**Statement of Disclaimer**

The High Temperature Test Unit (HTTU) was built primarily by students with the supervision of faculty, safety personnel, and maintenance and technical staff. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include failure of the device or infringement of patent or copyright laws. California Polytechnic State University, San Luis Obispo, and its staff cannot be held liable for any use or misuse of the project. This Mini High Temperature Testing Unit (MHTTU) system has high voltage components and can operate at high temperature. As with any system with high voltages or temperatures, the proper precautions should be followed. Users should adhere to the operating procedure at all times.
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Abstract

Lawrence Livermore National Laboratory has invested considerable effort in developing fireproof high-efficiency particulate air (HEPA) filters. Due to the nature of LLNL’s research, the air leaving its lab facilities must be filtered before it is released into the atmosphere; thus, each laboratory is equipped with large banks of HEPA filters through which all internal air is exhausted. Over the years, however, fires have erupted in the labs and entire banks of HEPA filters have been destroyed, resulting in repairs and crucial downtime that prove costly.

Engineers and scientists alike have been seeking a permanent solution to this problem, and one proposition is to make the filters themselves fireproof rather than installing sprinkler systems and other preventative measures to protect them, as is the current practice. The challenge is to make HEPA filters fireproof. HEPA filters are comprised of several critical components: the filter media material, the sealant, and the gasket. None of these components are designed to withstand any more than a few hundred degrees Fahrenheit, so LLNL solicited the help of Cal Poly senior project teams in investigating materials that might.

1.) Introduction

i. Problem Definition

Lawrence Livermore National Laboratory has investigated ways to improve the durability of its nuclear grade HEPA filters in the case of a fire. Cal Poly senior project teams have helped by constructing two testing units to observe how HEPA filters and their components respond to extreme temperatures and conditions. Our primary task as part of Team MicroFire was to conduct research on high temperature gaskets and sealants for use in the smaller of these two testing units, using the knowledge gained to build the unit’s testing chamber. For this, we utilized static tests in the absence of air flow to assess how materials behave at high temperature. Those that were best suited for the conditions were used to construct an airtight testing chamber. The design of the chamber was based on the parameters outlined on the following page in Table 1.
Table 1: Customer requirements for the MHTTU

<table>
<thead>
<tr>
<th>Spec. No.</th>
<th>Parameter</th>
<th>Requirement/Target</th>
<th>Tolerance</th>
<th>Risk</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature</td>
<td>Withstand 1000 to 1300 °F</td>
<td>Min</td>
<td>M</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>Differential pressure</td>
<td>1 to 6 in H2O</td>
<td>Min</td>
<td>L</td>
<td>A, T</td>
</tr>
<tr>
<td>3</td>
<td>Heat loss</td>
<td>Improve on full scale HTTU</td>
<td>Min</td>
<td>H</td>
<td>A, T, I</td>
</tr>
<tr>
<td>4</td>
<td>Filter types</td>
<td>Accommodate rectangular and tube filters</td>
<td></td>
<td>M</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>Weight</td>
<td>Less than 20 lb</td>
<td>Max</td>
<td>L</td>
<td>T, I</td>
</tr>
<tr>
<td>6</td>
<td>Size</td>
<td>2' x 3' compartment space</td>
<td>Max</td>
<td>L</td>
<td>A, I</td>
</tr>
<tr>
<td>7</td>
<td>Cross section airflow</td>
<td>Uniform</td>
<td>-</td>
<td>M</td>
<td>A, T</td>
</tr>
<tr>
<td>8</td>
<td>Chamber visibility</td>
<td>Clear viewport(s)</td>
<td>-</td>
<td>M</td>
<td>I, S</td>
</tr>
<tr>
<td>9</td>
<td>Accessibility (loading time)</td>
<td>Less than 10 minutes</td>
<td>Max</td>
<td>M</td>
<td>I</td>
</tr>
<tr>
<td>10</td>
<td>Safety</td>
<td>No posed hazards</td>
<td>-</td>
<td>M</td>
<td>A, T, I</td>
</tr>
<tr>
<td>11</td>
<td>Operators required</td>
<td>One</td>
<td>Min</td>
<td>L</td>
<td>I</td>
</tr>
<tr>
<td>12</td>
<td>Lifetime</td>
<td>Infinite lifetime</td>
<td>Max</td>
<td>M</td>
<td>I</td>
</tr>
<tr>
<td>13</td>
<td>Maintenance</td>
<td>Minimum manual cleaning required</td>
<td>-</td>
<td>H</td>
<td>I</td>
</tr>
<tr>
<td>14</td>
<td>Vibration</td>
<td>None specified</td>
<td>Min</td>
<td>L</td>
<td>A, T, I</td>
</tr>
</tbody>
</table>

The requirements in Table 1 above include the tolerance for the parameter (how much variance we expect it to encounter), its risk posed to the completion of the project on time, and how its compliance will be determined (through Analysis, Testing, Investigation, and Similar Products). The final chamber was to be able to hold and test various sizes and configurations of samples including a cylindrical tube filter. Once the chamber was built and tested to ensure that it will comply with the requirements, dynamic tests on different filter components were performed. Ultimately, the hope was that LLNL would be able to continue research with the completed MHTTU to further investigate the development of fireproof HEPA filters.

ii. Project Management

Our project team, Team MicroFire, consists of mechanical engineering undergraduates Angelica Ramirez, Julian Samayoa, and Matt Keeble. The project will be managed best by dividing tasks by team member strengths. Our project management plan is outlined in Table 2 on the following page.
Table 2: Project development areas divided among team members

<table>
<thead>
<tr>
<th>Team Responsibilities</th>
<th>Matt Keeble</th>
<th>Angelica Ramirez</th>
<th>Julian Samayoa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications Officer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edit and Organize Final Submittals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organize Project Purchases with Sponsor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specialized Responsibilities</td>
<td>3D Solid Modeling and Technical Drawings</td>
<td>Lead Machinist</td>
<td>FMEA/ Safety Coordinator</td>
</tr>
<tr>
<td></td>
<td>Fluids Analysis</td>
<td>Stress Analysis</td>
<td>Thermal Analysis</td>
</tr>
<tr>
<td></td>
<td>Refine Static and Dynamic Testing Plans</td>
<td>MHTTU Chamber Prototype Build Plan</td>
<td>Dynamic and Static Build Samples</td>
</tr>
<tr>
<td></td>
<td>Material Selection</td>
<td>Prototype Aesthetics</td>
<td>Data Output/Results</td>
</tr>
<tr>
<td></td>
<td>Sealant Specialist</td>
<td>Filter Media Specialist</td>
<td>Gasket Specialist</td>
</tr>
</tbody>
</table>

2.) Background

i. Previous Senior Project Teams

Preceding our project was a joint effort by previous Cal Poly project teams (Icarus, CP HEPA, and Hi-Top) to create a full scale testing unit for investigating HEPA filters at high temperatures and flows, but it was not practical for conducting a large quantity of tests quickly. Thus, a smaller, more accessible testing unit became desirable. Team Phoenix, another senior project team who began working in Fall 2013, was tasked with creating the inlet and outlet sections of a miniature model of the HTTU. We will be working concurrently with Team Phoenix to complete the MHTTU by fitting it with the portion of the unit used to test and observe samples (referred to as the “testing chamber”). This testing chamber must be easily accessible so samples can be quickly placed and secured within, while standing up to extreme temperatures and pressure differences.
Team Phoenix worked first on the Miniature High Temperature Test Unit. They were in charge of supplying the air flow and bringing the unit up to the desired temperature. Their design is shown below in Figure 2:

Figure 1: HTTU Design created by Team Icarus

Figure 2: MHTTU Concept designed by Team Phoenix
ii. Current State of the Art

Lawrence Livermore National Laboratory is currently working on developing fire resistant HEPA filters. As part of their Ceramic HEPA Filter Program they are researching and designing a fire resistant filter that will continue to perform despite exposure to heat, flame, moisture, corrosion, and loading. The ability of a filter to endure these conditions will be of extreme importance in nuclear and chemical facilities which pose considerably high fire hazards. We are providing a basis for which the selection and implementation of new HEPA filter materials and designs can be based on. Ideally, our efforts will provide potential cost savings and improvements in safety and environmental advancements (Mitchell and Bergman et al., 2012). Currently, Lawrence Livermore National Laboratory’s Industrial Partnership Office is working on ceramic filters. It is common to use filters made from glass fiber, but they are fragile and can be easily damaged. Ceramic HEPA filters survive elevated temperatures, moisture, corrosion, and fires better than the existing technology. These filters increase safety of operations, minimize contamination issues, longer operational life of filters, longer shelf life of filters, minimize operational downtime due to maintenance outages, fewer interruptions in the manufacturing process, lower life cycle costs, lower support system and regulatory compliance costs, lower waste disposal costs (Meike et al., 2014).

iii. Existing Products

There have been other facilities that have developed similar systems for testing HEPA filters at high temperatures. The ICET (Institute for Clean Energy Technology) facility at Mississippi State University has a tunnel that is being modified to operate at 1000°F and 1000 CFM. They test HEPA filters (ceramic, fibrous glass, and sintered-metal media) under several different conditions. Previous Cal Poly project teams have addressed the problem of how to test the newly developed filters. These teams constructed the HTTU so that testing of materials, components, and filters could be performed at high temperatures and flows simulating a fire. Team Icarus was initially tasked with designing the device and fixture to test a full sized HEPA filter. It was targeted to test ceramic filters, but it was capable of testing non-ceramic filters and seal performance in temperatures as high as 1000°F (Brown and Dong et al., 2012). The second Cal Poly team, CP HEPA, added to the function of the device by implementing a data acquisition unit and a control system. The system has control system parameters for filter face temperatures up to 1300°F, flow rate from 5 to 250 ACFM, differential pressure from 1-6 in H2O, and torch control (Gainer and Goupil et al., 2012). The last team working on the HTTU was Hi-Top. Team Hi-Top added a spot flame test, a high temperature camera, a method to test filter seals for leaks at high temperatures, and viewing ports. They decided to use a high temperature ceramic glass for the viewport over other options such as fused sapphire or fused quartz due to its cost and transparency. To be able to document what the effects of temperature had on the filters they used an Internet Protocol camera for ease of connectivity and high resolution (Frandeen and Schill et al., 2013). We will be considering the designs of these teams as well as developing our own unique ideas and improvements.
iv. **Applicable Standards**

**DOE-STD-3020**: DOE Technical Standard, Specification for HEPA Filters used by DOE Contractors  
**ASME NQA-1 Certification**: Nuclear Quality Assurance-1  
**IEST–RP–CC001.3**: HEPA Criteria  
**MIL-STD-282 Method 102.9.1**: HEPA Criteria

3.) **Design Development**

i. **Supporting Preliminary Analysis**

The following is a summary of the preliminary analysis used to determine the range of possible steel, insulation thicknesses, viewport requirements and clamp selection. A complete list of each analysis is also included in Appendix G.

**Thickness Range of Stainless Steel**

One of the main requirements in procuring materials is the size and type of steel required to construct the high temperature testing unit. The thickness of stainless steel is an important variable since it is crucial to control the amount of heat conducted to the outside environment. It also allows us to control the warm up time of the system. Based on the approved chamber design, heat transfer calculations were first generated. Since the main use of the testing unit requires operation at a constant temperature of 1300°F, stainless steel AISI 304 is the best choice for the application.

Using the required volumetric flow rate we can determine the amount of air mass flowing through the system. If we then use the mass flow rate, specific heat of air, and the temperature drop across the chamber we can determine the amount of heat that is lost to the surrounding steel.

\[
\dot{m} = \rho_{air} \dot{V} \\
\dot{q} = \dot{m}C_p\Delta T
\]

The amount of heat through the surrounding steel is then used as the actual heat transfer delivered by convection and conduction to the testing unit. This heat is transferred radially in all directions. In order to analyze this transfer we need to treat the chamber as a circular pipe with heat flow running on the inside and transferred to the outside. A hydraulic diameter is used instead and determined from the following equation using cross sectional area, \(A_c\), and perimeter, \(P\):

\[
D_h = \frac{4A_c}{P}
\]
The Nusselt number is then determined for the cross sectional dimensions and used to determine the convection coefficient \( h_1 \).

\[
h_1 = \frac{NuK_f}{D_h}
\]

Using thermal resistance analysis on the test chamber with the hydraulic diameter we are able to determine the outer theoretical radius of the test chamber. This outer radius is then taken back into the hydraulic diameter to calculate the radius of the rectangular cross sectional area.

\[
\dot{q} = \frac{(T_1 - T_2)}{2\pi h_1 r_1 L + \frac{\ln (\frac{r_2}{r_1})}{2\pi R_{steel}} + 2\pi h_2 r_2 L}
\]

Results:
- Steel thickness calculated from heat transfer analysis: \( t = 0.078" \)
- Range based on available steel sizes: \( 0.0625" \) (16 gauge) < \( t < 0.1250" \) (11 gauge)
- Final design thickness based on welding capability: 12 gauge

**Thickness of Insulation**

Similarly the thickness of the insulation is calculated and the results used to plot the temperature on the outside surface of the temperature versus the thickness of the insulation. Using the technical data for Gemcolite FG-23, it was determined that the R value for the specific insulation used is \( R=0.25 \text{ W/mK} \). **Figure 4** shows the resulting graph:

![Figure 4: Plot of the insulation thickness versus the temperature of the outside surface of insulation](image-url)
At an insulation thickness of 2-3 inches the outside temperature of the insulation decreases by about 100 °F but at an additional increase of 1 inch of insulation the temperature drop is only an additional 50 °F. At this point it is more beneficial to include a secondary insulation that will increase the drop in temperature across temperatures lower than 300 °F. Therefore, the alumina silicate Gemcolite insulation will be used for high temperatures at the surface of the chamber and a mineral wool outer layer will be implemented to bring down the insulation outer surface from 288 °F to 188°F at a total thickness of 3 inches.

Thermal Finite Element Analysis of Viewports

Finite element analysis was performed on the viewports, which were of particular concern. Questions regarding heat transfer from the viewports, as well as internal contact between the lens and housing in the viewport were raised, so a model was made to analyze this feature. Details about the model, verification and process can be seen in Appendix G.

The primary results of interest were temperature distribution, heat flux, and any stresses caused by contact between the viewport lens and housing. As it turned out, the fused-quartz lens experienced considerably less thermal expansion than the steel housing, so there were no contact stresses generated between the parts. It was not inconceivable that the lens could even cause the housing to yield or undergo plastic deformation if the contact stress was great enough, but, as the PEEQ plot in Appendix G shows, the only plastic region in the model was along the threaded surface, especially at the seated corner. The contour plot of the Mises stress, shown in Figure 5, caused further surprise, as the maximum stress in the model was found to be 1.07 GPa, when the yield stress of carbon steel is more on the order of 0.2 GPa. Thus, virtually the entire viewport around the threaded region would experience yielding. Similar results were observed in the chamber body model, leading to the conclusion that we either underestimated our material properties or restricted the models with too strict of boundary conditions. Discussing these concerns with the manufacturer confirmed that the viewport would indeed handle the conditions without yielding.

Thermal analysis, on the other hand, gave more encouraging results. Contour plots of heat flux and temperature distribution in the viewport are shown below in Figure 6. A major concern

Figure 5: Deformed Mises stress plot generated in 3-D, reporting a maximum Mises stress of 1.07 GPa.

Figure 6: Deformed contour plots of the model, generated in 3-D, showing heat flux magnitude (right) and temperature distribution (left). The maximum heat flux was 55.6 kW around the viewport’s threads and the minimum temperature was 890°C at the exterior of the viewport lens.
from Team MicroFire is that a large amount of heat will be lost from the viewport lens (which cannot be covered with insulation) and, thus, the efficiency and maximum attainable temperature of the system will suffer. The heat flux magnitude plot shows that nearly all of the heat will escape through the viewport housing, which can be insulated. The temperature at the exterior surface of the viewport was also of interest, as a viewer will in theory be able to use the viewports to observe samples as they are being tested and thus a person’s face will come into close proximity with the viewport. The temperature distribution plot gives a minimum exterior surface temperature of 890˚K or 617˚C (~1105˚F) in the lens; a temperature drop of roughly 90˚C (~195˚F) from the interior temperature. This is obviously much too high of a temperature for contact with a human’s skin, so users should exert caution when using the viewports, making observations from a safe distance.
Thermal Stress

The most significant load experienced by our test chamber will result from the thermal load that occurs when the chamber goes from room temperature to 1300°F. An approximation of the stress was required to select a number and size of clamps that would be adequate for our purpose.

Assumptions:
- strain is only occurring in the normal direction ($\varepsilon_{xx} = 0$)
- Factor of safety of 2
- Pressure rating of clamp is 600 psi

Analysis:

The thermal stress was calculated for the properties of stainless steel using the equations below.

$$\sigma_{xx} = \frac{E}{1 - \nu^2} (\varepsilon_{xx} + \nu \varepsilon_{yy}) - \frac{E \alpha \Delta T}{1 - \nu}$$

$E$ is the Young’s modulus of the material, $\nu$ is Poisson’s ratio, $\alpha$ is the thermal coefficient of expansion, and $\varepsilon$ is the strain in the axial or normal direction. To calculate the strain in the normal direction the following equation was used:

$$\varepsilon_{yy} = \alpha (T_f - T_i)$$

$T_f$ is the final temperature experienced by the chamber and $T_i$ is the initial temperature. This value was used in determining the number of clamps we would need. The number of clamps was determined using the following equation based on the load experienced by the chamber and where it would be applied:

$$C = \frac{\sigma_{xx} N}{AP}$$

$N$ is the factor of safety, $A$ is the total area of the flange, and $P$ is the pressure rating of the clamp.

Results:
- Thermal stress $\sigma_{xx} = 79.2 \text{ ksi}$
- Number of clamps required per intersection is 4
ii. **Design Iteration Process**

“Cartridge” Design

![Figure 7: “Cartridge” chamber design](image)

The first chamber concept came weeks into the project during an organized brainstorming session. The major concern being considered was how to quickly, securely, and safely load and unload test samples into and out of the chamber. Inspired by a video game console such as the Nintendo 64, this chamber design was referred to as the “cartridge” design and featured vertical grooves in its interior walls into which a test fixture would slide via slots in the top of the chamber, as shown in Figure 7. This concept was our primary concept for some time and went through several weeks of development. We considered it a strong design because it allowed for the very rapid exchange of test samples, of which there were two instead of one, and the fixtures themselves were universal, meaning they could hold any filter component. The cartridge concept was eventually discarded, however, due to several concerns. The first major concern from our sponsor was that the viewports were too narrow, and their spacing would make it difficult to see into the chamber at all. Because of their equal spacing on either side of each test sample, we believed that visibility would not be an issue, but the second major concern was not easily overcome. The fixtures we intended to fit into the slots in the chamber seemed useful in theory, but the problem brought up by our sponsor was that it would be difficult to make the fixtures airtight. We did not consider that, when testing filter media samples, all air has to go through the sample rather than around it, so we began generating ideas on how to seal the fixtures. Since the only sealant material we had knowledge of or access to was Blu-Jel from Flanders that burns at 350°F, we discarded the idea in the hopes of developing another.

![Figure 8: Testing fixture for the cartridge design](image)
Once the cartridge concept was abandoned, we had frequent concept generating sessions to come up with a new way of sealing filter media samples into the chamber. However, this required new knowledge into options for high temperature sealants and gaskets, so after some research we determined that a sectioned chamber held together by flanged interfaces would be a promising design. Similar to the full scale HTTU, the chamber would be built from separate sections that would be bolted or clamped together. We also needed to remedy the viewport concern from the cartridge design, so we began investigating round, prefabricated viewports that could be purchased rather than manufactured from scratch. The idea that resulted was our first “sectioned” design, and can be seen in Figure 9.

With the “sectioned” design, fixtures would again be used to hold samples like in the cartridge concept, but with this design the fixtures would be sandwiched at the flanged interfaces between each section of the chamber to ensure an airtight seal. This was also our first implementation of a slanted faceplate, which was an important solution to the viewport problem because it allowed us to orient the viewport such that it was aimed right at the test samples. The flanged interfaces in this design were to be bolted together, and the bolted sections would then be clamped to the base plate. However, we continued to run into issues. The slanted face plate decreased the area of the vertical face plate below it, preventing it from accommodating the 2” inlet pipe used in the existing system. In addition, we were advised that our sponsor would prefer clamps to bolts, if possible, and the aerodynamics of the chamber were questioned. Thus, it was determined that this design required further
improvements.

“Arched” Sectioned Design

Figure 10: “Arched,” sectioned chamber design

The “arched” sectioned concept was our first truly promising design. It provided ample room for a viewport on the slanted faceplate while still accommodating the 2.5” inlet and exit piping. However, it still had issues that conflicted with our customer preferences.

Our sponsor did not believe the slanted inlet base would benefit the chamber, but would instead hinder it by obstructing flow at the inlet. We also became aware to speculation that air at 1300°F rises very quickly, and if we angled the flow up at the inlet, all of the air would effectively flow across the ceiling of the chamber with little flow at the floor. If this were the case, samples would not be exposed to the specified conditions, and would burn more on the top than on the bottom. Pressure drop tests would also be influenced, as the flow distribution in the chamber would not be uniform, so the pressure drop would depend on the location of the measurements being taken. The design was hopeful, but it was not adequate, so an alternative concept was proposed.
“Viewport Mounting Block” Design

Figure 11: “Viewport Mounting Block” chamber design

Certain characteristics of this design were similar to our previous sectioned designs, including the flanged interfaces, the slanted faceplate, and the round viewport. However, it is important to note the improvements this chamber makes on those characteristics. The viewport was the main improvement, as we did not actually have an acceptable viewport selected in any of our previous designs. The viewport required a tapped hole in the faceplate, and would need to be faced to remove excess threading to increase visibility.

We also changed the inlet section of the chamber, keeping the slanted faceplate but removing the slant from the base of the inlet so that it was flat. The chamber’s cross sectional area thus expanded past the 2.5” x 6” sample area desired by our sponsor, so we designed flow guide plates to converge the flow from a large cross sectional area to our desired test sample area. The flow guide plates concept can be seen installed a previous inlet section in Figure 12.

Figure 12: Example of the flow guide plates featured in the above chamber design
4.) Description of Final Design

i. Final Design Model

![Figure 13: Final chamber concept design](image)

Shown above is a solid model of our final chamber design. It features several key improvements not seen in prior designs, including weld-on fittings of different sizes for accommodating instrumentation and viewports, while also including folded corner strips to help guide the sections together during clamping. Not shown in the drawing are the “jigsaw” pins and corresponding holes that allowed the chamber to be held together after it was bent but before it was welded.
ii. Detailed Design Description

Final Chamber Design

Several important changes were made from the previous designs to arrive at our final concept. The manufacture of prior designs was based heavily on speculation, as no contact had been established with a welder. Expert opinions from our sponsor and project advisor dictated that the welding for the chamber would be outsourced to a professional, as had been the case with the full scale HTTU, but the previous welder was not available for the MHTTU project. The first resource we consulted, therefore, was the campus welding instructor. He was very helpful, and put us on the path towards the final chamber design.

First, as a design consideration, it was determined that the “flow guide plates” were essentially creating wasted space between the interior and exterior surfaces of the chamber. The whole idea behind the miniature HTTU was to limit thermal mass in the hope of increasing the system’s efficiency, so the flow guide plates were eliminated. The welder also informed us that, contrary to our belief, a plasma cutter could not be used to cut the stainless steel sheeting used for construction. A water jet cutter was our best option, so our priority became generating 2-D manufacturing drawings to be sent to a local fabrication shop for water jet cutting. Another key recommendation offered by the welder was that we bend the cut outs into their corresponding three dimensional shapes rather than welding each individual flat piece together at angles. He proposed incorporating pins on the bent pieces and corresponding holes into the sides so the sections, once bent, could be held together like a jigsaw puzzle for easier assembly and welding.

As a result, the shape of the chamber was changed so the sides would be flat, requiring only one cutout each, and only the ceiling and floor would be contoured. We foresaw a problem with bending, however, because having too many bends in one cutout would cause it to bend over on itself too much, causing interference with the hydraulic break used for bending. This problem was solved by cutting the contoured piece of the inlet and outlet sections into two pieces, which could each be bent independently and welded together.

It is also important to note that the viewport mounting block was abandoned for our final design. The block would have required the procurement of a 2” bar stock of solid stainless steel, which was exceedingly expensive. Thus, we decided to ignore the NPT threads on the viewport and, instead, planned to weld around the hexagonal portion of the viewport housing, fixing it directly to the slanted faceplate of the chamber and simply allowing the threads to protrude all the way into the chamber. We feared interference with our static pressure probes, however, and our sponsor proposed the possibility of finding a threaded fitting that could instead be welded to the faceplate of the chamber, allowing the viewport to be threaded into the chamber after all. We were skeptical about finding an NPT threaded fitting with a 3” diameter, which seemed large, but after some searching we found what we were looking for, and for enticingly cheap. Two such fittings were obtained, allowing for the viewports to be screwed into the chamber as intended.
Similar fittings were also obtained for instrumentation. 5/8” holes had been cut into the chamber by the water cutter, as we did not know how many instruments we would need, and where they would be located, when we sent our drawings in to be cut. Therefore, we decided to error on the side of more location options rather than fewer, with the intention of plugging up the unnecessary holes as needed. The weld-on fittings we found were the perfect solution not only for filling these holes, but also for allowing for adjustable thermocouple locations. Thermocouples can be secured into any of the ports via a compression fitting, and threaded plugs (essentially hex bolts) can be screwed into ports that are unused.

**Specification Verification**

The design verification sheet included in Appendix D outlines the various product verification tests performed on the testing chamber and specific components used in the chamber. The plan also verifies the durability and composition of the sample materials tested through a series of static or oven tests that were performed prior to the manufacture of the testing chamber. The components tested include: Gaskets and sealants, thermocouples, welds, and viewports.
iii. **Cost Breakdown**

Since our effort comes several years into this project, there are some materials left over for us to inherit which cuts down on our costs. We also obtained free samples from sealant and gasket vendors for static testing so that we do not end up with excess material if a product ends up failing. We also benefit from attending a polytechnic campus, as the machine shops are free to use and equipment is, for our purposes, free to rent. We were able to cut, bend, and heat test samples on campus free of charge. We did have to outsource the major processes of the chamber (air jet cutting and welding). A breakdown of all our costs is seen in the tables below categorized into technician, travel, and equipment totals.

### Technician Total

<table>
<thead>
<tr>
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<td>Controls</td>
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**Total:** $ 775.00

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**Total:** $ 213.58

### Equipment Total

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<td><strong>Overall Total</strong></td>
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<td><strong>$5,166.65</strong></td>
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iv. **Material, Geometry and Component Selection**

The following summary list outlines the specific material and components used in the final designs of the project.

**Test Chamber:**

- T304 stainless steel 12-gauge is the primary metal composition for each section of the test chamber. Stainless steel allows us to increase service life and limit large deformations when large temperatures are expected on the interior surfaces of each section.

- Quartz lens viewports with a 3” viewing area and NTP threads provide a clear view into the testing section and at the same time prevent any air leaks from the system.

- Thermocouples with 3/16 sheath diameter and exposed ends, manufactured by Omega Engineering, provide a means to measure the temperature of the air flow through the system. Temperature readings can be taken at both the inlet and exit sections.

- Dwyer static probes, positioned at all three sections, are used to determine the velocity of the air flow.

- A wiring system is in place to add a second pressure transducer to the complete system. Currently one transducer is installed and a second transducer is available to obtain additional pressure readings.

- BriskHeat heating tapes are used to increase the performance and efficiency of the system. Two thermal tapes are positioned on the outside surface of the middle test section. A thermocouple is placed directly on top of the tape to provide the user with the tape temperature during operation. Test results with the use of the heating tapes are provided in the results section of the report.

- Weld fitting are used to install the thermocouples, static probes, and viewports to the test chamber. This allows the user to change the viewports or test any instruments in case of incorrect readings.

- Three layers of insulation are attached to the outside sections of the chamber. The first layer is immediately on the surface of the steel while a second layer is positioned above. The final wrapping layer keeps the insulation tightly fixed to the chamber.

- Stainless steel clamps are used to compress the flange sections of the chamber. The compressive force holds the test samples in place. Once the system cools the clamps can be removed and the sample can be removed.
v. Safety Considerations

This project requires close attention to safety. At high temperatures the test chamber can cause serious injuries to the user when performing the filter sample tests. In addition to the safety warnings in the instruction manual and on the testing chamber, we have also included a safety check list in Appendix G. Two of the major causes of injury have been determined to be the high temperature on the exterior of the chamber and the exhaust airflow. We have calculated the thickness of insulation that will reduce the temperature of the outside wall chamber; however we have also included a plan to construct a safety guard on the user side of the chamber to prevent injury to the user. Insulation for the exhaust pipe has also been included.

vi. Maintenance/Repair Considerations

Maintenance was an ongoing consideration throughout the design of the chamber. As samples will be burned within the chamber, it is likely that some will deteriorate and release debris that could interfere with the functions of the chamber. The main concern was obstruction of the viewport. Conveniently, the viewports are NPT threaded, and screw into threaded fittings that were welded onto the chamber. As a result, the viewports are not permanently attached to the chamber and can be unscrewed and removed for easy cleaning. Likewise, the fused-quartz viewport can also be removed from the metal housing itself for more thorough cleaning.

Instrumentation is not permanent either, and similar weld-on fittings were used to install the thermocouples and static pressure probes into the chamber via compression fittings. If an instrument were to fail, it could thus be removed and replaced.
5.) Product Realization

i. Description of Manufacturing Processes Used

Chamber Manufacturing

To construct the test chamber, two major processes had to take place: sheet metal fabrication and welding. The set of tasks was mostly be performed by us, Team MicroFire. We had assistance for rapid prototyping the filter media from Larry Coolidge, the head lab technician at Cal Poly. We outsourced the welding. The installing and programming of the measuring devices will be tasked to a Cal Poly graduate student who was in a previous LLNL group working on this project. An outline of these assignments is shown in Table 3:

<table>
<thead>
<tr>
<th>Job</th>
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<tbody>
<tr>
<td>Construct Test Fixtures</td>
<td>CalPoly Machine Shops</td>
<td>Team Microfire</td>
</tr>
<tr>
<td>Cut Sheet Metal</td>
<td>Creative Coast Cutting</td>
<td></td>
</tr>
<tr>
<td>Weld Chamber</td>
<td>CalPoly Ag Department</td>
<td>Instructor</td>
</tr>
<tr>
<td>Weld Chamber</td>
<td>CalPoly/ Allan Hancock</td>
<td>Welding Instructor</td>
</tr>
<tr>
<td>Rapid Prototype Filter</td>
<td>CalPoly 3D Printers</td>
<td>Team Microfire &amp; Larry Coolidge</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>CalPoly Labs</td>
<td>Grad Student</td>
</tr>
</tbody>
</table>

The first step was to translate our chamber design to a 2D layout to be cut out from TS304 Stainless Steel 16 gauge sheet metal. A copy of the layout can be found in Appendix D.

The chamber was reduced to 14 separate pieces (5 for each end section and 4 for the center section). The layout was designed to simplify the welding process. Sets of pins and holes were designed to hold the chamber in place when the pieces were bent. Therefore, simplified or no setup would be required to hold the pieces while welding. The size of the pins are 1/8" x 1/4". The holes were made slightly larger to avoid interference and provide a tolerance in the case that the location of the bends was offset. The metal pieces were bent using a hydraulic press. The limitations of the bend angles and gap spaces were kept in mind when determining how many overall pieces were required. Too large of a piece would cause an interference and limit the bend angle.

Welding was a primary process in completing the test chamber. All welds were done by the MIG welding process using T308 stainless steel welding rods. The first round of welding was to attach the sheet metal pieces, fixtures, couplings, and other attachments together. The second
round was to seal the pins to make sure that the chamber was airtight. Due to the thinness of the metal and the amount of heat required for stainless steel, warping was a major concern. Limited warping was needed at the flanges. The flanges had to remain parallel to avoid gaps for air to escape at the test sections. After all welding was completed, the flanges had to be straightened out through hammer and anvil.

The final step of completing the chamber was to attach the viewports, fittings, and plugs. The threaded pieces (plugs and viewports) were wrapped with nickel-steel anti-seize tape before screwed in place. The fittings for the static pressure taps were put in place with a Grafoil gasket.

**Insulation**

Three different layers of insulation were attached to the chamber in an attempt to maintain the highest temperature. The first layer of insulation was a high temperature ceramic strip. This layer was created to protect the second layer of insulation from the highest temperatures experienced directly from the metal.

*Figure 14: Chamber end section with first layer of insulation*
Next, the chamber was covered with a silica fiberglass layer attached by stainless steel wire. The fiberglass provided the bulk of the insulation.

The last layer of insulation is a high temperature insulation wrap. This layer was added to completely seal the chamber into neat and easy to handle components and to add more thermal resistance. The wrap was unrolled and applied around the entire chamber then sprayed with warm water. The wrap was allowed to dry for hour to set before handling again.

**Figure 15:** Chamber end section with first and second layer of insulation.

**Figure 16:** Assembled chamber with all three layers of insulation
Test Fixture Manufacturing

A test fixture was designed to allow sealant materials to be tested within the final design of the test chamber. The engineering design specifications require a test fixture design that resembles the actual operating conditions of the filter sealants and creates a pressure drop across the sealant sample. Initially the design incorporated smaller flanges with bolts acting as the compression mechanism, as shown in Figure 17. Linear ports are also included in order to relieve some pressure across the chamber section. This design did not take into account the final dimensions of the flanges currently on the test chamber. The current small flanges on this design allows air to leak out of the chamber since the cross sectional flanges are larger in area than the flanges on the fixture. As the design of the chamber evolved, the test fixture design also evolved. If this test fixture were used in the final version of the test chamber, the heated airflow would also move around the rectangle reservoirs. Therefore, the center rectangle section was completely enclosed on all four sides. The manufacturability of the product also played an important role in the design process. We initially decided to use 16-gauge stainless steel. However, while welding each section of the build, the thin sections of the design began to warp and deform. The alternate steel thickness of 12-gauge was used instead to construct the final design of the pressure test fixture.

Figure 17: Original pressure drop fixture top (left) and modified pressure drop fixture (right)

The modified design solves these issues and accomplishes the engineering specifications set out by our sponsor. The main characteristics of the final design includes: a pressure drop across the sealant sample, knife edge fins that protrude into the sealant, Flange size equal to that in the testing chamber, and pressure relief holes on the bottom section of the fixture. Once the testing sample is loaded into the fixture, the fixture is attached to the chamber using the compression clamps on both the test fixture and chamber. The sealant is then set directly in front of the hot air flow, which creates a pressure drop across the sealant. Other sealant compounds can be added below or above the main sealant to test the amount of heat that the first layer of sealant can take.
Future Recommendations for Manufacturing

Future recommendations for manufacturing when using such thin steel is to be wary of how the piece is cut due to rough edges and how pieces are to be welded together. It is strongly advised to prepare CAD files to be specifically cut by a water jet specialist or a laser steel cutter. This would give clean cuts that are more accurate, easier to work with, and easier to weld. It is
essential to use a relatively thick steel gauge if possible to prevent extensive warping of the flange section. However there are a few tradeoffs when considering this option. While thicker steel experiences less warping it requires more heat to weld, tougher equipment to cut and bend, and costs more. With smaller gauge stainless steel, a low welding bead would need to be dropped periodically instead of welding large section to also prevent excessive heating of the material.

When putting together a chamber with unconventional geometry, special attention needs to be given to the angles of the part, especially when bending. Common angles such as 45 degrees and 90 degrees are recommended because they are easier to adjust for when using equipment and it will be more likely that pieces fit together during assembly. If using the pin method to put pieces together a fit together during assembly.

Future manufacturing of the test fixture would require specific care to be taken when to prevent fluid leakage. The main component that needs to be tested in the test fixture is Blu Jel. A specific amount of Blu Jel reactant components needs to be mixed and cured inside the test section reservoirs. Therefore, no leakage can be allowed during manufacturing of the test fixture. Additionally, a test fixture that accommodates any cylindrical shape filter can also be manufactured. Figure 19 illustrates a potential version of a test fixture that accommodates a 1.5-inch diameter filter. The challenge during this design is to verify that all the airflow entering the system is delivered into the cylindrical shape filter. The current design can be used to develop the current idea into a final design that will address these issues or future groups can potentially generate a new design.

![Figure 19: Possible cylindrical test fixture design for manufacture](image)

### ii. Rapid Prototyped Filter Design

Filter media samples were designed to be rapid prototyped. The samples have a 2.5"x6" cross-sectional flow area. The overall thickness of each sample is dependent on the individual layer thickness and the total number of layers. The 3D printer at Cal Poly has a minimum limit of
The available materials are ABS plastic and Epoxy Resin. Due to the large file generated by having a high number of arcs and linear relations, only the program for the epoxy resin material was suitable for our use.

One of the most important considerations when designing the filter media was to keep the pressure drop across the filter at a minimum. Preliminary analysis was done to estimate what this pressure drop would be based on pore size and number of pores. Each sample is treated as a composite material. It was assumed that the flow going through the filter is laminar flow at steady-state. Based on these assumptions, Darcy's Law was used to calculate the pressure drop.

The specific surface area and the porosity are dependent on the individual design of the filter. An excel document was created to estimate the properties of the filters that were designed. The physical characteristics that were altered were: number and width of layers, number and width of gaps, length, height, and number and size of holes (pores) per layer.

From the values input into the document, the void volume and the total volume were calculated. The void volume was calculated by summing the volume of the holes and of the gap layers. The total volume was determined from the overall volume (including gaps) by multiplying length, height and depth. Porosity, \( \phi \), was calculated by taking a ratio of void volume over total volume. The porosity is intended to be equal to or greater than 50%.

The next important value calculated was permeability, \( k \), by using the Kozeny-Carman equation:

\[
k = \frac{A \phi^3}{(1 - \phi^2)S^2}
\]

where \( A \) is the average area of the holes, \( \phi \) is the porosity, and \( S \) is the specific surface area. The specific surface area was determined by

\[
S = \frac{2(\text{Cross sectional area}) + 2(W_{\text{layer}})(L_{\text{layer}})}{\text{Total volume} - \text{Void Volume}}
\]

From the permeability the pressure drop can be calculated. The pressure drop was based off of Darcy's Law:
where $k$ is the permeability, $Q$ is the flow rate of air, $\mu$ is the dynamic viscosity of air, $L$ is the total length (depth) of filter, and $A$ is the cross-sectional area.

More detailed calculations for each filter can be seen in Appendix G.

Filter C

Filter C featured a new design to make removing the filler material an easier process. Filter C has a total of 6 layers with a .04” gap in between each layer. This gap has flow channels on either end of the filter to provide a path for the filler material to be washed out. A detail drawing of this filter can be found in Appendix G. Before the filter was printed, it was hypothesized that the pressure drop would be $3.53E-06$ psi and the porosity would be at 50.5%.

![Figure 20: Rapid prototyped Filter C](image)

This filter was rapid prototyped in epoxy resin. After printed it went through various methods to remove filler material. It was sprayed with a pressurized soap solution to remove the outer layers of support material. To remove the material in the holes and gaps it was placed in a vibrating machine filled with a soap solution for one hour. While not all of the material was removed, it was feared that a prolonged stay would start to deteriorate the filter itself. The filter was allowed to dry over night before being placed in a basic solution (Drano) which would help dissolve the support material. While we were able to remove most of the material, we were not able to completely unclog the filter. However, we found that the center (where most of the support material was removed) did allow air flow through the filter.

Filter D
Filter D has a total of 6 layers with a .02” gap in between each layer. This gap has support corners to reinforce the structure of the filter and maximize the space for filler material to be removed between the layers. A detail drawing of this filter can be found in Appendix D. It is hypothesized that the pressure drop would be $3.6 \times 10^{-6}$ psi and the porosity would be at 53%.

![Figure 21: Front view of Filter D](image)

**Future Filter Recommendations**

The biggest issue we faced in designing a filter was removing the filler material. Even with flow guides in place left for intentionally channeling out the filler material, it was not completely effective. In this case, both the filler material and the filter material are soluble in water; washing it in a soap or basic solution will deteriorate both.

Possible solutions for this problem are:

1. Using a machine that uses a different materials that are not soluble in the same liquid. (For example, ABS plastic and cellulose)
2. Individually printing each layer and then assembling the entire filter (minimal use of filler material)
3. Adding more channels or flow guides to remove filler material
6.) Design Verification

i. Static Test

A series of static tests were performed on various sealants and gaskets to see how they behave at high temperatures. These tests are static because they were performed in the absence of airflow. Our primary objective for these tests was to identify a material that would work well in our chamber, however, we were also looking to eliminate some materials that were completely unsatisfactory and not suitable to move on to dynamic testing.

A total of six static tests were developed:
1. Single Flat Plate Test - To observe the response of a thin layer of the material when exposed to extreme temperatures
2. Dual Flat Plate Test - To test the material under compression when applied between flat plates
3. Reservoir Test - To test the properties of the material when it is tested with a measurable depth
4. Joint Test - To test the properties of the material when applied at a 90 degree joint between surfaces
5. Torch Test - To test the damage done to samples when exposed to a direct flame
6. Air Tightness Test - To test if material placed between two plates could remain airtight after being exposed to high temperatures

A copy of the test plans and results are located in Appendix --.

Based on the results we determined a gasket material to be used at the ends of the intersections. We concentrated on finding a material that could withstand a temperature of 1300°F, create an airtight seal between the flanges, and be reused for multiple tests. Grafoil (a graphite gasket) satisfied all of our criteria. A generalized outcome of our results is shown in Table 4.

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<tr>
<td>Blu-Jel</td>
<td>Fails at 400°F</td>
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</table>
ii. Detailed Results

It took us some time to understand the true scope of our project. At first, we were under the naïve impression that we would purely be conducting materials research, and would be designing fireproof HEPA filters as the design component of our project. After sorting through the confusion, we learned that our project actually had little to do with research, and was instead concerned entirely with completing the MHTTU, which was devoid of a testing chamber. We were informed that research would only be conducted if time permitted once the testing unit was complete. Thus, the major result concerning our project, and the preceding MHTTU project for that matter, was the maximum operating temperature of the chamber. Of course, reducing the chamber’s settling time, or time to reach steady state, and reducing exchange time between samples were also of interest, but the top priority was maximum operating temperature.

Before we could heat the system, however, we had to prove that it was leak tight. Any leaks or failed components result in injury and erroneous data collection. We conducted a cold air leak test before starting heated testing. The problem was, clamps for flanged interfaces had not been delivered at the time of the test, and neither had the compression fittings for our thermocouples and static pressure probes, so the chamber was far from airtight. We improvised, therefore, using various plastic clamps for the flanges and duct tape to cover the instrumentation ports, and were able to assess the ability of the chamber to prevent leaks via physical inspection, putting our hands at each potential leak location and feeling for airflow.

Images of the chamber in this state are shown below in Figure 22:

**Figure 22:** Improvised cold air leak test setup

The first such test was inconclusive, as air escaped rapidly through the bottom side of each of the flanged interfaces. It was determined that the weight of the chamber sections alone was enough to pry the bottom of the flanges apart slightly, so a second test was performed. First, though, the flanges were hammered out on an anvil one last time to improve uniformity, and
the sections were mounted on trolley wheels so they were supported on the bottom rather than being suspended in a cantilever fashion. The next test showed major improvement, and we were given clearance to perform a hot test once the chamber was fitted with insulation.
A series of hot tests followed, each further improving the results from the previous test. The first hot test was conducted late in the evening, and we were not able to achieve a maximum temperature before we were asked to leave the machine shop where testing occurred. We came back the next day and finished the test, recording an initial maximum operating temperature of 650°F. This was the only test we had conducted by the time of the senior project expo, so this was our first published operating temperature.

Following the expo, three additional hot tests were conducted. Two thermal tapes – essentially resistance band heaters – had been procured from the manufacturer Briskheat that claimed 1400°F operating temperatures. They were wrapped around the center section of the chamber as a secondary heat source, but they had not yet been utilized. In addition, data collected in the previous tests had merely been observed, not saved, so these additional tests were used to generate settling time data for the chamber with and without the thermal tapes. Speculation told us that the implementation of the extra heating elements would increase the operating temperature of the chamber, but it was anyone’s guess how much. Beyond determining the new maximum temperature, we also wanted to check any changes in the settling time of the chamber when using the thermal tapes. Therefore, a heating test without the thermal tapes was again conducted, only this time temperature measurements were recorded throughout the test and saved afterwards. This data was then plotted to demonstrate the settling time of the unaided chamber. The next test marked the first use of the thermal tapes, but only one was used for safety reasons. A malfunction of the thermocouple in the exit section of the chamber rendered the data from this test useless, but we were able to observe an increase in the maximum operating temperature, which appeared to have increased to 740°F. Finally, the last heating test was conducted, again with only one thermal tape connected, and a plot was generated from the data. The plots from our intact heating tests are shown in the Figure 23.
7.) Concluding Remarks/Recommendations

Through this effort, we developed a greater understanding of what to expect during our engineering careers. It was our first educational experience that reflected the engineering industry outside of a school setting, which is paramount for emerging engineers. There are things one can anticipate when working on a design project, but there are others that simply cannot be foreseen without running into the problem and designing around it. Previously in our educational careers, we avoid these dilemmas by dealing purely with the theoretical realm of science, repeating analysis over and over without ever applying the knowledge to real world problems. This capstone project combined the theoretical and experimental worlds, demonstrating the value of each and showing that an accomplished engineer is one who respects them equally.

However, this project also showed the variance encountered within the mechanical engineering discipline. Our own team encompassed a broad range of talents and interests, and we dealt with many other individuals with greater differences still. In essence, theory and planning are necessary in projects such as this, but they will never be short of surprises. We spent the majority of our time designing in the theoretical realm, which proved very useful, but when it came to manufacturing, planning was not enough. We made schedules, factored in lead time, established early correspondence with third parties, and maintained a regular meeting schedule with our sponsor, but we were still hindered, and were left working on our project down to the very last day of the quarter. What we learned, after all was said and done, is that hindrances are simply a part of the design process, as much as preliminary analysis or procuring materials are. Furthermore, we developed a greater respect for scheduling, and learned that obstacles are no excuse for an incomplete product. We met our goals, but did not surpass them by much and were hoping to get much further with our material testing. As such, we have to relinquish our project and hope that future Cal Poly senior project teams will use it for valuable research.

While the MHTTU is complete, it has not been used for testing filter components. Additional fixtures need to be designed and implemented into the existing test section to gather data on the specific behavior of cylindrical filters. The current manufactured pressure fixture is currently ready to be used inside the chamber. Further tests can be developed to test sealant samples inside the test section.