Homework 11
OPTI 421/521

Below is an example from a 2016 course. The numbers may be different but the same basic procedure for designing the vacuum window can be followed.

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Problem 1: FINAL DESIGN REVIEW

ABSTRACT

This design is for an optical vacuum chamber window for an infrared system. The system must not degrade the optical performance while also retaining a vacuum and strength.

REQUIREMENTS

- Window will have a minimum 2-inch clear aperture
- Window shall be mounted to stainless steel flange shown.
- Window shall transmit wavelengths of 0.4 μm < λ < 1.0 μm
- Window shall induce less than half a wave of rms wavefront distortion at a wavelength of 633 nm
- Window shall perform under 1 atm outside pressure and 10^{-6} Torr inside pressure

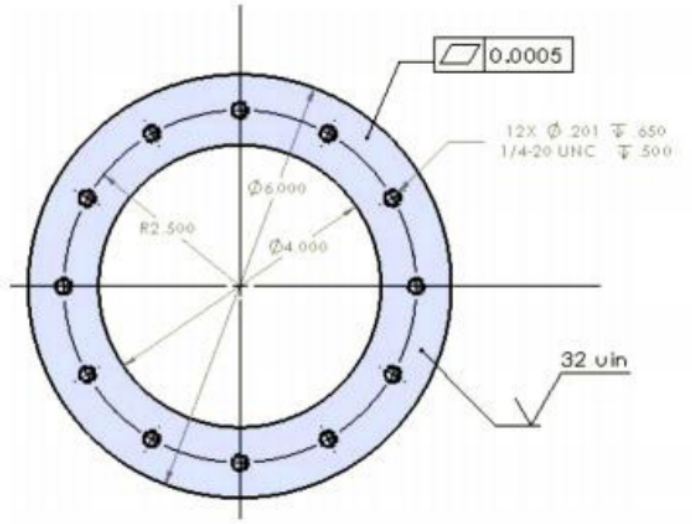


Figure 1. Interface Flange [*Requirements*]

DESIGN CONCEPT

The design for the vacuum window for this IR system satisfies all requirements:

- The 3-inch window satisfies the requirement by providing the system with a 2-inch clear aperture.
- The window assembly is free from the interface flange as a subassembly. The window assembly, along with an O-ring, is fastened to the interface using twelve, ¼-20 screws shown in Figure 6.
- The fused silica has a transmission range of 0.1 μm < λ < 2.5 μm which satisfies the requirement.

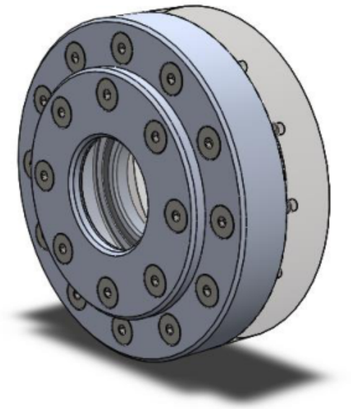


Figure 2. Isometric View

- The rms wavefront error due to the surface of the window is 41 nm which satisfies the distortion of less than 316 nm rms requirement.
- The window satisfies the requirement of surviving under pressure with a factor of safety of 129 for a ¾-inch thick blank of fused silica which satisfies the general requirement of a factor of safety of 4.

After satisfying the requirements, the secondary goal for the design is to keep it inexpensive, easy to manufacture and easy to assemble. The window is assembled with two custom 6061-T6 Aluminum parts, two O-rings, flat head cap screws and an off the shelf glass blank. The stainless steel flat head cap screws maintain a flat surface. Beveled edges reduce chances of cutting someone during assembly while also reducing the chance of the glass scratching. The custom parts are made from aluminum for easy machining and low weight (3.00 lbs).

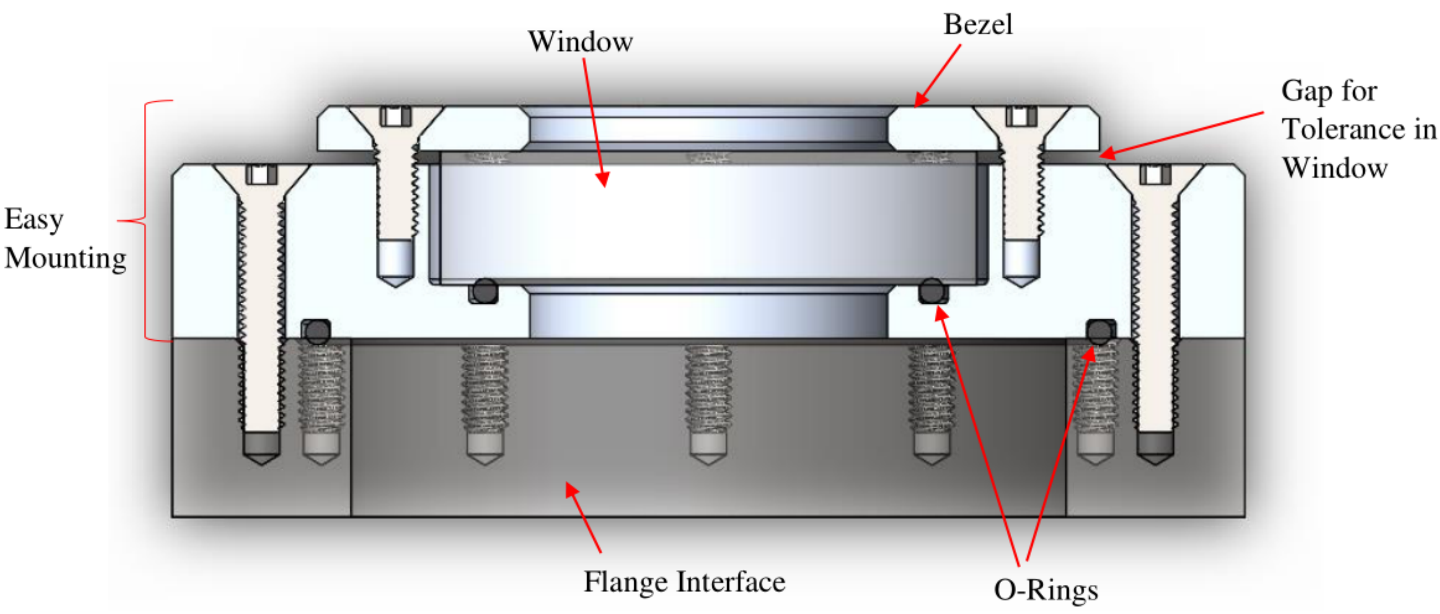


Figure 3. Cross Section

The window selected is a 3-inch diameter, ¾ inch thick dual surface fused silica flat from Edmund Optics. The part has a diametric tolerance of +/- .04 inches and a thickness tolerance of +/- .06 inches. The surface flatness specified by the manufacturer is λ/10. There is a gap between the bezel and the base due to the large thickness tolerance of the fused silica window. The clearance allows for the tolerance in the window so the bezel can apply the required pressure on the O-ring to get the ~20% required squeeze. There is also a diametric clearance for the window inside the seat due to its large diametric tolerance.

The O-ring selection is simple since the environment is a controlled lab. The only two criteria in consideration for selecting the O-ring are permeation rate and outgassing. Referencing Figure 4, butyl rubber and nitrile are both effective for this particular vacuum environment. For this design, butyl rubber is chosen due to its lower cost.

Vacuum Properties of O-Ring Materials

	Permeation Rate. H_2O tL/sec/lin. cm, 23°C, 50 % r.h.	Permeation Rate, He, tL/sec/lin. cm, 23°C	Outgassing Rate, tL/sec./lin.cm., 23°C	Temp-erature Limit, ° C	Relative Cost
Butyl	5×10^{-9}	3×10^{-8}	1×10^{-5}	86	Lowest
Nitrile	1×10^{-7}	9×10^{-8}	1×10^{-6}	135	Low
Flouro	6×10^{-9}	5×10^{-8}	3×10^{-8}. Pre-baked	150	Medium
Perflouro	2×10^{-8}	1×10^{-6}	3×10^{-8}	200	Highest

Figure 4. Cross-comparing the vacuum properties of the four commonest O-ring materials allows the proper tradeoff selection for any particular application [*Phil Danielson*]

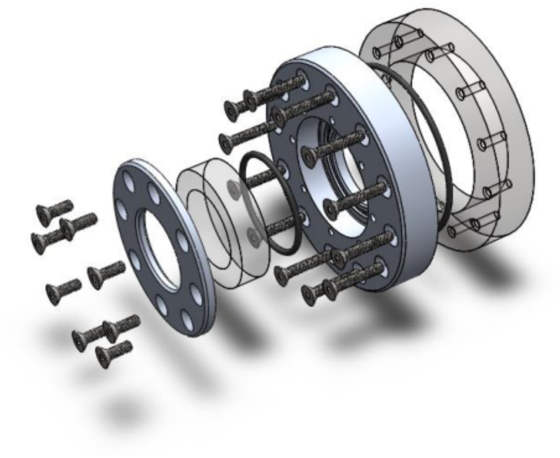


Figure 5. Exploded View for Top Level Assembly

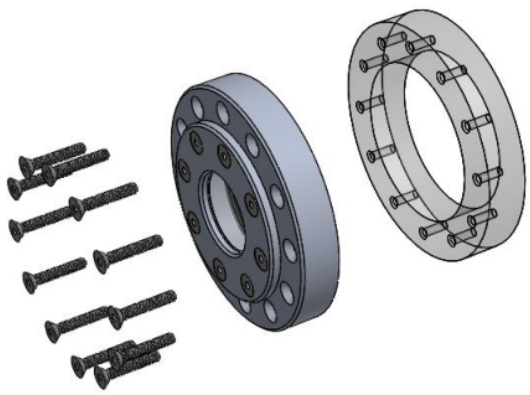


Figure 6. Exploded View for Assembling the Subassembly

ANALYSIS

- **Surface Irregularity**

$$\Delta W = \sqrt{\left(\Delta S_1(n-1)\right)^2 + \left(\Delta S_2(n-1)\right)^2 + \left(\Delta n \cdot t\right)^2}$$

Equation 1. Wavefront error for surface irregularities of plane parallel plate [*Jim Burge-Mounting of Optical Components*]

Assumptions:

$n = 1.458$

$\Delta S_1 = \Delta S_2 = \lambda/10$ (@633 nm)

$\Delta n = 0$

ΔW = 41.0 nm

Requirement ΔW < 316 nm rms

- **Window Strength**

$$\sigma_{max} \cong \frac{1}{4}\left(\frac{D}{t_w}\right)^2 \Delta P$$

Equation 2. Max stress of a plane parallel plate [*Jim Burge-Mounting of Optical Components*]

Assumptions:

$\Delta P = 14.7$ psi

D= 3 inches

t_w= .75 inches

σ_{max}=58.8 psi

- **Factor of Safety**

$$\text{S.F.} = \frac{\text{Modulus of Rupture}}{\text{Max Stress}}$$

Equation 3. Wavefront error for surface irregularities of plane parallel plate [*Oli Durney Practical Knowledge of Vacuum Windows*]

Assumptions:

Rupture Strength = 7600 psi (Fused Silica)

Safety Factor = 129

Requirement Safety Factor > 4

- **Window Distortion**

$$\Delta x = 0.0117\left(1-\nu^2\right)\frac{\Delta P\, D^4}{E_G t_W{}^3} \qquad OPD = 0.00889\left(n-1\right)\frac{\Delta P^2 D^6}{E_G{}^2 t_W{}^5}$$

Equation 4 & 5. Wavefront error for a plane parallel plate under pressure [*Jim Burge-Mounting of Optical Components*]

Assumptions:

$\Delta P = 14.7$ psi
$E_G = 1.06$ E7 psi
$t_W = .75$ in
D= 3 in
$\nu = .17$
n=1.458

Δx = 3.03 µin = 76.96 nm

OPD = 2.31 E-11 in = 0.0005842 nm (negligible)

Requirement ΔW < 316 nm rms

Total Weight (from SolidWorks model) = 3.00 lbs.

FABRICATION PLAN

Most parts are available commercial-off-the-shelf (Edmund Optics or McMaster-Carr). The two custom parts are manufactured primarily on a lathe but do require secondary operations on the mill for the screw holes (counter-sinks, clear holes and tapped holes).

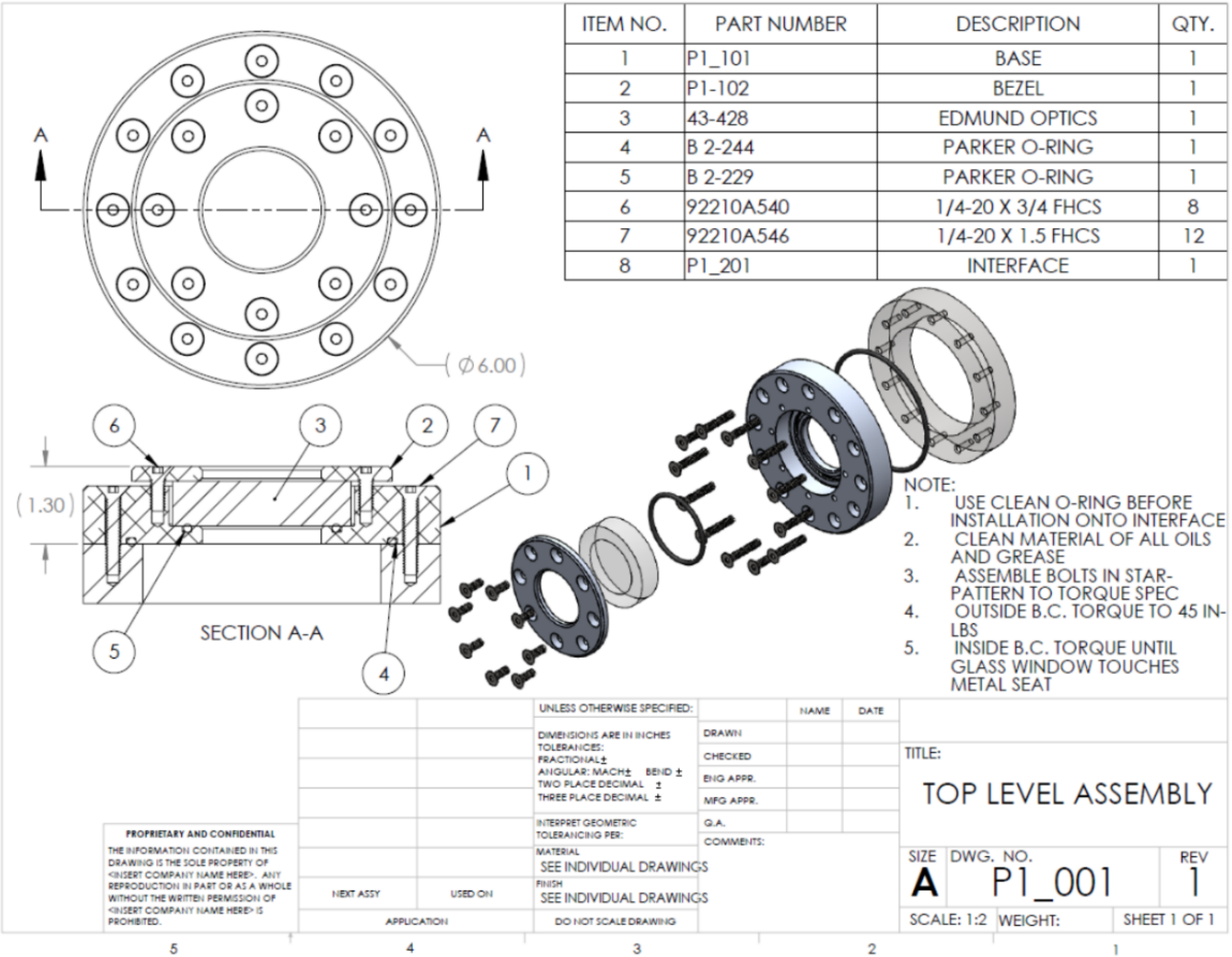
The subassembly is simple and requires dropping in the O-ring and then the window blank into the base as shown in Figure 5. The bezel is then fastened to the base according to the assembly drawing. This subassembly can be easily fastened to the interface using the twelve screws and an O-ring as shown in Figure 6. The O-rings and window should be handled with clean nitrile gloves to reduce introducing contaminants.

The project will cost about $1600 in parts and take about a week to receive all the parts and assemble.

TEST PLAN

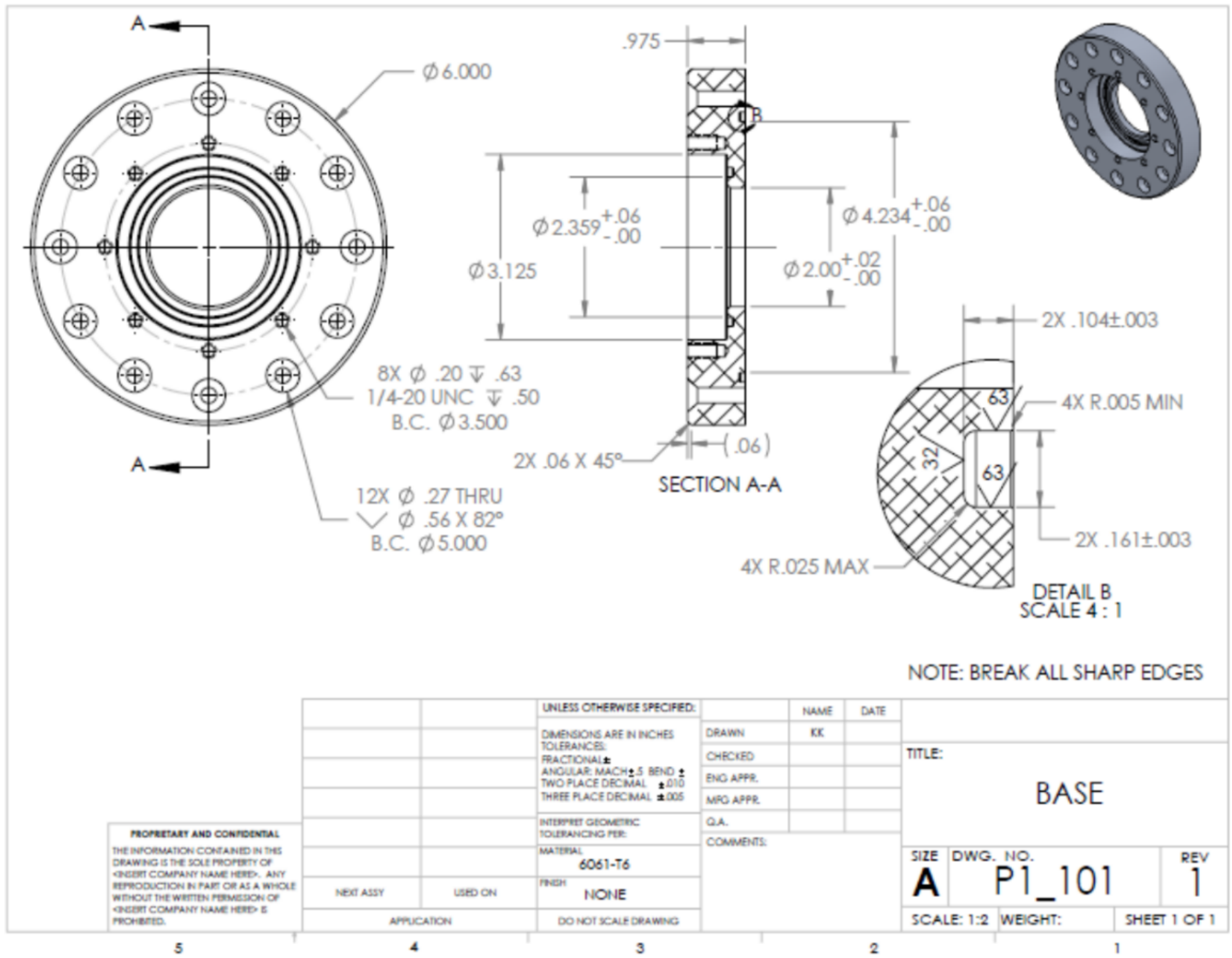
1. Fasten subassembly to interface flange of vacuum chamber with no camera inside the pressure vessel.
2. Lower pressure inside chamber until it reaches 10^{-6} Torr.
3. Verify that the window does not break and the chamber retains vacuum over time.
4. Repeat steps 1-3 with camera to verify optical performance of window.

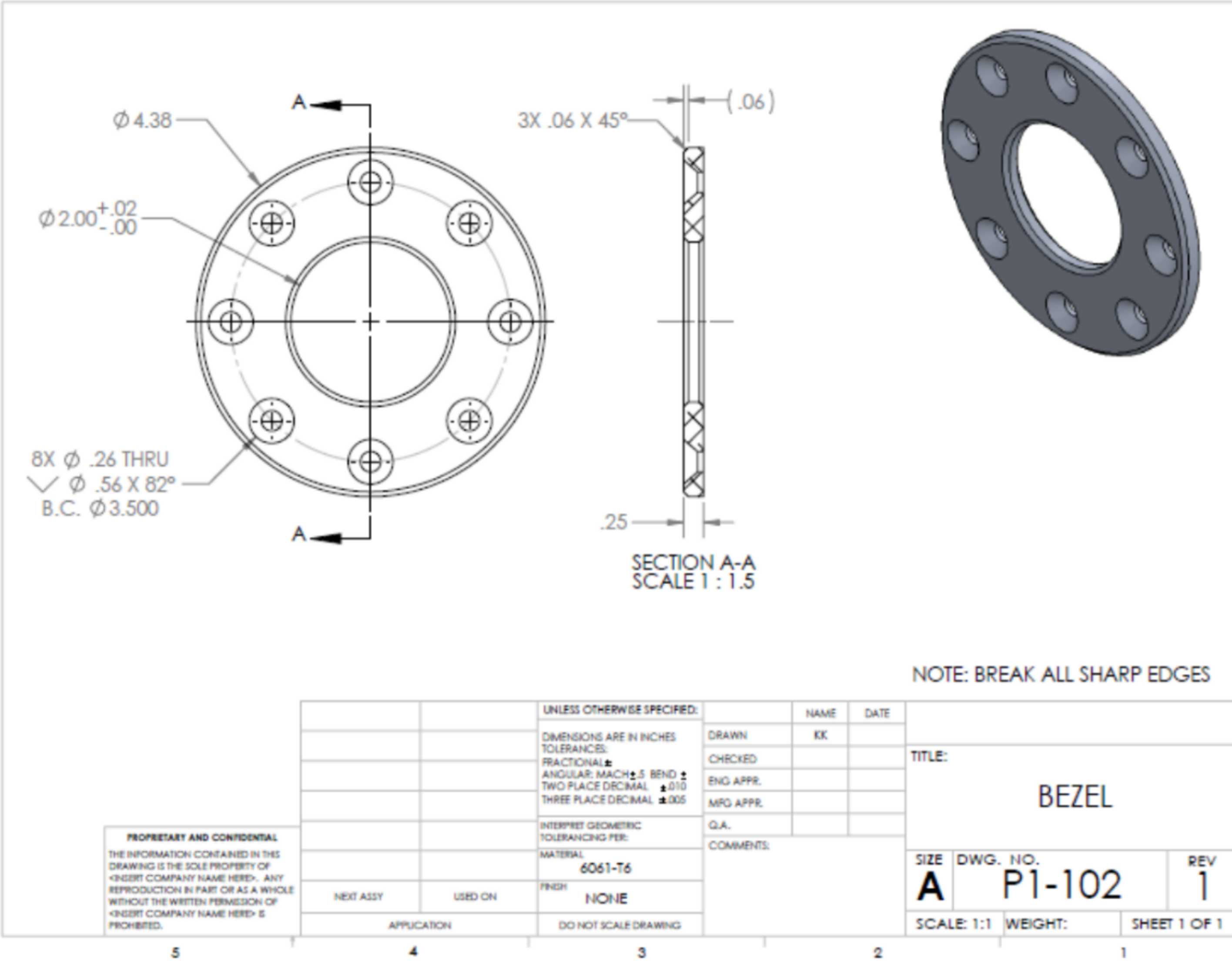
APPENDIX A: Drawings



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	P1_101	BASE	1
2	P1-102	BEZEL	1
3	43-428	EDMUND OPTICS	1
4	B 2-244	PARKER O-RING	1
5	B 2-229	PARKER O-RING	1
6	92210A540	1/4-20 X 3/4 FHCS	8
7	92210A546	1/4-20 X 1.5 FHCS	12
8	P1_201	INTERFACE	1

Kadlec7


Ø 6.000
8X Ø .20 ↧ .63
1/4-20 UNC ↧ .50
B.C. Ø 3.500
12X Ø .27 THRU
⌵ Ø .56 X 82°
B.C. Ø 5.000
.975
Ø 2.359 +.06 -.00
Ø 3.125
Ø 4.234 +.06 -.00
Ø 2.00 +.02 -.00
2X .06 X 45°
(.06)
SECTION A-A
2X .104±.003
4X R.005 MIN
2X .161±.003
4X R.025 MAX
DETAIL B
SCALE 4 : 1
NOTE: BREAK ALL SHARP EDGES
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± .5 BEND ±
TWO PLACE DECIMAL ±.010
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
KK
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BASE
SIZE
A
DWG. NO.
P1_101
REV
1
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


Ø 4.38
Ø 2.00 +.02 -.00
8X Ø .26 THRU
⌵ Ø .56 X 82°
B.C. Ø 3.500
A
A
3X .06 X 45°
(.06)
.25
SECTION A-A
SCALE 1 : 1.5
NOTE: BREAK ALL SHARP EDGES
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
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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ±.5 BEND ±
TWO PLACE DECIMAL ±.010
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061-T6
FINISH
NONE
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
KK
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
BEZEL
SIZE
A
DWG. NO.
P1-102
REV
1
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1

S

APPENDIX B: Detailed Analysis

No detailed analysis needed.

APPENDIX C: Trade Studies

No trade studies needed.

APPENDIX D: Lessons Learned

Through this design project I learned that there are some very simple shortcuts to doing detailed finite element analysis. There are usually general equations that can be solved for things that do not need to be engineered to precision tolerances, or at least for finding approximate orders of magnitude. For basic projects like this one, equations can be used for verification to reduce time spent by the engineer doing extremely laborious finite element analysis. I also learned that it is hard to find large, thick plane parallel plates off the shelf. Most plane parallel plates are either thin or about 2-inches in diameter.

APPENDIX E: Bill of Materials

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.	EST. COST	TOTAL COST	
1	P1_101	BASE	1	$700	$700.00	
2	P1-102	BEZEL	1	$300	$300.00	
3	43-428	EDMUND OPTICS	1	$560	$560.00	
4	B 2-244	PARKER O-RING	1	$12	$12.00	(PACKAGE 50)
5	B 2-229	PARKER O-RING	1	$13	$13.00	(PACKAGE 100)
6	92210A540	1/4-20 X 3/4 FHCS	8	$7.32	$7.32	(PACKAGE OF 50)
7	92210A546	1/4-20 X 1.5 FHCS	12	$6.56	$6.56	(PACKAGE OF 25)
8	P1_201	INTERFACE	1	$0	$0.00	
				GRAND TOTAL	**$1,598.88**	