High Pressure Manifold

1 GigaWatt Group

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Executive Summary

Dr. Dustin McLarty and the Clean Energy Lab Site (CESI) group at Washington State University have created a miniature battery cell made of VYSZion, a solid oxide material. Currently, the sole testing method for the fuel cell is a large pressurized chamber, which is far larger than required for testing and the end application of the battery. To optimize a testing device and display realistic operating conditions for the fuel cell, our team at Washington State University was recruited to design a high-pressure manifold. This manifold must be operable in temperatures of 650-800°C and pressures up to 10 bar. It must also have two inlets and outlets, one each for gas and air, and allow for insertion of temperature probes, pressure sensors, and electrical wires.

At the beginning of this project, we were tasked with creating a manifold that would house the fuel cell within the center of the structure. We also needed to create the pressure vessel that the manifold would sit in while the fuel cell was tested. During the second half of the semester, due to circumstances outside of the group's control, we were restricted in what we could do. This changed the objective of the project from creating and testing the manifold and pressure vessel to creating the plans and designs them. Thermal fluid studies to determine tube length and cartridge heater selection have been performed. A castable zirconia for the manifold has been selected based on highest chance of success. The manifold, its mold, the pressure vessel, and flanges have been designed and drawings provided to the client. All fittings and instruments connected to the pressure vessel have been modeled. A production and assembly procedure for both the manifold and pressure vessel has also been specified. Final submission to the machine shop for the pressure vessel and parts ordering will need to be completed by Dr. McLarty and his lab group. Following this, assembly of the manifold and pressure vessel according to the provided procedure will need to be performed. Final testing and analysis of the experiment can be achieved after the assembly is completed. Alterations to any parts in this project's design can be made if desired results from testing are not met in the future.

Introduction

The 1 GigaWatt group was tasked with delivering a high-pressure manifold to Professor Dustin McLarty and the CESI laboratory group. The lab group is testing VYSZion, a novel material for fuel cells, in an experiment to determine if VYSZion fuel cells can be used to replace conventional batteries for high powered systems. The design we were tasked with creating includes a ceramic manifold able to house one of these fuel cells for testing and a surrounding pressure vessel to contain the experiment. This design is to be used for testing a single cell at a time for the CESI lab group.

Our primary goals for this project are to design a manifold that can house a fuel cell and a pressure vessel capable of delivering gas to the manifold. The manifold is made of a zirconia ceramic and can withstand high temperatures. The pressure vessel is made of stainless steel and holds ceramic tubes that deliver heated and pressurized gas to the manifold. The vessel can withstand at least 10 bar of pressure. The manifold allows for electrical current from the fuel cell to be measured and the pressure vessel contains various sensors to record pressure and temperature during experimentation.

Professor McLarty's current lab equipment contains a furnace that is used for other experiments that we were able to base measurements on, such as gas line connections. We were also given requirements that we needed to include in our design parameters.

- The gas range would be between 650 to 800 degrees Celsius
- 4 temperature probes needed: two at inlet, two at outlet
- 2 pressure transducers
- 2 electrical pass-throughs for collecting current
- 2 electrical pass-throughs for collecting voltage
- Gas pressure can reach up to 10 bar
- Gas lines remain independent of one another

Based on these requirements, a zirconia ceramic cast was designed to cast the manifold. The pressure vessel design was created based on results of a thermo-fluid study of the gas that flowed through the experiment. The final product was determined to be a stainless-steel pressure vessel with zirconia gas tubes that connected to the casted manifold, which held the fuel cell.

Results/Discussion

Section 1: Manifold Material Selection

For the manifold material, a ceramic is needed due to a high working temperature. Based on initial recommendations of the lab group, cubic zirconia was originally considered. However, cubic zirconia is expensive and has a non-castability, so a regular zirconia was selected.

Zirconia has three phases: a monoclinic structure (<1150C), tetragonal structure (1150-2100C), and a cubic phase (>2100C). The high temperature phases can be stabilized by the addition of Yttrium oxide. Some cubic zirconia will convert back to monoclinic zirconia over time due to uneven heating. This causes volume changes in the manifold which could lead to cracking and failure.

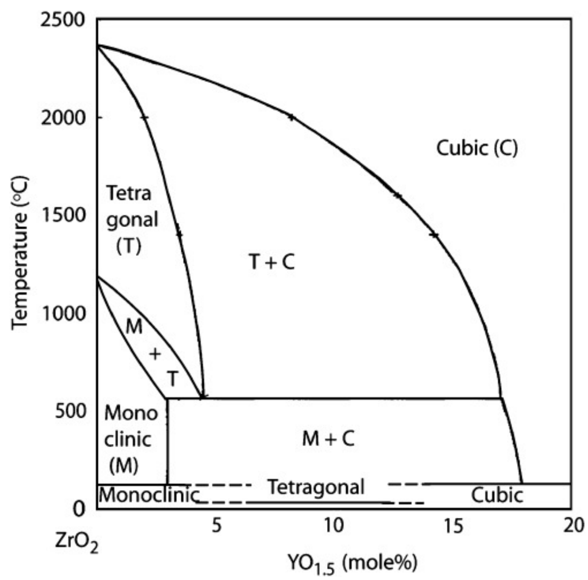


Figure 1. *Phase diagram of ZrO2 and YO1.5*

For the tubes, however, using cubic zirconia tubes was proposed. A zirconia tube will adhere better to stainless steel and the zirconia manifold. In addition, high temperature gases will be passed through the tubes for an indefinite amount of time. The composition of the selected tubes is 8 mol % Yttria stabilized Zirconia. This composition, with respect to the phase diagram in *Figure 1*, and how it is processed, should stabilize the cubic phase at the operating temperature. The tubes are also small enough meaning that heating will be more even, so changes in volume should be negligible. Tubes will be joined to the manifold via the leftover zirconia slurry. The large downside of these YSZ tubes is that they come with a price tag of 1062$. Therefore, alumina tubes were also proposed. These tubes cost between 100-200$, which is a significant decrease. However, alumina will not join with the manifold as well as the YSZ tubes since they are not the same material.

Precaution will need to be considered for the processing of the manifold. It is most likely that any failure in the entire part will be due to processing defects in the manifold or tubes. Ceramics are notorious for cracking during processing or post processing and can undergo fatigue cracking or failure over time. So, for post processing of the manifold, the voids, moisture, and binding agents will need to be removed slowly to avoid cracking. Typically, increasing the post processing time will decrease the number of micro cracks formed. Cracks and micro cracks due to processing will be a big problem in the final manifold part, as due to the high manufacturing temperature, it will be easier for those cracks to propagate and for dislocations to move.

The procedure is specified in Appendices Section A: Casting Mold Assembly Procedure.

Section 2: Manifold Design

A manifold was designed that will direct gas at and house a 1 cm diameter VYSZion fuel cell. There needed to be inlets and outlets at opposite sides with an angled approach towards the fuel cell, preferably with a 60-degree cut and 30 degree spacing.

Two different iterations of the basic design of the manifold were thought of initially, one being cube-like and the other being cylindrical. Provided in Appendices Section C: Initial Manifold Concepts is a basic sketch and understanding at the time of the manifold model idea conception. This can be compared to the final design seen in *Figure 2*.

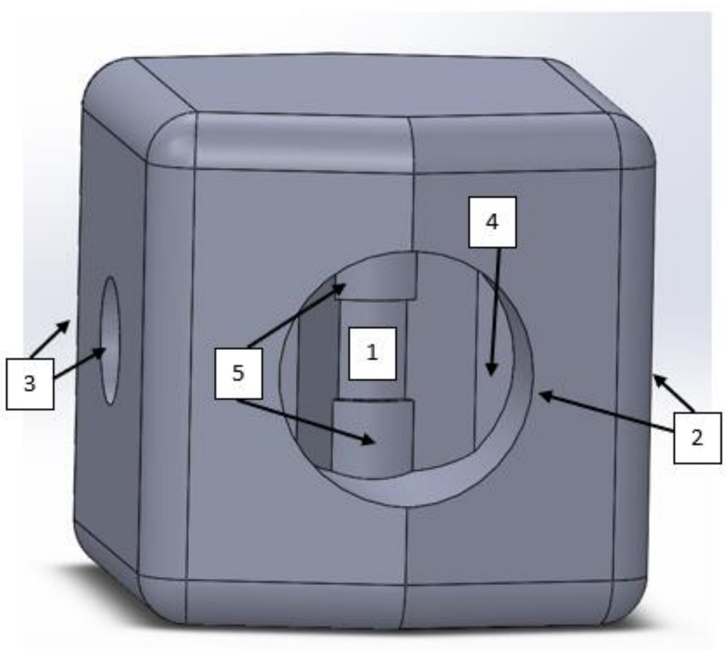


Figure 2. *Completed model of the manifold.*

The following list indicates what is present in the model:

1. Fuel cell in the center of the manifold.
2. Large tube entrances for the hot air and gas to enter (front and right sides), where it will push against the fuel cell.
3. Small tube entrances for the hot air and gas to exit (left and back sides).
4. Flat wall for the tubes to press up against. This is on all sides in the tube entrances and exits.
5. Fuel cell holder, where the fuel cell will be placed in between and held there. Wires will enter and exit on both sides of the fuel cell and should be protected by these holders.

Several of the major changes involved changing the basic shape from a cube to a cubic hexagon. The main reasoning behind that is so that there is a specific way the manifold would be placed inside the pressure vessel. The dimensions of the manifold needed to be big enough to provide enough insulation around the piping. The base measures 2x2x2 inches, with a 0.18-inch edge on the corned side. There are two different holes for the piping to fit in, with the large pipes measuring 1 inch in diameter and ½ inch for the smaller pipes. The edges of the manifold were softened as to provide better support for the overall structure. Initially, the manifold had an opening over the top of the fuel cell but was later filled in when more information was made known.

Section 3: Manifold Mold

With the main structure created, a mold needed to be created to cast the manifold. There was some talk about a 4-wall assembly with a 2-piece outer holder that would hold the walls together, as it would hopefully save on filler material that would be responsible for holding up the negative tubing in the mold. But it was decided initially to stick with a 2-piece set, as the mold will be melted off of the manifold after it is solidified, and that if the walls have trouble aligning, it could cause the cast to solidify incorrectly. The 4-wall cast could be tested to create the full cast.

Initially, the cast cut right through the middle of the manifold. However, it was discussed and decided that the piping should all remain on one part, as to provide uniformity in the finished model, and then have a lid that would be used to pour the Zirconia material inside. Two holes can be seen on top of the cover mold. These are where wires that connect to the fuel cell will be pushed through.

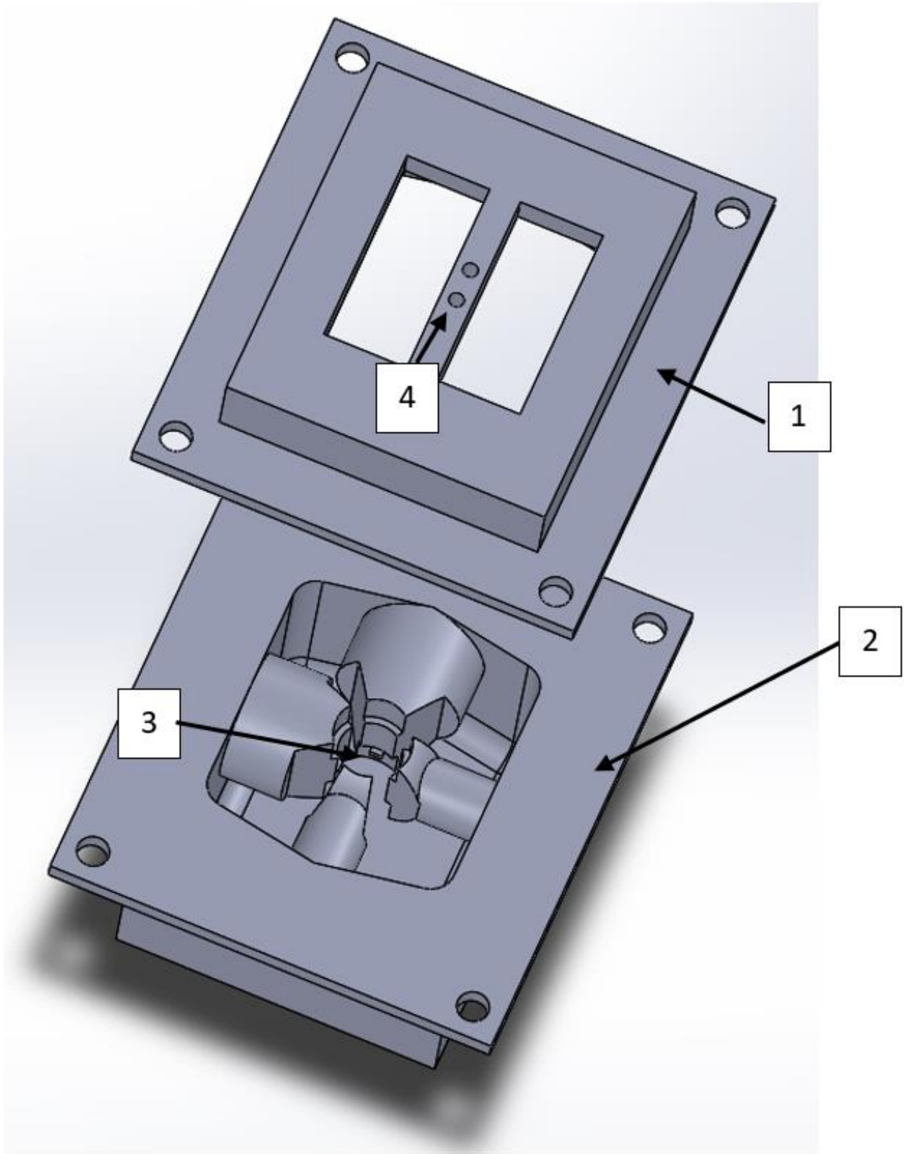


Figure 3. Negative mold for creating the manifold.

In *Figure 3*, the negative mold for the manifold is shown. The following are included within the negative mold:

1. Top plate for the mold, where holes can be used to align and bolt the mold together.
2. Bottom plate for the mold. With the negative areas to create cavities for the piping.
3. Area for the fuel cell to sit. There are notches within this area to help provide some support for when the fuel cell is placed within and the mixture is poured in.
4. Holes on the top of the mold for wires to come out. These should help keep the wires apart while pouring the mixture.

While creating the part, the fuel cell puck should be placed within the set area in the center of the cast, resting on the notches that help keep it up while the zirconia is being poured. The wires attached to the fuel cell snake through the holes on the top part. Then the two pieces should be glued and brought together, bolted with ¼ inch bolts in each corner hole. This will help keep the mold aligned and stay in place as the material is poured inside. Once set, the zirconia can be poured into the mold until it reaches the bottom surface of the wire bar.

After it is cast and has finished setting, the mold can then be melted off the finished manifold. If additional wires are needed, a drill can cut a couple of holes at the bottom of the manifold and be attached to the fuel cell if needed.

Section 4: Thermo-Fluid Design

The pressure vessel was designed based on the thermo-fluid parameters specified in the House of Quality (HOQ). To design an optimized system, a simulation needed to be performed to determine specifications for tube lengths and heating elements.

Using SOLIDWORKS Flow Simulation, the thermo-fluid study was created in these following steps:

1) A zirconia tube was modeled and then surrounded by another tube made of alumina silica for insulation.
   Two diameter sizes were made in order to optimize for the best design:
   - ¾ in
   - 1 in
2) A computational fluid dynamic study was created to find the temperature change within the zirconia tube that the gases will flow through.
3) A cartridge heater was modeled and placed within the zirconia tube for the simulation with variable heat fluxes.
4) The length of the zirconia tube and insulation tubes varied to find a length that will reach the desired temperatures.
5) After the simulation was completed the following specifications were determined:
   - Length of the tubes is 4.5 in
   - ½ in diameter cartridge heater with 250 W power output
   - Tube diameter of ¾ in

We performed calculations to find the temperature on the outer layer of the insulation. In Appendices Section D: Thermal Design Calculations and Section E: Thermal Flow Rate Calculations are the methods used and the results of these calculations.

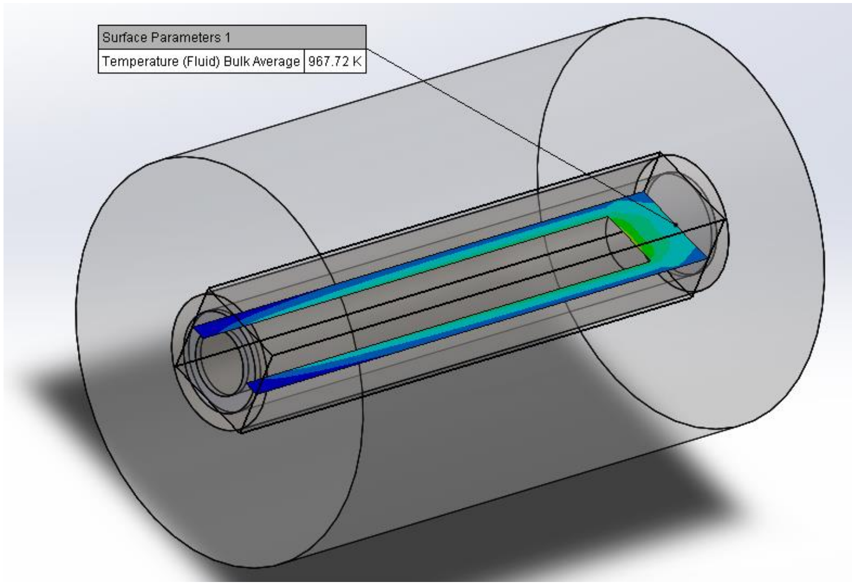


Figure 4. Thermal fluid study to determine exit temperature.

Since the two gases that will be used in the experiment are similar in composition, we were able to mirror the results of the study and make a symmetric design for the pressure vessel.

The result of the pressure vessel entrance contains:

- Two 4.5 in zirconia tubes with 1 in OD and ¾ in ID
- Two insulation tubes
- Two 250 W cartridge heaters

Section 5: Instruments

There are three different instruments which will be connected to the pressure vessel and provide feedback from the system:

- Cartridge Heaters
- Pressure Transducers
- Thermocouples

Due to the configuration of the Lenz fitting and required adapters, the cartridge heater must be longer than the previously determined length. The cartridge heaters will be 7.5 in in total length with 3.5 in of unheated length.

The unheated length is the portion that will sit within the fitting, and the portion that will be heated will be the originally determined length needed to heat the gases to desired operating temperatures.

Pressure transducer location changed from being toward the center of the pressure vessel downstream to the unheated portion of gas flow. As such, high temperature tolerance transducers were no longer needed. The new pressure transducers are:

- Heavy Duty Pressure Transducers (Honeywell)
    - Can withstand up to 35 bar

Thermocouples were selected based on ability to reach near the center of the cast manifold and NPT threading capability. Being able to read temperatures inside the manifold allows the CESI group to determine if the cartridge heater is heating the gas/air too high and adjust its power output. In the future they plan to add a PID feedback system to automatically adjust power output so gas/air into the manifold is always in the desired range.

Section 6: Pressure Vessel Design

With the specified temperatures and pressures into the casted manifold being much higher than ambient levels, a pressure vessel is required to maintain an ideal environment for testing. The following are key specifications the vessel was designed around:

- Inlet length is long enough for cartridge heaters to heat incoming air/gas to 650°C to 800°C.
- Bores are large enough that insulation, zirconia tubes, and manifold can be inserted.
- Each of the given requirements for sensors, electrical pass-throughs, and environmental conditions are met.

With these considerations in mind, an initial design for the pressure vessel was created.

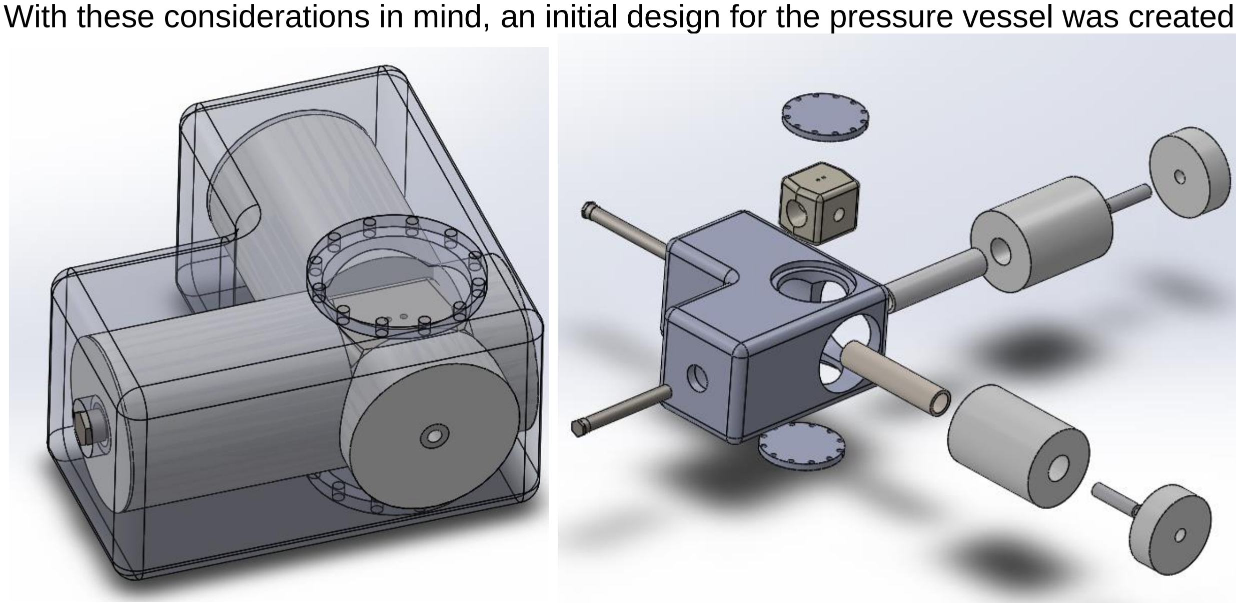


***Figure 5**. Initial pressure vessel design with exploded view.*

The design in *Figure 5* contained some parts used in the overall design but had some key flaws:

- The top flange was not necessary, electrical passthroughs could thread into the vessel itself.
- No attachments for how the cartridge heaters or ceramic tubes would connect to the vessel had been determined.
- Sealing for the large bore holes had not been determined.
- The thickness of the vessel is too small if a flange is to be connected to it.

After multiple design reviews and adjustments to the design, a refined version was modeled.

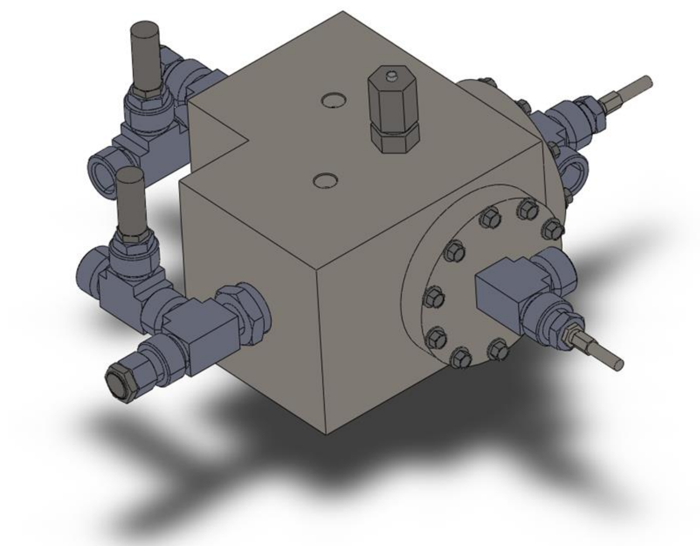


Figure 6*. Final pressure vessel design.*

This version included all attachments and instruments that would be connected to the pressure vessel. Design changes that were made from the original version:

- The ¼" NPT threaded holes on the top were changed from being for pressure transducers to being there as openings to pressurize the vessel. This change was made since the pressure transducers could be moved to the fitting configuration at the gas inlets.
- Size of the vessel was adjusted from 4" thick to 5" thick so the flange parts could fit around the vessel
- Insertion holes were chamfered so insertion of sensors and probes is a self-locating process.

- Gasket size was reduced to decrease surface area so a higher pressure can be reached to ensure a better seal.
- Graphite gasket was changed to Silicone O-rings. This change was made to increase sealing functionality as silicone O-rings are readily available at a smaller diameter
- Second O-ring added as backup in the event one either cannot withstand the temperature or pressure it is exposed to.
- Flange design was changed from flat face (FF) to raised face (RF). This creates a small gap between flange and the pressure vessel, so the flange is only touching the gasket, creating a tighter seal.

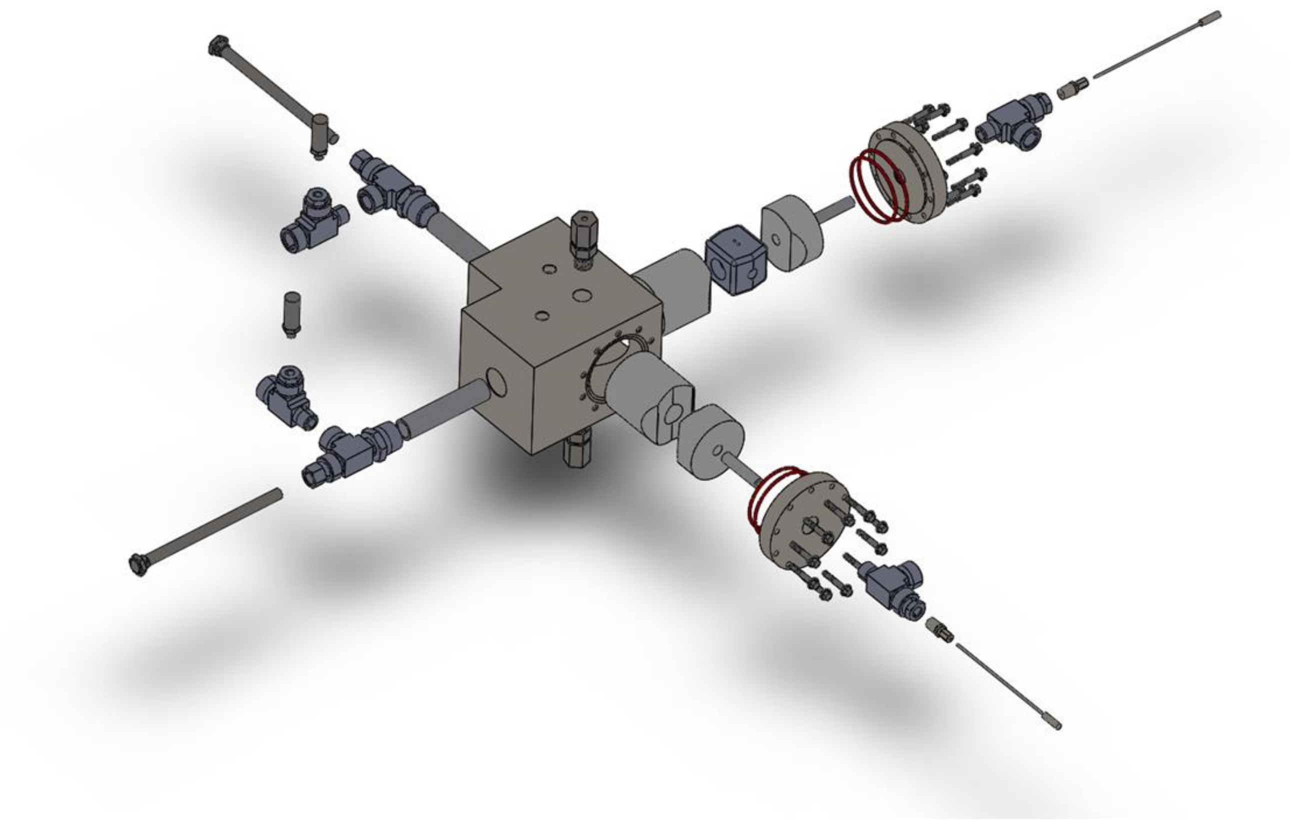


***Figure 7**. Exploded view of final pressure vessel design.*

Section 7: Gas Seal Selection

Once tube diameters were decided to insulate the high temperatures, the task of finding a way to route the gas, seal the system, while properly heating the gas arose. This becomes challenging due to having to think outside of the box when using manufacturer parts.

Initially, a Swagelok system was designed to connect a linear path from gas to manifold. The four part system, consisting of a NPT body, NPT to VCR converter, VCR tube butt weld, and a VCR coupling, with the cartridge heater in the tube weld, supported by a metal support ring designed by me. This was rejected by our client due to previous difficulties with Swagelok sealing. Instead, a Lenz seal configuration at the pressure manifold interface was proposed.

The Lenz seal was selected because the pressure manifold has a controlled hole size. A seal was selected based off the entrance hole, and an NPT reducer was selected to go down to the size of the cartridge heater. A Swagelok tee fitting was selected to house the cartridge heater on the straight end. This would allow for the gas to be diverted in and around the heater, with the NPT fitting of the heater to be sturdily sealed, instead of on its own fitting. *Figure 8* shows this configuration.

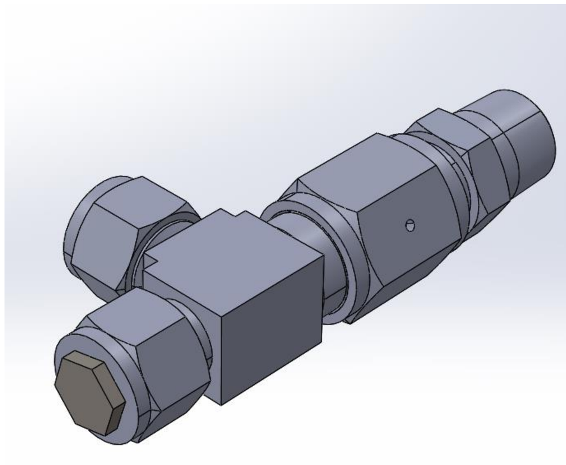


Figure 8. *Initial seal configuration.*

After a design meeting, we found we needed to create a similar but smaller connection seal for the exit gas/air. In this configuration, the tee would have had to be bored out to allow for the heater to sit in the tee fitting. If this happened though, the tee would break because there was not enough clearance in the piece. A new configuration was then created.

This configuration started with the Lenz seal again. The entrance needed a slightly larger seal than the initial one for the exit. A large enough tee fitting was then chosen, so the cartridge heater could fit. It was also important to decide what kind of connector, male or female, and what size was chosen because not every configuration of these two exists. A reducer was used to connect the Lenz seal to the tee fitting, and a different reducer was chosen to connect the cartridge heater to the tee. The tee fitting in this new configuration will need to be slightly bored out. *Figure 9* shows the entrance and *Figure 10* the exit. The entrance seal has one extra reducer than the exit seal.

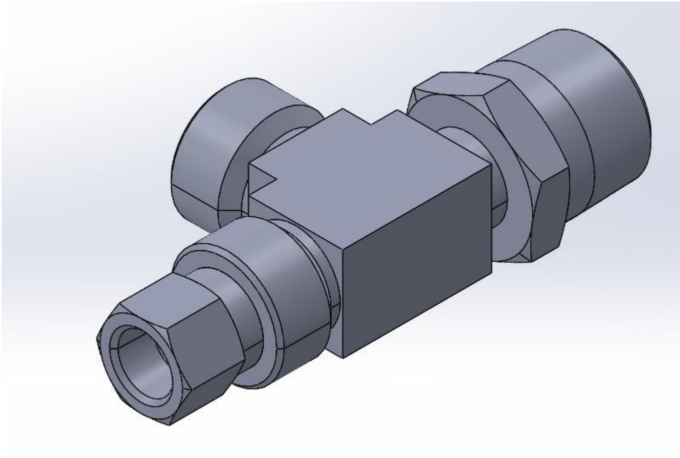


Figure 9. *Final entrance seal configuration.*

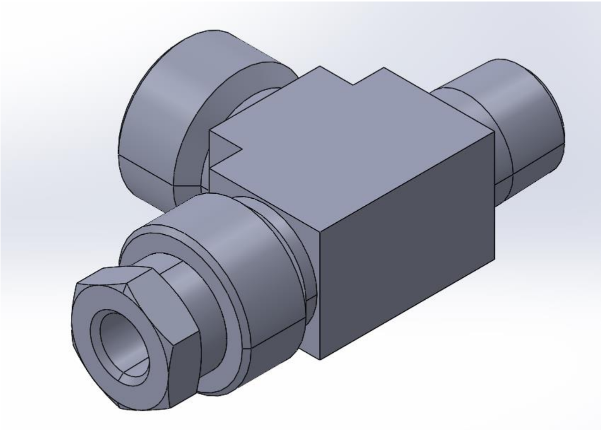


Figure 10. *Final exit seal configuration.*

With this configuration, the cartridge heater's unheated length was extended by a few inches. This ensures the gas will retain its heat in the ceramic tubes, and not get too hot in the metal fittings.

Next Steps

Using various materials, manufacturing techniques, and connectors our team was able to come up with a plan for creating a pressure vessel and manifold for a fuel cell that operates at high temperatures. Various calculation and material property checks were performed to ensure the success of the prototype. Additionally, the prototype meets all the high end of all requirements mentioned in the introduction.

The next steps that should be taken in this project is submission of designs to the machine shop when the quote for machining costs is received. Parts also need to be ordered. Assembly according to the procedure in Appendices Section A: Casting Mold Assembly Procedure and Section B: Pressure Vessel Assembly Procedure need to be completed and then testing can move forward. Additional changes that could be made to the project are optimizing the cost of the prototype and pressure vessel and adding safety features.

A safety feature that would be useful is a ceramic pressure sensor (needs to be ceramic because of the high temperatures). This would detect any unusual shift in pressure, whether too low or too high, and shut down the system to prevent catastrophic failure of the manifold and/or the pressure vessel. Although this is already a pressure sensor installed, this one would automatically shut the system down instead of needing someone to manually do it.

To reduce costs, it is possible that alumina tubes can be used instead of zirconia tubes to reduce the overall cost. Another change that can be made is to buy pre-manufactured a steel vessel with six inlets instead of machining one ourselves. This would significantly lower the machining costs. However, the flanges would still need to be added, so it would make assembly slightly more difficult. Design changes can also be made to reduce overall cost as well, as making it easier to machine will lower the machining costs.

Appendices

Section A: Casting Mold Assembly Procedure

Phase 1: Slurry Preparation

1. Mix the zirconia powder and water at a 100:12-14 ratio. A hydrophobic liquid can also be used in place of water at the same ratio, but moisture likely won't be a problem at these high temperatures
2. Mix thoroughly to get an even composition and start to eliminate air bubbles using an ultrasonicator and/or a vacuum chamber.
3. For the vacuum chamber, wait until it stops bubbling then remove the casting slurry.

Phase 2: Molding

1. 3D Print the two assembly pieces
2. Place Fuel cell in designated area in the center of the cast [3]
3. Apply paste to the faces that will meet together on both parts (bottom of [1], top of [2])
4. Thread the fuel cell wires through the top holes on the top cast part [4].
    a. Optional: drill two holes at the bottom of [2] if needed to thread the bottom wires
    b. Use some sort of stopper at the bottom to prevent leakage
5. Apply ¼ in bolts to the holes in [1] and [2] to align the cast and press together
6. Apply clamps to the cast as paste dries
7. Once set, pour the cast mixture into the mold until it fills up to the bottom of the wire beam
8. Once the mixture is set, melt off the printed mold to expose the finished manifold

Phase 3: Post Processing/Curing

1. Air dry the part overnight. The manual says 8 hours but should be extended.
2. Bake for 4 hours at 200 degrees Fahrenheit. For extra cautionary measures, heat up the furnace or oven slowly to ensure no cracks will form.
3. Cure at 250 degrees Fahrenheit for 3 hours, heating and cooling the furnace slowly.
4. (Alternate) If using the Hydrophobic liquid binder, cure at 450 degrees Fahrenheit for 1 hour instead of step 3. Use extreme caution in heating and cooling the part

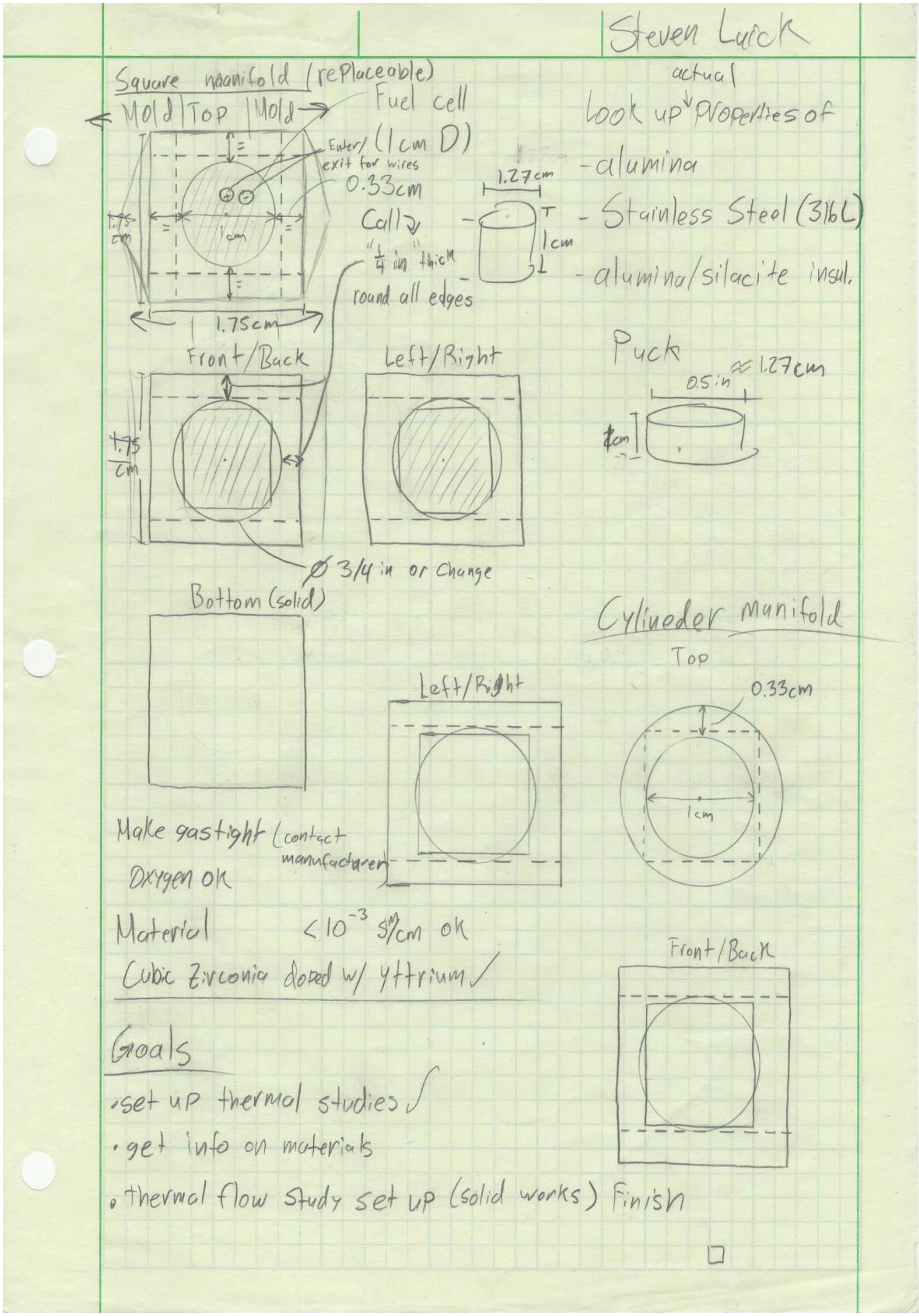
For reference, please see https://www.aremco.com/wp-content/uploads/2015/08/A0_Catalog_15.pdf, page 16

Section B: Pressure Vessel Assembly Procedure

1. Prepare ceramic insulation by wrapping around 1” OD zirconia tubes until insulation OD is 3”. Insulation should be 3” long.
2. Cut away excess insulation so it fits flush within pressure vessel and flush against respective wall of the manifold.
3. Repeat steps 1-2 for 0.5” OD zirconia tubes. Insulation should be 1.4375” long.
4. Through the large opening insert ceramic insulation for 1” OD tubes until flush with the opposite wall. Repeat for other side.
5. Place a 1” OD zirconia tube through insulation until at least ¼” length is exposed on the other side.
6. Apply ceramic paste to outside of both zirconia tubes at manifold connection and inside of manifold where connection will be made.
7. Attach free zirconia tube into manifold until it hits inside stopper.
8. Insert manifold into pressure vessel such that the attached zirconia tube goes through the empty ceramic insulation until it is exposed on other side of vessel.
9. Ensure the other 1” hole for the manifold is aligned with the previously inserted zirconia tube.
10. Push zirconia tube into manifold until it hits inside stopper and ensure connection is sealed.
11. Feed electronic wires through top and bottom holes of pressure vessel.
12. Place excess ceramic insulation to openings above and below the manifold to secure it in place.
13. Feed wire into electrical passthroughs.
14. Place the electrical passthroughs on the top and bottom of the pressure vessel and secure into place.
15. Screw 1” NPT Lenz fitting onto one of the zirconia tubes exposed end. Do not tighten fully.
16. Attach 1” to ½” NPT reducing bushing to long end of a Swagelok Tee adapter that will attach to the Lenz fitting.
17. Add ½” to 3/8” to opposite side of Tee adapter.
18. Attach Cartridge heater to 3/8” bushing so it goes through the Tee adapter.
19. Screw Swagelok Tee adapter onto Lenz fitting attached to pressure vessel.
20. Attach a second Swagelok Tee adapter perpendicularly onto the middle of the Tee adapter in the current assembly.
21. Add a ½” to 1/8” reducing bushing to the middle of the second Tee adapter.
22. Place the pressure transducer onto 1/8” bushing and secure.
23. Attach exposed opening of the second Tee adapter to the air/gas supply.
24. Ensure all connections are secure.
25. Repeat steps 15-24 for second zirconia tube.
26. Repeat step 6 for 0.5” OD zirconia tubes.
27. Insert 0.5” OD zirconia tube with insulation around it into opening until flush with manifold.
28. Repeat step 10.
29. Place the two silicon O-rings on the outside of the pressure vessel around the large opening.

30. Place the flange over the O-rings and secure onto pressure vessel using the ¼”-20 screws and the respective holes.
31. Add the 0.5” NPT Lenz fitting into the center of the flange on the second side and secure.
32. Add Swagelok Tee adapter to Lenz fitting.
33. Place the ½” to ¼” reducing bushing to long end of Tee adapter and secure.
34. Place the thermocouple into the first side and reducer and secure.
35. Attach exposed opening of the Tee adapter to the air/gas outlet.
36. Repeat step 24.
37. Repeat steps 26-36 for the second 0.5” OD zirconia tube.

Section C: Initial Manifold Concepts

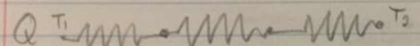


Section D: Thermal Design Calculations

$Q = hA\Delta T$ $\qquad L = 4\,in$

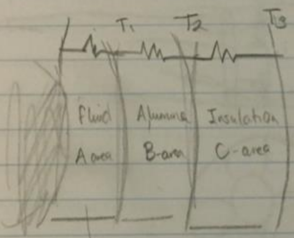
$Q = KA\Delta T$

$Q = \frac{\Delta T}{R} \qquad R = \frac{1}{hA} \qquad R\ \frac{L}{KA}$



$R_{fluid} + R_{Al} + R_{in}$

$K = 10.5\ W/mK \qquad 0.18\ W/mK$



$h = 10.45 - V + 10V^{1/2}$

$h = 10.45 - (.0346) + 10(.0346)^{1/2}$

$h - 12.27\ kcal$

$\frac{12.27\ kcal \times 1.16\ m^2/C}{1\ kcal}$

$h = 14.24\ W/mC$

$$Q = \frac{(T_1 - T_3)}{\frac{1}{(2\pi r L_1) h_1} + \frac{\ln(r_2/r_1)}{2\pi L_2 K_1} + \frac{\ln(r_3/r_2)}{2\pi L_2 K_2}}$$

$$R = \frac{1}{2\pi(0.00635)\,.1016\,m \cdot 14.24\,\frac{W}{m^2C}} + \frac{\ln(.00635/.00635)}{2\pi \cdot .1016\,m \cdot 10.5\,\frac{W}{mK}} + \frac{\ln(.0254/1.23\times10^{-2})}{2\pi \cdot .1016 \cdot 0.18\,W/mK}$$

$11.549 + 0.0429 + 6.032$

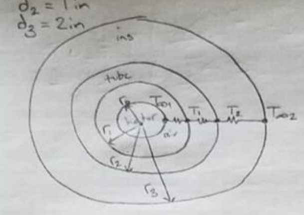
$R = 17.62$

$Q = \frac{\Delta T}{R} \Rightarrow 250 = \frac{370 - T_3}{17.62}$

$4406 = 370 - T_3$

$T_3 = 4036$

$d_0 = 0.5\,in$
$d_1 = 0.75\,in$
$d_2 = 1\,in$
$d_3 = 2\,in$



$h = 14.24\ W/m^2K$
$k_{tube} = 10.5\ W/mK$
$k_{ins} = 0.18\ W/mK$
$L = 4\,in$

$R_{tot} = R_{air} + R_{tube} + R_{ins}$

$R_{air} = \frac{1}{[2\pi(r_1 - r_0)L]h} = 34.65\ K/W$

$R_{tube} = \frac{\ln(r_2/r_1)}{2\pi L\, k_{tube}} = 0.0429\ K/W$

$R_{ins} = \frac{\ln(r_3/r_2)}{2\pi L\, k_{ins}} = 9.56\ K/W$

$\dot{Q} = \frac{T_{\infty1} - T_{\infty2}}{R_{tot}}$

$T_{\infty2} = T_{\infty1} - \dot{Q}R_{tot}$

$R_{tot} = 44.25\ K/W,\ R_{cond} = 9.60\ K/W$

$\dot{Q} = \cancel{250}\ W \rightarrow$ that number was wrong for this scenario

$T_{\infty1} = 1950\ K$

(air) $\dot{Q}_{conv} = 28.35\ W$

(walls) $\dot{Q}_{cond} = 69.75\ W$

(total) $\dot{Q}_{tot} = 37.33\ W$

Section E: Thermal Flow Rate Calculations

$$\frac{0.001}{60}\ \frac{m^3}{s} = 1\ SLPM \cdot \frac{1073.15}{273.15} \cdot \frac{1}{10}$$

$$4.24e{-5}\ \frac{m^3}{s} = 1\ SLPM$$

$$\dot{V} = 8.48e{-5}\ \frac{m^3}{s} = 2\ SLPM$$

$$\varnothing = 2.2\ in = 0.05588\ m$$

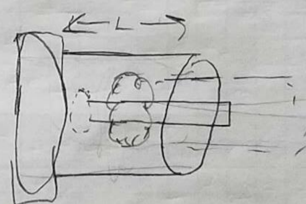
$$A = \left(\frac{d}{2}\right)^2 \pi = 0.00245\ m^2$$

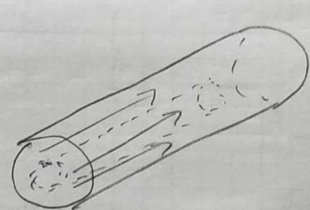
$$\frac{\dot{V}}{A} = \frac{(8.48e^{-5}\ m^3/s)}{2.45e^{-3}\ m^2} = 0.0346\ \frac{m}{s}$$

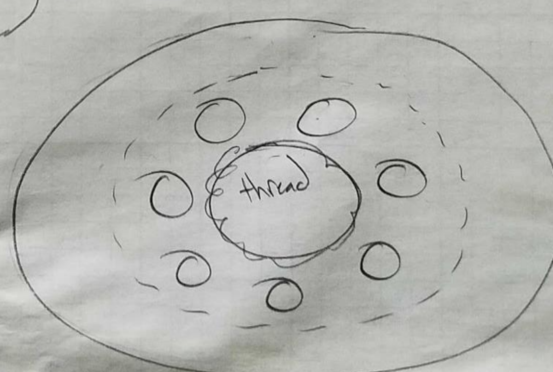
$$\frac{0.001}{60}\ \frac{m^3}{s} = 1\ SLPM \cdot \frac{1073.15}{273.15} \cdot \frac{1}{10}$$

$$SLPM = \dot{V} = 8.48e^{-5}\ m^3/s$$

$$LPM = \dot{V} = 3.33e^{-5}\ m^3/s$$

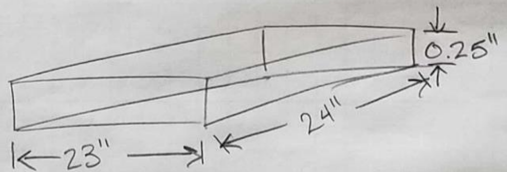






Section F: Insulation Forming Technique

alumina insulation



Cut into strips
wrap those strips
into cylinders

$V_{block} = 138 \text{ in}^3$

$\Sigma V_{cyl} = 64 \text{ in}^3$

Steps

1 - cut strips to length & circumference of tube
2 - wrap around tube, circumference increasing each iteration
3 - continue until OD is 8"

Section G: Bolt Mounting Calculations

Quick Calcs => Bolt Mounting

$A_s = \pi (3\text{in}/2)^2 = 7.069 \text{ in}^2$

$\Delta P = 10 \text{ bar} - 1.01325 = 8.986 \text{ bar} = 130.34 \text{ psi}$

$F_{gap} = A_s \Delta P = 921.37 \text{ lb}_f$

assume 50 bar on inside

$\Rightarrow FOS = 4 \Rightarrow F_{gap} = 20{,}091 \text{ lb}_f$

Bolt mounting done according to ASME Boiler & Pressure Vessel code
=> Section VIII
div 1
Appendix 2

each screw

$A_s = \pi \left(\frac{1/4}{2}\right)^2 = 0.0491 \text{ in}^2$

$Y_s = 64251.7 \text{ psi}$

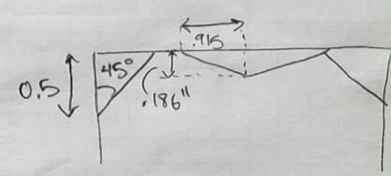
$F_{screw} = 3{,}153.95 \text{ lb}_f$

Can I even find this w/o paying $1K?

$\#\text{screws required} = \frac{F_{gap}}{F_{screw}} = 6.37 \approx 8$

$\text{w/FOS} = 6 \Rightarrow \#\text{screws} = 9.55 \approx \boxed{10}$

3.75" OD largest



angle = 10.26514046
dis = 0.36220472"
fillit = 0.19685039"

Section H: Manufactured Parts

Pressure Vessel

The pressure vessel is to be machined from a 7.5 in x 7.5 in x 5 in 316 stainless steel block. The specifications for this are based on the final pressure vessel design from Section 6: Pressure Vessel Design. Machining for this has been discussed with the machine shop at WSU but a quote has not yet been obtained from them.

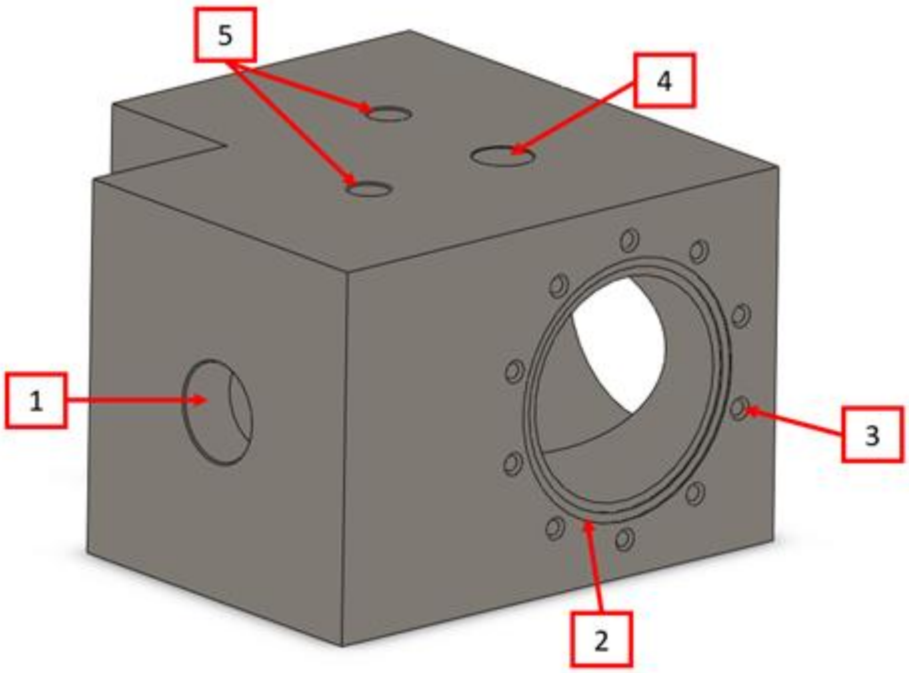


Figure 11*. Final pressure vessel design.*

Connection points onto the exterior of the pressure vessel, numbered in *Figure 11*, are as designated:

1. 1” NPT threaded hole for Lenz fitting attachment for gas/air inlet that goes in 0.75”. Cartridge heater with internal thermocouple is inserted at this point.
2. Flange connection with double O-ring seal. Both O-rings are 1/32nd” thick and the outer O-ring is a 3.5” diameter while the inner O-ring is a 3.25” diameter.
3. ¼-20 threaded holes are on a 4” diameter ring around the large holes and are 0.75” deep.
4. One ½” NPT threaded hole on top and bottom of pressure vessel where electrical pass-through will sit.
5. Two ¼” NPT threaded holes for insertion of CESI group’s fitting to pressurize the vessel itself. These are located 2.5” from the face of the inlet port.
6. Main bores are 6.5” deep and 3” in diameter.
7. Inlet and outlet sides in 1-3 are mirrored on the other side of the vessel.

Flange

A flange is required to seal the pressure vessel after all parts are inserted. It also allows for outlet air/gas configurations to be connected to the manifold. This will also be machined from 316 stainless steel.

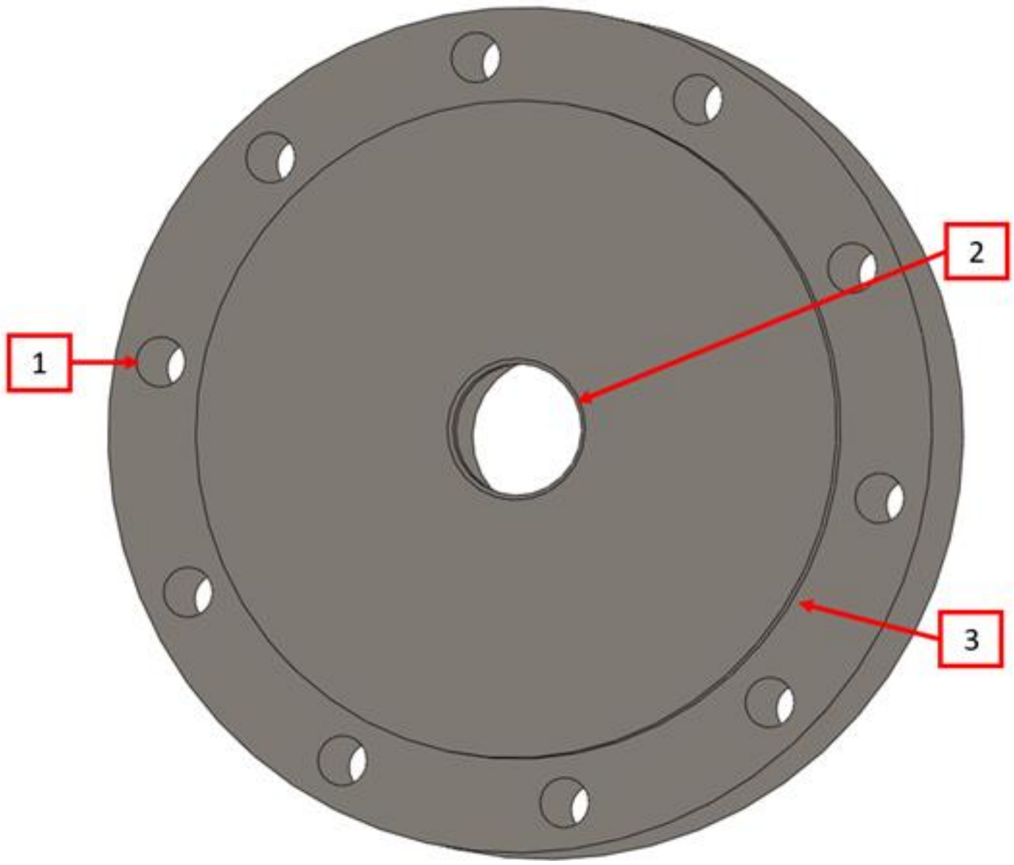


Figure 12. *Final flange design*

Connection points onto the flange, numbered in *Figure 12*, are as designated:

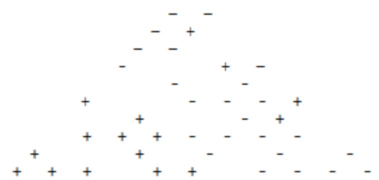
1. ¼-20 Clearance hole; passes through to other side of flange.
2. ½" NPT Lenz fitting attachment for gas/air outlet. A thermocouple is inserted through this connection.
3. 3/32" raised face to compress 1/32" diameter O-ring and create 1/16" gap between flange exterior and pressure vessel.

Section I: House of Quality

Correlations	
Positive	+
Negative	−
No Correlation	

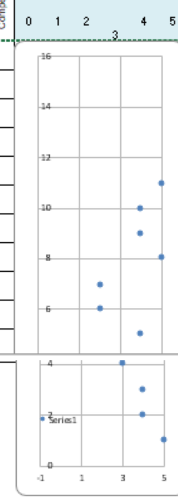
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

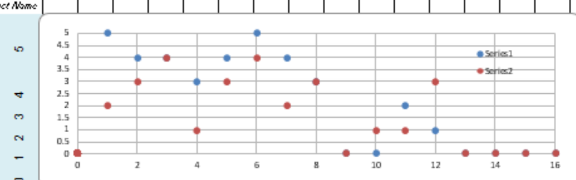


Row #	Weight Chart	Relative Weight	Customer Importance	Maximum Relationship	Column # / Direction of Improvement / Customer Requirements (Explicit and Implicit) \ Functional Requirements	1 ▲ High Temperature Range	2 ▲ Variable Sensor Readings	3 ◇ Flow Rate	4 ◇ Flow Operating Angle	5 ▲ Electrical Pass Throughs	6 ▲ High Pressure Range	7 ◇ Independent Gas Flow Channels	8 ▲ Operation Life	9 ▲ No Hazards	10 ▼ Price	11 ▲ Configurability	12 ▼ Weight	13	14	15	16	Our Product	Competitor #1: Lab Test Apparatus	Competitor #2: Product Name	Competitor #3: Product Name	Competitor #4: Product Name	Row #
1	IIIIIII	14%	8	9	Withstand of 650-800 degrees C	●	●	○	▽	○	○	▽	●	●	●	▽	▽					5	3				1
2	II	5%	3	9	4 Temperature Probes	●	●	▽	▽	●	▽	▽	○	○	●	●	○					4	2				2
3	II	5%	3	9	2 Pressure transducers	▽	●	○	○	●	●	●	○	○	○	●	○					4	2				3
4	IIIII	11%	6	9	2 slpm flow rate	○	●	●	●	○	●	●	○	○	○	○	○					3	2				4
5	IIIII	11%	6	9	60-90 degree flow chamber angle	○	○	●	●	▽	●	●	○	○	●	○	○					4	4				5
6	I	4%	2	9	2 electrical current pass-throughs	▽	●	○	▽	●	○	▽	○	○	○	○	○					2	3				6
7	I	4%	2	9	2 electrical voltage pass-throughs	▽	●	○	▽	●	○	▽	○	○	○	○	○					2	3				7
8	IIIIIII	14%	8	9	Pressurable to 10 barr	●	○	●	●	○	●	●	●	●	●	○	○					5	5				8
9	IIIIII	13%	7	9	Independent Gas 1/Gas 2	○	●	○	●	○	●	●	○	●	●	●	○					4	3				9
10	III	7%	4	9	Extended Operation Life	●	○	▽	○	●	●	●	●	●	●	○	▽					4	4				
11	IIIIII	13%	7	9	Ceramic Material	●	○	▽	○	○	●	●					●					5	3				10

Customer Competitive Assesment



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Row #
Target	High Tem pera	Sens or Num	Flo w Rate	Angl es	Pass Thro ugh	High Pres sure	Cha nnel s	Life Spa n	Haza rds	Pric e	Con figur atio	Wei ght					11
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9					12
Technical Importance Rating	596	632	464	536	429	729	686	477	552	648	373	332					13
Relative Weight	9%	10%	7%	8%	7%	11%	11%	7%	9%	10%	6%	5%	0%	0%	0%	0%	14
Weight Chart																	15
Technical Competitive Assessment: Our Product	5	4	4	3	4	5	4	3	0	0	2	1					16
Competitor #1: Lab Test Apparatus	2	3	4	1	3	4	2	3	0	1	1	3					
Competitor #2: Product Name																	
Competitor #3: Product Name																	
Competitor #4: Product Name																	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	



Section J: Bill of Materials

Product	Part Number	Company	Price per item	Quantity	Total	Link	Notes	Order Total
NSERTION CARTRIDGE HEATER 250W 120/240V STAINLESS STEEL NPT	TD50040KQ	Heating Elements Plus	$78.69	2	$157.38	https://ww	Requires 3.5" unheated length extension	$2,574.10
Conax Multi-wire Power Compression Seal Feedthrough (PL)	PL-18-A2-T	Conax Technologies	$120.00	2	$240.00	https://ww		
Ceramic Insulation Sheet for Furnaces Moldable, 1/4" Thick x 23" Wide x 2 Feet Long	93615K18	McMaster-Carr	$245.10	1	$245.10	https://ww		
O-Ring - 3" ID High-Temperature Silicone, 0.125" Actual Width	1169N303	McMaster-Carr	$12.50	2	$25.00	https://ww	Order with 3" ID	
O-Ring 3.25" ID High-Temperature Silicone, 0.125" Actual Width	1169N303	McMaster-Carr	$12.50	2	$25.00	https://ww	Order with 3.25" ID	
Super-Corrosion-Resistant 316 Stainless Steel Hex Head Screws Serrated-Flange, 1/4"-20 Thread Size, 1-1/2" Long	94302A105	McMaster-Carr	$11.70	3	$35.10	https://ww		
5/8" TUBE X 1/2" NPT MALE CONNECTOR	100-10-8	Lenz		2	$0.00	https://ler	Lenz did not respond to quote requests	
1 1/8"" TUBE X 1" NPT MALE CONNECTOR	100-18-16	Lenz		2	$0.00	https://ler	Lenz did not respond to quote requests	
Stainless Steel Pipe Fitting, Street Tee, 1/2 in. Female NPT x 1/2 in. Male NPT x 1/2 in. Female NPT	SS-8-ST	Swagelok	$66.90	6	$401.40	https://ww		
Stainless Steel Pipe Fitting, Reducing Bushing, 1/2 in. Male NPT x 1/4 in. Female NPT	SS-8-RB-4	Swagelok	$12.50	2	$25.00	https://ww		

Stainless Steel Pipe Fitting, Reducing Bushing, 1/2 in. Male NPT x 3/8 in. Female NPT	SS-8-RB-6	Swagelok	$12.90	2	$25.80	swagelok	
Stainless Steel Pipe Fitting, Reducing Bushing, 1 in. Male NPT x 1/2 in. Female NPT	SS-16-RB-8	Swagelok	$26.00	2	$52.00	https://wv	
Stainless Steel Pipe Fitting, Reducing Bushing, 1/2 in. Male NPT x 1/8 in. Female NPT	SS-8-RB-2	Swagelok	$12.10	2	$24.20	https://wv	
K type high temperature thermocouple with 1/4" NPT mounting adapter	WRNK-193	Auber Instruments	$30.00	2	$60.00	https://wv	
PX2 Series Heavy Duty Pressure Transducer Sealed gage, 0 psi to 500 psi, 4.75 V to 5.25 V input, ratiometric: 5.0 Vdc 10 %Vs to 90 %Vs output, 1/8-27 NPT, Micro M12 (IEC 61076-2)	PX2BN2XX500PSAAX	Honeywell	$25.56	2	$51.12	https://wv	
zirconia ceramic	646-N	Aremco	145$ for	4	$145.00	https://wv	
Zirconia Tubes (8 mol% Y)	31188	Stanford Advanced Materials	325*2 (fo	4	$1,062.00	https://wv	Tolerance is .5mm on all measurements
Nonporous Alumina Ceramic Tube 1" OD, 3/4" ID, 12" Long	8746K551	McMaster Carr	$131.98	2	$263.96	https://wv	Not included in total
Nonporous Alumina Ceramic Tube 1/2" OD, 1/4" ID, 12" Long	8746K19	McMaster Carr	$35.40	2	$70.80	https://wv	Not included in total

Section K: Additional Reference Images

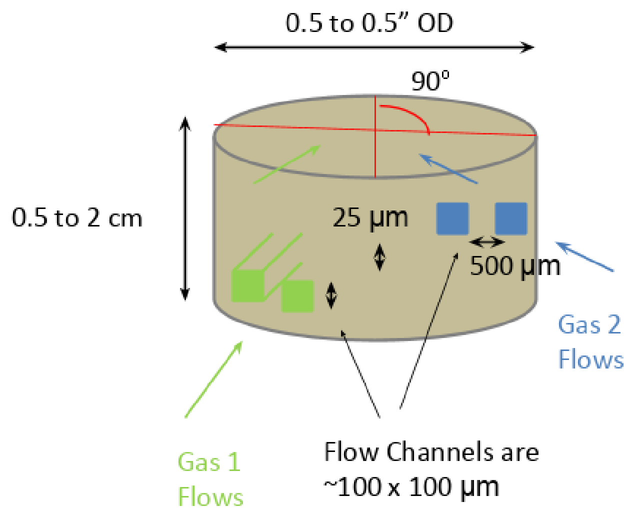


***Figure** 13. Fuel cell to be inserted into manifold.*

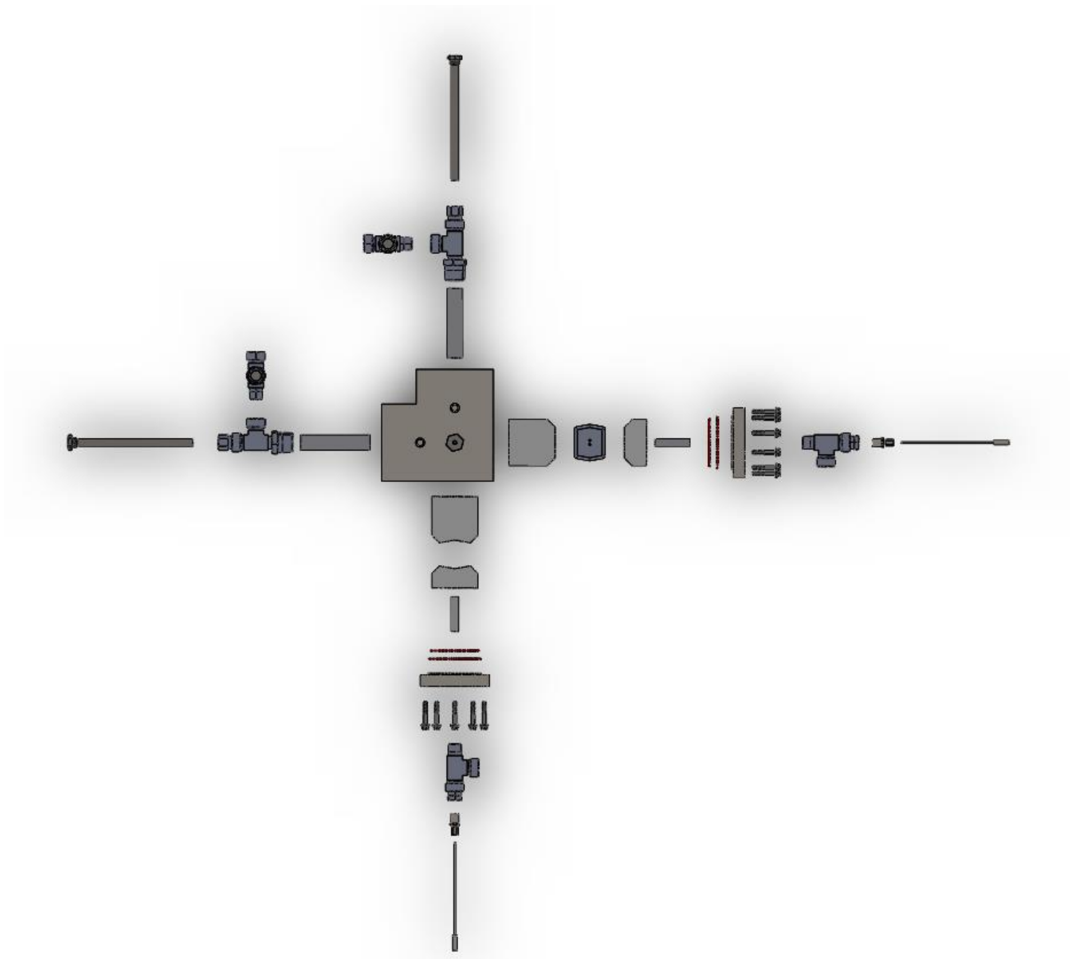


***Figure 14.** Top-down exploded view of full assembly.*

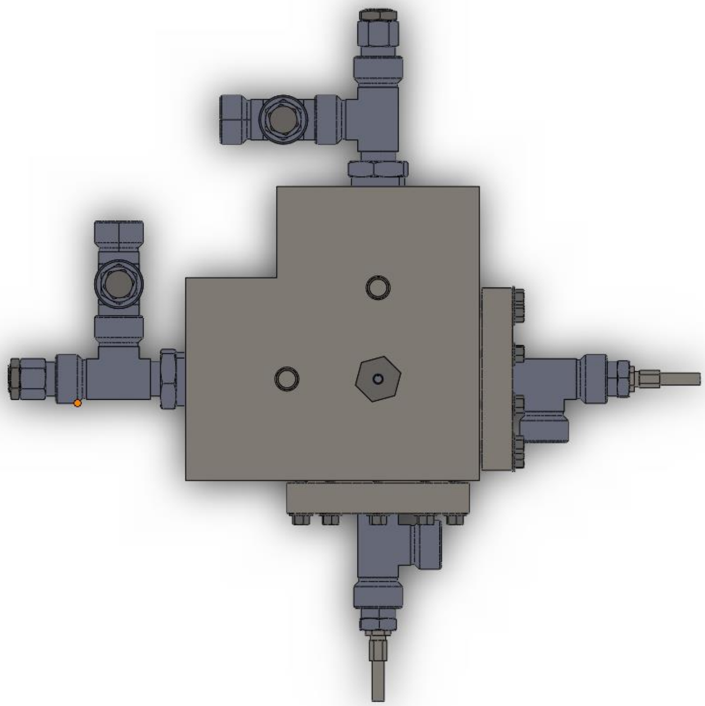


Figure 15. *Top-down view of full assembly.*

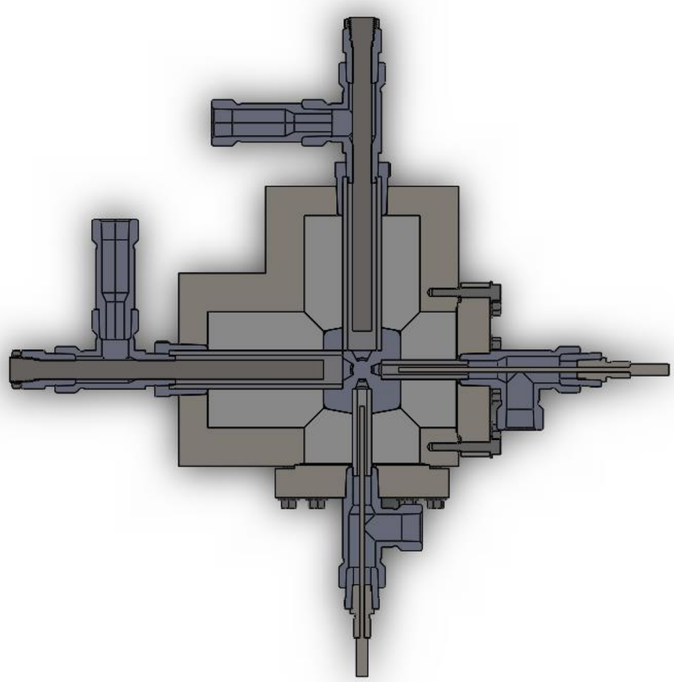


Figure 16. *Top-down split view of full assembly.*