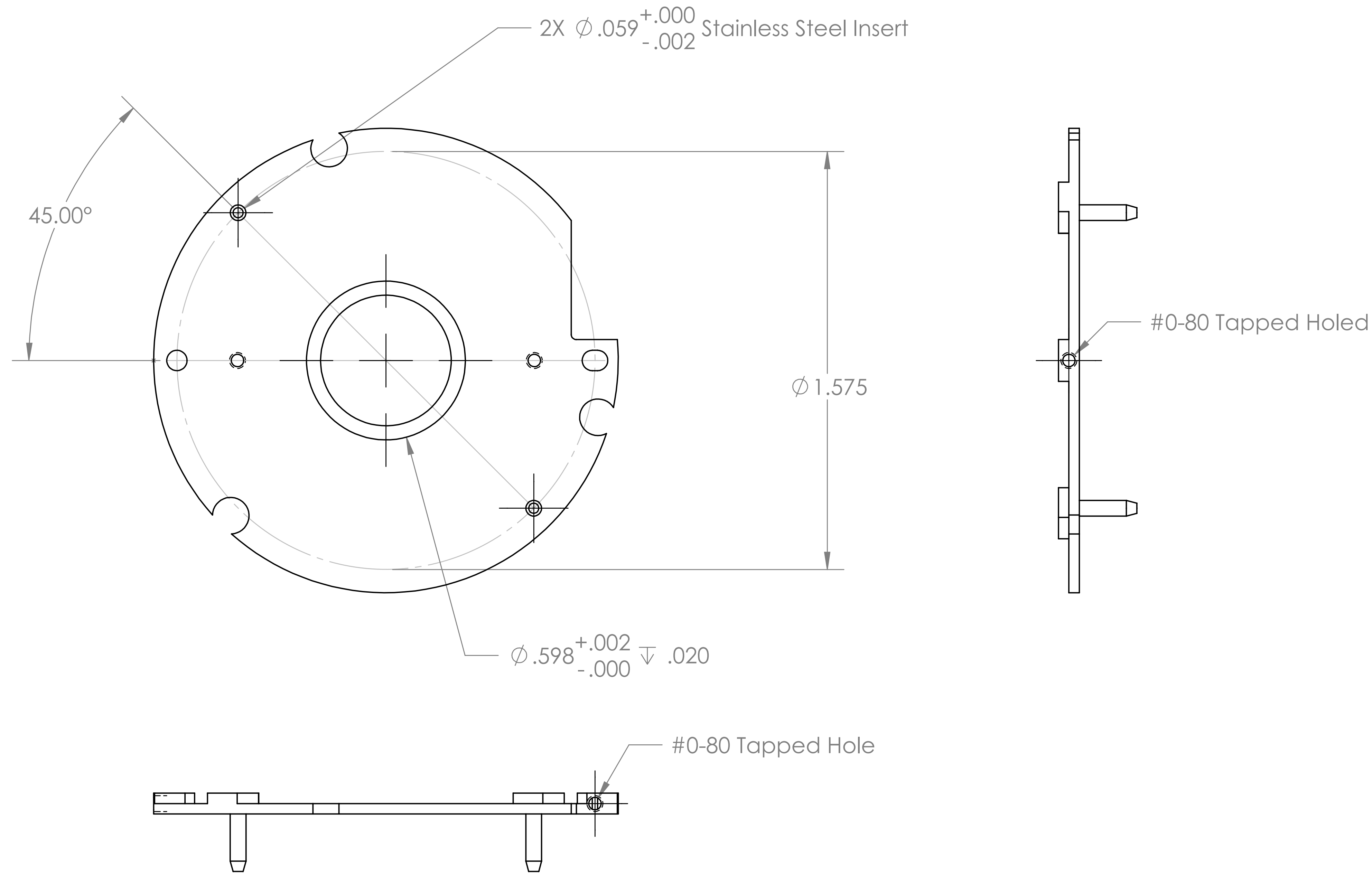
COMMENTS:

TITLE:

SIZE DWG. NO. REV

Beadscrew grip

SCALE: 5:1 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

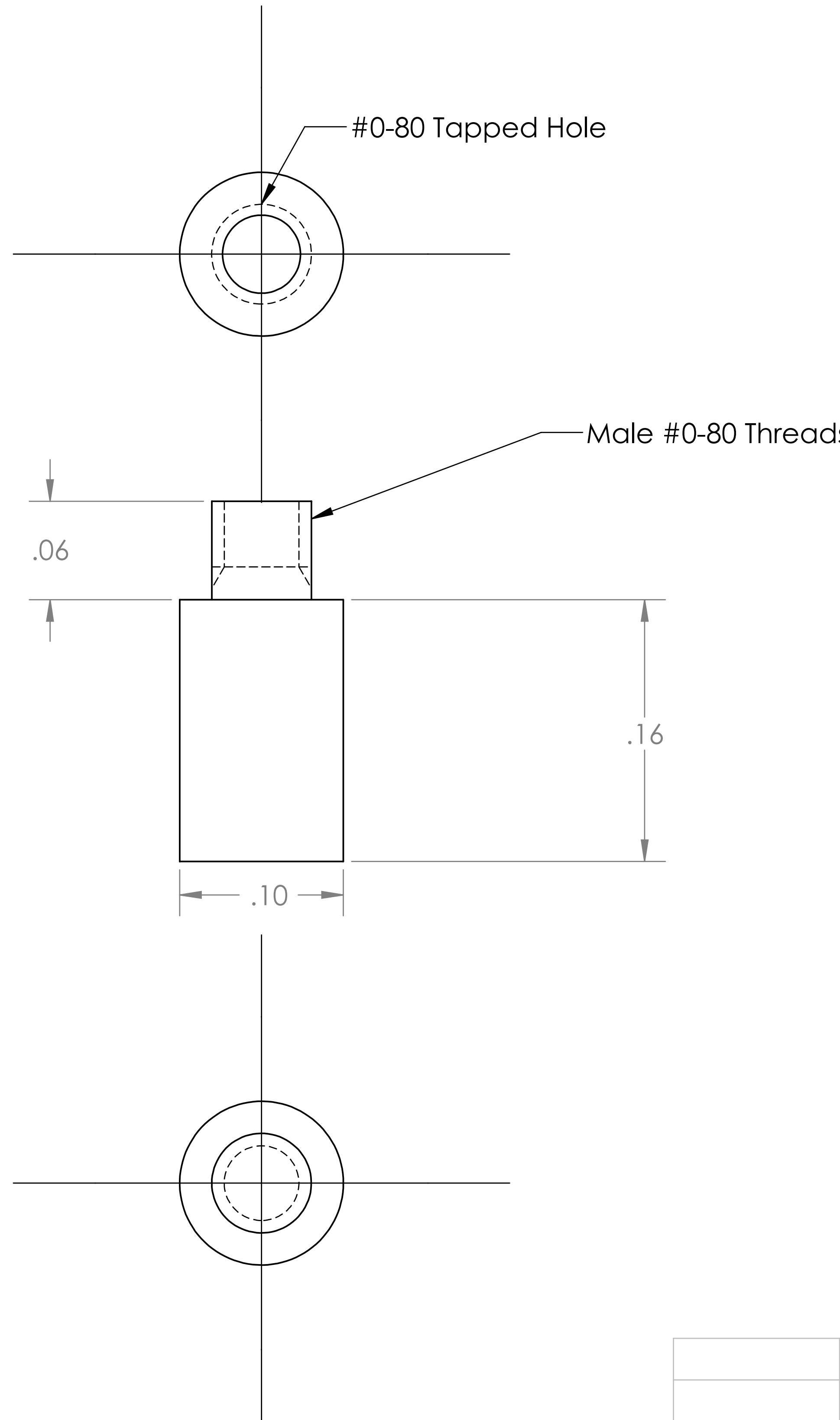
UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ±0.1° BEND ± TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.002	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL T6061 ALUMINUM	COMMENTS:		
FINISH BLACK ANODIZE			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE B | DWG. NO. El Pho[illegible]opter Ret Circ Glass | REV

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

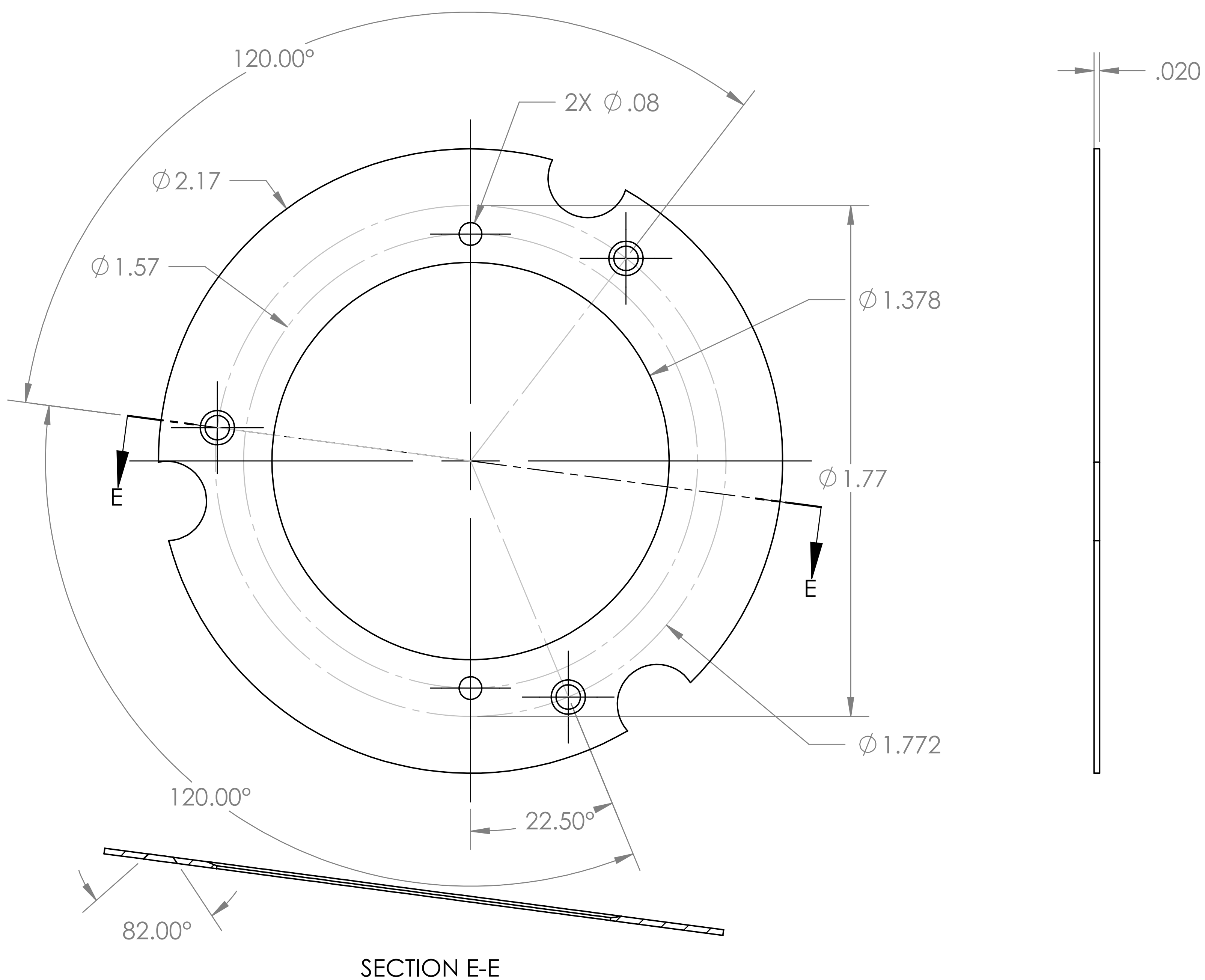


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ±0.1° BEND ± TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.002	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL T6061 ALUMINUM	COMMENTS:		
NEXT ASSY	USED ON	FINISH BLACK ANODIZE			
APPLICATION		DO NOT SCALE DRAWING			

PROPRIETARY AND CONFIDENTIAL

TITLE:

SIZE	DWG. NO.	REV
B	EL Circ Spacer	
SCALE: 10:1	WEIGHT:	SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

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

COMMENTS:

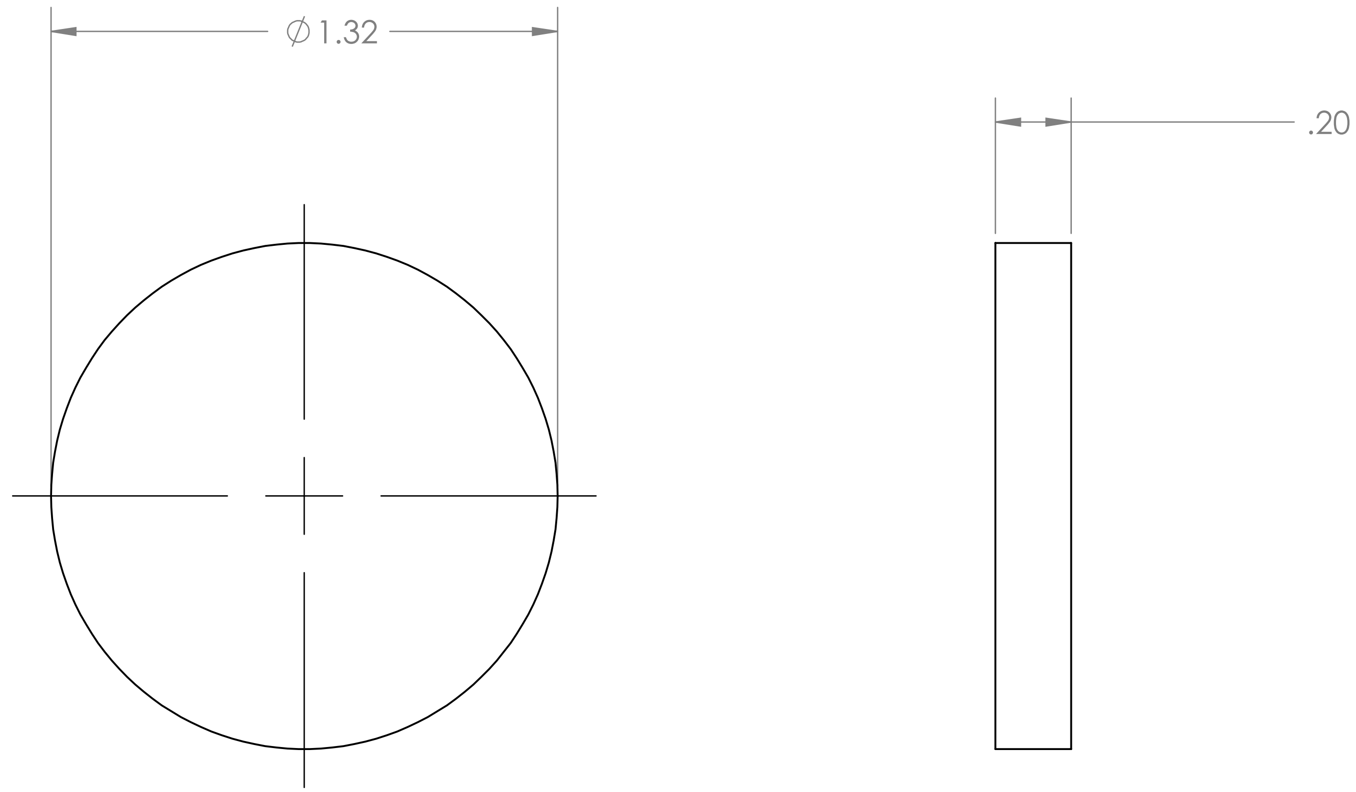
TITLE:

SIZE B DWG. NO. Circ Membrane Stretch Retai REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

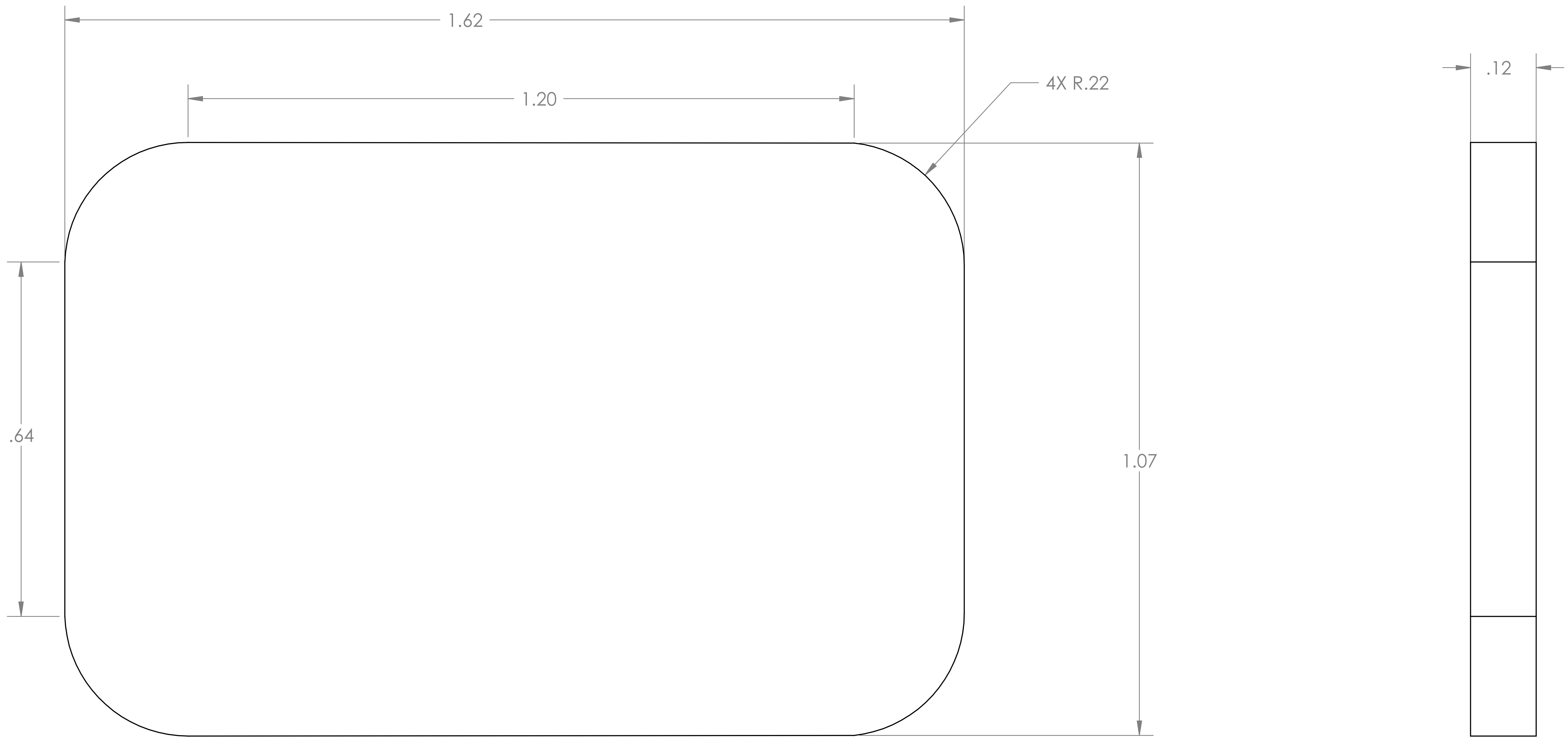
8 7 6 5 4 3 2 1

D C B A



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ±0.1° BEND ± TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.002	DRAWN			
			CHECKED			TITLE:
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL 1 wave glass	COMMENTS:			SIZE B DWG. NO. Base Glass Plate REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT: SHEET 1 OF 1

8 7 6 5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ±0.1° BEND ± TWO PLACE DECIMAL ±.01 THREE PLACE DECIMAL ±.002	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL 1 Wave Glass	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

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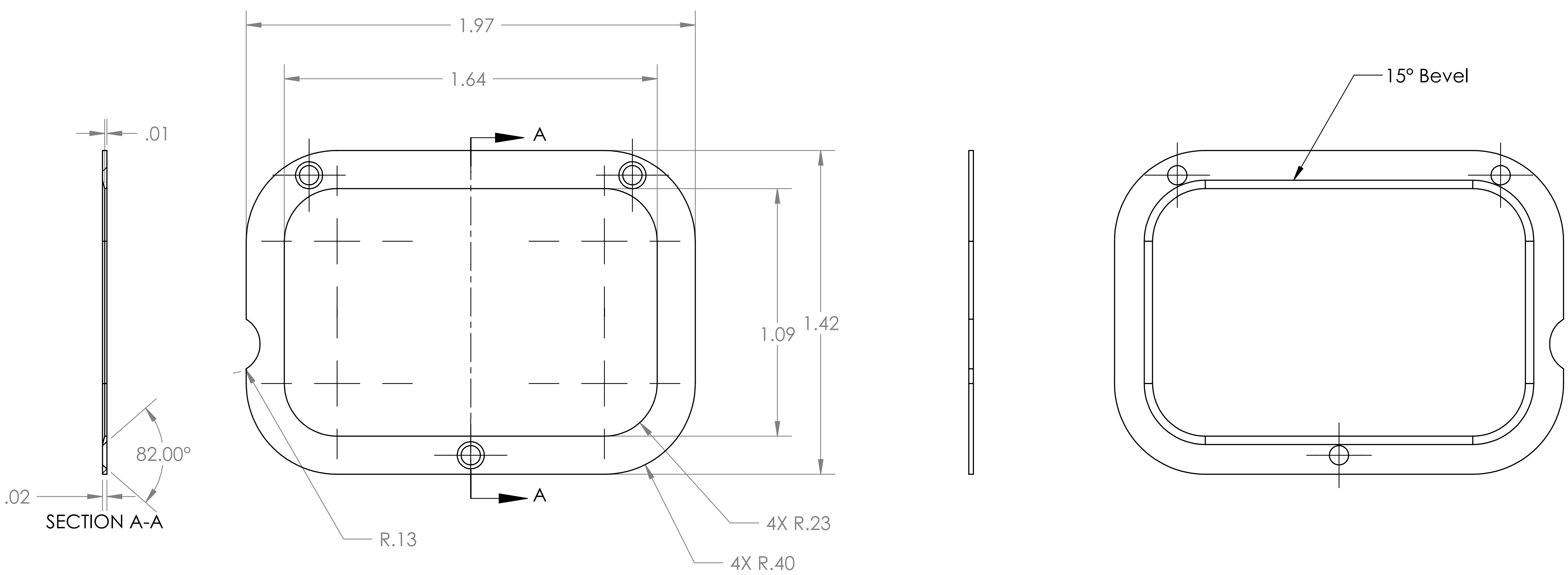
TITLE:

SIZE	DWG. NO.	REV
B	Base Glass Plate Astig	
SCALE: 5:1	WEIGHT:	SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: T6061 ALUMINUM

FINISH: BLACK ANODIZE

DO NOT SCALE DRAWING

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

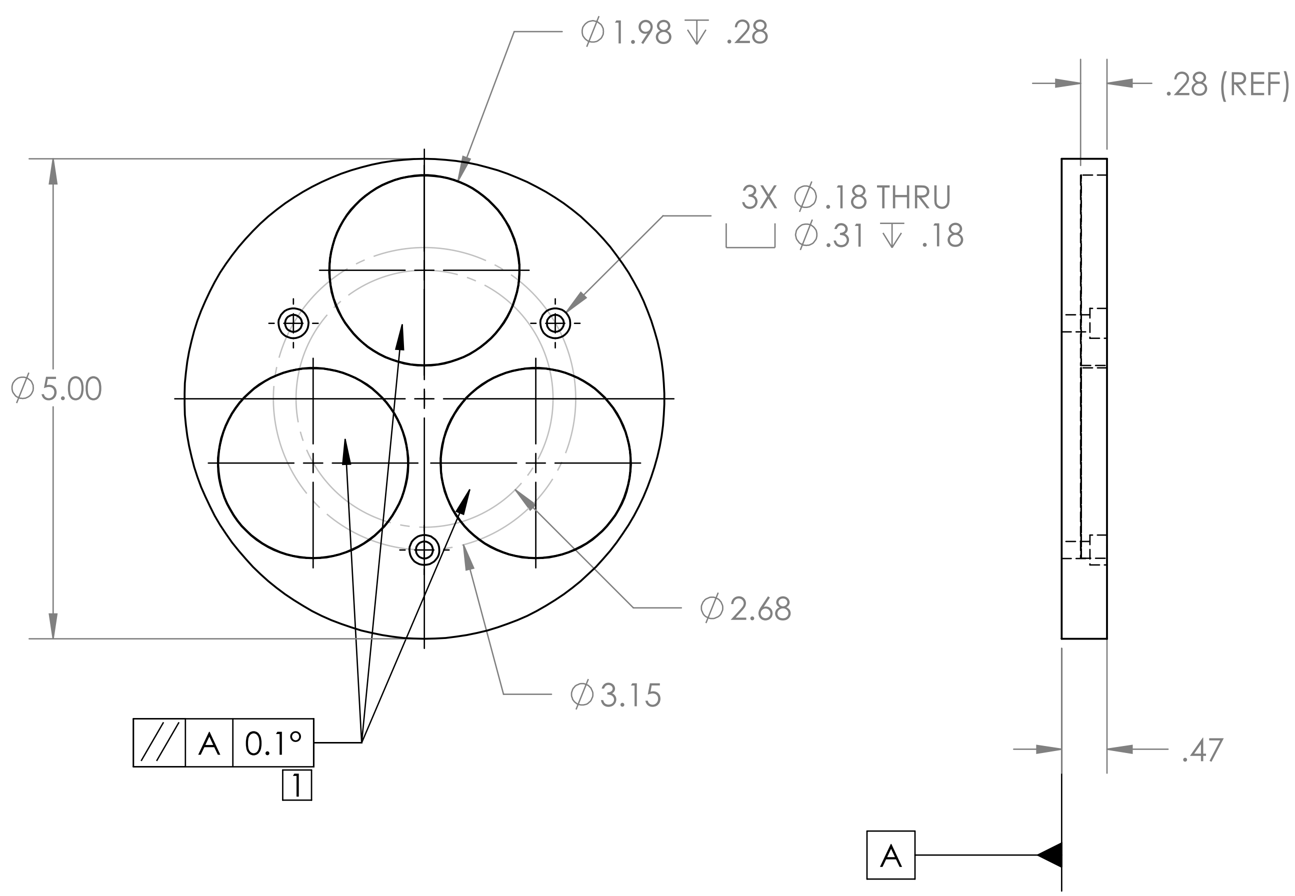
COMMENTS:

TITLE:

Astig Membrane Stretch Retai

SIZE	DWG. NO.	REV
B		

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



1. Polish Surface, and add 100 um radius relief at bottom of chamber.
2. All dimensions not explicitly shown can be assumed to be .01 inches.

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

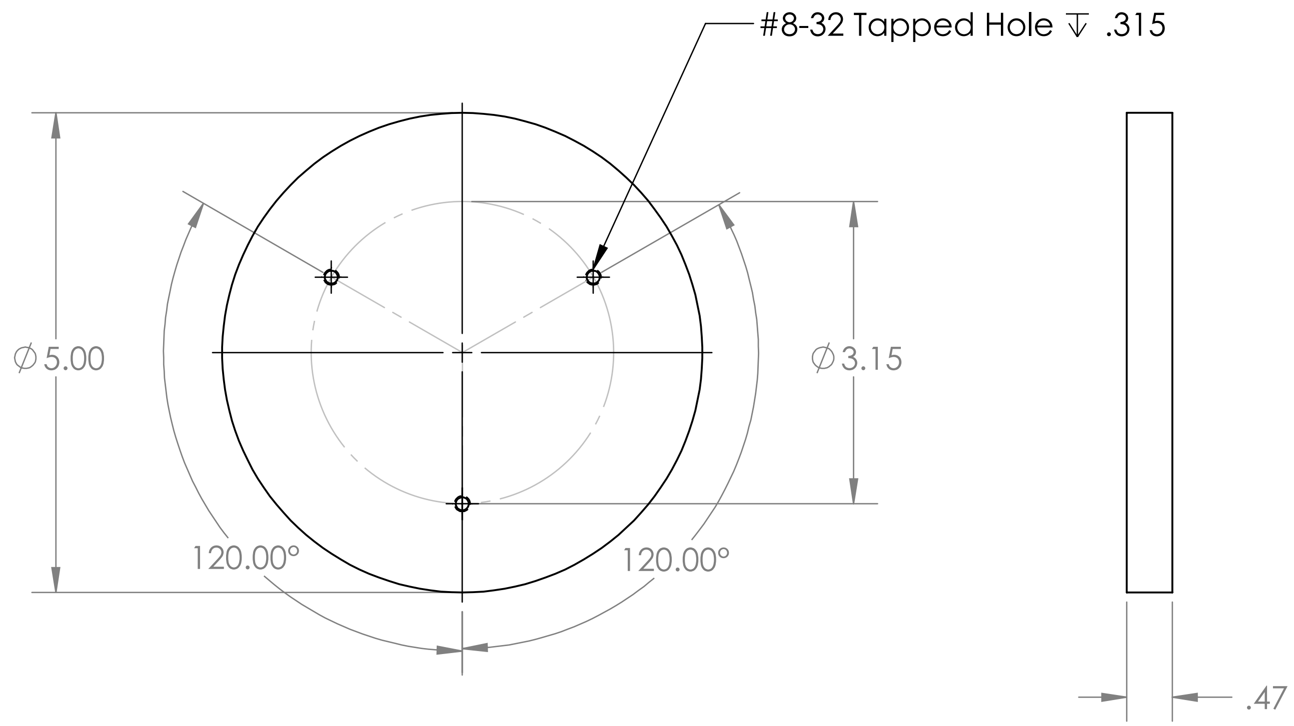
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B DWG. NO. 3 pc mold chamber REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



1. All dimensions not explicitly shown can be assumed to be .01 inches.

PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL T6061 ALUMINUM

FINISH BLACK ANODIZE

DO NOT SCALE DRAWING

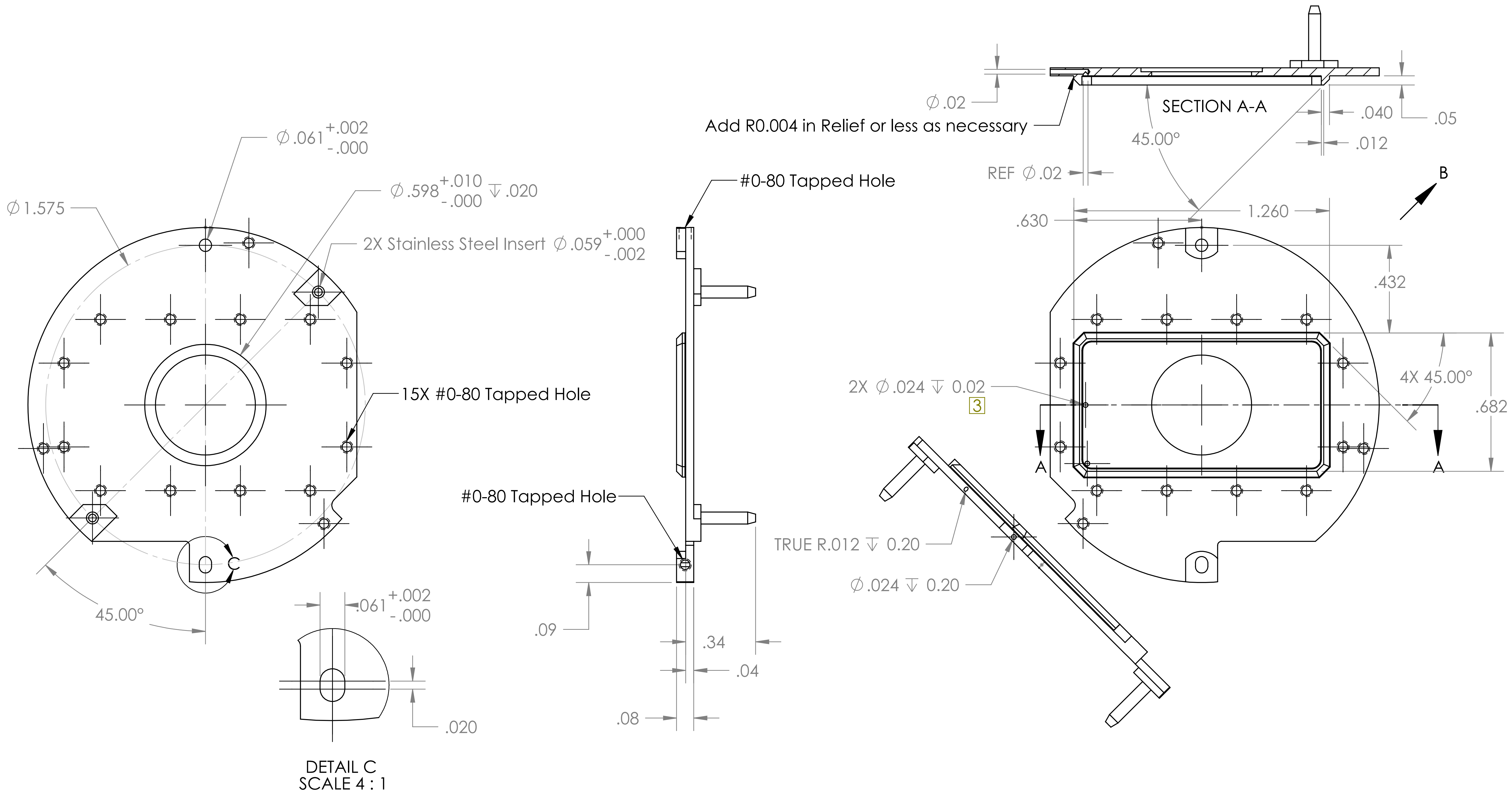
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE B | DWG. NO. 3 chamber Mold base | REV

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



1. All dimensions not explicitly shown can be assumed to be .01 inches.
2. This part mates with a duplicate part. It is flipped horizontally and rotated 45° clockwise to mate with itself. The pins are the mating features, and a 2mm thick glass plate sits between them in the circular hole feature (they mate with the curcular back sides facing each other).
3. These two holes must match up with the two holes bored into the thickness of the material such that they must be able to transfer fluid.

NEXT ASSY	USED ON		
APPLICATION			

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±0.1° BEND ±
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.002

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: T6061 ALUMINUM

FINISH: BLACK ANODIZE

DO NOT SCALE DRAWING

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

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
B	Rest Insert 3 second	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

Appendix 3: Lessons Learned

Lessons Learned

Lesson #1: I can never seem to learn this lesson, but it is imperative to start out looking at as broad of a scope as possible before doing any real design work. I wound up overhauling many of the most significant parts because I did not place enough forethought or analysis at the beginning of the project and wound up finding out that my assumptions were wrong, thereby drastically increasing the amount of work required.

Lesson #2: Yet another lesson I can't seem to learn, but design is about 25% of the work and documentation is about 75% of the work, and I always get that thought process reversed.

Lesson #3: Always make sure that any systems of motion and/or alignment are not overconstrained: it is very easy to get into the trap of trying to do everything based on machine tolerances instead of being able to make the system sloppier because the right constraints are used.

Lesson #4: I'm sure there will be lots of lessons when I actually build this thing in a month or so. I can never seem to avoid rework. By the way, I have not fully checked the drawings yet: just haven't had time.