Final Design Report

SEED Team #31: New Material for Hypersonic Leading Edges

Avrey Carifa, Colin Hodge, Dan Jordan

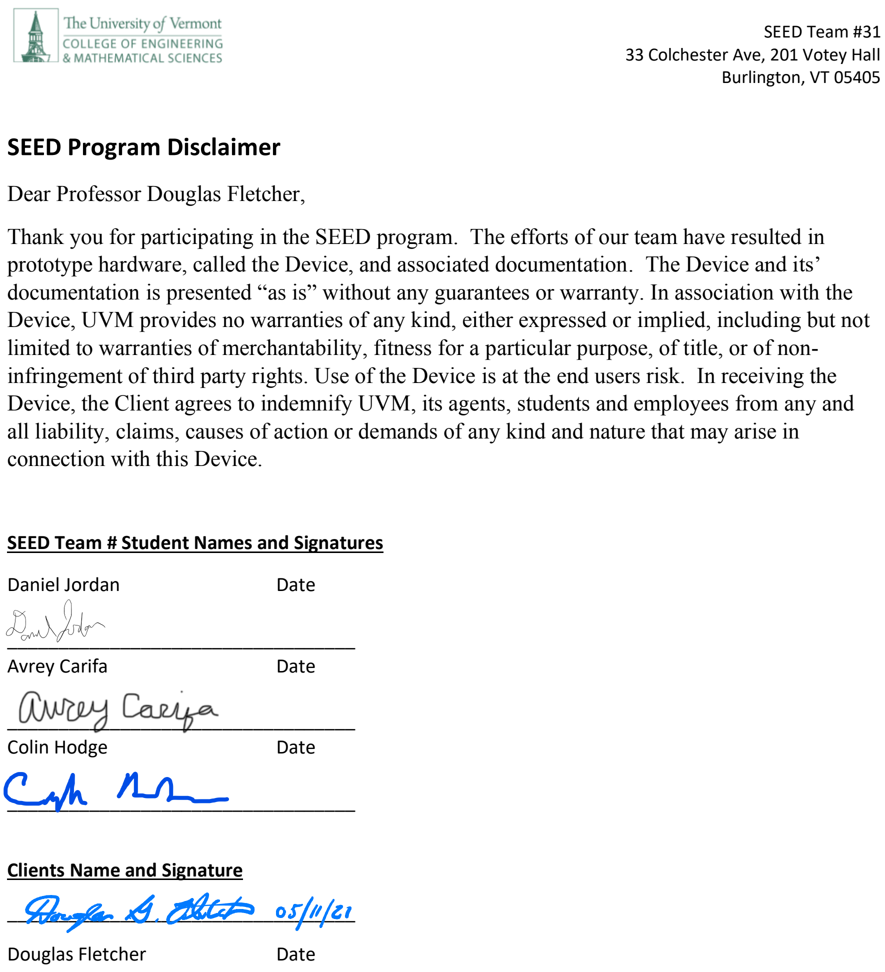
May 11, 2021

Date	**Revision**	**Release Notes**
4/24/2021	01	Initial release
4/28/2021	02	Completing sections
4/29/2021	03	Updating sections with analysis information
5/4/2021	04	Revisions and finalizing sections
5/9/2021	05	Final edits

Contents

1 Project Handoff

1.1 Disclaimer Form



The University of Vermont
COLLEGE OF ENGINEERING
& MATHEMATICAL SCIENCES

SEED Team #31
33 Colchester Ave, 201 Votey Hall
Burlington, VT 05405

SEED Program Disclaimer

Dear Professor Douglas Fletcher,

Thank you for participating in the SEED program. The efforts of our team have resulted in prototype hardware, called the Device, and associated documentation. The Device and its' documentation is presented "as is" without any guarantees or warranty. In association with the Device, UVM provides no warranties of any kind, either expressed or implied, including but not limited to warranties of merchantability, fitness for a particular purpose, of title, or of non-infringement of third party rights. Use of the Device is at the end users risk. In receiving the Device, the Client agrees to indemnify UVM, its agents, students and employees from any and all liability, claims, causes of action or demands of any kind and nature that may arise in connection with this Device.

SEED Team # Student Names and Signatures

Daniel Jordan Date

Daniel Jordan

Avrey Carifa Date

Avrey Carifa

Colin Hodge Date

Clients Name and Signature

Douglas G. Fletcher 05/11/21

Douglas Fletcher Date

1.2 Formal Memo

Dr. Fletcher,

Speaking for every member of SEED Team #31, we would like to extend our gratitude to you for helping us succeed during this abnormal academic year. We are aware of all of the responsibilities you have as head of the mechanical engineering department during an ABET accreditation year and are very pleased that you were able to make time to lead us through this project.

The following report is an accumulation of all of the detailed work that we have done throughout the 2020 - 2021 academic year for the creation of a sample holder to be used to test new materials for hypersonic leading edges. All the deliverables created for this project can be found completed and stored on EduSourced, which was used to organize the project all year. Actual documentation of analyses, technical drawings, and reports will be sent to you on May 13, 2021, at the normal weekly meeting time.

Below is a detailed list of artifacts related to the project we will be supplying:

1. Constructed Sample Holder - May 13, 2021
    - All Swagelok components purchased, including components used in the holder as well as extras.
    - 2 brass connection pieces for use with insertion probe, one with lofted design and one without.
    - Barbed piece to accommodate transpiration gas, and extras.
    - Porous sample with stainless steel bits adhered to the ends for testing, and any other extra porous samples.
    - Bent stainless steel piping and any extra piping not used.
    - Fully functional sample holder constructed by the SEED team.
2. Technical Documents - May 13, 2021
    - Heat transfer analysis simulation results, done in Simulia ABAQUS.
    - Thermal expansion analysis simulation results, done in Simulia ABAQUS.
    - Static load analysis simulation results, done in Simulia ABAQUS.

- Technical package including dimensioned technical drawings of custom made parts, sub-assemblies, and the full assembly of the sample holder. Drafted in SolidWorks.
- All prototype sample holder drawings, drafted in SolidWorks.

3. Incremental Reports - May 13, 2021
    - Preliminary design report, consisting of work completed for the first semester of the class.
    - Concept generation report, including early ideas and sketches for a final model.
    - Prior art report, to show early research and information pertaining to relevant topics of the project.
    - Engineering specifications that fully define customer requirements.
    - Verification plans and results, looking more in depth to the engineering specifications.
    - Failure Modes Effects Analysis (FMEA), to determine possible ways the constructed sample holder could fail.
    - Final design report, an accumulation of all of the work done by SEED Team #31

2 Project Design Details

2.1 Abstract

The leading edges of a spacecraft when entering a planets atmosphere receive the highest amounts of thermal loading. Due to this, a material must be used on these edges that is capable of being exposed to extreme thermal conditions in order to protect the payload inside the vehicle. Dr. David Marshall from the University of Colorado Boulder has recently developed a porous leading edge material which utilizes transpiration cooling to provide a heat shield. However, it is first necessary to test this new material to determine its heat shielding capabilities. Due to its novelty, there is no sample holder currently in existence that can hold the sample porous material in place for testing in the University of Vermont's Inductively Coupled Plasma (ICP) Torch facility while also supplying the required transpiration gas. To test the effectiveness of transpiration cooling on the new porous material, the porous sample holder design was created to carry and inject the transpiration gas through the sample holder and into the test material without leaking gas. The sample holder will also be able to actively monitor the transpiration gas flow pressure and control the flow rate of the gas. Unfortunately, due to issues related to the COVID-19 pandemic (and associated facility shutdowns), laboratory testing of the sample holder and sample material has not been completed yet. Next steps are to complete this testing as soon as possible, so further progress can be made with the development of the holder and experimentation of the material. Plans are already in the works to test the prototype sample holder and confirm its functionality in the few weeks following the submission of this report.

2.2 Problem Statement

The aerospace industry is one that is always evolving, as more is constantly being discovered on how to make frequent space and upper atmospheric travel not only safer, but more accessible. Although getting into the upper atmosphere is a huge feat on its own, traveling in it and returning safely is another. Upon reentry into Earth's lower atmosphere, there are extreme thermal loads present, which requires some form of heat shield to be present on the reentry vehicle in order to protect any payloads or human occupants that may be inside. Typically, an ablative or extremely heat resistant material is used on the outside of the reentry vehicle to allow for adequate insulation of the cabin.

An additional solution to protect against the intense thermal loads during upper atmospheric travel was to round the leading edges so they would be blunt enough to stop the heat from damaging the system. A commonly used material is a ceramic known as reaction cooled glass. Although effective as a heat shield, this material cannot withstand any water, which limited the days aircraft could be flown. Even though it has flaws, it was an industry standard for many upper atmospheric traveling vehicles. Now, leading edges for re-entry vehicles want to be designed to match more closely with NASA's X-43 Scramjet (Figure 1).

The porous leading edge material of CU Boulder will utilize transpiration cooling, which allows for a narrower leading edge of less radius, enabling spacecraft heat shielding to be easier to control, without failure due to thermal loading. Testing materials for heat shielding capabilities during this reentry phase is too expensive and risky to even attempt, so facilities have been constructed to recreate these conditions as accurately as possible for testing purposes. One such facility is the University of Vermont's Inductively Coupled Plasma (ICP) Torch Facility.

Figure 1: NASA's X-43 Scramjet

The UVM ICP Torch facility, located in the Discovery Science building, is used to recreate the upper atmospheric conditions experienced in reentry. Most recently, the lab has been studying materials that will be used for the leading edges of these reentry vehicles. The leading edge is the location of the vehicle that will experience the highest thermal loads upon reentry into the atmosphere. A new porous material has been designed and manufactured for use on the leading edge (Figure 2). The idea is that an injection gas will be pumped into the porous material and exit through the pores, thus creating a layer of gas around the material and the leading edge of the vehicle. However, due to its novelty, there is not a holder that exists to hold the sample porous material in place and monitor the conditions around it during testing in the UVM ICP torch facility. This new material was created in a lab at the University of Colorado Boulder by Dr. David Marshall, a material scientist specializing in design of materials for high temperature structures.

Figure 2: The New Porous Sample to be Tested in the ICP Torch

In order to create a holder to effectively be used during testing of this new permeable material, existing sample holder designs must be modified to be able to monitor the pressure conditions during testing and to allow for a transpiration gas to flow through the holder and into the sample. The flow of this gas must also be monitored to learn how its cooling effects will help to mitigate the temperature at the leading edge. To test materials under extreme thermal loads, a holder should be created out of materials with extreme thermal resistance so that it will not fail during testing. With the creation of a holder for the sample material, testing will be possible and progress will be made for developing an understanding of how this material can be used to make space travel more effective and safe.

As time goes on, flight and space travel are becoming more prevalent and travel in and around the upper atmosphere will not be going away anytime soon. Even though technology in this field is advancing, the problem of extreme thermal loads will not go away. In fact, they will increase in severity as the average speed of aircraft increases. Getting a grasp on the full extent of the temperature mitigation abilities of this new material now can allow for an increase in the scientific discoveries that come with upper atmospheric travel.

2.3 Client Requirements

In order to best meet the client's wishes for the sample holder, a prioritized list of customer requirements was created and is shown below. These requirements need to be met in order for Team #31 to produce a successful deliverable by the end of this project. The order of the requirements was determined based on feedback from the client and relative importance for achieving certain levels of functionality.

1. Hold the sample securely so that it will efficiently disperse the transpiration gas and so it does not fall in the plasma torch.

2. Attach to the existing insertion probe, to eliminate the need to create a new separate way to attach to the testing chamber.

3. Sample holder must be able to withstand the high thermal loading conditions provided by the ICP torch, if the testing conditions of the material are extremely high, the holder must work properly under the same conditions.

4. Sample holder must be able to contain the variable injection gas flow, and effectively inject it through the sample. This new material only works at mitigating these high thermal loads if the transpiration gas is efficiently pumped through the pores on it.

2.4 Working Design Concept

The UVM ICP torch facility test chamber, seen in Figure 3 is a stainless steel chamber designed to insulate the heat created by the plasma torch. Currently there are two probes that are being used to test samples, the "gooseneck" probe and the standard insertion probe. Both probes are controlled from the outside of the chamber and have different functionalities. The insertion probe (seen in Figure 4 and denoted by the red arrow) is what SEED Team #31 will be utilizing in the design of the sample holder.

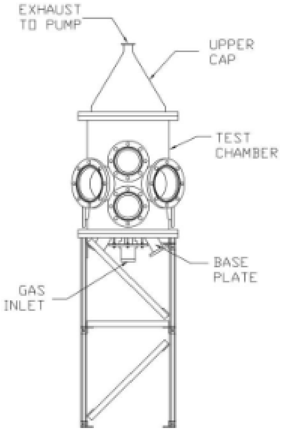


Figure 3: Labeled image of the ICP Torch Testing Chamber

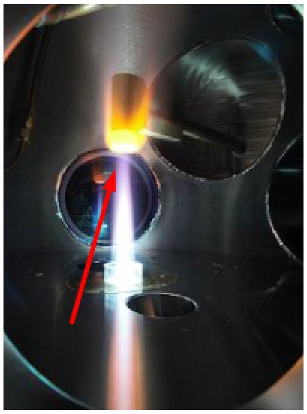


Figure 4: Insertion Probe During Testing

The proposed working sample holder design is made to securely attach to the existing standard insertion probe used in the UVM ICP Torch Facility, seen in Figure 5. The sample holder will connect to the probe at the end of the red arrow seen in Figure 4. Transpiration cooling capabilities are necessary for the cooling of the porous sample, thus the design is structured to interface with the internal piping of the insertion probe. This piping is accommodated for gas injection tubing of the transpiration gas.

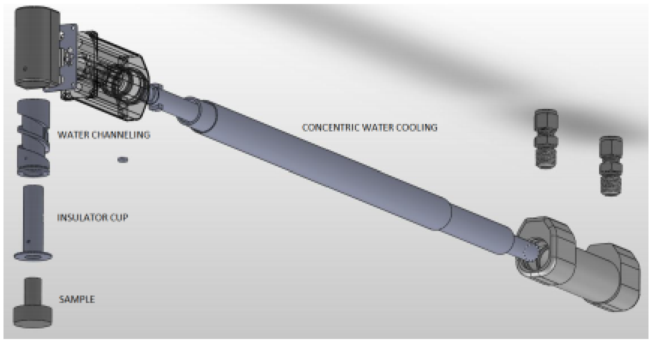


Figure 5: CAD model of the insertion probe

The portion in Figure 5 where the ”sample” is inserted into the ”insulator cup” is where the end of the new sample holder seen in Figure 7 will attach. Since the insertion probe is an existing design already incorporated into the torch facility, the maneuverability of the created holder is dependent on the three degrees of freedom that the insertion probe design already has.

Due to the first semester of the class consisting of a lot of research about all aspects of the project, a scaled up model of the sample holder was constructed to show progress through this phase of the class. PVC piping and PVC junction components were used to model stainless steel piping and Swagelok components. Poly tubing was used to model the flow of the gas internally. Throughout the course of the second semester, there were a few components that were changed during the development from the model in Figure 6 to the final design seen in Figure 7.

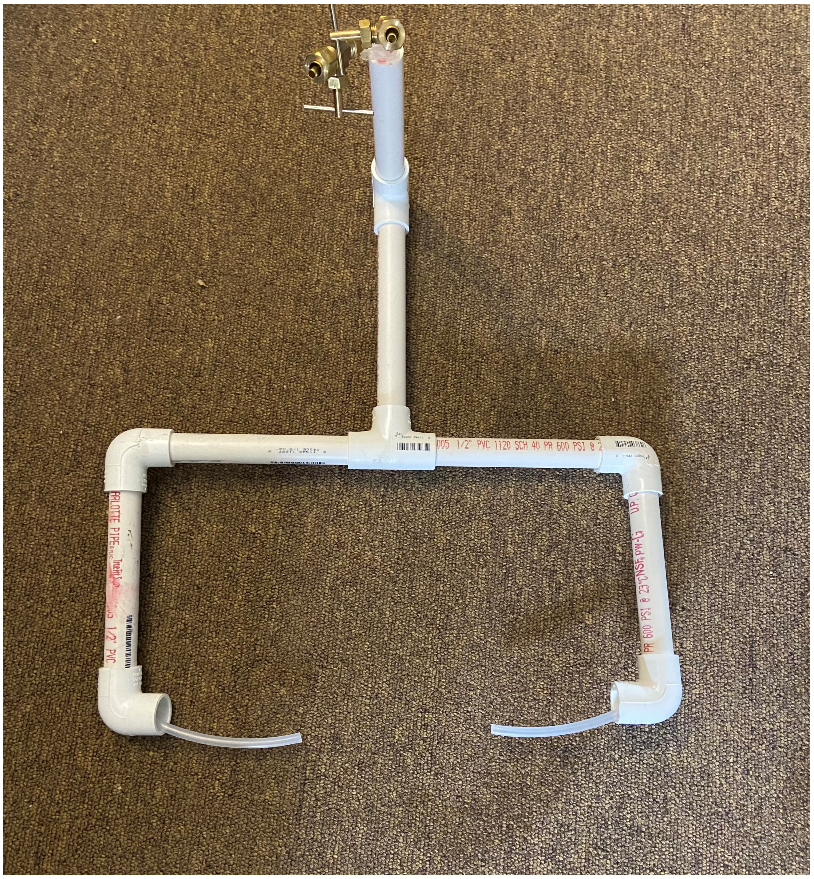


Figure 6: Scaled Up Model of Sample Holder

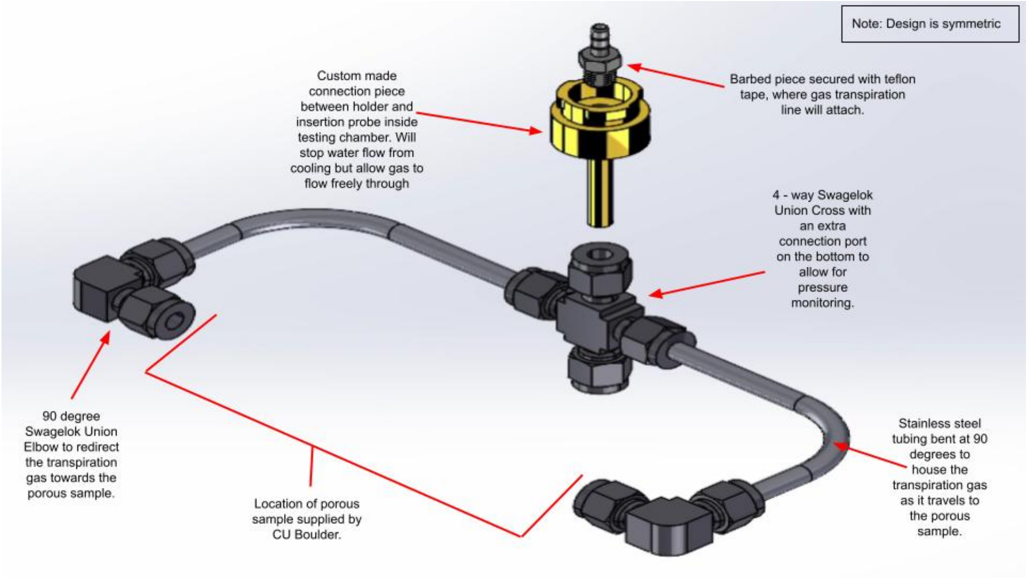


Figure 7: Labeled CAD model of the sample holder

The holder that has been designed this semester is made up of components that have been chosen to efficiently perform the tasks at hand. A labeled CAD model of the full sample holder design can be seen in Figure 7. The components that make up the entirety of the holder are explained in detail below. All of the intersections in the model (90° turns/Tee bends) are modeled after 316 stainless steel Swagelok fittings, which can be seen in Figures 8 and 10, to allow for a completely sealed system. This is necessary to avoid having any transpiration gas leak from the tubing.

Figure 8: 90° Swagelok bend

The far end of the holder, where the sample is attached in Figure 7, comes together as one piece that can be exchanged between tests and at the user's discretion. This portion of the sample holder contains molybdenum welded to the porous leading edge material and is to be provided from Dr. David Marshall of CU Boulder. A rough drawing of the porous sample configuration from CU Boulder can be seen in Figure 11. This shows how the molybdenum will interface with both the porous leading edge material and the 90° Swagelok bends.

Swagelok fittings are an industry standard when it comes to long lasting pipe connections. They pride themselves on not only establishing secure fittings, but remaining secure under extreme environmental conditions. The fittings utilized by Team 31 are able to maintain a dependable performance in a vacuum and under the extreme thermal loads present in the testing chamber. Computer aided design models of the two fittings we will use (90° bends and 4-way union cross) can be seen below in Figures 9 & 10. The purple line represents the boundary of the flow within the fitting, and the blue line represents the middle of the flow.

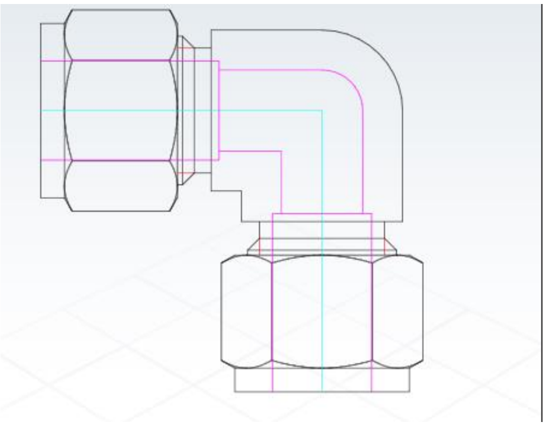


Figure 9: 90° Swagelok bend Front 2D CAD view.

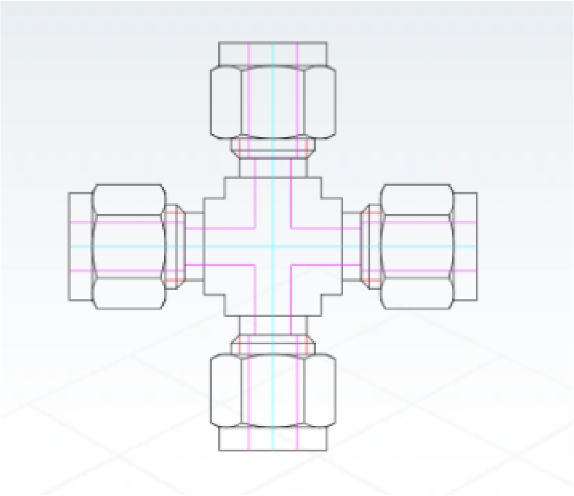


Figure 10: Swagelok Union Cross Front 2D CAD view.

The connecting pipes between all of the Swagelok fittings were modeled as 316 stainless steel. The sample holder was originally modeled in ABAQUS to determine how brass and copper as the piping material would react under the thermal loads present in the chamber. With the results from these analyses, it was determined that both materials would be capable of meeting the requirements, however, a group decision was made by Team 31 and Client Dr. Douglas Fletcher to use 316 stainless steel as the working material to match the other 316 stainless steel components in the design. More information on this study can be seen in Section 3, the analysis portion of the report.

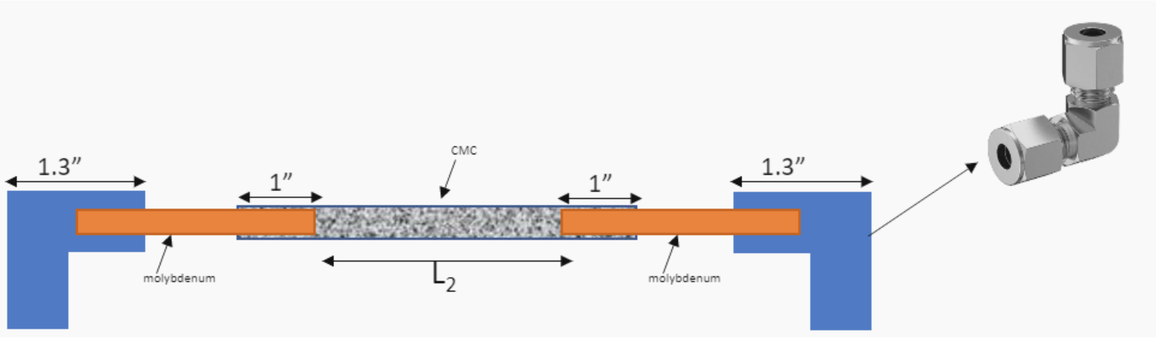


Figure 11: Far end of holder where sample is attached

As for the connection between the insertion probe and the newly designed holder, a pre-existing gas injection holder design, seen in Figure 12, for ablative material plugs was modified to establish a rigid connection between the new holder and the insertion probe.

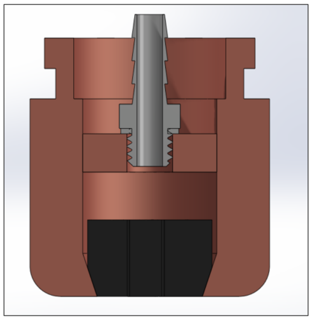


Figure 12: Gas injection holder

The connection piece's twist and lock mechanism designed by the Team 31 was first 3D printed at the UVM Fabrication Lab to test whether the connection to the insertion probe would be secure enough to support the entirety of the sample holder. The designed piece can be seen in Figure 13 (white), attached to its respective component from the insertion probe (bronze color).

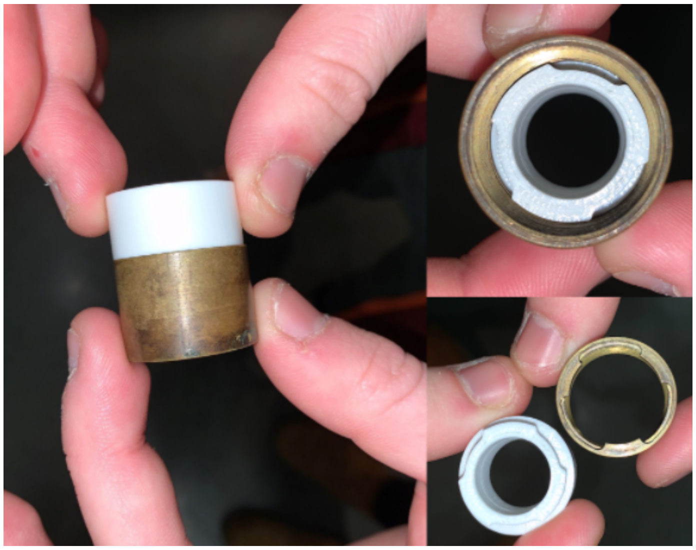


Figure 13: Testing of 3D Printed Connection Prototype

Once the connection was tested and confidence in the security of it was present, design on a more robust and final model of the piece was drafted and can be seen in Figure 14. Once machined, the connection piece's twist and lock mechanism was tested again and confirmation of this can be seen in Figure 15.

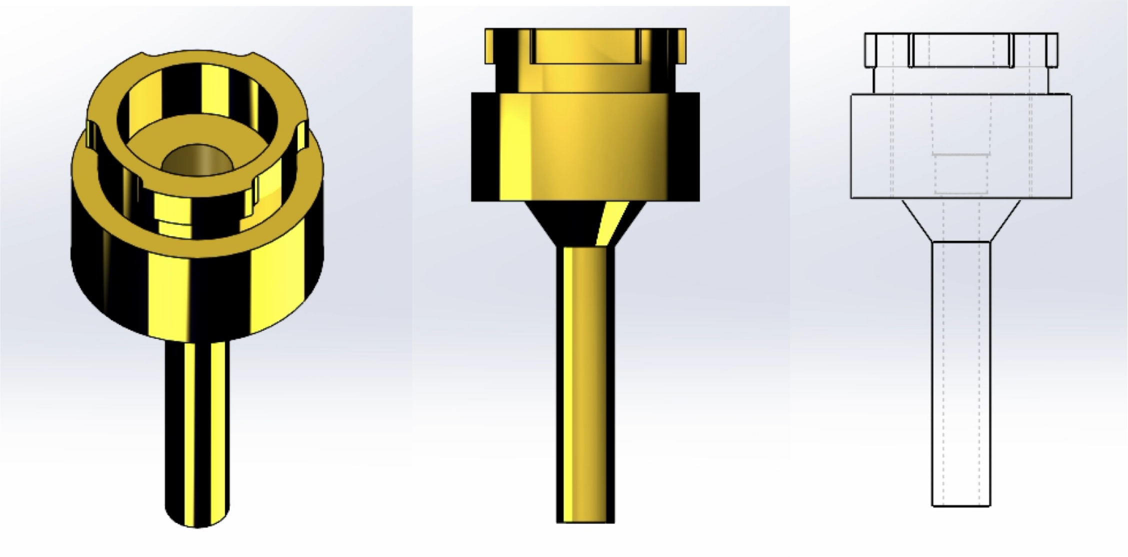


Figure 14: 3D Model of the insertion probe to porous sample holder connection piece.

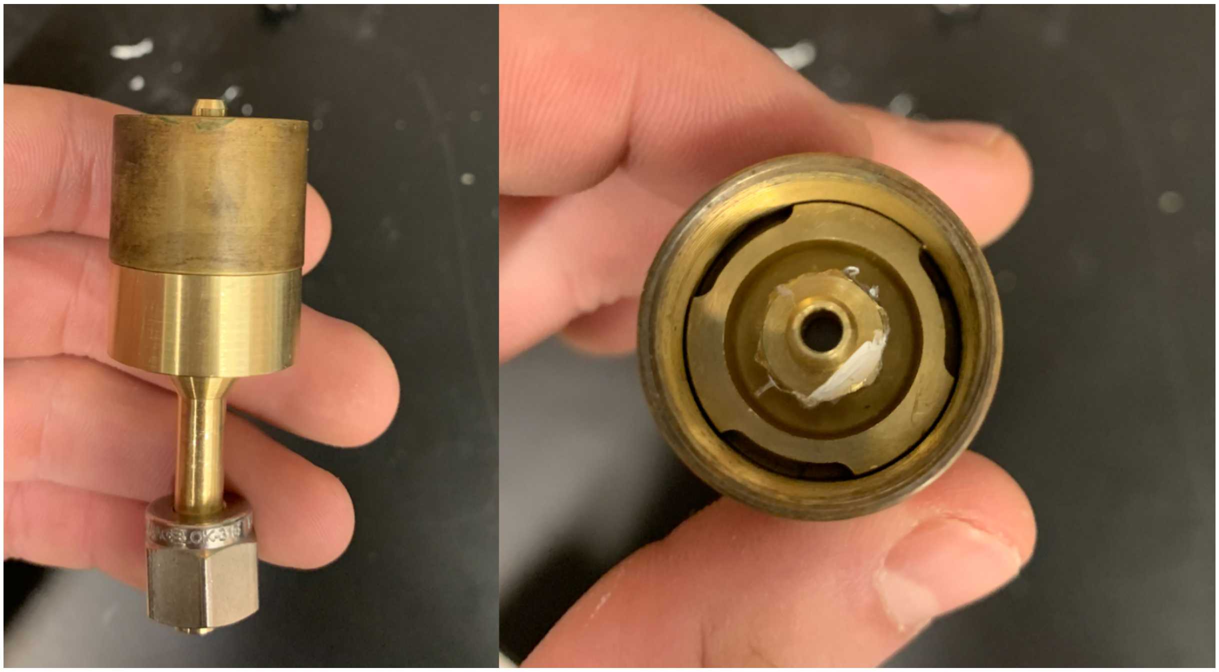


Figure 15: Connection piece being twisted and locked into the insertion probe interface

The goal for this design was to securely connect the porous sample holder to the insertion probe via twist locking mechanism, while also allowing for the transpiration gas to freely flow into the holder and blocking the water coolant present in the insertion probe from entering the sample holder. To interface with the gas tubing from the insertion probe, a McMaster-Carr barbed tube fitting was screwed into the connector piece and secured using teflon tape. The gas tubing will fit over the barbed piece, allowing the transpiration gas to flow from the insertion probe to the sample holder with no gas leaks. A 3D model of the connection piece sub-assembly can be seen in Figure 16.

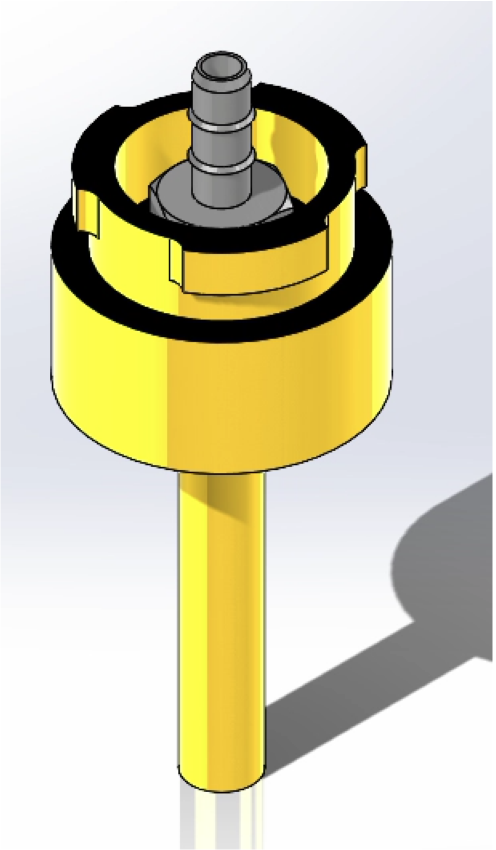


Figure 16: 3D Model of the connection piece sub-assembly.

For the connection piece, the bottom tubing is modelled as 1/4" outer diameter piping to connect to the Swagelok union cross securely. The connection piece was submitted to Doug Gomez of the UVM IMF Lab to be machined. The original connection piece drawing submitted can be seen in Figure 17.

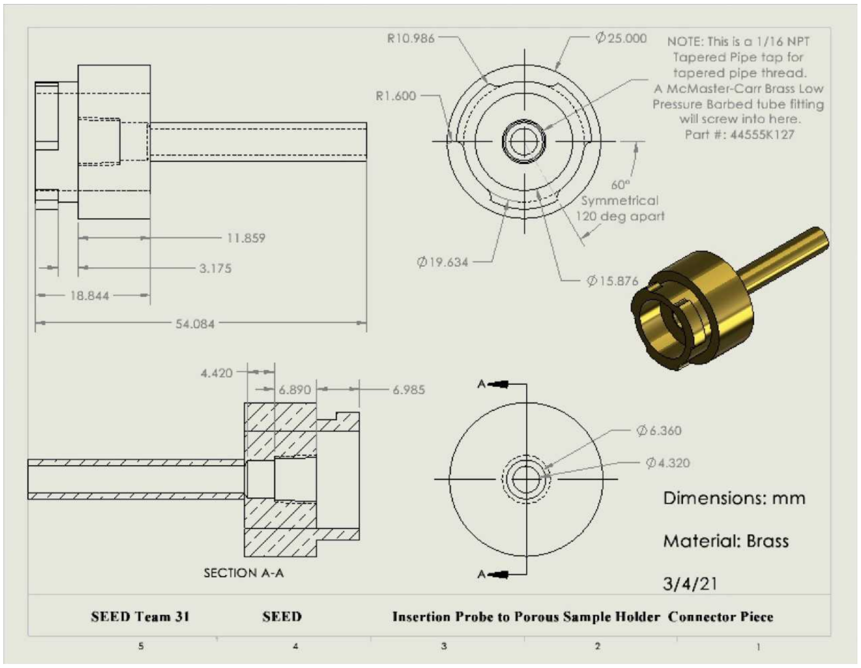


Figure 17: Original connection piece design and drawing.

After review of the drawing, Mr. Gomez expressed concern about concentrated stress occurring at the junction between the shaft and the main component due to a lack of material, potentially leading to failure. With this in mind, Team 31 included a lofted portion in the design where the shaft and main body meet for added strength.

After final discussion with the client, Dr. Douglas Fletcher, the connection piece design and drawing were finalized. The material chosen was brass and correct tolerances were included for the final drawing to be manufactured. The finalized technical drawing is seen in Figure 19, as well as in the sub-assembly drawing in Figure 20 and the machine connection piece in Figure 18. Once manufactured, measurements were taken to confirm that the connection piece was made within the specified tolerances (noted in the technical drawing). After confirmation that the piece was made to standard, the client was notified that the team was ready to move forward in the design process. The final technical drawing of the sample holder assembly, with a complete parts list and accurate dimensions, can be seen in Figure 21.

Figure 18: Machined brass connection piece with the barbed tube fitting.

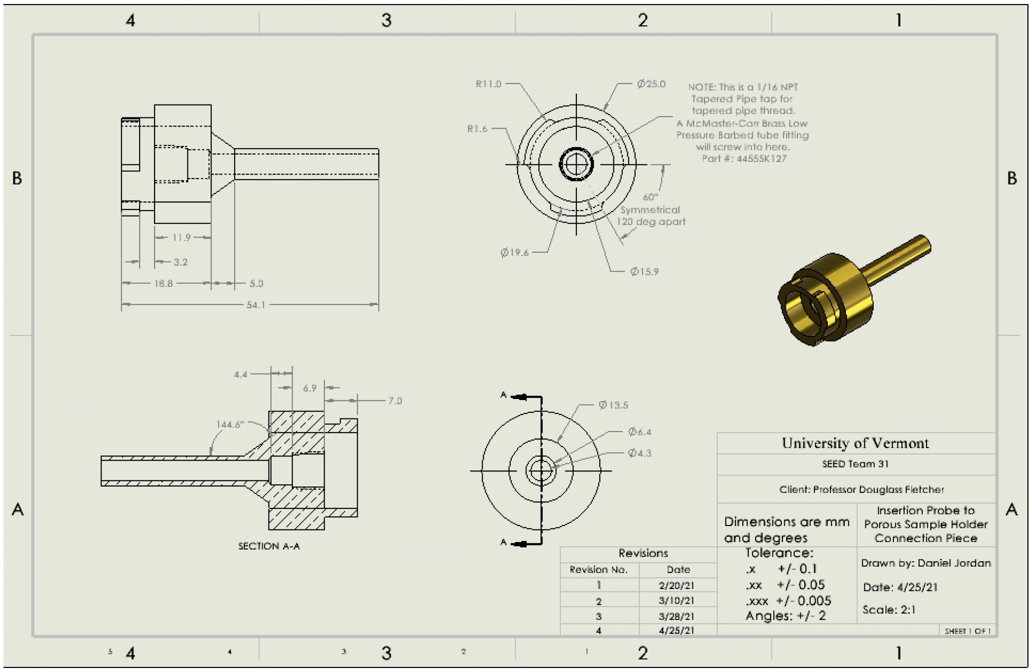


Figure 19: Technical Drawing of the Connection Piece

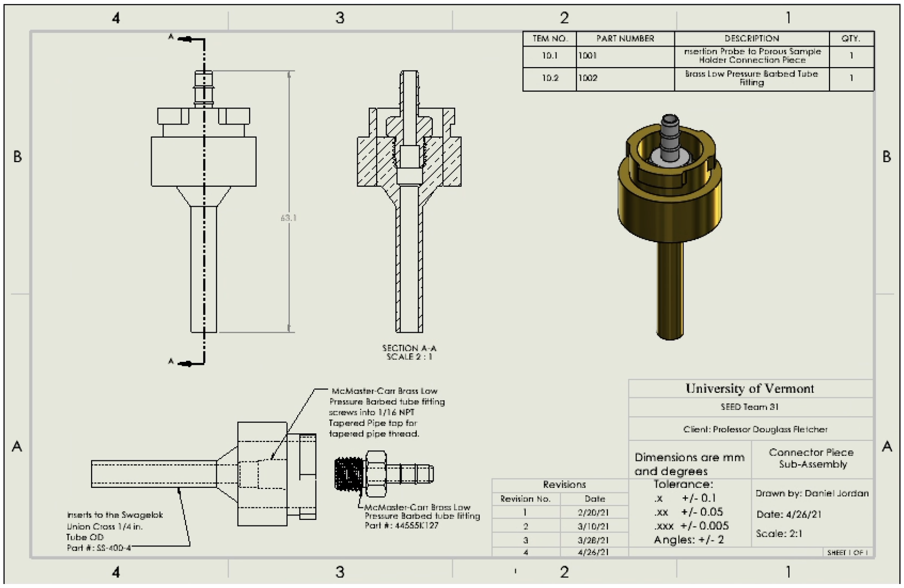


Figure 20: Technical Drawing of the Connection Piece Assembly

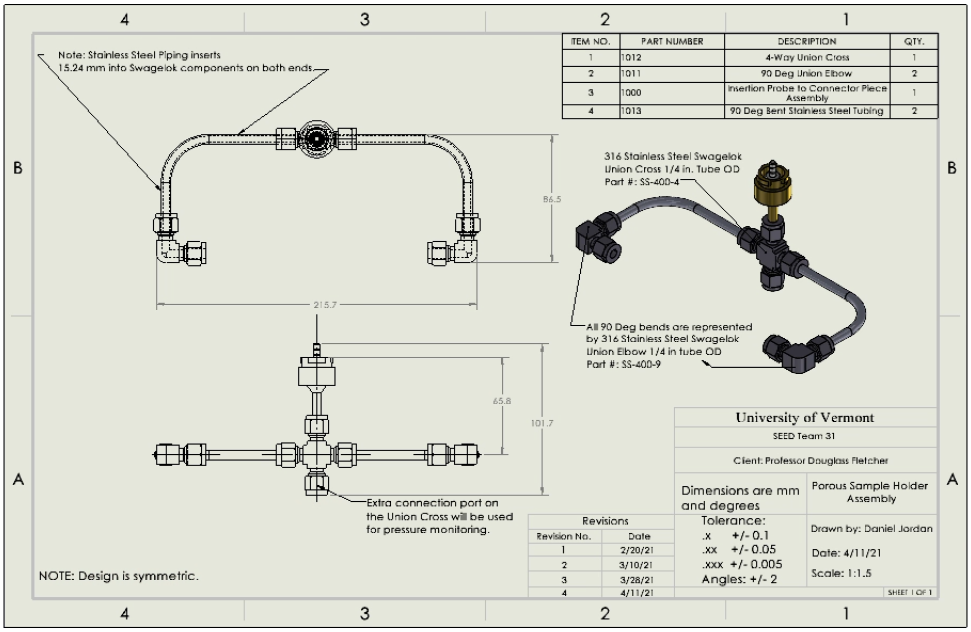


Figure 21: Technical Drawing of the Sample Holder Assembly

As stated in Section 2.2, the porous leading edge material was designed and created in a lab by Dr. David Marshall of CU Boulder. Unfortunately, an updated version of the sample was not received before the end of the year. Using the engineering skills developed through this project as well as guidance from the client, an early version of the sample material was attached to small pieces of stainless steel piping using a high temperature adhesive. These attachments will allow for the sample to interface with the prototype sample holder. The final result can be seen in Figure 22, and will be tested in lab as soon as possible.

Figure 22: Physical Model with attached Porous Sample

3 Analyses

3.1 Analysis: Heat Transfer Study

The objective of this analysis is an understanding of the heat transfer on the sample holder during testing. This understanding will be used to determine the best material for the sample holder (either copper or brass). Copper and brass were chosen as the two working materials due to their high thermal conductivities and low specific heats. These results will also provide information regarding the necessity of water cooling in the design. A note must be made that this analysis was conducted in the first semester prior to a conversation with Client, Professor Douglas Fletcher, in which it was decided to use 316 stainless steel as the piping in the design. This decision was made to match the 316 stainless steel already utilized by Swagelok for the joints in the design, and for the look of the sample holder design to be uniform. This will also be beneficial in terms of thermal expansion, in which it is known that design components of the same material will have the same expansion properties when under thermal loading.

The analysis was run in two steps on ABAQUS, the first being a steady state heating step and the second being a transient cooling step. In order to conduct a heat transfer study in ABAQUS, properties of conductivity, specific heat, and density are necessary for each working material. The equation for heat transfer is written as follows:

$$Q = m \times c \times \Delta T \tag{1}$$

Where Q is heat transfer, m is mass, c is specific heat, and ΔT is change in temperature. These parameters must be known, as the program utilizes the equation for heat transfer on a small and elemental scale. In addition to the general heat transfer equation, the simulation uses heat transfer equations for conduction, convection, and radiation because these are the specific processes in which the heat will be transferred. The equations for heat transfer in terms of conduction, convection, and radiation are as follows:

$$Q_{cond} = \frac{tkA\Delta T}{d} \tag{2}$$

$$Q_{conv} = h_c A \Delta T \tag{3}$$

$$Q_{rad} = \sigma A \Delta T \tag{4}$$

In Equations 2, 3, and 4, A is surface area, ΔT is change in temperature, k is thermal conductivity, t is time, d is thickness, h_c is heat transfer coefficient, and σ is the Stefan-Boltzmann constant.

3.1.1 Loading Conditions

To simulate the thermal loading provided by the ICP torch, a surface heat flux load of $3\frac{W}{mm^2}$ is placed on the surface of the porous material during heating. Upon full extension of the plasma torch, the torch only covers about two inches of the porous sample surface, thus the heat flux loading is modelled to cover two inches of the sample's surface, which can be seen as dimension L_2 in Figure 11. A constant temperature boundary condition of 7000K is also placed on the sample surface. This is because the plasma will have a maximum temperature of about 7000K during testing, and will be constantly in contact with the sample surface. During cooling, the sample holder no longer has any loading provided by the porous sample, or a constant temperature boundary condition.

3.1.2 Assumptions

The test chamber in which the sample and sample holder will be placed into for testing is seen in Figure 23. The ICP torch testing chamber operates as a vacuum, thus it is safe to assume that there would be no heat transfer due to convection during the heating step.

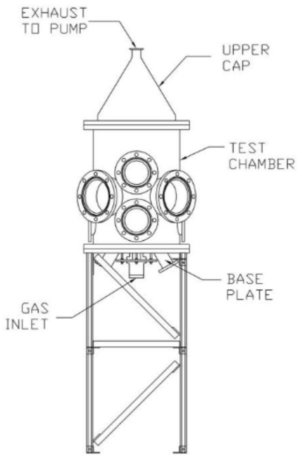


Figure 23: Scaled drawing of the ICP torch test chamber[1]

The ambient air near the torch during testing is is known to be between 400 and 500K, which decreases to around room temperature near the chamber walls. To simulate vacuum conditions and know ambient air conditions, only conduction and radiation interactions were input to ABAQUS during the heating step. To establish radiation interactions, emissivity values must be known for each material, along with the respective surrounding ambient temperatures. With a known range of air temperatures during the heating phase, the ambient temperatures for the front of the sample holder were placed at 500K, 450K at the mid-section, and 400K at the back of the sample holder where it would attach to the insertion probe. The ambient temperature locations in relation to the sample holder can be seen in Figure 24.

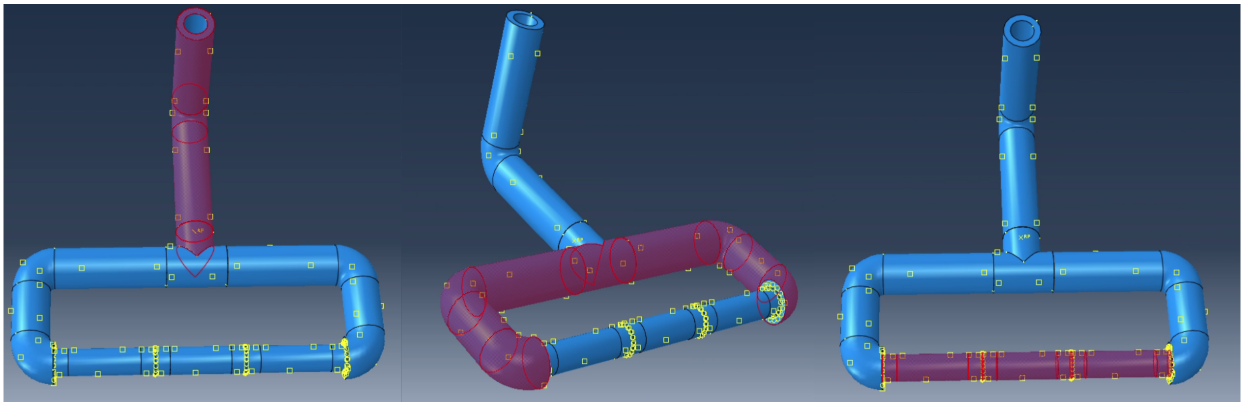


Figure 24: Air temperatures surrounding the sample holder from left to right: 400K, 450K, 500K.

A pre-defined temperature field of 293K was placed on all nodes of the sample holder before the heating step to indicate that the holder will be starting at room temperature. During cooling, the holder will be simulated as being outside the testing chamber at room temperature. Since the holder is no longer in a vacuum at this point, convective losses will be simulated, along with conductive losses during cooling. To establish convective interactions, surface film conditions were placed on all surfaces exposed to the air, where input of the free air heat transfer coefficient and temperature of the surrounding air was necessary. All interfacing parts of the sample holder are also assumed to have no thermal resistance during both steps. This simplification was made to make modelling of the ICP torch's testing conditions and sample holder interactions more attainable.

3.1.3 Results

Temperature versus time graphs were obtained for both copper and brass during the heating and cooling steps. Results were taking from the portion of the sample holder seen in red in Figure 25.

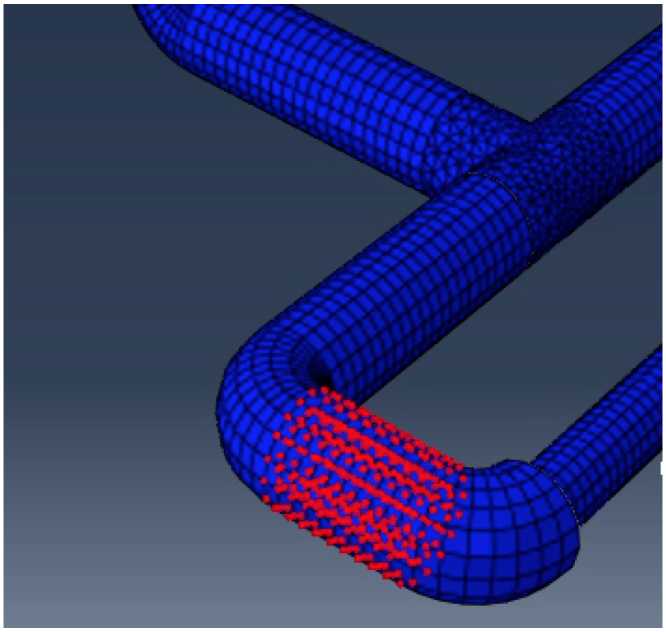


Figure 25: Portion of the sample holder being analyzed.

This portion of the sample holder was chosen to be analyzed because it is the section of material being tested that is closest to the plasma. The maximum temperature attained by the copper at this portion of the holder was 789.15K, while the maximum temperature of the brass was 775.87K. The temperature versus time graphs for the heat step of both materials can be seen in Figures 26 and 27.

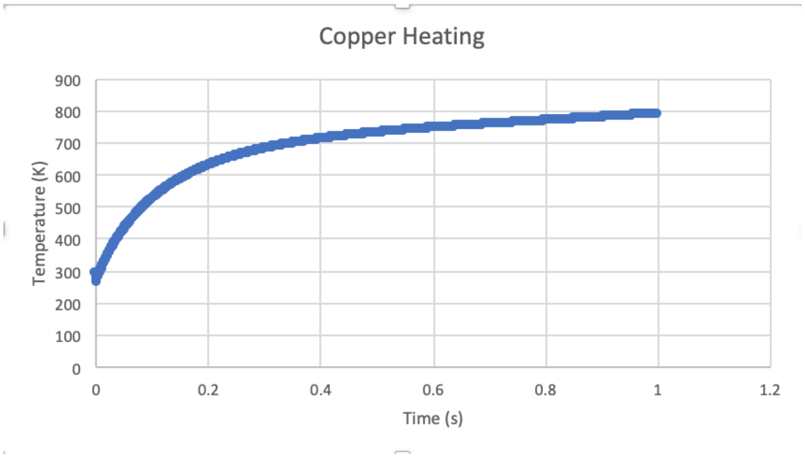


Figure 26: Copper heating step Temperature vs. Time graph

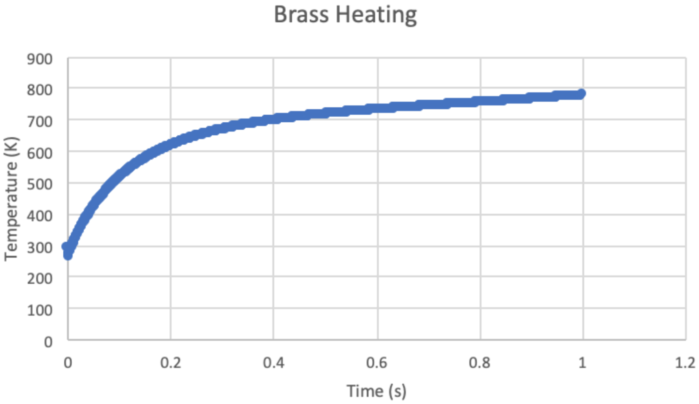


Figure 27: Brass heating step Temperature vs. Time graph

With both maximum temperatures being well below the respected melting points of the materials (1357.5K for copper and 1205.4K for brass), neither metal is at risk of failure. The temperature versus time graph for the cooling step of both materials can be seen in Figure 28.

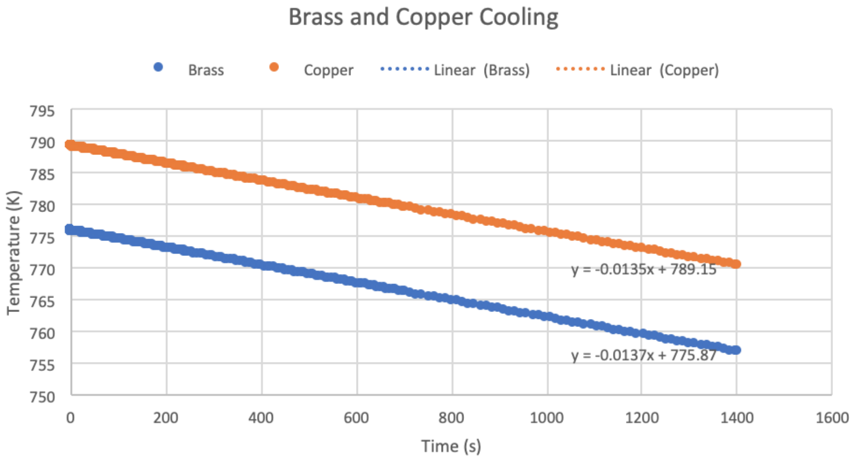


Figure 28: Brass and Copper cooling step Temperature vs. Time graph

The rate of cooling from both materials can be seen from the negative slope on the temperature vs. time graph in Figure 28. Copper had a cooling rate of -0.0135 K/s while brass had a cooling rate of -0.0137 K/s. With both materials reacting very similarly in terms of maximum temperature during heating, and cooling rates during the cooling, it can be confirmed that either material would work well in the sample holder design. However, brass will be chosen as the working material. Although cooling rates and temperature data are very similar between both materials, brass reached an overall lower temperature value than copper during maximum loading, and also maintained a slightly faster cooling rate. It is now known that both materials can withstand the thermal conditions provided by the plasma torch without melting, but it has not been determined if yield stressing will occur due to thermal expansion. Brass has a higher yield stress than copper, which will be important to consider with such high changes in temperature occurring during testing. If there were to have been noticeable differences in cooling rates between copper and brass, then the material with the faster cooling rate would have been chosen. In terms of water cooling, it has been decided that this will no longer be necessary in the design due to the temperatures of both materials not reaching values close to failure. Additionally, the transpiration gas that will be flowing through the internal piping to be injected to the porous sample was factored into the decision to not have water cooling. Although the main purpose of the transpiration gas is to study its heat shielding capabilities with the porous sample, it will also provide some cooling capabilities to the internal walls of the piping and holder. Prior to conducting this study, the client, Professor Douglas Fletcher, hinted that water cooling may not be necessary in the design due to the experimental conditions and presence of the transpiration gas, however, this study was conducted to confirm this theory and to see the capabilities of copper and brass in the design.

3.2 Analysis: Thermal Expansion

In order to ensure the sample holder design will not fail, an analysis on the thermal stressing due to thermal expansion of the materials under ICP torch loading must be completed. Using ABAQUS, a one step, steady-state coupled temperature displacement study was done to simulate the thermal expansion effects on the sample holder due to the heat flux loading supplied. Using conclusions obtained from the heat transfer study, the materials chosen for analysis in this study are brass and stainless steel. The goal is to determine if failure due to thermal stress will occur. Similar to the prior analysis in Section 3.1 this study was conducted prior to the decision to use stainless steel as the piping material.

To perform this study, material properties such as mass density, thermal conductivity, specific heat, Young's modulus, Poisson's ratio, yield stress, and thermal expansion coefficient must be known and input to the program. A coupled temperature displacement analysis in ABAQUS works similarly to a heat transfer analysis in the sense that heat flux and nodal temperature data is achieved, however, the temperature and heat flux data is then used to determine thermal stress data relevant to the heating achieved. As a finite element analysis (FEA) software, ABAQUS uses Equations 1, 2, 3, and 4 along with equations for thermal expansion, strain, elastic modulus, and thermal stress at the elemental level. The equation for thermal expansion is:

$$\Delta l = \alpha l_0 \Delta T \tag{5}$$

Where Δl is thermal expansion (represented as the change in length), ΔT is change in temperature, l_0 is initial length, and α is thermal expansion coefficient.

Strain is calculated using the following:

$$\varepsilon = \frac{\Delta l}{l_0} \tag{6}$$

Combining Equations 5 and 6, strain can now be written as:

$$\varepsilon = \frac{\alpha l_0 \Delta T}{l_0} \tag{7}$$

The equation for elastic modulus is shown in Equation 8, where stress is represented by σ.

$$E = \frac{\sigma}{\varepsilon} \tag{8}$$

Now, combining Equations 7 and 8, and solving for σ, the equation for thermal stress can be found:

$$\sigma_{thermal} = E\alpha\Delta T \tag{9}$$

3.2.1 Loading Conditions

Similar to the conductive heat transfer analysis, the thermal loading of the ICP torch is modelled as a surface heat flux load of $3\frac{W}{mm^2}$ on the porous sample surface, along with a constant temperature boundary condition of 7000K on the same surface. An encastre boundary condition was also placed on the portion highlighted in red on Figure 29 to eliminate movement in all directions from that surface. This was established to replicate the rigid connection that exists between the sample holder and the insertion probe.

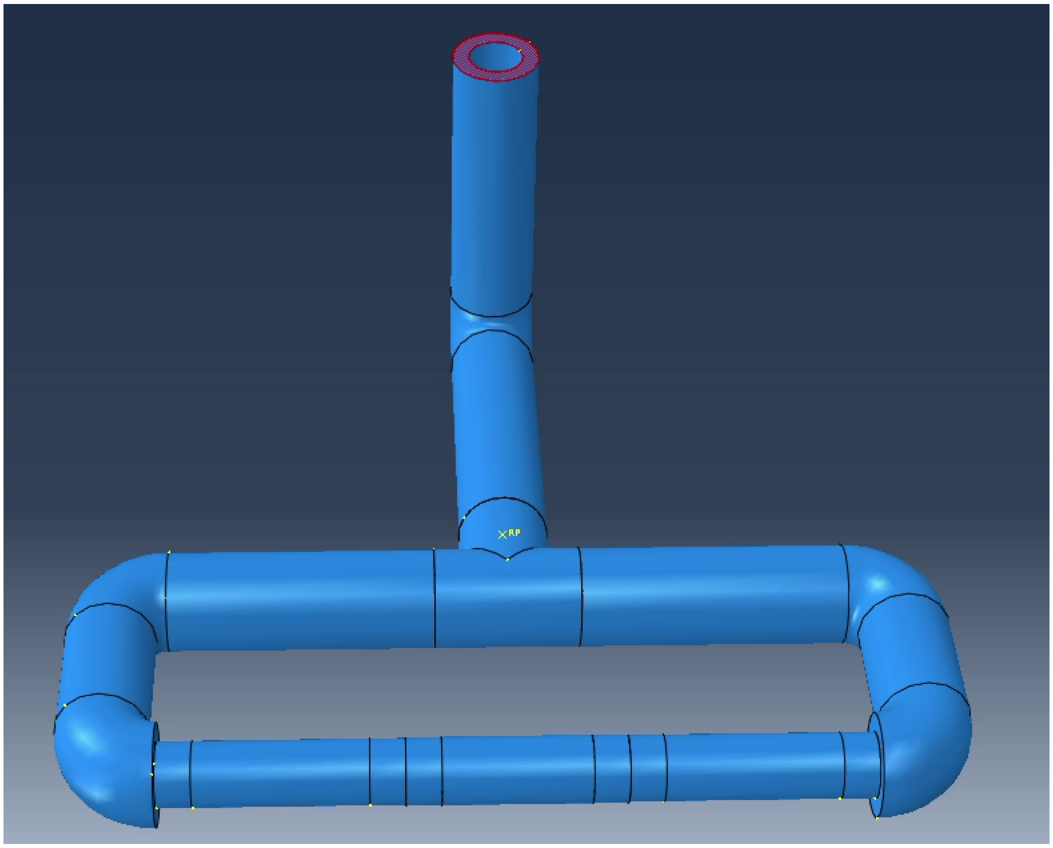


Figure 29: Portion of sample holder where the connection to the insertion probe is established.

3.2.2 Assumptions

During this study, results will only be obtained during heating, in which the holder will be held in the vacuum sealed test chamber seen in Figure 23. Due to this, convective heat transfer is negligible, and only conduction and radiation interactions are established. These interactions are defined in the same manner as in the heat transfer analysis. A pre-defined temperature field of 293K was placed on all nodes of the sample holder before applying heat to indicate that the holder will be starting at room temperature. Each part within the model assembly is connected using tie constraints to tie together all nodes between different part interfaces. As mentioned before, the use of tie constraints in ABAQUS when performing heat transfer studies will equate temperatures at matching nodes; this is a simplification made to the analysis, as the tie constraint will assume there is no thermal resistance across differing material part interfaces. In a coupled temperature displacement study, tie constraints are also used so that interfacing surfaces move together when under loading.

For this investigation, observations will be made on the brass and stainless steel 90° bend portions of the holder only to see if failure occurs due to thermal stressing. The front end of the sample holder containing the porous sample and molybdenum pieces will be ignored. This is due to the fact that Team #31's counterpart from the University of Colorado Boulder has already studied the effects of thermal expansion on the sample and molybdenum under loading. They have confirmed the validity of using these materials in testing.

3.2.3 Results

Due to large temperature differences between the pre-defined temperature field of 293K and the final temperature of the heating step, thermal expansion will occur in both the axial and circumferential directions. Figure 30 shows the distribution of von Mises stress at all points on the sample holder design, while Figure 31 shows a blown up image of the color and stress scaling used in Figure 30.

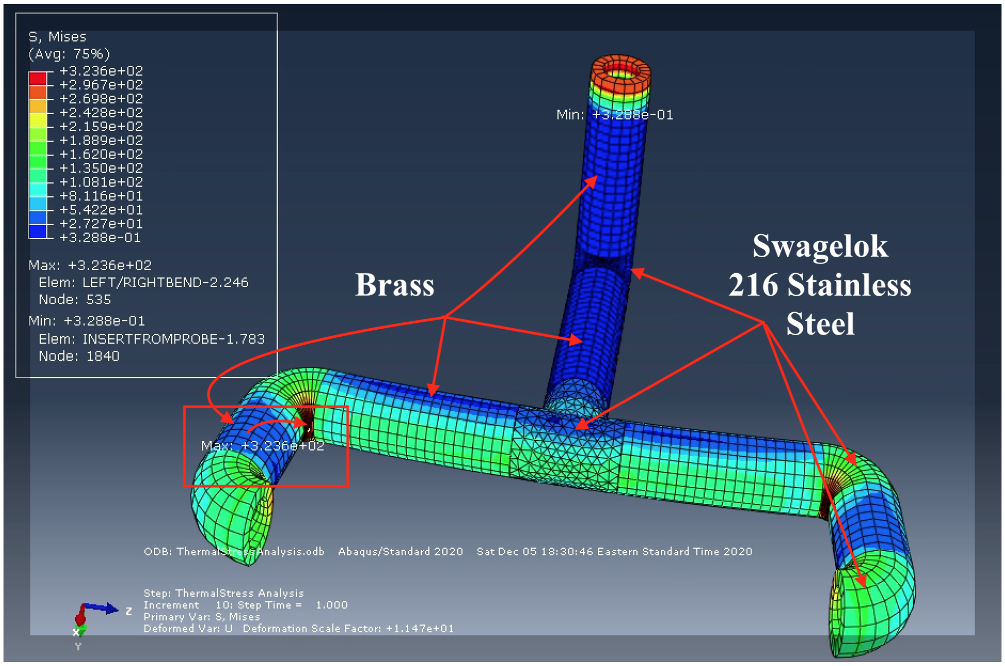


Figure 30: Von mises stress due to thermal expansion.

```
S, Mises
(Avg: 75%)
    +3.236e+02
    +2.967e+02
    +2.698e+02
    +2.428e+02
    +2.159e+02
    +1.889e+02
    +1.620e+02
    +1.350e+02
    +1.081e+02
    +8.116e+01
    +5.422e+01
    +2.727e+01
    +3.288e-01

Max: +3.236e+02
  Elem: LEFT/RIGHTBEND-2.246
  Node: 535
Min: +3.288e-01
  Elem: INSERTFROMPROBE-1.783
  Node: 1840
```

Figure 31: Expanded image of color-coated von mises stress parameters during max heat flux loading.

Boxed off in red on Figure 30 is the maximum von Mises stress in the sample holder design with a value of 323.6 MPa. All stress results seen are in units of MPa. Von Mises stress is often used as a measurement for ductile materials, such as metals, in the engineering field to determine if the given material will yield or fracture under the applied loading. Given that the materials used throughout the sample holder are all ductile metals, von Mises stress will be compared to the material's known failure stress to determine the possibility of failure under the ICP torch.

The portion of the design in which the maximum von Mises stress occurs is on the inner bend of the Swagelok fitting, which can be seen and is pointed to in Figure 30. This maximum stress occurs on both Swagelok fittings in the back section of the holder, as the design is symmetrical. With a ultimate strength of 515 MPa, the stainless steel portion is not at risk of failure. A factor of safety was calculated to be 1.59 and can be seen in Equation 11.

$$FS_{StainlessSteel} = \frac{515MPa}{323.6MPa} \tag{10}$$

$$FS_{StainlessSteel} = 1.59 \tag{11}$$

Based on the color distribution from Figure 30 and the stress values corresponding to colors seen in Figure 31, no portion of the brass is at risk of failure. This can be confirmed in ABAQUS by looking at the maximum and minimum von Mises stress values on just the brass portions of the sample holder that are of concern. Across all brass portions, the maximum stress achieved was 194.8 MPa, which can be seen highlighted in red on Figure 32. Although this value is very close to the brass yield stress of 195 MPa, it is still much lower than the 360 MPa ultimate stress of brass. A factor of safety for the brass portion was calculated to be 1.85 and can be seen in Equation 13.

$$FS_{Brass} = \frac{360MPa}{194.8MPa} \tag{12}$$

$$FS_{Brass} = 1.85 \tag{13}$$

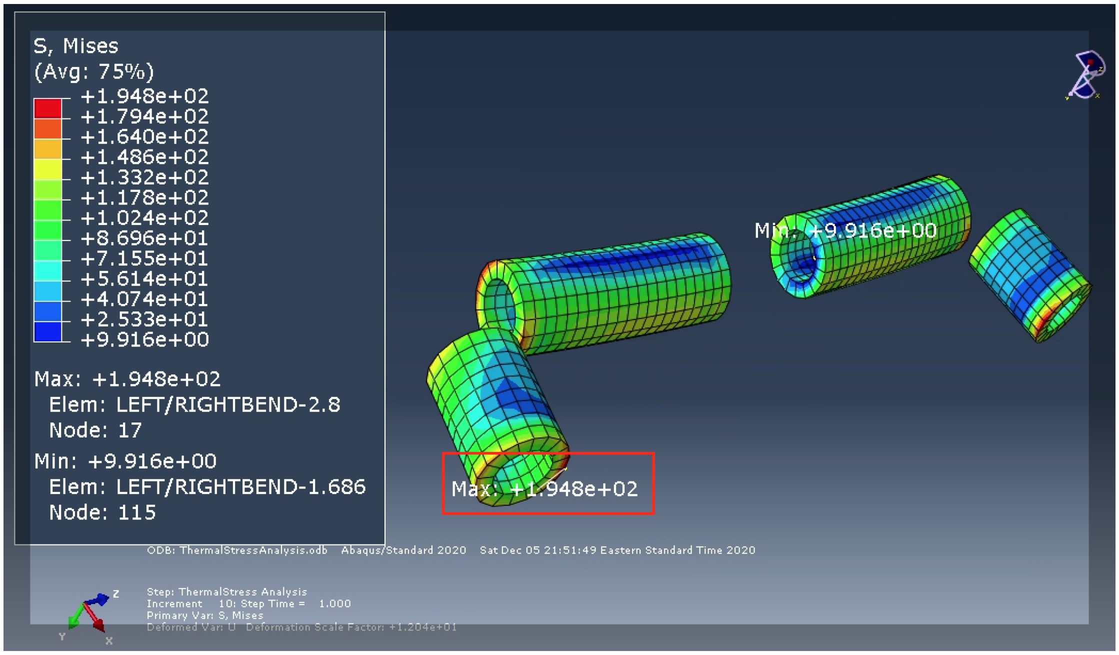


Figure 32: Maximum Von Mises stress on brass portion of the sample holder

This analysis was also modified during the spring semester to include 316 stainless steel as the piping material rather than brass. The von mises stress data can be seen in Figure 33. With 316 stainless steel as the piping material the stressing on the swagelok bend increased to 405.4 MPa, which is still below the ultimate stress of 515 MPa.

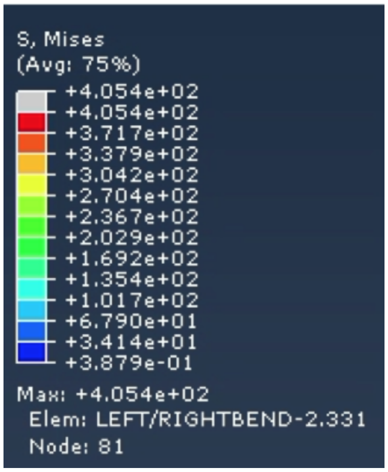


Figure 33: Von Mises stress with stainless steel as the piping material.

Internal cooling due to the transpiration gas flow throughout the design will have a positive effect on these values and most likely bring factors of safety up even further. For future analyses, it may be helpful to include the flow of the transpiration gas through the internal piping, however, too little is currently known of the type of gas, and pressure at which to inject due to the novelty of Project 31. Once further testing is done in lab and more information is gathered, this analysis can be built upon to achieve even more accurate results.

3.3 Analysis: Static Loads

One of the customer requirements for Project 31 is that the sample holder shall be able to securely hold the porous sample over the plasma torch. To complete this requirement, a rigid connection to the insertion probe must be established and the geometry of the design must be strong enough so that the sample will not sag and fall into the torch. To test the rigidity of the current sample holder design, a static load analysis will be run on ABAQUS to determine if the design can support it's weight with negligible deformation and stressing. The materials identified for this analysis are brass, stainless steel, molybdenum, and the porous sample. Material properties of modulus of elasticity, yield stress, density, and Poisson's ratio are necessary for all materials to run this study. The analysis will be run simulating the sample holder attached to the insertion probe, with gravity acting as the only load on the structure. No other forces will be present on the sample holder other than gravity. In order to simulate this, ABAQUS will be calculating stresses and displacements from the force acting on the sample holder due to it's weight. The basic equations used for a static FEA stress analysis begin with an expression of Newton's Second Law, where F is the force, σ is stress.

$$\nabla \cdot \sigma + F = 0 \tag{14}$$

In correlation with Equation 14, Equations 7 and 8 are also used. These governing equations are broken down into matrix form by the software, so that finite element analysis can be performed on all degrees of freedom for each node and element. The basic equation for force of a static analysis broken into element matrix form can be seen as:

$$\{\vec{F}\} = [K]\{u\} \tag{15}$$

In this equation $\{\vec{F}\}$ is the force vector broken down into component form, [K] is the stiffness matrix, and {u} is displacement broken into component form.

3.3.1 Loading Conditions

Gravity will be simulated as the only load applied on the sample holder. With gravity present as the loading scenario, the only forces acting on the holder will be due to weight in the downward, y-direction.

3.3.2 Assumptions

An encastre boundary condition will also be on the sample holder in the spot highlighted in Figure 29. This constrains movement in all directions of the holder at that position to signify a rigid connection being made to the insertion probe. Tie constraints are also placed on all conjoined surfaces, such that all interfacing parts react simultaneously. Since the only force acting on the holder is due to weight, the motion of the holder will be simplified to only stress and displacement in the y-direction.

3.3.3 Results

The maximum stress applied on the holder during the analysis was found to be 1.451 MPa, while the maximum displacement was found to be 0.001932 mm. These forces can be seen in Figures 34 and 35.

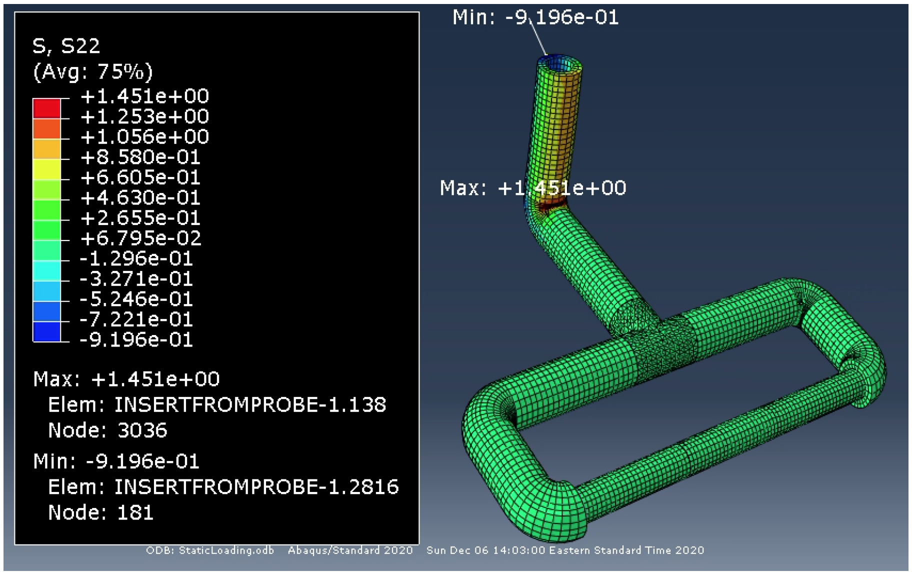


Figure 34: Stress of the sample holder under gravity load in the y-direction.

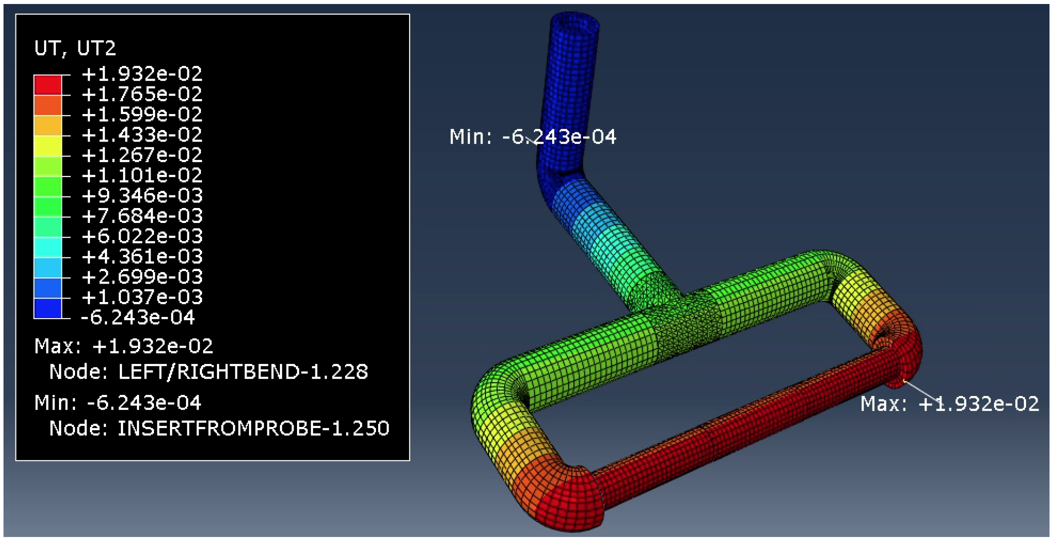


Figure 35: Displacement of the sample holder under gravity load in the y-direction.

From Figure 34, the maximum stress occurs on the inside bend of the furthest back Swagelok fitting. The Swagelok bends are modelled as stainless steel, which has a yield stress of 195 MPa. With a maximum stress of 1.451 MPa acting on the stainless steel it can be confirmed that the part is far from failure. Therefore, stressing due to weight of the holder design can be seen as negligible. Similarly, the deformation can also be characterized as negligible due to the maximum displacement value being minuscule. Thus, it can be concluded that the tubing and design of the sample holder will be rigid and strong enough to support its weight when attached to the insertion probe.

3.4 Engineering Specifications

Of all the engineering specifications that Team 31 identified and verified, the prototype design has been able to meet all of the specifications. Specifications 10 and 20 were met by selecting stainless steel as the main material to use for the assembly of the prototype. Specification 30 was met by designing the prototype with simplicity in mind. The Swagelok connections between the sample and the sample holder allow for quick, simple, and secure connections to be established while still allowing for easy swapping out of samples. Specification 40 was met by dimensioning the prototype with adequate tolerances to ensure that the provided sample material would be able to interface properly with the holder. Specification 60 was met by selecting parts and materials for the prototype with cost in mind, so that the best materials for the lowest possible cost were being used. Specifications 50 and 70 have not been verified yet, but these specifications were kept in mind when creating the design of the prototype. They will be tested once the prototype has been fully assembled, with all of the Swagelok connections properly tightened. Specifications 10, 20, 40 and 70 are design constraints and 3 out of 4 of them have been met, however, because specification 70 has not been verified yet, the total design constraint success is still currently a fail. Overall, the engineering specifications for this prototype has a 66% pass relative pass percentage since five specifications are passes and two are unverified. The complete engineering specifications spreadsheet can be found in the appendices (Section 5.2).

3.5 Conclusion

Overall, the project is a success when compared to the problem statement and client's expectations. The exact problem statement was to design a sample holder that would enable testing of a novel porous material provided by the University of Colorado Boulder in the University of Vermont's ICP Torch facility. The main customer requirements and expectations for the sample holder prototype are as follows:

1. Hold the sample securely so that it will efficiently disperse the transpiration gas and so it does not fall in the plasma torch.
2. Attach to the existing insertion probe, to eliminate the need to create a new separate way to attach to the testing chamber.
3. Sample holder must be able to withstand the high thermal loading conditions provided by the ICP torch, if the testing conditions of the material are extremely high, the holder must work properly under the same conditions.
4. Sample holder must be able to contain the variable injection gas flow, and effectively inject it through the sample. This new material only works at mitigating these high thermal loads if the transpiration gas is efficiently pumped through the pores on it.

When comparing the produced prototype to the list of requirements, it can be seen that the prototype was designed with all the functionality needed to be a success.

Using the likert scale from the sprint reviews, it can be estimated that our client has a satisfaction level of 5. This can be predicted because the delivered prototype meets all requirements and consistent communication with our client throughout the year has allowed us to ensure that a product which meets expectations is being delivered. Due to the busyness of Professor Fletcher during the final weeks of the semester, the sample holder has yet to be tested, however testing will be done at his convenience.

There are various adjustments that could be made to the prototype design in order to improve the overall product. When the official porous sample material is received by the client, Team 31 recommends that the prototype design be adapted to remove the front Swagelok elbows where the sample attaches to the holder. This would reduce weight, allowing the sample holder to be more stable overall during testing. This could not be accomplished during the course of SEED because an official sample material was needed in order to identify how to best remove the Swageloks from that area of the design. Another recommendation for future work is to perform testing of the sample holder and sample configuration in the ICP chamber with temperature and pressure measuring devices in place to identify the areas of the holder that are under the most stress from high temperatures and pressures. This would allow for improvements to be made in specific areas of the prototype design. Collecting data from temperature measurements will help to determine if a cooling mechanism needs to be incorporated within the design. The pressure measurements will allow for a better gauge of the specific pressure stresses the prototype will be experiencing during routine testing, so predictions can be made for the life cycle of the prototype and where the highest risk failure areas are located.

4 Project Reflection

4.1 Impact Statement

One of the biggest risks for Team 31's sample holder design is the possibility of the holder loosing structural stability and sagging into the plasma torch during testing. A professional decision was required when addressing this risk to ensure that the connection between the sample holder and insertion probe is secure enough to reduce the chances of the sample sinking into the torch. This needs to be avoided because it would result in the destruction of the sample material. It is the responsibility of the engineers on this team to design a sample holder that will maintain its material properties and not compromise the any of the testing procedures. To address this risk, professional engineering decisions were required to determine ways to reduce weight on the front end of the sample holder to lessen the potential degree of sagging. The team decided to address this risk by running simulations to determine the potential weight effects on the sample holder in order to find the optimal combination of weight and material type to ensure a minimal displacement of the sample during testing. The ultimate decision was to eliminate Swagelok joints in the back and, instead, bend the piping to the front Swagelok bends. This eliminated a total of 105.02 grams from the total weight of the sample holder. The impact was the safety of the testing sample and ensuring that the sample will not be damaged and ruin experimental data during testing. This is beneficial for the client because the inabilities of the sample holder will not effect the data being extracted during testing. By recognizing the impact of the sample holder created by Team 31 on hypersonic leading edge material testing, the design was carefully chosen to enhance success.

An additional risk for Team 31's sample holder design is the overheating of the sample holder during testing. A professional decision was required when addressing this risk to ensure that the sample holder would not overheat, since this would cause a degradation in the holder's material properties and the potential for the holder to fail during testing. This needs to be avoided because it would result in the destruction of both the sample holder and the sample material, which would be financially and time costly failure. It is the responsibility of the engineers on this team to design a sample holder that will not overheat during testing and compromise the testing procedures. To address this risk, professional engineering decisions were required to determine the optimal material to build the sample holder prototype out of and if any form of cooling needed to be incorporated into the design. The team decided to address this risk by running simulations with different materials to determine which material should be chosen and if a cooling mechanism was required. The ultimate decision was to manufacture the sample holder out of stainless steel and to not incorporate cooling with the initial prototype. The option for cooling mechanisms to be added later is still in place, however, the team decided to run physical tests on the sample holder and collect actual, experimental temperature data first before making a final decision about cooling mechanisms. The impact was the strength and security of the sample holder and ensuring that the sample holder will not fail during testing, which would damage the sample material and ruin the collected experimental data. This is beneficial for the client because the potential failure of the sample holder will not effect the data being extracted during testing. By recognizing the impact of the sample holder created by Team 31 on the completion of sample material testing, the prototype materials were carefully chosen to enhance success.

4.2 Lessons Learned

Because this was the first major project that all members of SEED Team 31 were a part of, it made way for many lessons to be learned throughout the 2020-2021 academic year. Obviously many issues that teams most likely experienced are derived from the COVID-19 pandemic and not being able to have the in person luxuries that make projects like this come together, Team 31 is no exception. SEED Team 31's client being a professor (Dr. Douglas Fletcher) at UVM may seem like a recipe for constant communication on this project, but that was hardly the case.

This year at UVM is a year in which the ABET Accreditation of the engineering department is reviewed, this takes a heavy toll on the work load of the hardworking department head of the mechanical engineering department, which happens to be Team 31's client, Dr. Douglas Fletcher. The student members of the team were also undergoing constant heavy work loads due to other course work to wrap up senior year, as this project was a small part of what needed to be completed to graduate. On top of that, pandemic restrictions made it so that the team could not just stop in to Professor Fletcher's office or lab in passing to ask clarifying questions on the project.

All of these reasons led to a difficult time establishing constant communication between team members and the client. It became hard to progress in some portions of the project because of fear of the progression heading in the wrong direction due to lack of clarifying communication with the client, as well as work that does get done ending up not being useful to the project. This slowed the progress of the project over time as the team did not want to have to do the work twice and, therefore, became complacent with their work.

After all these factors had been effecting the teams work, the resulting conclusions were made and applied to the how the team viewed work for the rest of the academic year. Firstly, the team started to work on all deliverables, sprint reviews, and sprint retrospectives as early as possible. This was done because if there was an issue due to communication troubles in the middle of a sprint, there would already be essentially what was the ”skeleton” of the work already done. When communication between client and team did happen it was easy to fill in information and get work done if everything was set up from the beginning.

Secondly, the team found many other ways of communicating between each other and with the client. Of course there is always emails, but those can get lost in inboxes easily. A team member was enrolled in a class that the client was teaching in person, which allowed for a weekly in person check in that required no appointment set up. Microsoft Teams was also used to schedule weekly meetings and to directly message the client when information was needed at a moments notice. Messages on this platform seem to get to the recipient quicker than emails do. Later in the fall semester, the team also utilized their assigned ”mentor” more to assist them in all aspects of the project, conveniently the same team member was also enrolled in an in person class they were teaching as well.

Based on the experiences highlighted above, a conclusion of recommendations can be given to future engineers who encounter similar problems. One recommendation is that getting work done early may seem like an obvious thing to do but it is more important to set yourself up to get work done early than it is to get the actual work done early. Setting yourself up and creating what was called the ”skeleton” of the work makes it easy to understand what actually needs to get done. When the time comes to sit down and complete some task, all the key steps and components you need are already highlighted for you, and at that point it becomes just ”filling in” work. A second recommendation is that there is always other forms of communication. It might seem like emails are the obvious way to go, and for most groups that might be the case. Any way you can establish another form of communication can set you up for success, even if that communication is just a passing conversation.

4.3 Project Retrospective

Many of the chosen Kaizens impacted the team throughout the academic year, obviously some were more helpful than others. During Sprint 4, the communication between team and client was becoming difficult due to the busy schedules of both parties. This made it hard to progress forward with the project, but the team developed a Kazien to try to propel their work as far forward as possible. The Kaizen developed was that when communication was lagging, to put progress into the team's hands and do as possible without the aid of the client.

This was chosen because due to the rapid deadlines that were approaching as it was imperative that work get done in a timely fashion. It was decided that the Kaizen could be measured through whether or not there was a working prototype completed by the end of the following sprint. At the end of sprint 5, a prototype was not fully complete due to manufacturing holds and waiting on shipments, but the Kaizen was able to keep the team on track and improve performance during the entirety of the sprint.

Since it was the first time any team member had used SCRUM there were some struggles with it in the beginning, but SEED Team 31 became very comfortable with many aspects of The Scrum Guide as the semester progressed. One of these aspects was the idea of transparency, meaning that there is a common standard for all things being worked on and completed in the project. As in many teams, every member works better at different things, and that is no different for this team. Each member fell into different undefined roles during the project, but in the beginning of the year the idea of transparency was applied, and a common understanding of the definition of done, in-progress, and yet to be attended to were laid out. This allowed the team to get items on the project backlog done in their own ways while allowing for it all to come together in the end with no issues. This is a tactic that all team members will apply to their future projects.

With the success of many aspects of The Scrum Guide, there were a few aspects applied that did not work well for the team. Three college seniors (even with a shared major) have extremely different schedules, this makes it hard to have meeting times at the same time every week, let alone every day. The aspect of a

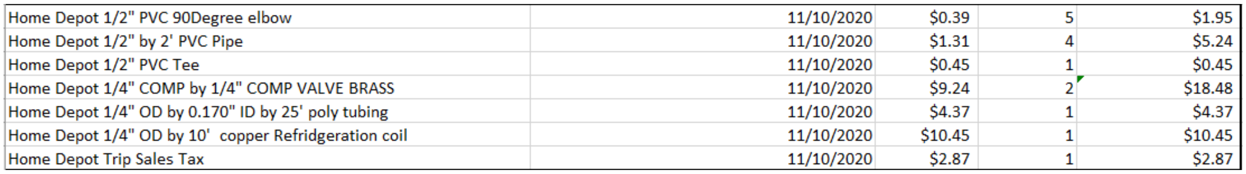
”Daily Scrum” became harder and harder for the team as the academic year progressed, sometimes meeting 15-20 min a week was a struggle. Deciding when the next scrum will be at the end of the current scrum is a way that this aspect should be modified. That way if there is a lot of tasks to be completed in between there can be a long amount of time in between, and if only a few things to get done the time in between can be short. That way the scrums that do happen have more fair deadlines for the work being done at that specific time.

4.4 Product Review

Throughout the year, Team 31 established their sprint goals as smaller milestones towards the eventual completion of the sample holder prototype. These goals included creating a preliminary design, finalizing the design, building a scale model of the physical prototype, altering the design of the holder, and ultimately producing a final physical prototype. There were some delays with these sprint goals, which resulted in them being pushed to the following sprint. These delays were due to communication difficulty between Team 31, the client, and the CU Boulder counterparts. Another round of delays was due to the ICP Torch lab being shutdown for a period of time, which limited our ability to test the final prototype. Despite all of these difficulties, both the client and the development team are satisfied with the product the team delivered. The finalization of the prototype sample holder means that testing will be able to commence as soon as the sample material is obtained. The rationale for the level of satisfaction is based on the regularly high scores that Team 31 received from their client during every sprint review. There are no discrepancies in levels of satisfaction that need to be commented on. The final product backlog can be found in the appendix (Section 5.3) of this final design report. The only remaining item that is essential to project success is the testing of the sample holder in the ICP torch chamber. This item has not been completed yet due to scheduling difficulties with the lab and our client. Ideally, team 31 will be able to perform testing in the week following the submission of this report.

4.5 Budget Review

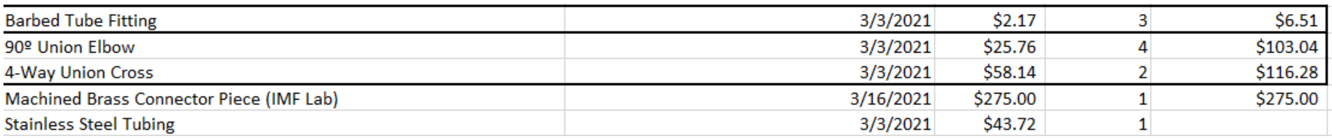
For the whole year SEED Team 31 was given a budget of $7,500, which was more than enough to prototype many different aspects of the final model. Throughout the course there were a few major items purchased, for the end of the first semester the team wanted to have a physical prototype to show progression in the early stages of design. The model constructed was made out of PVC piping components, poly tubing, refrigeration coil (ended up not being used), and brass valves. A list of all components and their respective price can be seen below Figure 36, and a photo of this early model can be seen above in the working design concept portion of the report, Figure 6. The total price for this receipt was $43.81.



Home Depot 1/2" PVC 90Degree elbow		11/10/2020	$0.39	5	$1.95
Home Depot 1/2" by 2' PVC Pipe		11/10/2020	$1.31	4	$5.24
Home Depot 1/2" PVC Tee		11/10/2020	$0.45	1	$0.45
Home Depot 1/4" COMP by 1/4" COMP VALVE BRASS		11/10/2020	$9.24	2	$18.48
Home Depot 1/4" OD by 0.170" ID by 25' poly tubing		11/10/2020	$4.37	1	$4.37
Home Depot 1/4" OD by 10' copper Refridgeration coil		11/10/2020	$10.45	1	$10.45
Home Depot Trip Sales Tax		11/10/2020	$2.87	1	$2.87

Figure 36: Early Model Spending

The spring semester was when most of the spending took place, as that where the final components for the sample holder were researched and purchased. The final model was constructed out of only a few different components, and because of its symmetrical design there were only a few specific components ordered. Stainless steel piping was used to connect 1 stainless steel Swagelok 4-Way Union Cross to 2 90° Union Elbows, double of what was needed was purchased simply to have extra pieces. The piping was borrowed from the ICP torch lab so it did not effect the budget. A custom brass connector piece was modeled in Solidworks and sent to the IMF lab for construction and was the most expensive portion of the sample holder, screwed into the top of the brass piece were barbed tube fittings to accommodate the transpiration gas, like many other components extras were ordered. The total for this receipt was $500.83, seen in figure 37



Barbed Tube Fitting		3/3/2021	$2.17	3	$6.51
90º Union Elbow		3/3/2021	$25.76	4	$103.04
4-Way Union Cross		3/3/2021	$58.14	2	$116.28
Machined Brass Connector Piece (IMF Lab)		3/16/2021	$275.00	1	$275.00
Stainless Steel Tubing		3/3/2021	$43.72	1	

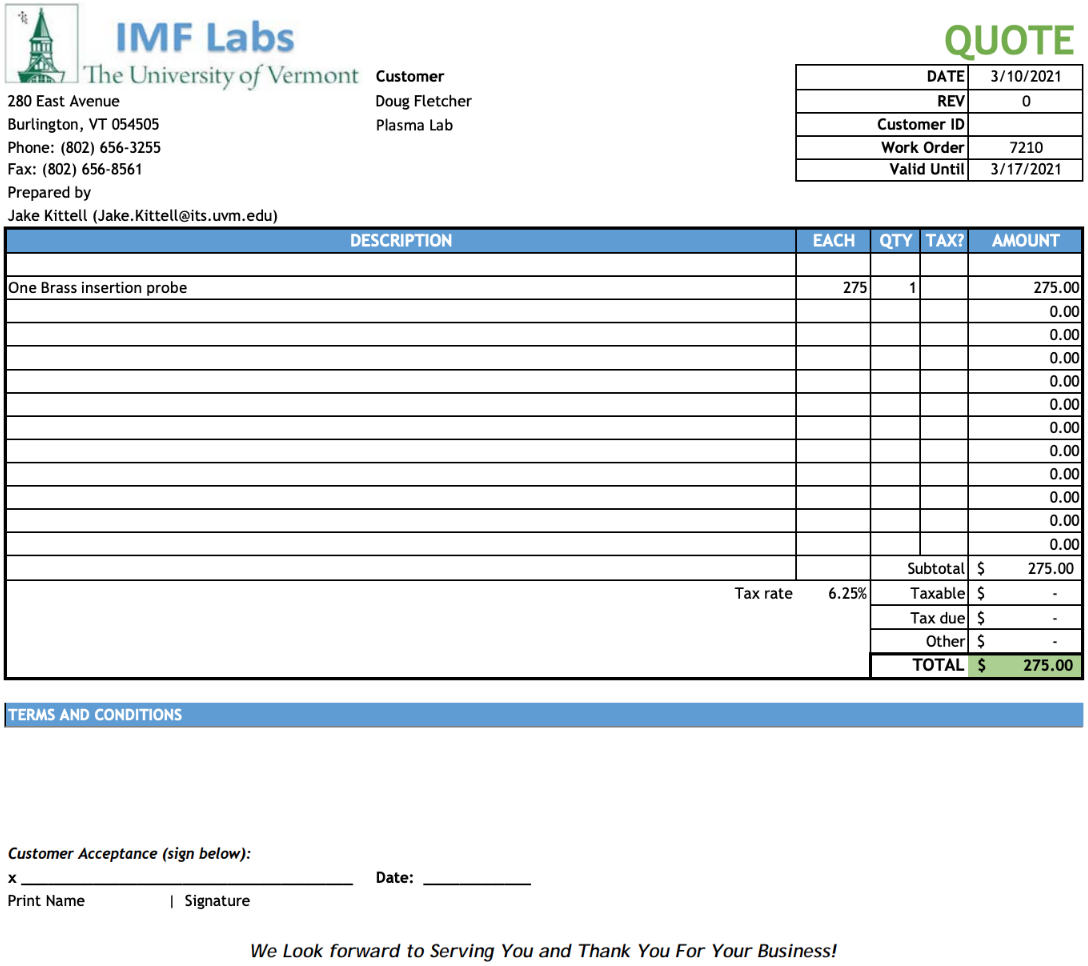
Figure 37: Final Model Spending

Both these receipts summed together brings the total amount spent to \$588.36, or 7.8% of allotted budget. This leaves \$6911.64 left to replicate the final design of the sample holder should it need to be reconstructed to test other cylindrical components in the ICP Torch facility. The successful budget management was due to the fact that many early prototypes were developed virtually using SolidWorks, which is supplied by the university for free. This allowed rapid prototyping virtually at no expense, and when the time came to create a physical model there was plenty of money left to no have to worry about going over budget. Going forward SEED Team 31 now has a better idea on how much money items like this will cost, and in the future creating many more physical models would improve success in future projects. This would allow the team to have a better understanding of how these physical models would perform, but this is hard due to the COVID-19 pandemic, where it is just easier to prototype virtually.

5 Appendices

5.1 UVM IMF Lab Quote and Information

The connection piece drawing was sent to three machinists to see which could create the connection piece in the most cost effective way. The drawing was sent to the UVM Machine Shop, Jake Kittell of the UVM IMF Lab, and Doug Gomez. Both the UVM Machine Shop and Doug Gomez were the cheapest options, while the IMF lab required payment. The machining quote from Jake Kittell of the UVM IMF Lab can be seen in Figure 38 and has been included in the budget if this piece needs to be manufactured again. Although Mr. Kittell was not chosen as the machinist, a quote for the price of machining the part was still provided. Doug Gomez however was chosen as the machinist due to convenience and his quick response. Brass material was provided by Mr. Gomez for free, along with the machining of the part. The only purchase necessary was the 1/16 NPT tap for the threading. Aside from this Doug also had great suggestions for improvements in the design, such as the addition of more material where the shaft meets the main component and correct tolerance. This feedback was very helpful and influential to the final connection piece design.



IMF Labs
The University of Vermont
280 East Avenue
Burlington, VT 054505
Phone: (802) 656-3255
Fax: (802) 656-8561
Prepared by
Jake Kittell (Jake.Kittell@its.uvm.edu)

Customer
Doug Fletcher
Plasma Lab

QUOTE

DATE	3/10/2021
REV	0
Customer ID	
Work Order	7210
Valid Until	3/17/2021

DESCRIPTION	EACH	QTY	TAX?	AMOUNT
One Brass insertion probe	275	1		275.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
				0.00
		Subtotal		$ 275.00
Tax rate	6.25%	Taxable		$ -
		Tax due		$ -
		Other		$ -
		TOTAL		**$ 275.00**

TERMS AND CONDITIONS

Customer Acceptance (sign below):

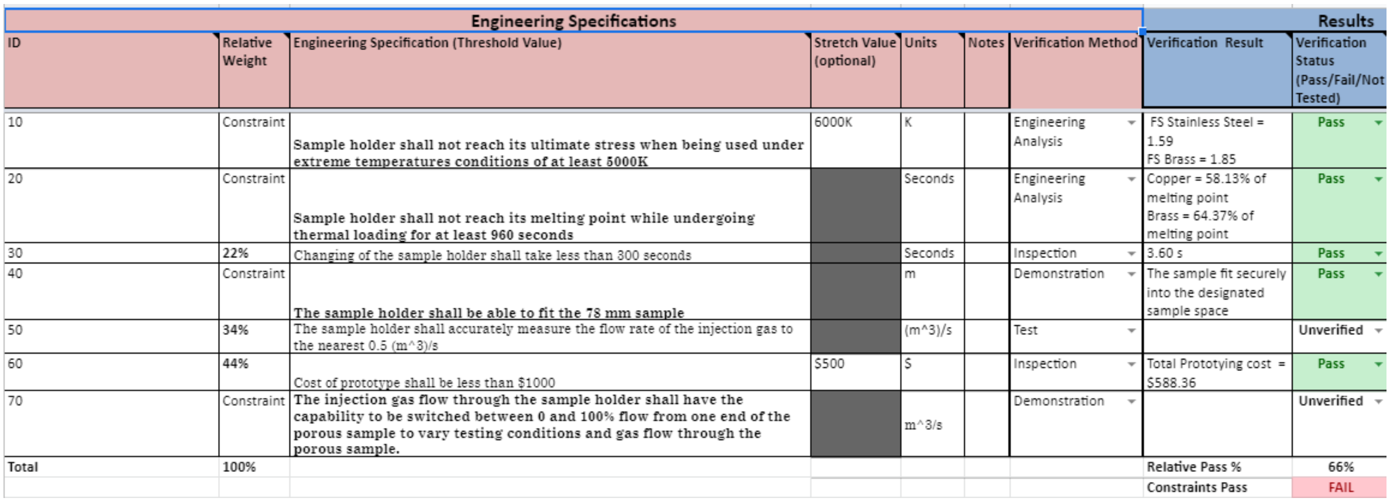
x ______________________________ **Date:** __________

Print Name | Signature

We Look forward to Serving You and Thank You For Your Business!

Figure 38: UVM IMF Lab Quote for the custom brass connection piece machining.

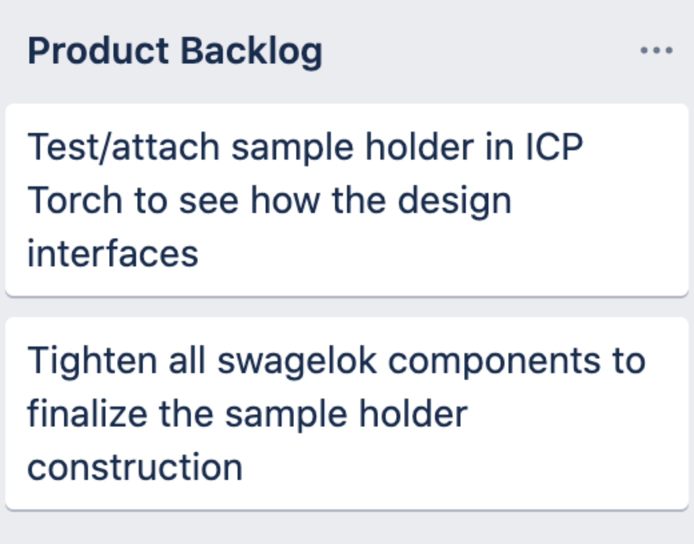
5.2 Engineering Specifications Document Image



Engineering Specifications							Results	
ID	Relative Weight	Engineering Specification (Threshold Value)	Stretch Value (optional)	Units	Notes	Verification Method	Verification Result	Verification Status (Pass/Fail/Not Tested)
10	Constraint	**Sample holder shall not reach its ultimate stress when being used under extreme temperatures conditions of at least 5000K**	6000K	K		Engineering Analysis	FS Stainless Steel = 1.59 FS Brass = 1.85	Pass
20	Constraint	**Sample holder shall not reach its melting point while undergoing thermal loading for at least 960 seconds**		Seconds		Engineering Analysis	Copper = 58.13% of melting point Brass = 64.37% of melting point	Pass
30	**22%**	Changing of the sample holder shall take less than 300 seconds		Seconds		Inspection	3.60 s	Pass
40	Constraint	**The sample holder shall be able to fit the 78 mm sample**		m		Demonstration	The sample fit securely into the designated sample space	Pass
50	**34%**	The sample holder shall accurately measure the flow rate of the injection gas to the nearest 0.5 (m^3)/s		(m^3)/s		Test		**Unverified**
60	**44%**	Cost of prototype shall be less than $1000	$500	$		Inspection	Total Prototying cost = $588.36	Pass
70	Constraint	**The injection gas flow through the sample holder shall have the capability to be switched between 0 and 100% flow from one end of the porous sample to vary testing conditions and gas flow through the porous sample.**		m^3/s		Demonstration		**Unverified**
Total	**100%**						**Relative Pass %**	**66%**
							Constraints Pass	FAIL

Figure 39: Engineering Specifications

5.3 Final Product Backlog



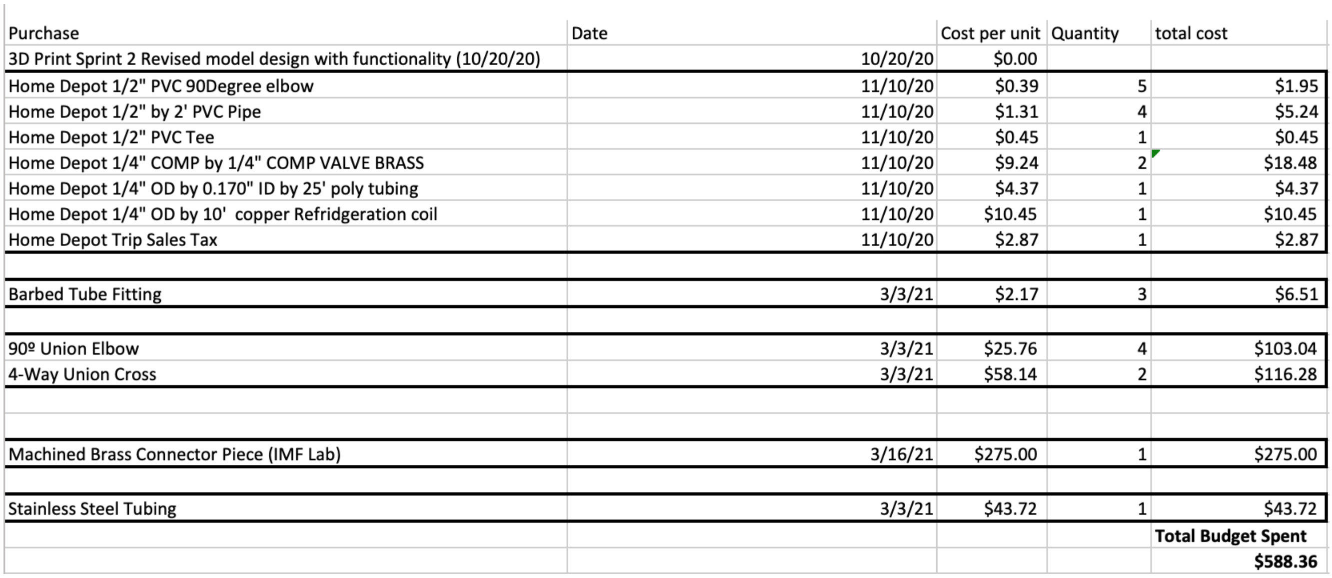
Product Backlog

Test/attach sample holder in ICP Torch to see how the design interfaces

Tighten all swagelok components to finalize the sample holder construction

Figure 40: Product Backlog for SEED Team 31

5.4 Budget Spreadsheet



Purchase	Date	Cost per unit	Quantity	total cost
3D Print Sprint 2 Revised model design with functionality (10/20/20)	10/20/20	$0.00		
Home Depot 1/2" PVC 90Degree elbow	11/10/20	$0.39	5	$1.95
Home Depot 1/2" by 2' PVC Pipe	11/10/20	$1.31	4	$5.24
Home Depot 1/2" PVC Tee	11/10/20	$0.45	1	$0.45
Home Depot 1/4" COMP by 1/4" COMP VALVE BRASS	11/10/20	$9.24	2	$18.48
Home Depot 1/4" OD by 0.170" ID by 25' poly tubing	11/10/20	$4.37	1	$4.37
Home Depot 1/4" OD by 10' copper Refridgeration coil	11/10/20	$10.45	1	$10.45
Home Depot Trip Sales Tax	11/10/20	$2.87	1	$2.87
Barbed Tube Fitting	3/3/21	$2.17	3	$6.51
90º Union Elbow	3/3/21	$25.76	4	$103.04
4-Way Union Cross	3/3/21	$58.14	2	$116.28
Machined Brass Connector Piece (IMF Lab)	3/16/21	$275.00	1	$275.00
Stainless Steel Tubing	3/3/21	$43.72	1	$43.72
				Total Budget Spent
				$588.36

Figure 41: Purchase backlog for SEED Team 31.

6 References

[1] D. G. Fletcher, J. M. Meyers, and W. P. Owens, "Development of a 30 kW Inductively Coupled Plasma Torch for Advanced Aerospace Material Investigations," *The University of Vermont*, February 2012.

[2] Pure Copper Material Properties. (n.d.). Retrieved December 06, 2020, from http://www-ferp.ucsd.edu/LIB/PROPS/PANOS/cu.html

[3] The Online Materials Information Resource. (n.d.). Retrieved December 06, 2020, from http://www.matweb.com/search/datasheet.aspx?matguid=5edc39d3b0fd44efa9fdd90d049c3737

[4] Brass Material Properties Data Sheet. (n.d.). Retrieved December 06, 2020, from http://www.matweb.com/search/DataSheet. aspx?MatGUID=d3bd4617903543ada92f4c101c2a20e5

[5] Dunbar, Brian. (n.d.). X-43A Aircraft. Retrieved from https://www.nasa.gov/centers/armstrong /history/experimntal_aircraft/X-43A.html

[6] What is Von Mises Stress?: SimScale Finite Element Analysis. (2020, October 09). Retrieved December 05, 2020, from https://www.simscale.com/docs/simwiki/fea-finite-element-analysis/what-is-von-mises-stress/

[7] SS-2-UT-3. (n.d.). Retrieved December 06, 2020, from https://www.swagelok.com/en/catalog/Product /Detail?part=SS-2-UT-3

Technical Documentation Package

SEED Team #31: New Material for Hypersonic Leading Edges
Avrey Carifa, Colin Hodge, Dan Jordan

May 11, 2021

Date	**Revision**	**Release Notes**
4/10/2021	01	Initial release
4/21/2021	02	Updating verification methods
4/28/2021	03	Updating verification results
5/11/2021	04	Final Edits

Contents

1 Design Documentation

1.1 System Overview

The following images have been taken from the full solidworks assembly of SEED Team 31's Sample Holder Design for Hypersonic Leading Edge Material Testing. The name of this file is SEED Sample Holder Assembly(VFinal).SLDASM and can be found following the instructions in Section 3.

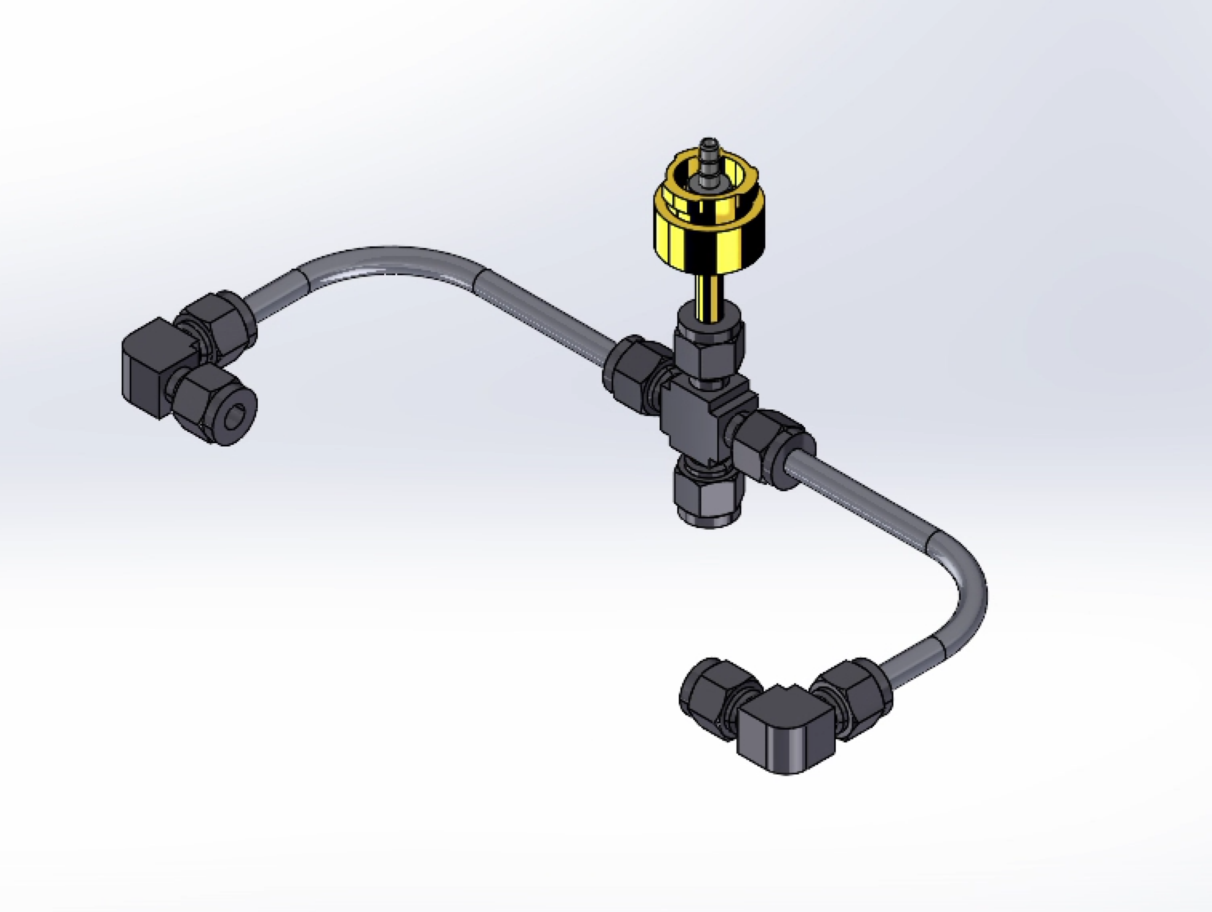


Figure 1: Sample Holder Assembly

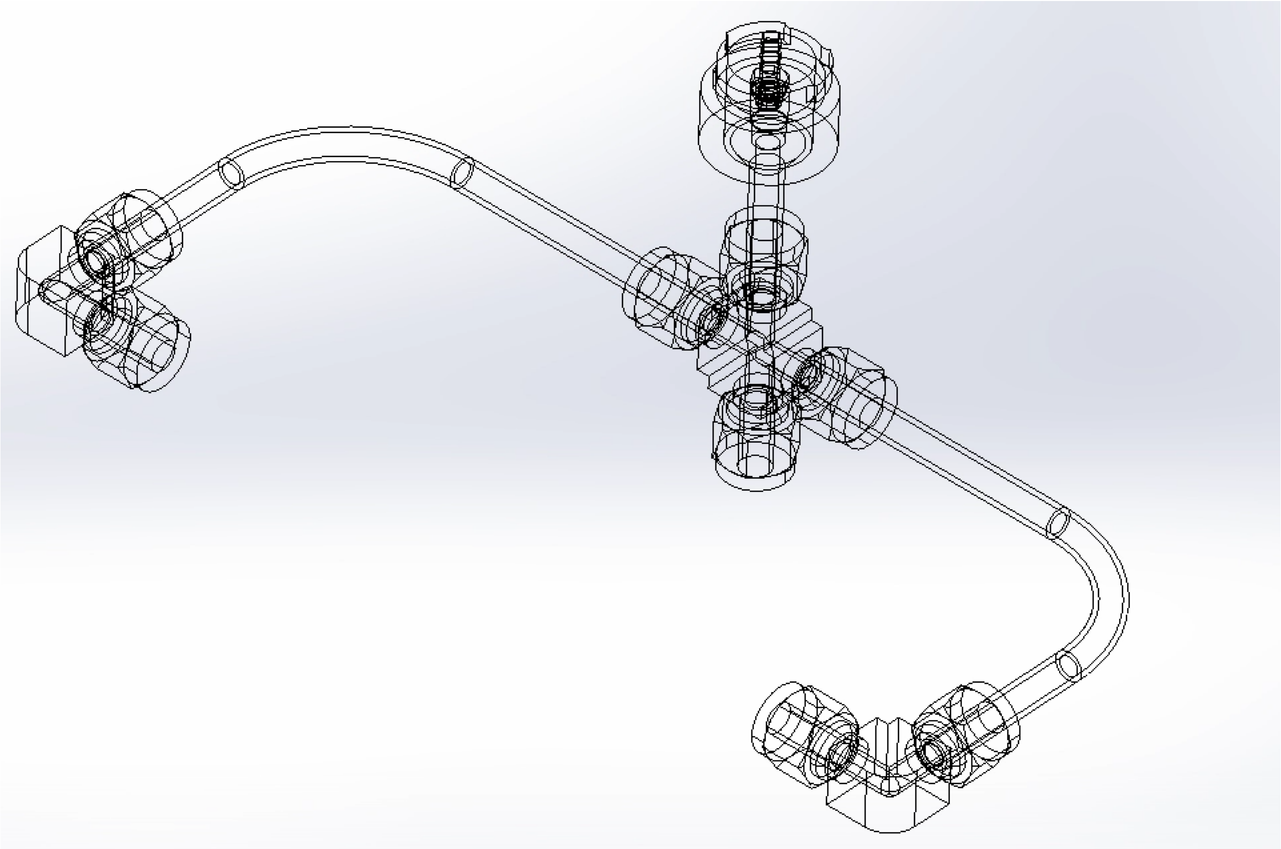


Figure 2: Sample Holder Assembly in wire frame view to show inner piping.

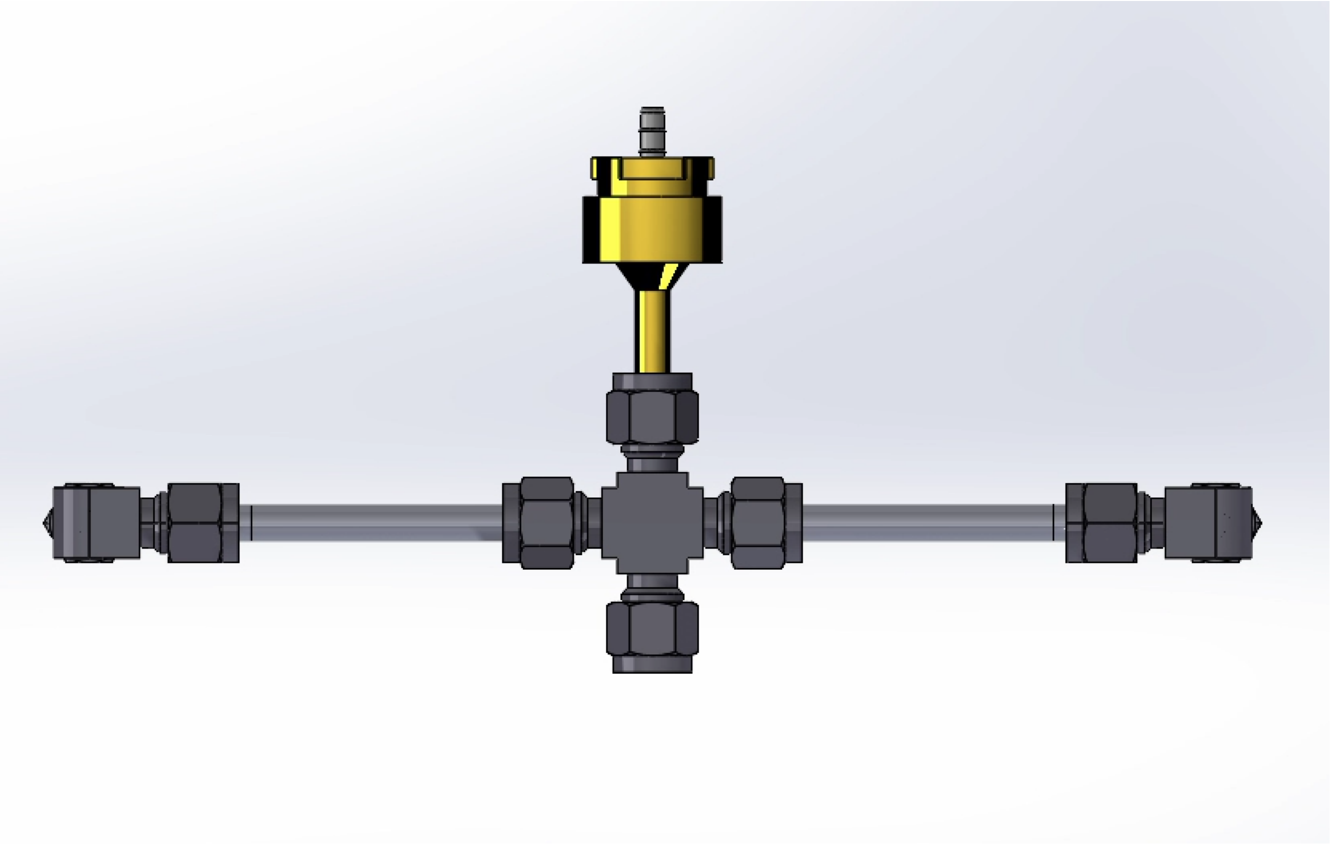


Figure 3: Sample Holder Assembly front view

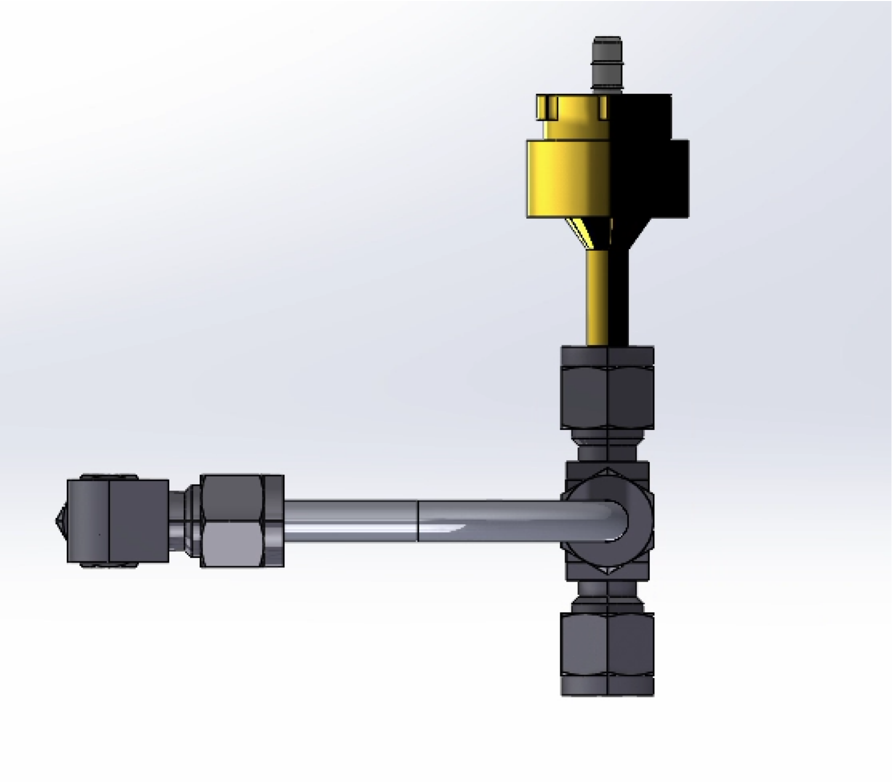


Figure 4: Sample Holder Assembly right side view.

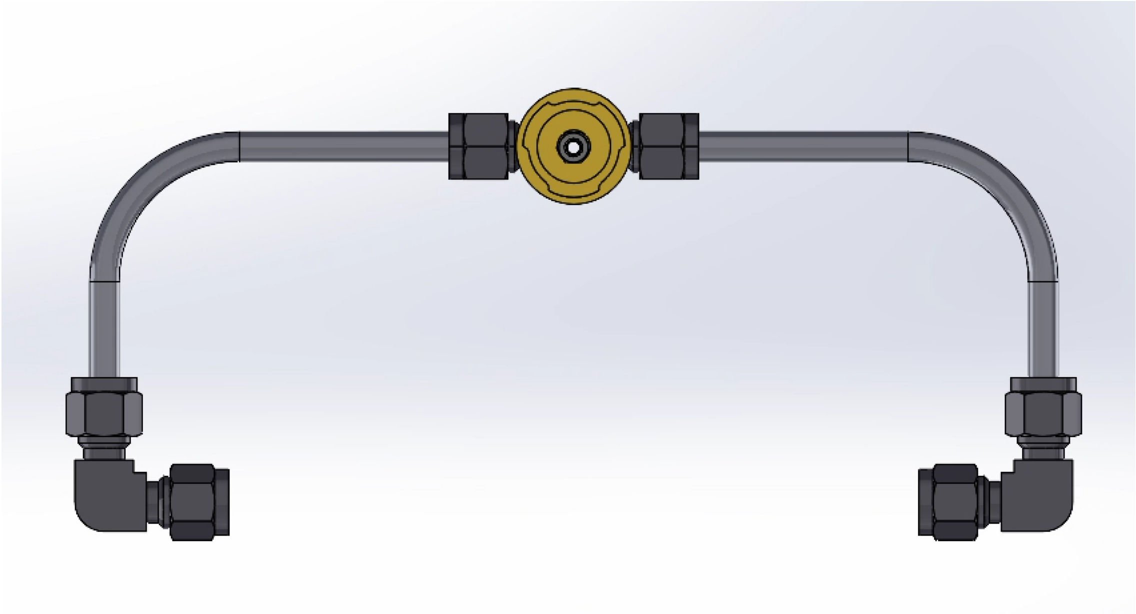


Figure 5: Sample Holder Assembly top view.

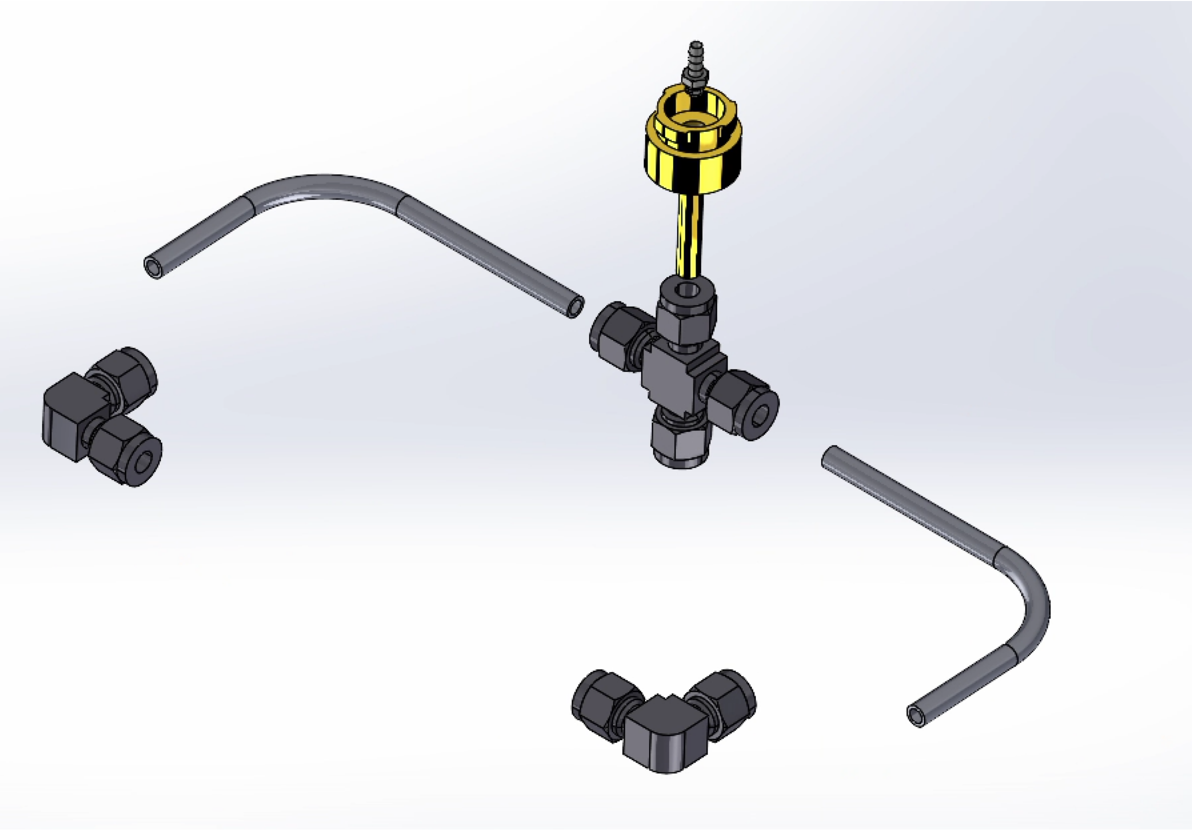


Figure 6: Exploded Sample Holder Assembly.

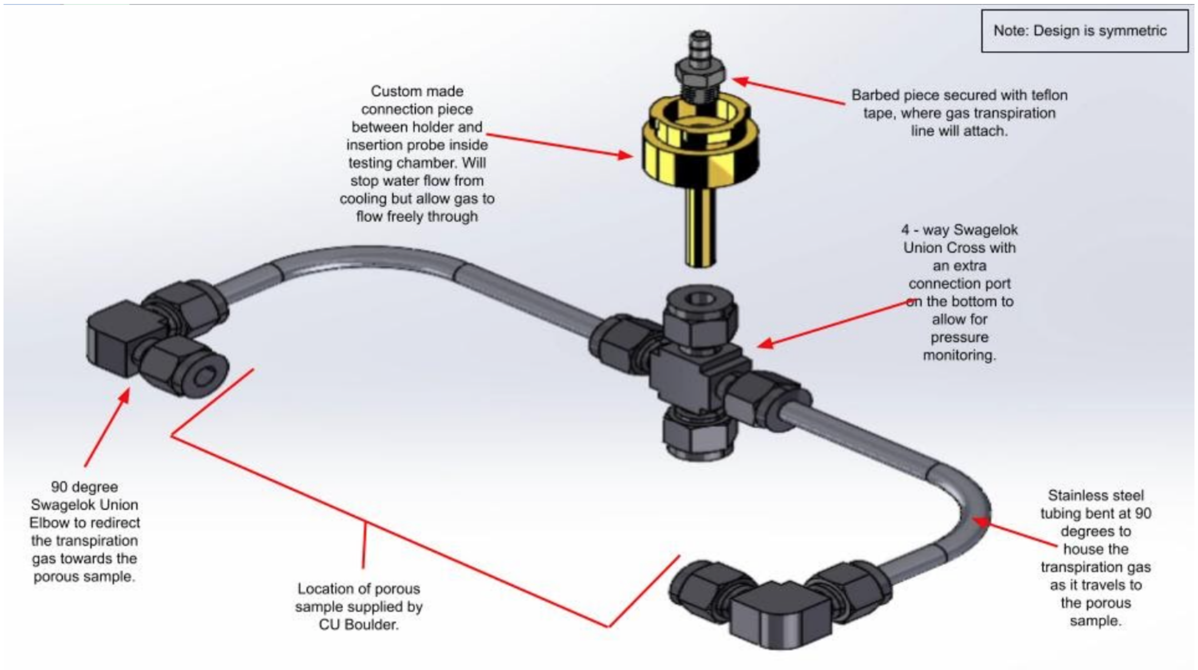


Figure 7: Sample holder component descriptions.

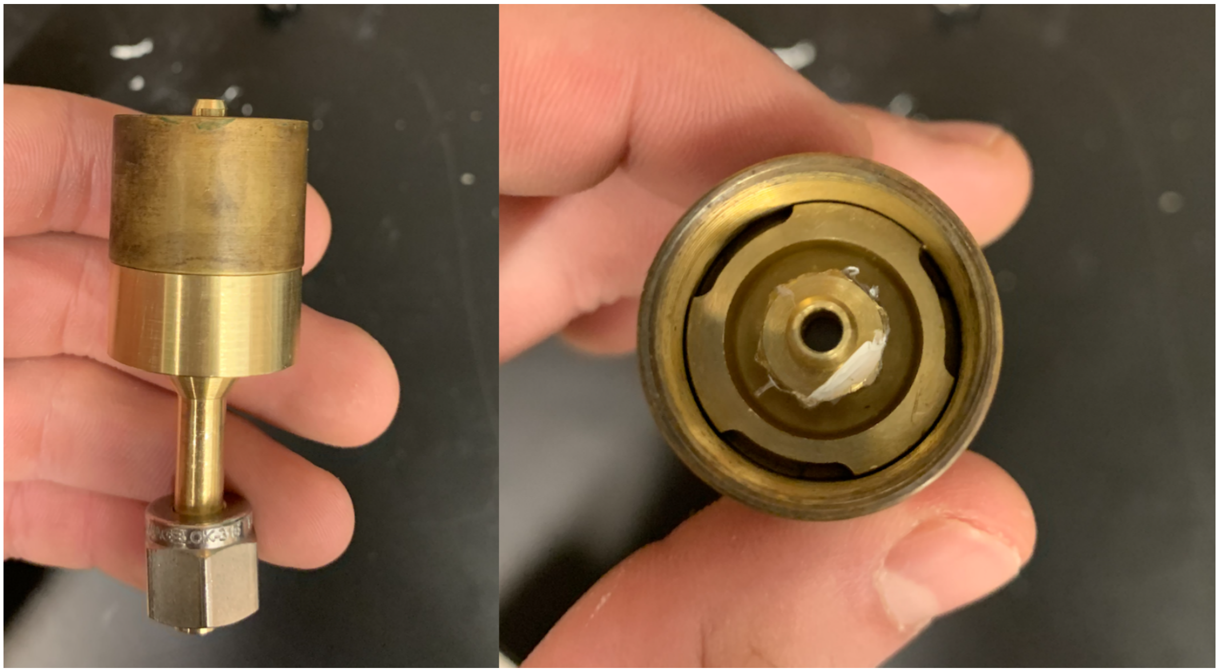


Figure 8: Twist and lock mechanism to attach to insertion probe.

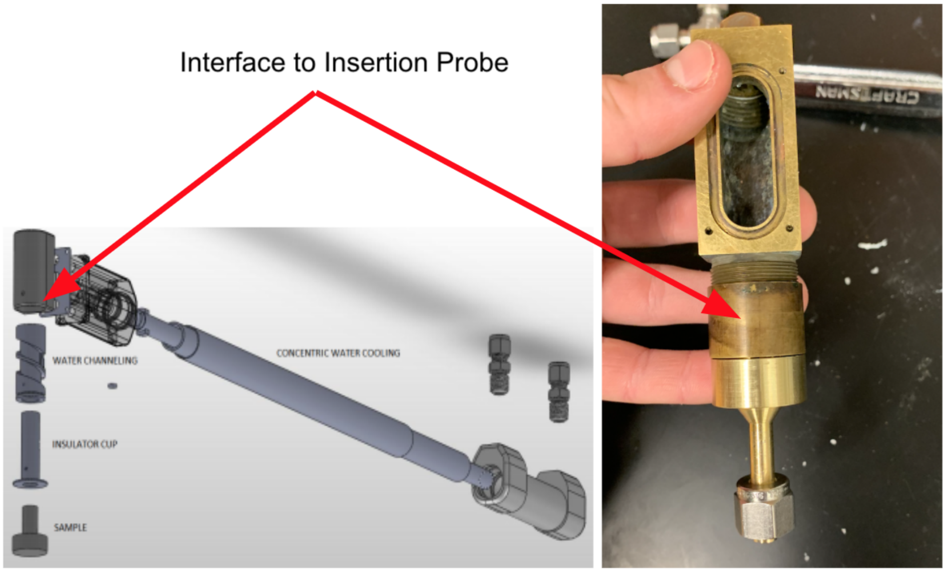
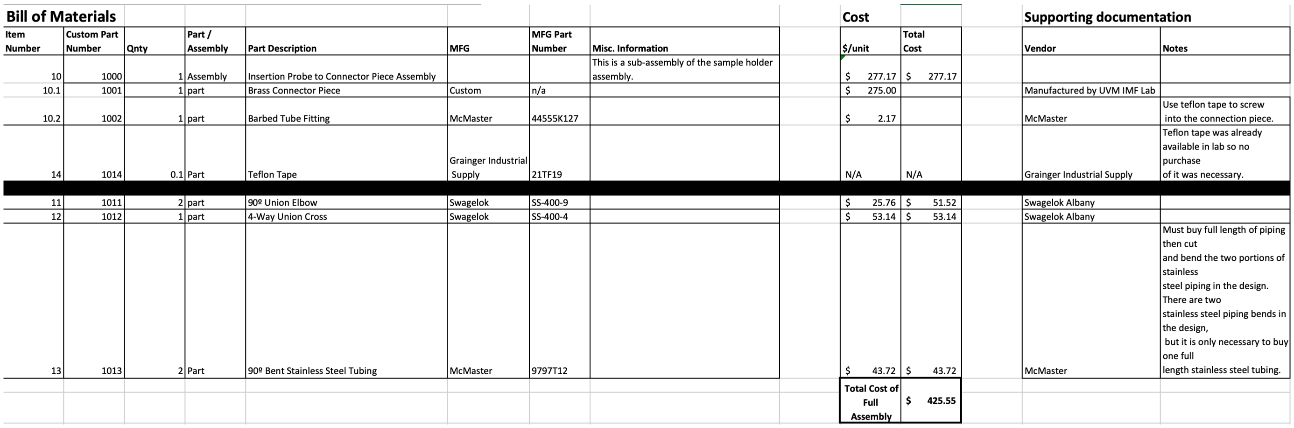


Figure 9: Interface between insertion probe and sample holder

Figure 8 is used to show the twist and lock connection between the connection piece and insertion probe, while Figure 9 is used to show where the sample holder will interface with the insertion probe.

1.2 Bill Of Materials

The following image was taken from BoM Sample Holder.xlsx file. The location of this file can be found in 1.



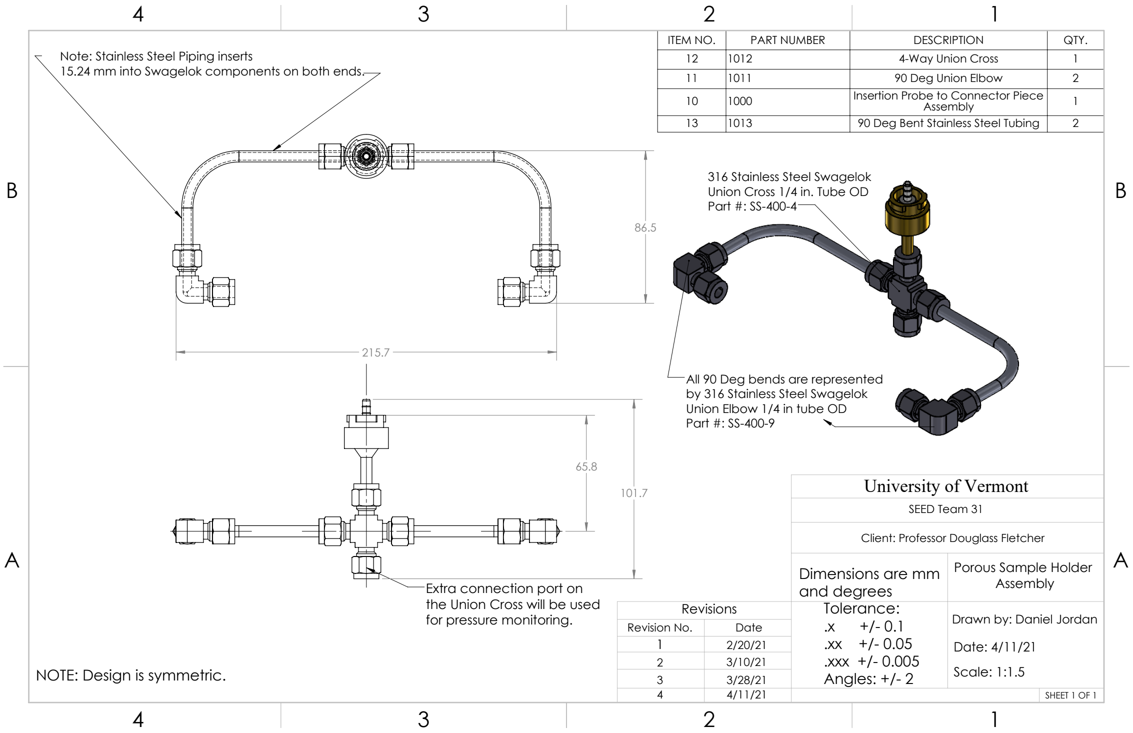
Bill of Materials								Cost		Supporting documentation	
Item Number	Custom Part Number	Qnty	Part / Assembly	Part Description	MFG	MFG Part Number	Misc. Information	$/unit	Total Cost	Vendor	Notes
10	1000	1	Assembly	Insertion Probe to Connector Piece Assembly			This is a sub-assembly of the sample holder assembly.	$ 277.17	$ 277.17		
10.1	1001	1	part	Brass Connector Piece	Custom	n/a		$ 275.00		Manufactured by UVM IMF Lab	
10.2	1002	1	part	Barbed Tube Fitting	McMaster	44555K127		$ 2.17		McMaster	Use teflon tape to screw into the connection piece.
14	1014	0.1	Part	Teflon Tape	Grainger Industrial Supply	21TF19		N/A	N/A	Grainger Industrial Supply	Teflon tape was already available in lab so no purchase of it was necessary.
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
11	1011	2	part	90º Union Elbow	Swagelok	SS-400-9		$ 25.76	$ 51.52	Swagelok Albany	
12	1012	1	part	4-Way Union Cross	Swagelok	SS-400-4		$ 53.14	$ 53.14	Swagelok Albany	
13	1013	2	Part	90º Bent Stainless Steel Tubing	McMaster	9797T12		$ 43.72	$ 43.72	McMaster	Must buy full length of piping then cut and bend the two portions of stainless steel piping in the design. There are two stainless steel piping bends in the design, but it is only necessary to buy one full length stainless steel tubing.
								Total Cost of Full Assembly	**$ 425.55**		

Figure 10: Bill of Materials

2 Mechanical Documentation

2.1 System Level Assembly Drawing

The following drawing image was taken from the SEED Sample Holder Assembly(Vfinal).SLDDRW file. The location of this file can be seen in Table 1.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
12	1012	4-Way Union Cross	1
11	1011	90 Deg Union Elbow	2
10	1000	Insertion Probe to Connector Piece Assembly	1
13	1013	90 Deg Bent Stainless Steel Tubing	2

Note: Stainless Steel Piping inserts 15.24 mm into Swagelok components on both ends.

316 Stainless Steel Swagelok Union Cross 1/4 in. Tube OD Part #: SS-400-4

All 90 Deg bends are represented by 316 Stainless Steel Swagelok Union Elbow 1/4 in tube OD Part #: SS-400-9

Extra connection port on the Union Cross will be used for pressure monitoring.

NOTE: Design is symmetric.

University of Vermont
SEED Team 31
Client: Professor Douglass Fletcher
Dimensions are mm and degrees
Porous Sample Holder Assembly
Tolerance:
.x +/- 0.1
.xx +/- 0.05
.xxx +/- 0.005
Angles: +/- 2
Drawn by: Daniel Jordan
Date: 4/11/21
Scale: 1:1.5
SHEET 1 OF 1

Revisions

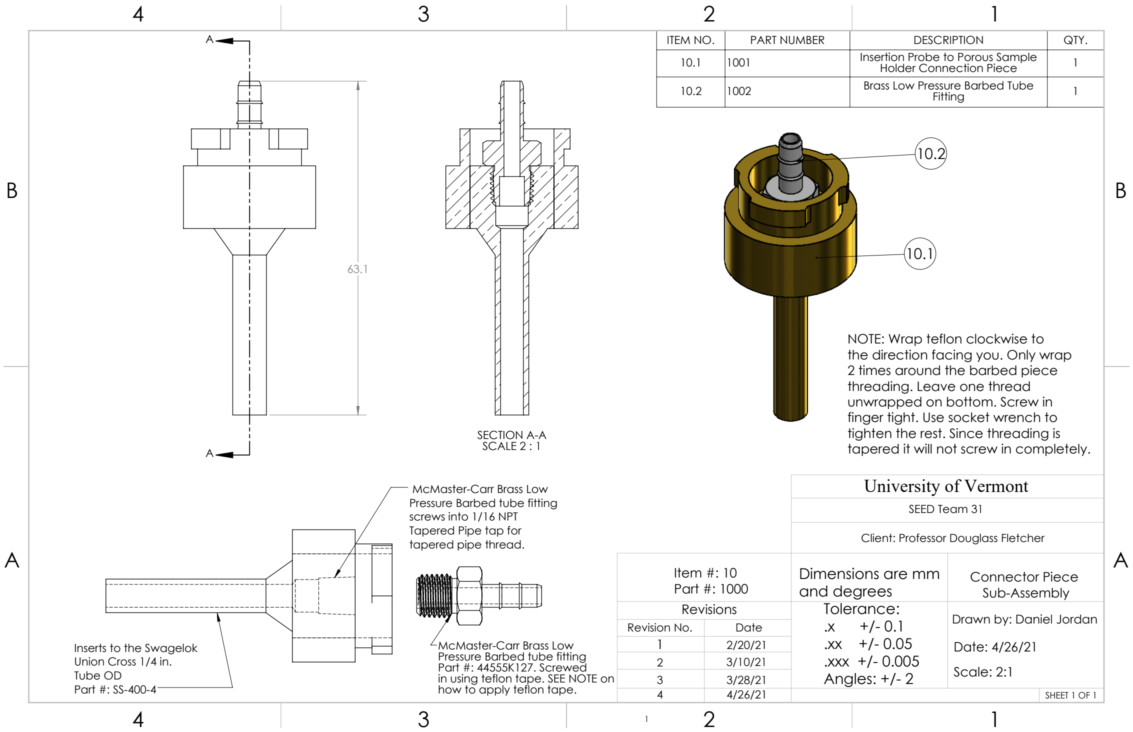
Revision No.	Date
1	2/20/21
2	3/10/21
3	3/28/21
4	4/11/21

Figure 11: Sample Holder Full Assembly Drawing

2.2 Sub-Assembly Drawing

2.2.1 Connection Piece Sub-Assembly Drawing

The following drawing image was taken from the SEED Connector Assembly(V2 with barbed piece).SLDDRW. The location of this file can be seen in Table 1.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
10.1	1001	Insertion Probe to Porous Sample Holder Connection Piece	1
10.2	1002	Brass Low Pressure Barbed Tube Fitting	1

NOTE: Wrap teflon clockwise to the direction facing you. Only wrap 2 times around the barbed piece threading. Leave one thread unwrapped on bottom. Screw in finger tight. Use socket wrench to tighten the rest. Since threading is tapered it will not screw in completely.

McMaster-Carr Brass Low Pressure Barbed tube fitting screws into 1/16 NPT Tapered Pipe tap for tapered pipe thread.

Inserts to the Swagelok Union Cross 1/4 in. Tube OD Part #: SS-400-4

McMaster-Carr Brass Low Pressure Barbed tube fitting Part #: 44555K127. Screwed in using teflon tape. SEE NOTE on how to apply teflon tape.

University of Vermont
SEED Team 31
Client: Professor Douglass Fletcher

Item #: 10
Part #: 1000

Revisions	
Revision No.	Date
1	2/20/21
2	3/10/21
3	3/28/21
4	4/26/21

Dimensions are mm and degrees

Tolerance:
.x +/- 0.1
.xx +/- 0.05
.xxx +/- 0.005
Angles: +/- 2

Connector Piece Sub-Assembly

Drawn by: Daniel Jordan
Date: 4/26/21
Scale: 2:1

SHEET 1 OF 1

Figure 12: Connection Piece Sub-Assembly

2.3 Parts Drawings

2.3.1 Brass Connector Piece Drawing

The following drawing image was taken from SEED_Connection_design_2_drawing.SLDDRW file. The location of this file can be seen in Table 1.

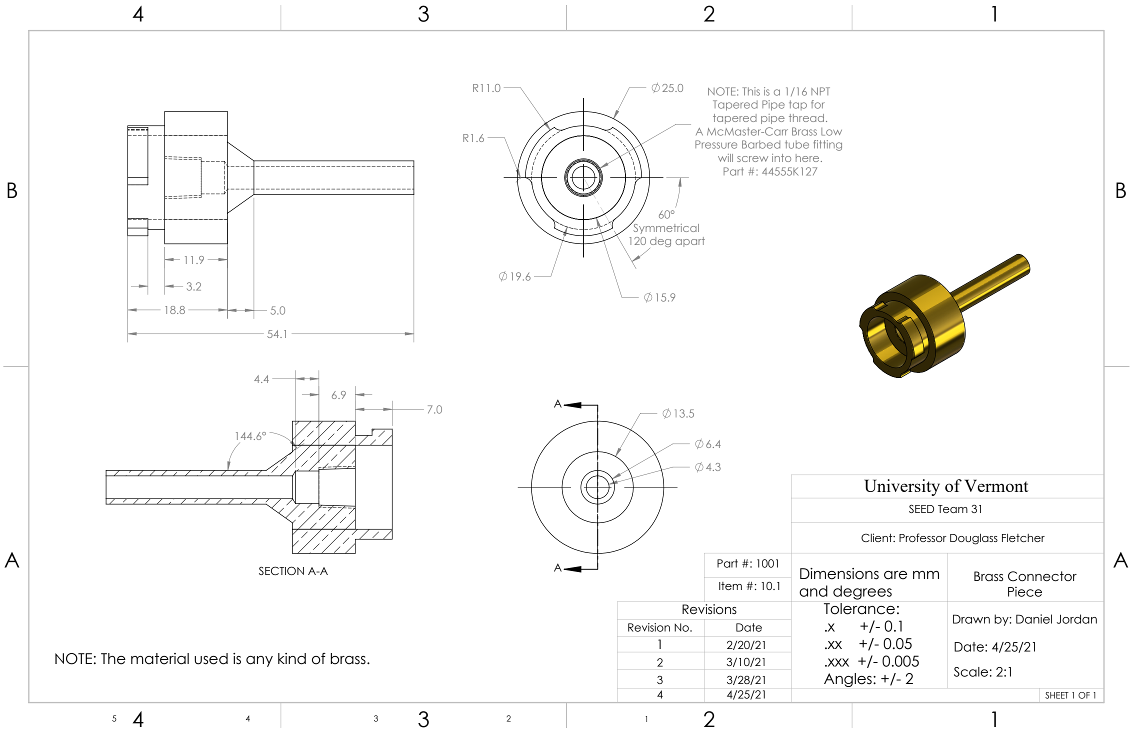
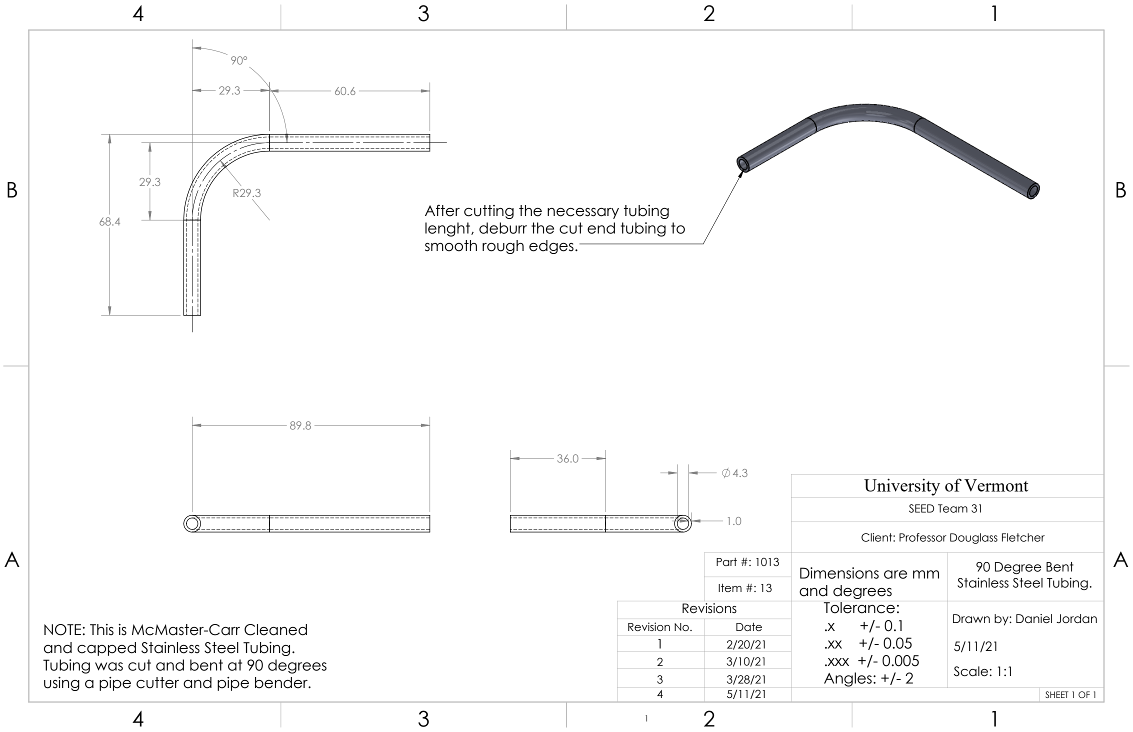


Figure 13: Brass Connector Piece Technical Drawing

2.3.2 90 ° Bent Stainless Steel Tubing Drawing

The following drawing image was taken from SEED SS Tubing(VFinal.SLDDRW file. The location of this file can be seen in Table 1.



After cutting the necessary tubing lenght, deburr the cut end tubing to smooth rough edges.

NOTE: This is McMaster-Carr Cleaned and capped Stainless Steel Tubing. Tubing was cut and bent at 90 degrees using a pipe cutter and pipe bender.

Figure 14: 90 ° Bent Stainless Steel Tubing

3 Design Files

All SolidWorks drawings, parts, and assemblies can be found in the SEED Tech Package folder in the UVM Senior Design Project 2020-2021 Folder in the plasma lab drive. Directions to plasma lab drive can be found below.

1. On virtual votey or a UVM desktop open up files.
2. Right click on network.
3. Click map network drive.
4. In the box for folder type $\backslash\backslash netfiles02.uvm.edu \backslash plasmalab$. NOTE: There are no spaces in this directory location name.
5. Click finish
6. Click the folder called "UVM Senior Design Project 2020-2021.
7. Click the folder called SEED Tech Package Drawings.

Table 1 matches the file name with the actual name of each part, assembly, and drawing.

Table 1: Directory to all files for this Project.

Location (From the Plasma Drive)	**File Name**	**Description**
UVM Senior Design Project 2020-2021/SEED Tech Package	All 3D Models.zip	Solid models for the project
UVM Senior Design Project 2020-2021/SEED Tech Package	All Technical Drawings.zip	Custom part and assembly dra
UVM Senior Design Project 2020-2021/SEED Tech Package	BoM Sample Holder.xlsx	BOM for entire system

4 User Operation Manual

SEED Team 31's project was the creation of a sample holder for testing a porous leading edge material in the UVM Inductively Coupled Plasma (ICP) Torch Chamber. The features associated with this product are as follows:

4.1 Required tools for construction of sample holder

- Pipe cutter (able to cut 1/4 inch OD pipe)
- Pipe bender (able to bend 1/4 inch OD pipe)
- Thermally resistant adhesive
- Wrench
- Socket Wrench
- Teflon Tape
- Deburrer for pipe cuttings

4.2 Components needed for construction of sample holder, follow by the quantity required

- McMaster-Carr 6 ft long 1/4 inch OD stainless steel piping (1)
- Swagelok 90 degree Union Elbow, 316 Stainless Steel (2)
- 4-way Union Cross, 316 Stainless Steel (1)
- McMaster-Carr Brass Low Pressure Barbed Tube fitting. (1)

4.3 Step by step guide to assembling sample holder

1. Begin by cutting two 129mm portions and two 52mm portions from the stainless steel piping using the pipe cutter. Refer to Section 4.4 on how to properly use a pipe cutter
2. Once all portions of piping are cut, deburr the ends that have been cut.
3. Using the pipe bender, bend both sections of piping into a 90 degree turn of the correct dimensions. Refer to 4.6 on how to properly use a pipe bender.
4. The porous sample configuration can then be set up using the high temperature adhesive for metals and the two 52mm stainless steel piping portions.
5. Place a coating of the adhesive on one end of each of the stainless steel pipes, then still the side with adhesive a small distance into the porous sample. This should be done carefully so the sample is not damaged. This adhesive coating must dry for 24 hours before use in the testing chamber.

6. Now, place the ends of the stainless steel that are not inserted in the porous sample, into the respected 90° swagelok bends.
7. Insert the bent stainless steel piping into the swagelok 90° bends, then inserting the opposite ends into the 4-way union cross.
8. Before placing the brass connection piece into the 4-way union cross, the brass low pressure barbed tube fitting must be wrapped in teflon tape, then screwed into the brass connection piece.
9. To use the teflon tape, wrap the tape clockwise to the direction facing you. Only wrap two times around the barbed piece threading. Leave one thread unwrapped at the bottom to make the initial thread easier.
10. Screw the barbed piece finger tight into the brass connection piece, then using a socket-wrench tighten the rest. Since the threading is tapered it will not screw in completely.
11. Once the barbed piece is screwed in, insert the piping end of the connector piece into the top of the 4-way union.
12. Once all parts are inserted to the swagelok components, the swagelok components may be tighten. Reference Section 4.5 on how to fully secure swagelok pipe fittings. When tightening, ensure the front end of the sample holder containing the porous sample is parallel to the ground. In the tightened form, this end should be parallel with the ground for proper testing in the chamber.

4.4 How to use a Pipe Cutter

1. Open the cutter by turning the feed handle counter clockwise and place the cutter on the solidly held pipe so that the rollers are in contact with the pipe.
2. Turn the feed handle clockwise until the cutter makes contact with the pipe
3. Rotate the cutter a full 1.25 rotations
4. Tighten the feed handle clockwise further.
5. Rotate the cutter a full 1.25 rotations. Repeat the process of rotation and tightening until the pipe is cut off.
6. Deburr the cut ends

4.5 How to fully secure Swagelok pipe fittings

1. This installation works for all 1 inch and under OD.
2. Your Swagelok fitting should include: a fitting body, a nut a front ferrule, and a back ferrule, listed in decreasing size.
3. WARNING: Swagelok connections are to be almost permanent, removing both ferrules after tightening is very difficult and may damage components
4. Make sure pipe has been cleanly cut and all burrs are removed from the end of the pipe.

5. Unscrew nut and both ferrules.
6. Put the nut around the pipe, followed by the back ferrule, then the front (smaller diameter side closest to the edge of the pipe).
7. Insert the the tube with the pre-swaged ferrules into the fitting until the front ferrule is seated against the fitting body.
8. Tighten nut until resistance is felt, slightly tighten the nut once more.
9. A secure connection is now in place.

4.6 Bending Pipes

1. Pipe should be cut before it is bent into place.
2. Place pipe in notch that closest matches its diameter.
3. Secure pipe in place where bend is required.
4. While holding pipe down, lower bender arm until it matches the desired angle (notches on side to indicate angle of bending)
5. *DISCLAIMER* Pipe might have to be bent farther than required due to elasticity