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High-Temperature Vacuum Furnace Attachment for a Standard Tensile Tester

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ENTITLED

High-Temperature Vacuum Furnace Attachment for a Standard Tensile Tester

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High-Temperature Vacuum Furnace Attachment for a Standard Tensile Tester

By

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SENIOR DESIGN PROJECT REPORT

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Abstract

In this thesis, we outline the development of a low-cost high-temperature vacuum furnace attachment for a standard tensile tester at Santa Clara University. The project aims to expand the material testing capabilities of the university, promoting sustainability and enhancing safety in engineering applications. By focusing on design considerations, manufacturability, and economic viability, the team strives to create an accessible and efficient tool for advancing materials science research.

The initial phase of this multi-year project involves constructing a water-cooled vacuum chamber, which is crucial for the overall furnace system. This phase sets the foundation for subsequent developments, including the integration of a high-temperature heating system capable of reaching up to 2000 °C and the development of a sophisticated control interface for precise temperature regulation and data acquisition. We aim for this attachment to increase accessibility of materials testing under extreme conditions, providing valuable insights into material behavior and advancing research opportunities in material science. The project emphasizes a phased development approach to ensure long-term success and scalability, benefiting researchers, students, and the broader scientific community.

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Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Objective

The goal of this senior design project is to build a low-cost high-temperature furnace to expand the material testing capabilities of Santa Clara University. Additionally, by developing a low-cost alternative to expensive commercially available equipment, we aim to make high-temperature material testing and manufacturing accessible to a large number of institutions and expand the field of high-temperature materials science. Given the ambitious nature of our project, its complexity, and the constraints of our team size and budget, we recognized early on that achieving our objective would require a multi-phase approach spanning several senior design projects. For the 2023-2024 project term, our group has focused on constructing the water-cooled vacuum chamber, which is a critical component of the overall furnace system.

The initial construction of the water-cooled vacuum chamber is a significant milestone, setting the stage for future work. Subsequent senior design groups will focus on designing and integrating the heating system capable of reaching temperatures up to 2000 °C, developing a sophisticated control interface for precise temperature regulation and data acquisition, and implementing advanced insulation techniques to optimize thermal efficiency and safety. Through this phased development approach, we aim to build a versatile, high-performance vacuum furnace attachment that not only meets the immediate needs of Santa Clara University's material testing programs but also serves as a scalable model for other institutions and research organizations.

1.2 Background and Motivation

1.2.1 Motivation

In developing a high-temperature tensile tester at Santa Clara University, we are aiming to advance the frontiers of materials science while embodying and promoting a range of positive ethical implications. This project aligns with the university's strategic vision and the mission of its School of Engineering through its multipurpose nature. It contributes to the advancement of sustainable technologies by enabling the testing of materials under extreme conditions. This can lead to the development of more efficient, durable, and environmentally friendly materials, thus reducing environmental impact. Furthermore, our project provides a practical educational platform, enhancing our understanding of materials science, product development, and mechanical engineering. This hands-on experience is invaluable in cultivating practical skills and ethical considerations among future engineers.

Additionally, the ability to test materials at high temperatures will enhance safety and performance in various engineering applications, from construction to aerospace, by preventing material failures and improving the efficiency of systems, such as in the development of higher-efficiency jet engines. This directly contributes to safer engineering practices. Moreover, by expanding SCU's material testing capabilities, our project supports not only local industries but also potentially facilitates broader collaborations and contributions to global technological advancements, aligning with principles of community engagement and global responsibility. In essence, our project is not just a technical endeavor but also a commitment to responsible, innovative research practices, economic sustainability, and interdisciplinary collaboration, resonating with the ethical values and educational excellence promoted by Santa Clara University.

1.2.2 Background

Our project's focus on the development and testing of materials under high-temperature conditions is underscored by a range of pioneering studies. Researchers in China and the United States delved into the thermoplasticity of high-titanium content steel alloys, using a thermomechanical simulator furnace to replicate manufacturing processes at temperatures up to 1300 °C [1]. This research provided crucial insights into material behavior under extreme heat, directly relevant to our objective of high-temperature material testing.

Similarly, the construction of a high-temperature vacuum chamber by Schwartz at MIT for testing materials in fusion reactors, where temperatures soar to 1000 °C, aligns closely with our goals [2]. This study, alongside Johnson and Killpatrick's evaluation of nickel-based alloys for Space Shuttle heat shields, which involved testing in conditions simulating shuttle reentry, added depth to our understanding of materials' performance in harsh environments [3].

Moreover, Taylor's development of a tensile testing apparatus capable of reaching 5400 °F provides a benchmark for testing materials near their melting points, essential for understanding the deformation behavior of refractory metals [4]. This is complemented by research done by the University of California and Lawrence Berkeley National Laboratory on the high-temperature joining of alumina, emphasizing the need for maintaining mechanical properties at elevated temperatures [5].

From these studies, we drew the foundational knowledge and inspiration for our project. They highlight the various applications of high-temperature material testing and provide a detailed overview of current methods and challenges, supporting our ambitious goal of reaching a target temperature of 2000 °C.

2 Professional Issues and Constraints

2.1 Civic Engagement

With our project, we aim to expand the capabilities of non-governmental organizations such as universities and research institutes, expanding access to high-temperature material testing and manufacturing facilities. A low-cost research tool makes the field of high-temperature materials research accessible to a wider range of institutions. The role of these institutions is highly important, serving as a foundation for innovation and facilitating the transfer of knowledge to future leaders in this research area. This pursuit is both technical and educational in nature and has provided us with the opportunity to evaluate and discuss the role of public organizations in advancing both technological and societal welfare.

In addition to our primary goals, during the development of our project, we were engaged in discussion on how various public organizations influence the field of materials science. We spoke with materials science researchers and existing market leaders in the development of this project to learn more about the kinds of requirements that needed to be met for projects similar to the one that we are undertaking. Additionally, we explored how governmental bodies are involved in the field by setting industry standards and funding initiatives. For example, agencies such as the National Science Foundation (NSF) may be actively involved in supporting groundbreaking research through the offering of grants. Our project was entirely funded by a grant provided by Santa Clara University, and future work on this project will require significant funding from similar funding initiatives.

2.2 Science, Technology, and Society

During the development of our product, we have placed a high level of importance on discussions about its impact on both the scientific community and society at large. By enabling advanced materials testing, our project supports research that can lead to the development of more efficient and environmentally friendly technologies. This has the potential to reduce energy consumption and greenhouse gas emissions, contributing to a more sustainable future.

We believe that there is a significant relationship between our project and society. On one hand, the technology enables critical research that can drive scientific advancements. On the other, it is a product of societal needs for more efficient and sustainable technologies. It will allow for greater access to a tool that can facilitate groundbreaking materials research that can lead to the development of more environmentally friendly and quality of life improving technology, connecting technological innovation and societal progress.

While our project aims to yield numerous benefits, we also considered potential consequences. Positive outcomes might include the advancement of sustainable technologies and increased safety in engineering applications. However, potential negative consequences could arise, such as the environmental impact of energy-intensive testing processes or the unforeseen technical challenges in maintaining the equipment. Additionally, we acknowledge that our product could potentially be used in the development of harmful technology or applications not aimed at societal betterment; however, we hope it will not be utilized in such a manner. Reflecting on these possibilities allows us to proactively address and mitigate adverse effects, ensuring our work contributes positively to society.

By recognizing the complex relationship between technology and society, understanding the science behind our innovations, and evaluating their social impacts, we are aiming to fulfill our obligation to consider the broader implications of our engineering endeavors. Our high-temperature tensile tester is not only a technical achievement but also a tool for societal progress, reflecting the interconnected nature of science, technology, and community.

2.3 Ethical Considerations

In developing the motivation to pursue this project, we considered several ethical questions. One of the key issues we wanted to address was ensuring responsible use of the equipment we were building to prevent misuse or unsafe experimentation. In addition to this, we considered the implications of our research on the environment and broader society and ensured we were adhering to codes of ethical conduct as specified by our university and professional societies.

2.3.1 Ethical Misuse Concerns

Our primary concern is that our project will be used for unethical purposes. There is inherently nothing unethical about our project itself, as it does not harm individuals or the environment when used as intended. Instead, it serves to advance knowledge and contribute to technological progress. However if it is used for unethical purposes, such as the development of weapons or knowingly developing a technology which is damaging to the environment, it becomes unethical to build. We have weighed these concerns with the good outcomes we know our project could help develop once it is out of our hands, and we determined that the only way we can ensure that our project does not contribute to unethical ends will be to leave it with an institution with clearly defined ethically good intentions. In addition to the comprehensive measures we have taken to address potential safety and environmental concerns, we will be leaving the project to be completed and used by Santa Clara University, an institution which prides itself on its Jesuit values. We are certain that the institution that trained us as engineers will not misuse our project for unethical pursuits.

2.3.2 Economic

Our high-temperature vacuum furnace attachment for tensile testers is meant to be a cheaper alternative to custom build models of the same product that have costs in the range of hundreds of thousands of dollars. With our product, we are aiming to make research in the realm of material behavior at high temperatures more accessible; thus, allowing for the generation of more knowledge in this area.

We carefully managed a $2000 budget by recycling materials and conducting extensive finite element analyses (FEA) to minimize prototyping costs. Recognizing that the project's total cost will likely range between $6,000 and $10,000, we planned for future funding needs and economic sustainability. This included considering grants and potential income from offering high-temperature material testing services. We also accounted for the cost of borrowing funds, ensuring these expenses are factored into the service pricing–this analysis can be seen in Section 8.2. By balancing immediate budget constraints with long-term financial planning, our project aims to be economically viable and sustainable, benefiting both the university and the broader engineering community.

2.3.3 Health, Safety, and Usability

Throughout the development of our high-temperature tensile tester furnace, we prioritized health and safety by adhering to strict guidelines and conducting thorough stress analyses to prevent catastrophic failures. Our design ensures the chamber can reliably achieve and maintain temperatures up to 1700 °C while incorporating specialized atmospheres for safe testing. Occupational Safety and Health Administration (OSHA) standards and ASTM International guidelines govern the design and use of high-temperature testing equipment, ensuring that our product meets stringent safety requirements. Ethically, we are committed to preventing harm to users by incorporating safety features such as robust cooling systems to keep external temperatures below 100 °C, thereby reducing the risk of severe injury *via* contact, and by conducting stress analyses prior to construction of the chamber to ensure catastrophic failure will not occur under operating conditions.

Relevant health effects we considered include thermal burns, exposure to harmful gasses, and physical injuries from equipment failure. Ensuring safe operation at high temperatures and maintaining a secure atmosphere within the chamber are paramount to protect users from these risks. The design includes secure and easily disassembled components for maintenance, proper pass-throughs for instrumentation, and connections for vacuum and argon fill tanks to ensure safe operation. We also considered human-centered design for user-friendliness, ensuring clear interfaces and a reliable door mechanism to minimize potential injury. Our commitment to safety extends to compliance with relevant laws and ethical considerations, ensuring our product is safe and reliable for use by trained lab technicians and researchers.

2.3.4 Manufacturability

In assessing the manufacturability of our high-temperature tensile tester furnace, several key considerations come to light. Based on our projections, we believe that our product can indeed be built, leveraging existing materials and technologies, but careful attention must be paid to ensure precision and reliability. We initially explored using recycled materials from our machine shop, which not only reduced costs but also minimized waste. This approach highlighted that there are often simpler, more cost-effective methods to achieve our goals than initially anticipated.

Development time is a significant factor, as prototyping and testing high-temperature systems require meticulous planning and execution. The need for multiple analyses and iterations, particularly in FEA software, can extend development timelines. However, this is crucial to avoid costly mistakes in the physical prototyping stage.

Cost issues are inherently tied to the quality and availability of materials, especially for components that must withstand extreme temperatures. While our initial budget was $2000, the overall project cost is estimated to range from $6,000 to $10,000. This includes expenses for electrical, control, insulation materials, and heating elements. To manage these costs, future funding and grants will be essential.

Manufacturing the project could present challenges such as sourcing specialized materials and components, ensuring compatibility and safety of all parts, and achieving the desired temperature range and atmosphere control. Potential problems include delays in material procurement, unforeseen technical issues during assembly, and maintaining strict safety standards throughout the manufacturing process. Addressing these challenges requires a well-coordinated effort, thorough planning, and flexibility to adapt to unforeseen obstacles, ensuring the final product meets all operational and safety requirements. Section 6 contains more information regarding the actual manufacturing process we went through to develop our product.

2.3.5 Sustainability

Sustainability in our high-temperature furnace project encompasses both narrow and broad senses. In the narrow sense, we ensured that our product is viable and useful over time by designing it to be repairable and adaptable. We left adequate clearance in the design to allow for future retrofitting with newer technologies, which extends its lifespan and usability.

This focus on longevity and adaptability ensures that the product will not become obsolete quickly and can be updated to meet evolving needs.

In the broader sense, our project contributes to a sustainable economy by aiding in the development of new and more efficient energy technologies. By enabling high-temperature material testing, our tensile tester furnace can support research into advanced materials that are crucial for developing more efficient and environmentally friendly energy solutions. This, in turn, helps reduce the environmental impact of energy production and promotes the sustainable use of resources.

2.3.6 Environmental Impact

Environmental considerations are integral to our project. We sourced our stock metal from suppliers who recycle, and used waste cuts of metal whenever possible, minimizing the use of new raw materials and reducing waste. This approach not only conserves valuable resources but also lowers the environmental footprint of our manufacturing process.

Our tensile tester furnace is designed to assist in the development of technologies that have a positive environmental impact. By facilitating the testing of materials under extreme conditions, it supports the creation of more efficient energy technologies, such as advanced alloys for high-efficiency engines and renewable energy systems. These advancements can lead to reduced greenhouse gas emissions and lower energy consumption, contributing to environmental protection.

However, we are mindful of the environmental impact associated with the production and operation of our tester. The energy required to reach high temperatures and maintain specialized atmospheres could contribute to resource use and emissions. This consumed energy while conducting experiments in a small university research lab would be easily offset by the energy savings resulting from the use of advanced materials on an industrial scale. Still, we are committed to optimizing the efficiency of our design to minimize energy consumption and exploring renewable energy sources for its operation where feasible. By addressing these environmental issues, we aim to create a product that not only advances materials science but also aligns with principles of sustainability and environmental protection.

2.4 Customer Needs

We are trying to serve materials science research labs by providing them with an affordable piece of equipment to expand their testing capabilities. Our overall need-finding activities consisted of correspondence with potential customers, and stakeholders in our project, and research on other existing products that are comparable to our vacuum furnace.

Our product has two general customer segments: large, well-funded materials labs and smaller, less-funded labs. We are primarily trying to serve the smaller labs, as we aim to keep the cost of our product low enough for it to be affordable; however, a low-cost vacuum furnace attachment may also be attractive to larger labs as an alternative or supplement to larger, custom-made vacuum furnaces depending on their exact needs and budget allocation.

The broader stakeholders of our product include other companies that have developed similar products, such as Materials Research Furnaces (MRF) (Allenstown, NH) and Centorr Vacuum Industries (Nashua, NH), who are either affected by our product drawing away their customers or who may be interested in further developing our product. Additionally, with our senior design product plan, a major stakeholder in our project is the future senior design team who will be inheriting our project and will have to work with our final product. It is in our best interest to make our product as easy to work with and expand upon as possible.

2.4.1 Materials Science Researchers

For customers, we reached out to two materials scientists, Dr. Marks, and Dr. Sepehrband, to arrange interviews about what features they would like to see in a product like ours. We were able to have a long in-depth conversation with these researchers on the features they would like to have and would require for a furnace attachment for the materials science lab's tensile tester.

Some of the requirements that we have found to be most pertinent to high-temperature tensile tester furnace development are as follows. The tester must be capable of reaching temperatures between 1200 °C to 1300 °C for testing and up to 1700 °C for sintering. It should function as a furnace for heat treating materials at 1800 °C and should be equipped to operate in a vacuum or specialized atmosphere to achieve the desired temperature conditions. The tester should include connections for vacuum pump fittings and inert atmosphere fill tanks, with a preference for using argon at 1 atmosphere for fill and vent processes. It should have an internal space with a minimum size and a hot zone diameter of 4 inches. Additionally, the furnace should be removable from the tester, include a thermocouple passthrough with a compression fitting for temperature measurement within the hot zone, and have a rough vacuum gauge with a range of 0 to -30 inHg in addition to a higher precision vacuum gauge to determine the exact vacuum quality. Preferred features include room temperature or cooling water capacity saturation, ease of use, a good door seal, and adequate door clearance. The customer requires this high-temperature tensile tester furnace for materials testing purposes.

2.4.2 Industry Stakeholders

To gather additional information regarding potential customers we reached out to industry stakeholders, including MRF and Centorr; companies that build high-temperature vacuum furnace attachments for tensile testers to learn more about their products' capabilities and the features that their customers are interested in. We met with MRF and had a very comprehensive discussion on their furnaces' capabilities, the challenges involved with reaching our goal temperature, and the features that their customers request. Additionally, we reached out to Dr. Schwartz, an MIT graduate who, as his senior design project, built a high-temperature furnace attachment for a tensile tester to test materials for use in fusion reactors. Overall, these meetings allowed us to better assess the scope of our project and the challenges we may face during development to ensure the quality of our product.

After assessing input from stakeholders in the industry and individual customers, it became evident that high-temperature tensile testers serve a diverse range of clients, with prominent users including national laboratories, universities, military branches like the Navy and Army, and various government research facilities. This clientele, distinct from typical industrial users, mainly employs these testers for research and development purposes, particularly those engaged in advanced composite materials. Key requirements identified among these customers revolve around the need for reliable and reparable machines, and in applications such as factory assurance testing. These testers must meet stringent quality control standards, ensuring accurate measurements of tensile strength and deformation properties at elevated temperatures where material performance can significantly vary. Additionally, adaptability and versatility in equipment are essential, given the dynamic nature of research in these sectors.

2.5 Design Constraints

Our product benchmarking process consisted of compiling a list of 20 design and performance characteristics, tabulating the performance of existing vacuum furnace products on those metrics, and determining which of those characteristics we hope to achieve with our product. Systems similar to the one we are designing have been built by others before and are often custom-made for each application. This means that there are only a few benchmarks that are critical for us to meet: vacuum level, cooling capability, heating, and pressure rating. These characteristics are fundamental to the operation of the vacuum furnace and must be met. Additionally, there are constraints that we must work within, such as the physical space available on our tensile tester, which must be met. Many of the other characteristics are less critical and are often up to the customer's personal choice.

2.5.1 Addressed Needs

Our design approach for the high-temperature tensile tester furnace placed paramount importance on addressing the customer's needs for the requested temperature range. We were committed to ensuring that the system could safely reach temperatures within the range of 1200 °C to 1300 °C for testing, and potentially up to 1700 °C for sintering, while simultaneously serving as a standalone furnace if necessary. Additionally, we prioritized the chamber's ability to maintain a specialized atmosphere to safely reach and maintain temperatures in the testing range, with due consideration given to the specialized requirements of materials testing. Furthermore, we ensured an adequate hot zone with a diameter of at least 4 inches to accommodate various specimen sizes and geometries, providing flexibility in testing. The ease of disassembly of the furnace was another key point, as it enhances maintenance so that the tensile tester can regain its regular function.

To accommodate data acquisition for research, we ensured sufficient clearance for pass-throughs for thermocouples, vacuum gauges, and other instrumentation to facilitate accurate temperature monitoring and control. Equally important was the presence of clearance for vacuum pump fittings and argon fill tank connectors, critical for achieving the desired performance. We have integrated an optimal water cooling solution into the chamber to prevent overheating and maintain a safe working environment taking the flow rate and temperature of the coolant supplied by the Material's lab into account. To maximize user-friendliness, we were mindful of incorporating elements of human-centered design with clear interfaces to prevent potentially dangerous user error and promote accessibility. Lastly, we ensured a robust door mechanism that considers internal clearance requirements and maintains a secure seal will be constructed with the customer's preference for door functionality in mind.

3 System Definition and Overview

3.1 System Definition

Our system consists of a low-cost, heated vacuum furnace to modify a standard tensile tester machine to test the mechanical properties of material samples at temperatures reaching 2000 °C, utilizing integrated water-cooling on critical components, dynamically sealed testing rams, and pass-throughs for instrumentation and power. To bring test samples up to high temperature, they will be placed at the center of a hot zone equipped with heating elements capable of producing temperatures up to 2000 °C. Additionally, this hot zone will be inside a vacuum chamber, which is needed to prevent the heating element from burning up in an oxygen environment. The water-cooling system serves to keep critical components, such as instruments, seals, and the vacuum chamber cooled to ensure their functionality and integrity. The dynamic seals on the top and bottom tester rams seal the vacuum chamber while allowing the water-cooled tensile tester rams to move freely and perform a test sequence without interference. Instrument and power pass-throughs also keep the vacuum chamber sealed while allowing data and sensor connections through, such as for a thermocouple, as well as pass-through power bus bars for the central heating elements. A visual outline and the material testing process is shown in Figure 1. For the 2023-2024 project term, due to the project scale we determined an appropriate project scope would be to construct the water-cooled vacuum chamber portion of the furnace, leaving the heating element, water-cooled rams, and internal thermal design to future senior design groups

3.2 Subsystems

The high-temperature tensile tester furnace consists of 4 subsystems: Structural, Cooling, Pass Throughs, and Seals. A 3D printed mockup of the system showing a conceptual design is shown in Figure 2. The structural subsystem encompasses the structural walls of the vacuum chamber, the mounting solution to attach the chamber to the tensile tester, the door hinge mechanism, and the rams. For this system, structural analysis and simulation will be used to validate the design. The cooling subsystem encompasses the thermal management system, including the cooling jacket on the vacuum chamber, the cooling loops in the rams, and the water supply plumbing from SCU's Sobrato Campus for Discovery and Innovation (SCDI) refrigerated water supply. For this subsystem, thermal analysis and simulation will be performed to validate the design and measurements of the available water supply. The Pass Throughs subsystem encompasses the electrical and thermocouple penetrations into the vacuum chamber in addition to the gas and vacuum connections. The seals subsystem includes the dynamic ram seals, the door seals, and the wall cooling panel seals.

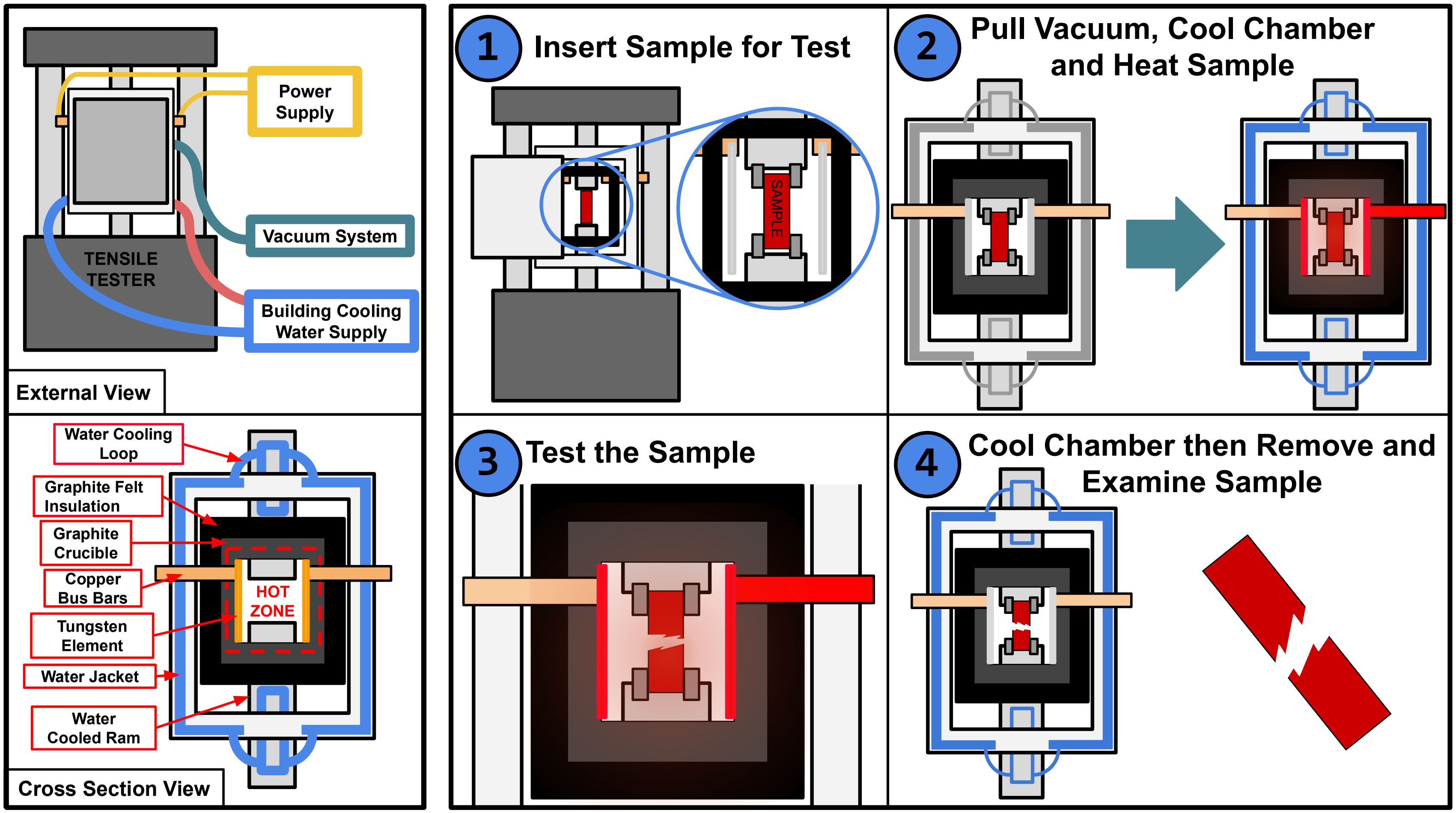

Figure 1: Concept of operations diagram (Credit: Manu Bodagala).

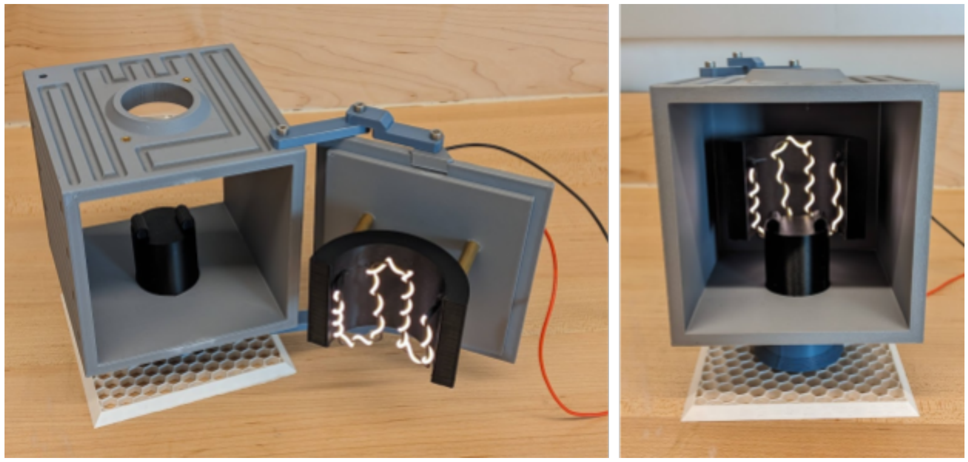

Figure 2: A 3D Printed Scale Mockup Showing the integration of a heat shield, bus bars, and model LED heating element (Credit: Peter Schumacher).

3.3 Systems Level Overview

3.3.1 Structural

The chamber walls must be strong enough to withstand the pressures generated by pulling a vacuum inside the chamber. When a vacuum is pulled, the internal volume of the chamber is emptied of air, which results in a very low internal pressure while the exterior pressure remains constant at approximately 14.7 pounds per square inch (psi). In order to withstand this pressure load without deformation, which could result in a catastrophic implosion of the chamber, the walls of the chamber must be sufficiently strong, while also accommodating the cooling system and mounting points. Additionally, the chamber must be securely mounted to the tensile tester frame, which will support the chamber's weight and prevent it from moving while in operation. The mounting solution needs to carry the weight of the chamber and will need to resist any moments due to uneven loads, such as the doors being opened. Finally, the doors of the chamber, which will weigh a significant amount, must be mounted to the chamber with hinges so that they can be easily swung open by the furnace operator. The hinges will need to be strong enough to withstand the weight of the doors and the cooling system attached to them while fully extended. The structural design of the rams will need to ensure that they can sustain the same loading conditions that the existing tensile tester rams can withstand, while also accommodating the cooling system and mounting solution to the tensile tester hydraulics and experimental apparatus inside the furnace.

3.3.2 Cooling

The cooling subsystem is critical for ensuring the safe operation of the furnace, as without it the exterior temperature of the chamber may become dangerously hot and the structural integrity of the chamber may be diminished. The cooling system will consist of a chilled water cooling loop which circulates around the exterior surface in order to transfer the heat away from the chamber, keeping the chamber temperature low. The room in SCDI which houses the tensile tester is already plumbed with a refrigerated water supply which cools the hydraulic power unit of the tensile tester, and this water supply can be utilized for cooling the chamber. Additionally, the rams which enter the chamber and are in close proximity to the hot zone must also be water-cooled to ensure they do not become dangerously hot or weakened by the high temperature.

3.3.3 Pass Throughs

The furnace needs several penetrations into the vacuum chamber to accommodate key instrumentation and equipment. The central hot zone where the heating of a material sample occurs requires both heating elements and a temperature probe to control the temperature of the furnace. This will entail pass throughs in the door where water-cooled electrical bus bars will enter the chamber to supply power to the central heating element and a long thermocouple probe to measure and allow control of the temperature. Additionally, the chamber requires several gas plumbing connections to manage the inlet and outlet of different gasses to control the atmosphere on the inside of the chamber. For pulling a vacuum inside the chamber, a tree of fittings and instruments, including a vacuum outlet, vent inlet, and vacuum gauge are required, and for pressurizing the inlet with an inert gas, a separate inlet for a gas cylinder and pressure gauge is required. All of these pass throughs must be placed at specific locations on the chamber walls, and the cooling solution must avoid interfering with their installation.

3.3.4 Seals

All penetrations, opening hatches, and pass throughs into the chamber must be sealed to maintain the desired atmosphere on the inside of the chamber. For the preservation of the heating element, which can ignite and destroy itself in the presence of an oxygen environment, the internal atmosphere of the chamber must either be a low-pressure vacuum or an inert gas, such as argon. Both of these cases will result in a pressure differential against the exterior pressure, and therefore sufficient seals are required to isolate the inside atmosphere, which will be achieved through o-ring seals. The door seals are static, as the doors will remain closed when the chamber is in operation, however the rams, which penetrate through the top and bottom of the chamber, must be able to reciprocate in and out when in operation to perform a material test. This will require a dynamic o-ring seal, which can maintain the pressure differential while the rams slide past it. Additionally, the water cooling solution will require sealing to prevent the leakage of water, which could compromise the effectiveness of the cooling system. This will entail a gasket-style seal to keep the water contained within the chamber walls, with cover panels compressing the seal material.

4 Design Process

The design process of this project consisted of two stages. First, we conducted several ideation sessions where we assembled multiple different concepts to best implement the features required and requested by the customer, and then we performed tradeoff analyses of the best concepts to finalize which design choice would proceed. A whiteboard concept sketch of the chamber size is shown in Figure 3. Next, we began the physical design process in the computer aided design (CAD) software Onshape, where the features were drawn and assembled in a computer model. During this stage we determined the dimensions and details of the final components, keeping in mind the manufacturing processes we had available to us.

4.1 Trade-off Analyses

Two main tradeoff analyses were performed in the design process for this project. These analyses were used to select the main material used in the construction of the chamber, and the method used to cool the chamber. For each analysis 5 options were chosen and 5 criteria were selected to make the decision. Each criterion was weighted to represent the importance that it had in the decision making process. Each option was then either rated or ranked based on the criteria and the values for each option was combined using a weighted average to determine the final result.

4.1.1 Cooling Method

For the cooling method, the 5 possible methods considered were: machined paths, copper tube, immersion, whole side panel, and air cooling. Simple drawings describing these options are given in Figure 4. The machined paths option has channels cut into the surface of the chamber which water from SCDI's chilled water system will flow through to cool the chamber walls. The copper tube option has a copper tube wrapped around and coupled to the main chamber with either a thermal compound or soldering. Chilled water then flows through the tube to cool the chamber. The immersion cooling method had a larger box built around the 4 sides of the chamber which was then flooded with chilled water to cool the inner chamber. The whole side panel simplified some of the immediate challenges of the immersion method by just flooding two sides of the chamber with the water flowing through a large cut out area. Finally, air cooling consisted of fins being either machined into or attached to the surface of the chamber, with a fan blowing air across the fins to cool the chamber.

The 5 criteria selected for this analysis were: the cooling capacity, the cost to implement the solution (with lower cost being better), the ease at which the solution could be machined,

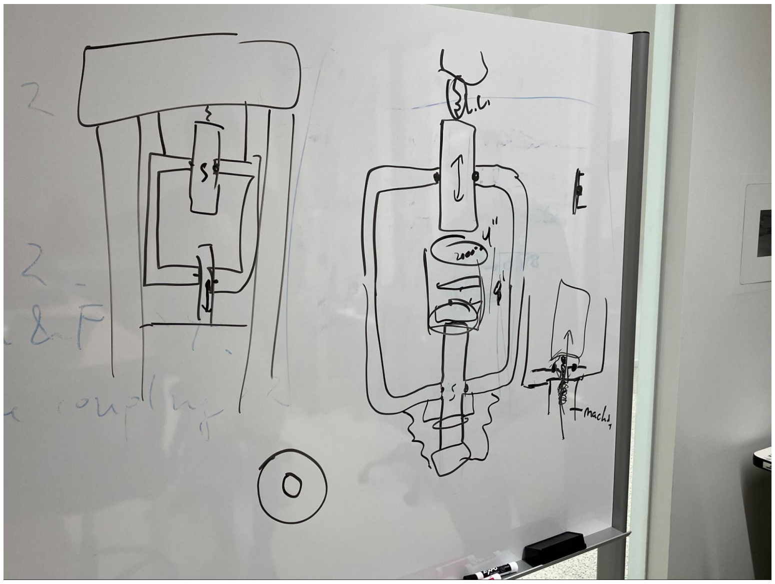

Figure 3: An initial whiteboard concept sketch showing the chamber structure and ram penetrations (Credit: Alejandro Mendez-Reynoso).

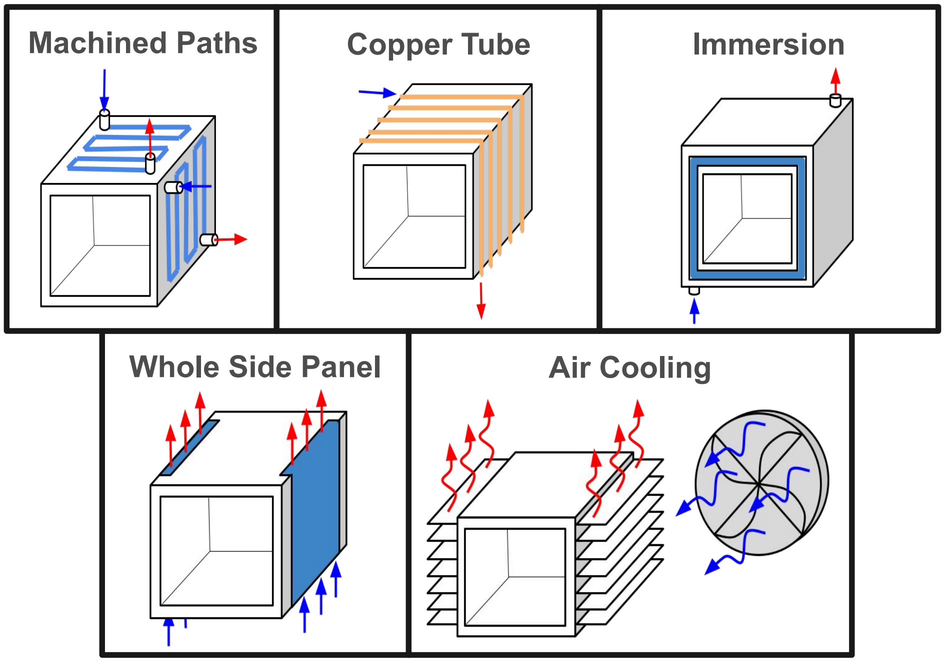

Figure 4: Cooling options discussed in trade-off analysis for chamber cooling method (Credit: Benjamin Spielman).

Table 1: Trade-off analysis data for cooling method selection, see Figure 4 for example drawings of each method.

	Machined Paths	Wrapped Copper Tube	Immersion	Whole Side Panel	Air Cooling
Cooling Capacity (25%)	5	4	2	3	1
Cost (20%)	4	2	3	5	1
Machinability (15%)	2	5	4	3	1
Assembly (15%)	5	1	3	4	2
Simplicity (25%)	5	1	2	3	4
Results	4.4	2.7	2.7	3.6	1.8

the ease at which the solution could be assembled, and the complexity of the solution. Machinability and assembly were both selected as criteria because some options like the copper tube are extremely easy to machine, but much more challenging to assemble. Since two criteria are directly related to the manufacturing of each option, they were both weighted at 15% importance to the final solution. The complexity and cost of the solution were both weighted at 20% because a more complex solution would take either more time, more work, or more complex equipment to create, and higher costs could quickly consume the budget available for the project. Lastly, cooling capacity was rated as the most important factor because if the chamber cannot be effectively cooled, functionality at high temperatures would be significantly more challenging without risking damage to the tensile tester, damage to the SCDI building, or the safety of the operator.

Solutions were ranked against the other solutions for each of the 5 criteria. This method was chosen because at the point of performing this analysis there was no way of quantitatively rating any option. The final ratings and overall score for each material is available in Table 1. This analysis showed that machined paths were the best suited cooling method for the chamber.

4.1.2 Structural Material

For the structural material, the 5 options chosen were: 3003 aluminum, 6061 aluminum, mild steel, stainless steel, and copper. The 5 criteria were the material's physical strength, corrosion resistance, machinability, cost (with lower cost being better), and heat transfer capabilities. Physical strength and heat transfer capability were determined to be the most important for the chamber walls because of the need to withstand a vacuum, and the need

Table 2: Trade-off analysis data for chamber material selection.

	3003 Aluminum	6061 Aluminum	Mild Steel	Stainless Steel	Copper
Strength (25%)	3.5	3.5	4.5	5	1
Corrosion Resistance (20%)	3	4	1	5	4
Machinability (15%)	5	5	1	1	5
Cost (15%)	4	3	5	2	1
Heat Transfer (25%)	3.5	4	2	1	5
Results	3.7	3.9	2.7	3.0	3.2

to cool the chamber walls. The corrosion resistance of the material was deemed the second most important factor because the panels of the chamber are going to be in contact with water for long periods of time, and corrosion would cause many different problems including both polluting the chilled water system and potentially weakening the panels. The least important criteria were deemed to be the machinability and cost of the material. While these criteria were least important, the weights assigned were both 15% compared to 25% for physical strength and heat transfer capabilities, meaning they were still significant to the decision process. Cost was chosen as one of the criteria because the budget provided by Santa Clara University for this project was $2,000. Machinability was selected because machining was a significant part of the manufacturing process used in this project.

The ratings for each material were agreed upon as a group based on various material properties and more qualitative information relevant to each criterion, with a higher rating being better. The final ratings and overall score for each material is available in Table 2. This analysis showed that 6061 aluminum was the best suited material for the structural material.

4.2 Seals

The design of the sealing features of the chamber is critical to ensure the desired operation of the chamber, as without a specialized atmosphere, the heating element will be damaged or destroyed. The O-ring groove design for the static door seals and dynamic ram seals is critical to ensure a proper seal is established between the sealing faces with sufficient compression of the o-ring. As o-rings are most readily available in standard sizes, we determined that we would work around available sizes to both reduce cost and to apply manufacturer recommended o-ring groove dimensions and tolerances. Parker O-Ring, the manufacturer of the o-rings we used in this project, provides a design guide which details the machined dimensions and tolerances needed for each standard o-ring size in order to achieve a desired seal quality. For a static vacuum seal, such as on the doors, Parker specifies a 0.16 in wide, 0.106 in deep groove for a dash 2 o-ring size. For a reciprocating shaft vacuum inner-diameter seal, which we will machine on the inside of the ram bores, Parker specifies a 0.189 in wide, 0.123 in deep groove on the inner diameter of the sealing surface, with a 0.003 in clearance between the shaft and bore for a dash 2 o-ring size. Additionally, for a reciprocating vacuum seal, they recommend multiple o-rings in series to achieve a better seal quality, so we will install two on each ram. [6]

The seals for the water cooling channel cover panels had several possible designs, including another system of o-rings, a rubber gasket, or a curing liquid rubber seal material. An o-ring seal would entail a machined o-ring groove which circles along the perimeter of the cooling channels which would be compressed between the chamber and the cover panel. This would require the additional machining of an o-ring groove. We determined that due to the complexity of the cooling channels and the challenges of designing around available standard o-ring sizes, an o-ring seal would not be suitable for sealing the water channels. A rubber gasket seal would entail a sheet of rubber sandwiched between the chamber and the cover panel which would be cut to size and cut around the channel geometry and would not require any additional machining to accommodate. While this would produce a custom-fit sealing gasket which could be easily removed, it would be significantly more expensive than a liquid solution, as it would require purchasing very large sheets of gasket material to accommodate the size of the gaskets. A liquid curing gasket would entail a liquid silicone material which would be extruded onto the chamber, sandwiched between the chamber and cover plate, and then cured, forming a solid custom gasket which easily accommodated the channel geometry. We decided this would be the best of the seal options for this project, as it is relatively inexpensive and can produce a custom gasket very easily without wasting too much material or requiring additional machining.

4.3 Structural Design

With the choice of a machined channel cooling design, the structure of the chamber would need to be made out of relatively thick plates which could accommodate the depth of the cooling channels and the mounting of other hardware. The exact thickness and size of the wall and door panels was initially set to a very conservative 1 in, which would ensure sufficient thickness for both strength and the machining, however the exact final dimensions would be determined based on the results of preliminary FEA analysis. We found a 14.5 in cube with

0.75 in wall thickness could withstand the vacuum pressure load while accommodating 0.3 in deep cooling channels, while also providing sufficient material thickness for accommodating tapped mounting holes for additional necessary hardware.

In order to support the weight of the chamber from the tensile tester, there are several options, including supporting the bottom of the chamber, connecting the chamber to the tensile tester uprights, and hanging it from the upper crossbar of the tensile tester. While supporting the chamber from the bottom would be mechanically simple, the tensile tester deck does not have the structure necessary to support any significant weight. Additionally, this area is reserved for the machine controls and hydraulic plumbing, which would both be obstructed by the chamber resting on them. Supporting the chamber *via* clamps from the tensile tester uprights would keep the structure of the chamber away from the mechanisms of the tensile tester and resist any moments placed on the chamber, however significant analysis of the friction interaction between the clamps and uprights would need to be performed to ensure it does not slide down the uprights and can support the full weight of the chamber. Hanging the chamber from the crossbar of the tensile tester once again keeps the chamber away from the mechanical components of the tensile tester, while fully supporting the chamber's weight from a portion of the tensile tester which is designed to support the extremely high loads of mechanical testing, however this would not resist any moments applied to the chamber, such as the weight of the doors when opened. We decided to combine these last two choices by supporting the weight of the chamber from the crossbar using eyelets and turnbuckles, while adding smaller clamps to the uprights to resist twisting moments on the chamber. This keeps the chamber away from the controls of the tensile tester, rigidly secures it against moments, and allows the hanging position of the chamber to be adjusted by screwing the turnbuckles.

In order to connect this mounting solution to the chamber itself along with the addition of the door hinges, we added mounting rails to the top and bottom of the chamber. These rails are bolted onto the chamber to allow them to be removed and modified by future groups if they require support for additional hardware, without requiring modifications on the actual chamber which would be too large to modify on the Bridgeport mills available in the machine shop. These rails act as the mounting point for the hanging eyelets, the attachment points for the upright clamps, and the attachment point for the door hinges.

4.4 Future Groups: Keep Out and Mounting

As the project scope for the 2023-2024 term is limited to the vacuum chamber, we had to consider the placement and installation of hardware that future groups might add. This primarily consists of penetrations into the chamber such as the bus bars powering the heating element, the instrumentation, and locations where we intend for the vacuum and gas connections to be installed. From our research into similar vacuum furnaces made by MRF and others, we decided to place a “keep-out zone” on both chamber doors where the cooling channel geometry would avoid a central surface, allowing for the addition of bus bar and thermocouple pass throughs by future senior design groups. These areas are clear of any features such as cooling channels or bolt holes which might impede the area where future groups will add additional hardware, allowing for the easy modification of these parts as needed.

5 Analysis

5.1 Structural

The structural analysis of the chamber was performed using Solidworks' Simulation Add-in. Stress simulations of the chamber structure were performed at several stages during the design process in order to determine the required dimensions of the chamber walls, and once determined and all the machined features were added to the chamber design, a final high detail simulation was performed to determine that the final manufactured design had a sufficient factor of safety.

In order to determine the simulation parameters, the loading conditions and material type and behavior must be considered. The chamber will experience the highest load when a 14.7 psi exterior pressure load is applied to the entire exterior surface. The chamber will be constructed out of 6061 Aluminum, which varies in strength depending on the temper, with higher strength achieved with a T4 or T6 temper. The supplier we sourced the stock from did not specify whether the stock is tempered, and the strength of the weld joints between the plates is unknown, so to be conservative the untempered 6061 alloy material setting available in Solidworks will be applied, which has a much lower yield strength of 55 MPa compared to the tempered alloys which can achieve yield strengths up to 240 MPa. Additionally, when in operation the center of the furnace chamber will reach extremely high temperatures which will heat up the inner chamber surface significantly. Aluminum becomes weaker as its temperature increases, with the yield strength of untempered 6061-O decreasing to 38 MPa at 100 °C [7]. As the cooling system is required to maintain below a 100 °C maximum exterior temperature, this is the maximum operating temperature the aluminum chamber will experience. From these material properties, we determined that a yielding factor of safety of 2 on the chamber when operating at room temperature would be sufficient to account for both the uncertain temper and thermal strength degradation.

5.1.1 Preliminary Simulation Runs

Initial, fast stress simulations were performed to determine the maximum size and thickness of the chamber which could be achieved while withstanding the pressure load. Initially the chamber was set to a 12 in cube with 0.4 in thick walls and the material set to 6061 Aluminum alloy. The vacuum pressure was modeled in Solidworks as a 14.7 psi pressure load applied to four of the external surfaces (Figure 5). In order to calculate the stresses, Solidworks requires the system to be fixed in at least one location, so the front and back door seals were chosen. This fixture represents the inner seal of the door, which will support the walls and prevent

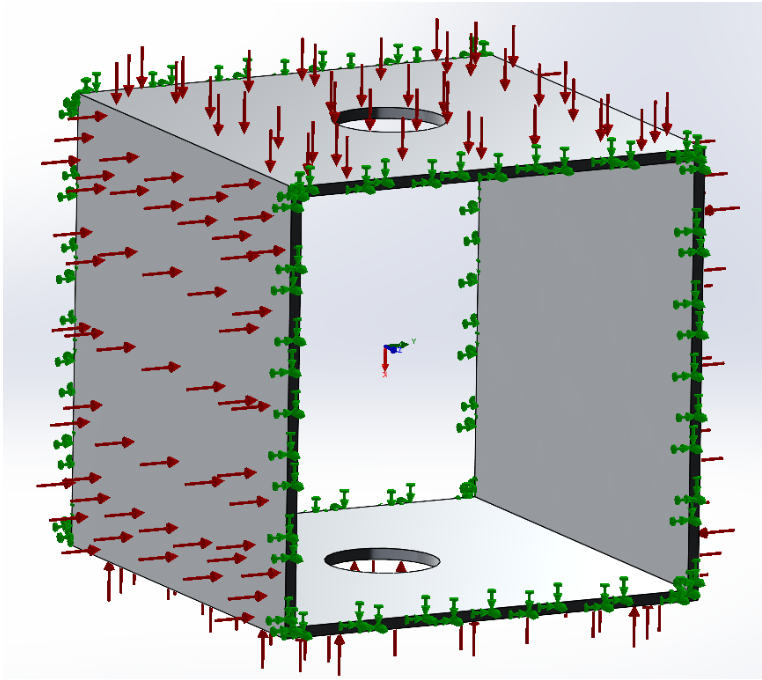

Figure 5: Preliminary Solidworks vacuum pressure simulation set-up with sides in contact with doors fixed.

deformation, resulting in the maximum deformation and stress occurring in the center of the walls. Additionally, the walls do not include the machined water-cooling channels due to the difficulty of modeling and simulating those features. In order to ensure the stress simulation results are still applicable to the final design with the machined channels, the modeled wall thickness represents the minimum wall thickness necessary, with the channels machined into additional material thickness.

The results of the stress simulations show a maximum stress of 37 MPa develops at the center of each edge of the walls, with significantly less stress developing near the center of the walls (Figure 6). This maximum stress is close to but does not exceed the yield strength of 6061 alloy, which is 55 MPa, however the results show that additional wall thickness may be required to achieve a sufficient factor of safety on the chamber walls. As the system is symmetric and the dimensions of the door panels will be similar to the walls, these results should be representative of the stresses present in the door walls as well.

The displacement simulation of the chamber shows a maximum displacement of approximately 0.53 mm occurring at the center of each wall panel. The displacement direction is towards the center of the chamber, which does not interfere with the functioning of other subsystems. The largest concern is the rams and ram seals, which fit through the top and

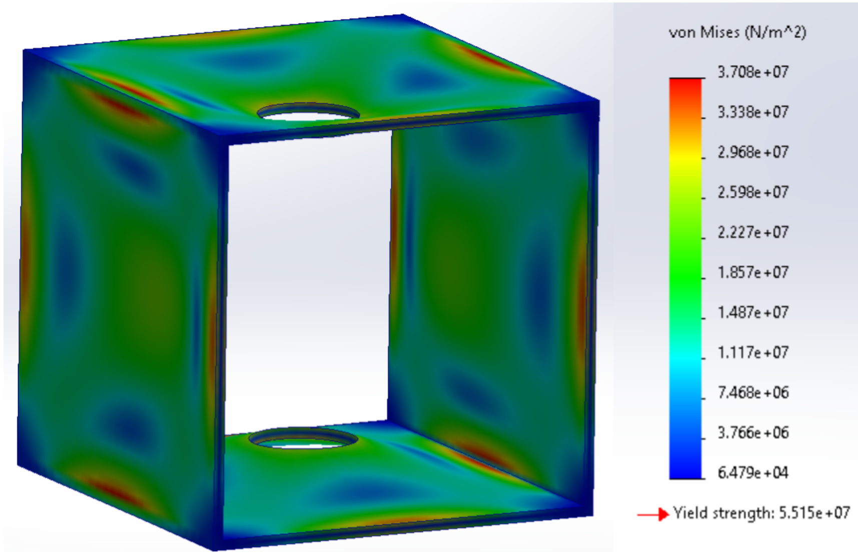

Figure 6: Preliminary Stress simulation results with sides in contact with doors fixed.

bottom holes in the chamber, however with purely vertical displacement on these faces, this will not affect the function of the rams. For other subsystem designs and future integration of the heating element, any internal components may be best mounted to the corners of the chamber walls to ensure the small amount of deflection does not significantly move such components, if sub-millimeter movement is of concern.

5.1.2 Final Design Simulation Results

With the general sizing of the chamber verified with the preliminary results, additional features could be added to the chamber. In order to accommodate the cooling channel depth and the drilling of mounting holes, the wall thickness was increased significantly to 0.75 in. This also allowed for the total chamber size to be increased by 2.5 in on all sides due to the additional strength provided by a greater thickness. For the final design stress simulation, a completed CAD model, with every bolt hole and cooling channel feature modeled, was simulated in Solidworks to verify the strength of both the chamber and the door panels. This simulation had the same uniform pressure loading condition and fixturing location as the preliminary simulation and the finest mesh quality was selected. The mesh of the chamber and door panel is shown in Figure 7.

The results of the simulation show a maximum stress in the door of 24.3 MPa and a maximum displacement 0.0714 mm (Figure 8), while the chamber experiences a maximum stress of 25.4 MPa and a maximum displacement of 0.091 mm (Figure 9). Stress concentrations can be seen along the middle of each edge in both the door and chamber; the areas where the material narrows between the channels and on the inside corners of the chamber develop

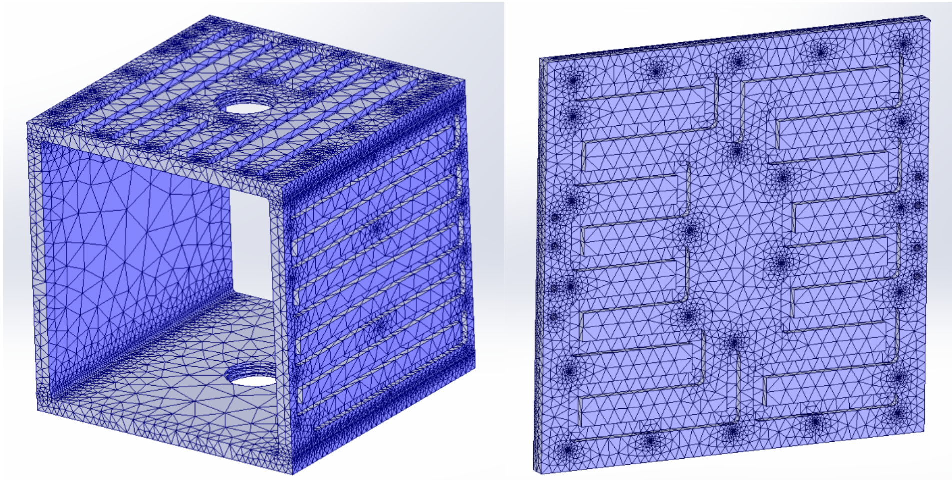

Figure 7: Chamber and Door Mesh

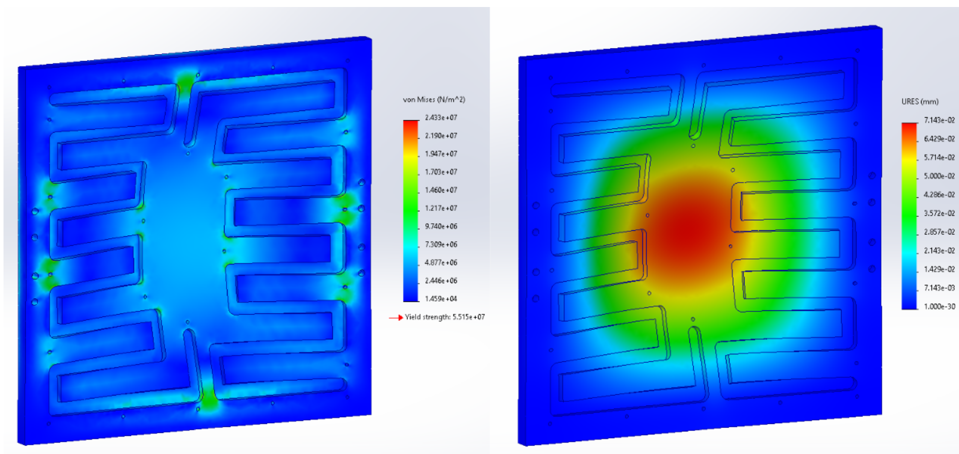

Figure 8: Door Stress (Left) and Displacement (Right) Simulation Results

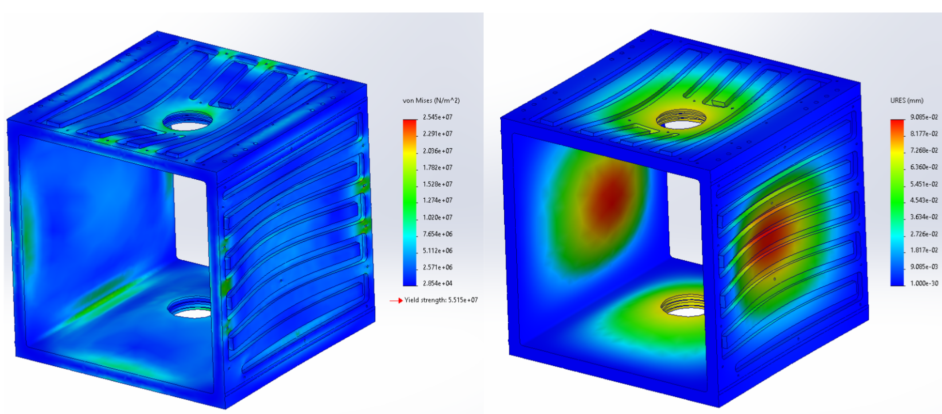

Figure 9: Chamber Stress (Left) and Displacement (Right) Simulation Results

higher stress. The maximum displacement occurs in the center of each panel, where the material sags inward, however as with the preliminary simulation results, the displacement is insignificant, and will not interfere with the rams, as the displacement is purely vertical along the ram holes, nor will it affect the internal heat shielding and heating element placement. The overall lowest factor of safety is approximately 2.167, which indicates that the chamber will not yield, even when operating at its maximum temperature and pressure load.

5.2 Cooling Capability

The cooling analysis was also completed using FEA, this time in COMSOL. This allows for the modeling of complex interactions between conduction and convection without the need to simplify the geometry of the chamber. The goal of this analysis was to determine the capabilities of the cooling channels to ensure effective cooling of the chamber surface to below 100 °C. The use of FEA also allows for rapid modification of the model to keep up with design changes and results from physical tests to achieve more accurate results.

5.2.1 Simulation Setup

The general structure of the analyses was a system made up of 3 main parts: panel, fluid, and cover. The panel and cover are both modeled as 6061 aluminum ($C_p = 896\,\mathrm{J\,kg^{-1}\,K^{-1}}$, $k = 167\,\mathrm{W\,m^{-1}\,K^{-1}}$, $\rho = 2700\,\mathrm{kg\,m^{-3}}$ [8]), and the fluid is water (properties sourced through COMSOL's built-in material library). The main boundary condition was a uniformly distributed heat rate (defined in Watts) applied to the inside face of the panel. Manual testing of the flow rate of the chilled water system found that the total flow rate was $1.74\,\mathrm{L\,s^{-1}}$. This total flow is split into 6 paths, one for each panel in the final chamber, meaning that the flow rate for each panel is $0.29\,\mathrm{L\,s^{-1}}$. Due to model geometry within COMSOL, the inlets and outlets for the fluid channels had an area of $1.26 \times 10^{-4}\,\mathrm{m^2}$, meaning the inlet velocity of the fluid for each channel is $2.3\,\mathrm{m\,s^{-1}}$. The inlet temperature (including effects from cooling the tester's hydraulic system) is currently unknown, and for the purposes of this analysis was assumed to be 20 °C.

To complete this analysis, solutions were calculated for each type of panel: ram, door, and side. Each panel type had two classes of simulations run: fast, and accurate. Fast simulations split the calculation of the fluid flow and heat transfer into two steps. The fluid flow would be calculated first irrespective of temperature changes in the fluid, and then any heat transfer solutions would be calculated afterwards. This allowed for many heat transfer cases to be tested quickly. This would be done by parameterizing the heat flux boundary condition and solving for a range of values. The results from the fast simulations would then be examined to find the highest heat flux a plate could handle without surface temperatures exceeding

100 °C. This value was then used in an accurate simulation to confirm cooling capabilities for each panel. The accurate simulations solved heat flux and fluid dynamics concurrently to take into account any possible changes in the water properties due to temperature.

5.2.2 Limitations

At this moment, there are some significant limitations to these simulations that are critical to the final performance of the furnace.

- The inlet water temperature is currently unknown.
- The heat flux is applied uniformly.
- The final design of the furnace, specifically the heating elements and insulation, is also unknown.
- These analyses focus on one plate at a time.

The inlet water temperature is a very important parameter in the performance of the cooling channels. At higher temperatures the water, while having a slightly higher conductivity, will also have a lower amount of total energy it can absorb before either the water starts to boil, or the surface of the chamber exceeds 100 °C. This means that the inlet temperature is vital to accurately determine the expected performance of the furnace. Currently, the chilled water system built into SCDI (which the furnace will be connected to) is set to 15 °C. However in between the chilled water system and the furnace will be the hydraulic unit of the tensile tester, which has its own cooling needs. As mentioned previously, these analyses were performed with the assumption that the incoming water would be at 20 °C, but should the incoming temperature to the furnace be significantly higher than that the analyses would have to be re-performed with more accurate information to produce more accurate results.

The distribution of the heat flux is likely to be concentrated towards the center of each panel. This is not easily accounted for without knowing the final design of the internal components of the chamber, and the specific methods of heat transfer between the heating elements and the chamber walls. For the sake of simplicity, these initial analyses ignored this fact, but future analyses with more concrete information about the design of the furnace as a whole will be able to be more accurate.

Expanding on the final design of the furnace, some areas of the plates are designated as keep-out zones for the cooling channels to allow for future components like power and sensors to

Table 3: Results from cooling capability simulations.

Panel Type	Max Heat Flux (kW)	Max Fluid Temperature (°C)	Max Surface Temperature (°C)
Side	24	57	99
Ram	30	66	96
Door	30	69	>100
Door	18	50	97

be added. These areas have no designed cooling at this time, which means these simulations cannot take into account possible future modifications like adding the cooled bus-bars to power the heating elements. These modifications could have a significant effect on the cooling performance that necessitates future analysis after their design is complete.

Finally, each simulation only includes one panel. Once the furnace is completed, 4 panels will be permanently welded together, which allows for heat to flow from one panel to another. This means that the difference between one single panel and 6 panels working together could affect the final performance of the system, especially when it comes to heat transfer methods like radiation and convection. Quantifying these methods of heat transfer are both reliant on knowing the internal design of the furnace, which as mentioned earlier is not known at this time.

5.2.3 Analysis Results & Conclusion

Solutions for these simulations (see Table 3) show that the ram panels can experience a heat transfer load of up to 30 kW before violating surface temperature requirements, and the side panels can handle up to 24 kW. It is worth noting that the heating element will emit no more than a few hundred Watts, and at most a couple of thousand, so we are confident in the robustness of our cooling solution.

Since the door panels will undergo significant modification before the furnace is completed, the central area of the doors is left unaltered as a keep-out zone for the cooling channels. This means that there is a significant amount of energy concentrating in that area that cannot be accounted for when determining whether this design satisfies surface temperature requirements. At a heat flux of 30 kW, the only area above 100 °C is within the keep-out zone at the center of the plate (see Figure 10). Ignoring the uncertainties of the keep-out zone and strictly limiting the surface temperature to under 100 °C, the new maximum heat flux the door can sustain is 18 kW. In all 3 panels, the maximum fluid temperature is significantly under 100 °C, while the maximum surface temperature for side and ram panel types is around 100 °C.

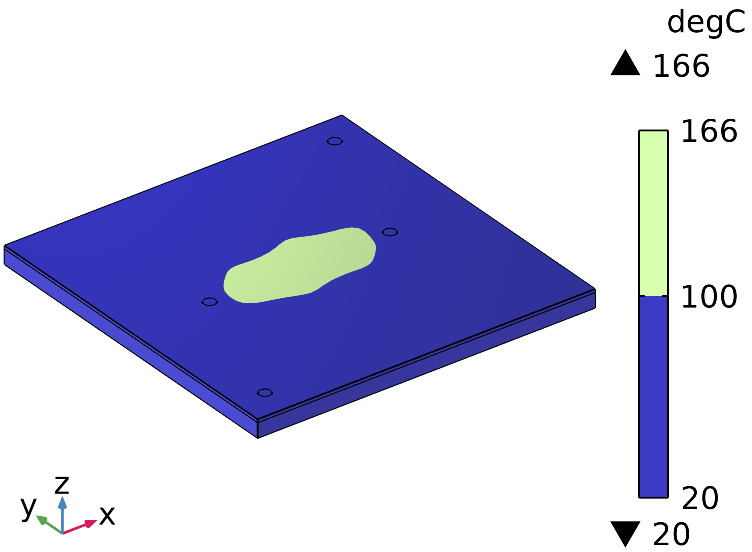

Figure 10: Contour plot separating temperatures >100 °C and <100 °C for a door panel, heat flux of 30 kW.

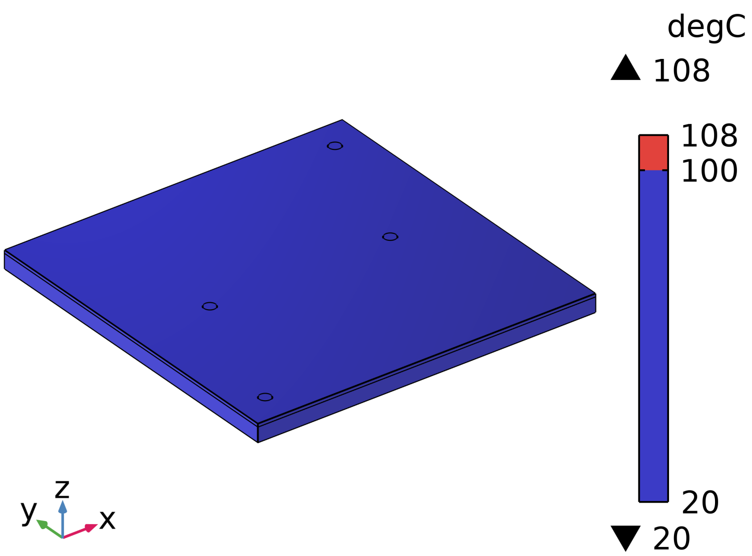

Figure 11: Contour plot separating temperatures >100 °C and <100 °C for a door panel, heat flux of 18 kW.

All together, this analysis and the results suggest that the chamber should theoretically be able to effectively cool the furnace with heat generation up to approximately 144 kW with no effective factor of safety. The results of this analysis provide vital information for future groups, both in the form of information about the projected capabilities of the furnace, required information that needs to be gathered to improve the quality of those projections, and knowledge about how to expand these analyses in the future to better predict the capabilities of the furnace.

6 Manufacturing and Integration

6.1 Structural

6.1.1 Sizing and Machining

To begin the manufacturing process, we started with six 0.75 in thick, 15 in $\times$ 15 in 6061 aluminum panels. With the final chamber having a volume of 1.76 ft^3, four of the panels would have to be machined down to 14.5 in $\times$ 14.5 in and the last two being 13.5 in $\times$ 14.5 in so that when the panels are being prepared to be welded, they would form a 14.5 in cube. The machining was done manually with the Bridgeport Manual Mill. shown in Figure 12.

To have the chamber be able to be attached to the tensile tester, the rams of the tensile tester must be able to pass through the top and bottom of the tester. We decided to have 3 in diameter stainless steel rams go through the chamber, so this would mean a 3 in diameter passthrough will also need to be machined into the top and bottom panels of the chamber. This process must have extremely tight tolerances so that once the chamber is welded, the rams of the tester aren't impeded during operation to avoid any effects on the load cell.

Other structural components of the chamber would be the hinges, and the mounting blocks of the chamber. These parts of the chamber focused more on the alignment of the bolt holes since they had to perfectly match the alignment of the bolt holes on the panels. The hinges must align with each other and the door panels. The tolerances were done by making sure that at least one side of each block was aligned with each other and that the manual mill maintained a consistent surface to align the blocks. We also kept a consistent spacing of the bolt holes for the blocks and the panels.

6.1.2 Welding

Our plan in the beginning of the manufacturing process was to weld the chamber together using the welder located in SCDI. We asked Josh Frazzitta, the machinist in SCDI who is trained to operate the welder, if he would perform the welds and believed the welder would be powerful enough to weld the panels together. Additionally, to verify the capabilities of the welder, we used it to repair a small mistake cut we made on one of the chamber panels and it performed very well. Unfortunately, several issues arose once we attempted to weld two of the panels together. First, the welder began exhibiting electrical issues, where it would occasionally dump a large amount of power into the weld causing it to blow out, which had the potential to damage the components, and second Josh ran into issues sufficiently heating the plates to ensure the quality of the weld (Figure 13). Despite the use of a heating plate,

Figure 12: Bridgeport Manual Mill (Left) and HAAS CNC Mill (Right)

the thermal mass of stacking multiple plates together to weld is too much for the welder to overcome, and the electrical issues risk damaging the machined components. Ultimately, we determined that to overcome these issues we would need to find a welder outside the school.

While we haven't had the opportunity to weld the chamber together, we've prepared each of the panels to be welded. Utilizing a 45° chamfer bit, we added a chamfer on the edges of the panels that would be in contact, so that the weld bead can be added to create a secure and airtight connection. Due to how sensitive the load cell is on the tensile tester, any disruption in the ram operation could prove detrimental. To circumvent this, the $3 \in$ diameter stainless steel ram will be used to align the top and bottom panels to ensure proper alignment during the welding process, as shown in Figure 14.

6.2 Cooling Channel Machining

As mentioned previously, we decided to machine a 0.3 in deep water channel into each of the panels of the chamber. All of the machining on these panels had been done manually, however due to the limit of the range of motion and the time it would take to manually machine each of the water channels, the HAAS CNC Mill (Figure 12) was used instead. This allowed for us to automate the milling process and was able to fulfill the 14.5 in travel distance needed to machine the channels. Each of the panels' water channels only took roughly 20 to 30 minutes to complete which saved us time from manually machining each of the panels.

Figure 13: Close-up photo of cold welds due to insufficient power and too cold base material.

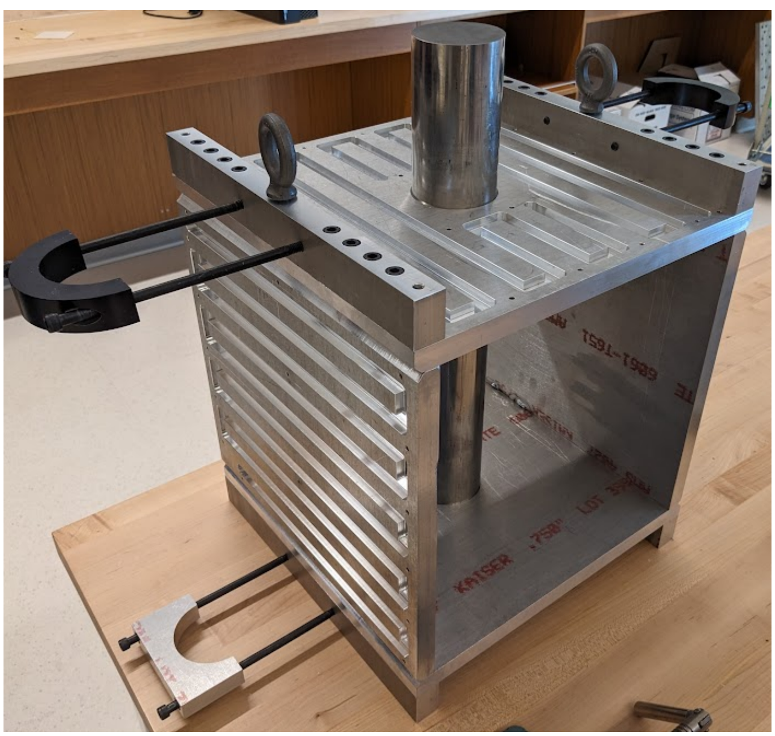

Figure 14: Chamber Panels stacked, aligned, and prepared for welding.

6.3 Pass Throughs

The accommodation for pass throughs which future groups may add during the manufacturing process primarily consisted of clearly marking out the keep-out zones and programming the cooling channel path to avoid these areas. We left a 3.5 in by 6.5 in oval-shaped zone in the center of the doors for the installation of the bus bars and thermocouple penetrations. Additionally, a 1 in by 1 in zone was left on the corners of the side panels to accommodate the addition of the gas management fittings, including a vacuum outlet and gas cylinder inlet. We purchased a vacuum fitting tree to install in one of these gas keep-out zones in order to test the vacuum quality and leak rate of the chamber, however the exact gas plumbing hardware will be left for a future group to determine.

6.4 Seals

6.4.1 O-Ring Seals

The machining of the o-ring grooves is one of the most important operations we performed during the manufacturing process, since an insufficient o-ring seal will prevent the chamber from holding a vacuum. For the door seals, the grooves and door seal step were machined on the HAAS CNC mill, as it is both the only machine in the shop with the size capacity to accommodate the dimensions of the milling operation. Additionally, the automated CNC operation allowed for the groove to be cut quickly and precisely from the CAD model of the part. The ram o-ring seals were a significantly more challenging operation, as they were placed on the inside of the ram bore. This required a specialized t-slot cutter, which cuts a square profile on its side, allowing the cutter to be first inserted into the bore and then moved into the side of the material. This operation was done on the Bridgeport mill, which can be programmed to follow limited 2D CNC paths. First the bore was roughly machined to size using an end mill following a circular pocket cutting path and then the o-ring grooves were cut. As the t-slot cutter has a relatively thin shank while also having a large diameter cutting bit, the spindle speed and feed speed of the groove cutting operation was critical to both achieve a clean finish on the part so as not to not break the tool by stressing it too much. For this operation, the spindle speed was set to a relatively slow speed of between 800 and 1100 rev min^{-1}, and the feed rate was set to the lowest speed the bridgeport could be set at: 1 in/min. A photo of the groove cutting operation is shown in Figure 15. After the grooves were finished, the final bore diameter was cut with the appropriate tolerance to fit the ram, allowing a very close, tight fitting seal with the o-rings. The ram o-rings installed in the grooves are shown in Figure 16.

Figure 15: T-Slot cutter machining the ram o-ring seal.

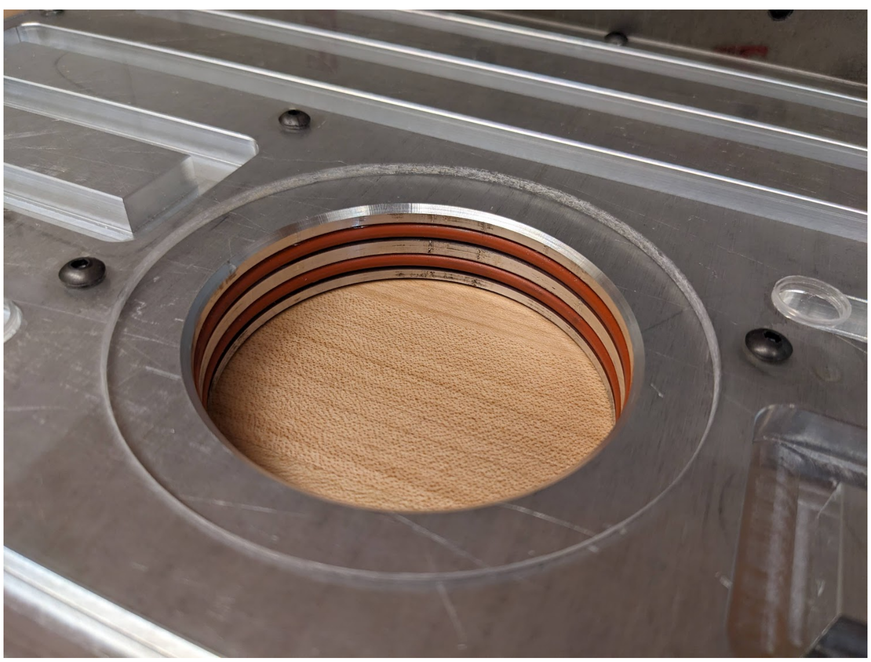

Figure 16: Ram O-Ring Seals

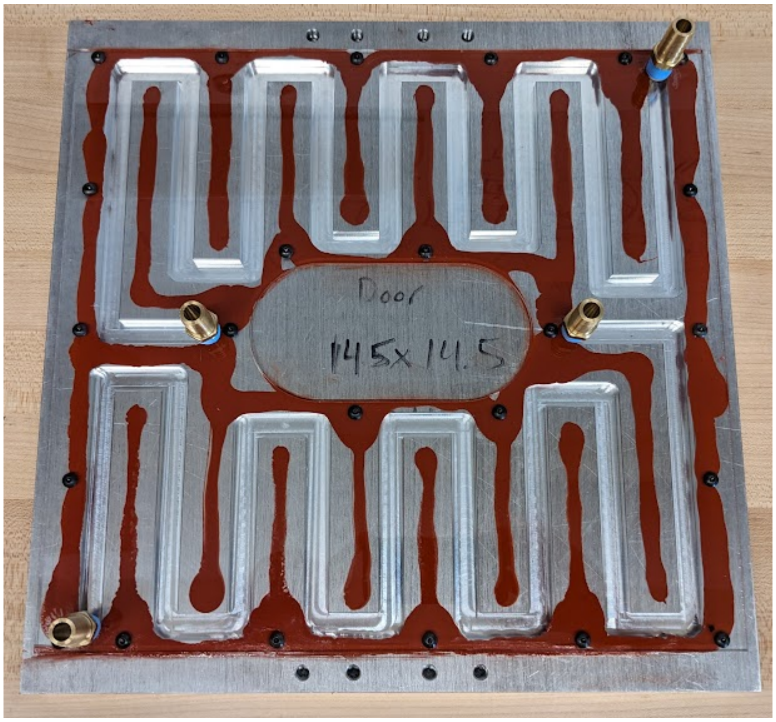

Figure 17: Cured liquid silicone sealant under an acrylic cover panel.

6.4.2 Cooling Channel Seals

The cooling channels are sealed with cover sheets made of 0.125 in aluminum and held on with a large number of small screws. To attach these panels, the bolt holes were drilled during the channel cutting CNC operation on the HAAS mill, and then tapped with the thread of the screws. To drill matching screw holes in the cover sheets, we decided to laser cut acrylic templates, both to act as a transfer template for drilling the aluminum sheets. This also served as a visual aid during our senior design presentation as it allowed for the machined cooling channels to be seen underneath. These were cut on an Epilog CO2 laser cutter with the bolt pattern on the chamber panels, and then used to transfer drill marks to the aluminum sheets, which were then drilled by hand. To seal the panels, we used a curing silicone liquid, which was first extruded onto the panel using a caulk gun, and then loosely sandwiched between the panel and sheet, as seen in Figure 17, and allowed to cure for 24 hours. After curing, the sheet was tightened down to improve the seal.

6.5 Tensile Tester Integration

The chamber itself is going to be suspended onto the tensile tester during operation. This is due to the lack of support at the base of the tester. Utilizing existing bolt holes at the top of the tester, we sized and machined blacks of aluminum to adapt the top bolt holes into a

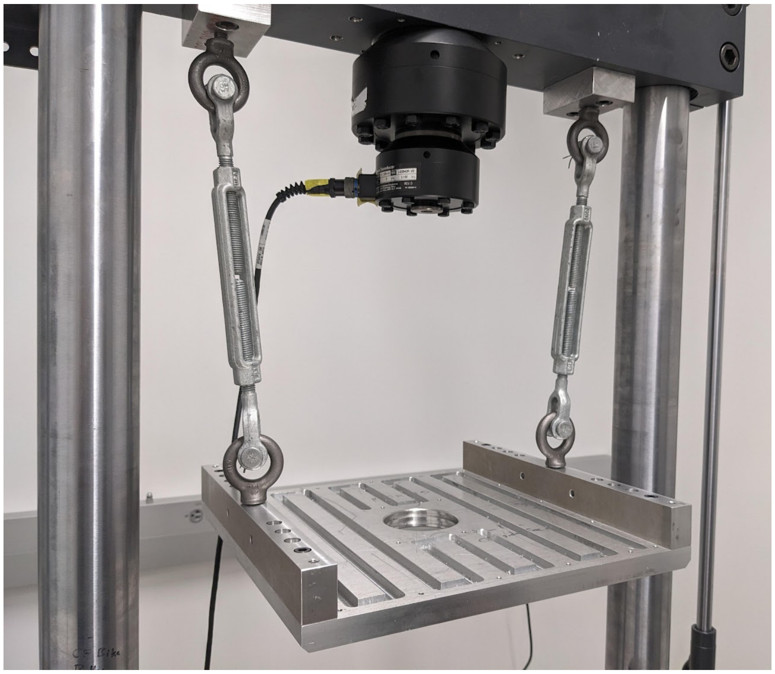

Figure 18: Top panel of chamber attached to top crossbar of the tensile tester.

single, centered M12 size bolt hole to attach eye bolts onto. We are also using turnbuckles to suspend and adjust the height at which the chamber is resting as shown in Figure 18.

To prevent any moments from occurring while the chamber doors are open and to prevent any swaying during operation, we have also machined brackets to stabilize the chamber by attaching to the side rails of the tester. These brackets are not intended to support any weight but only to stabilize the chamber laterally.

7 Tests and Results

7.1 Vacuum Seals

Unfortunately, as the chamber has not yet been welded together, we were unable to perform a test of the vacuum seals. We will provide a procedure detailing the process needed to seal and assess the chamber in the event that this group cannot complete this task so that a future group can complete it.

To align the chamber for welding, first insert the 3 in diameter ram stock into the bore of the bottom panel and slide it through until the bottom panel can sit flat on a surface. Next, have a partner stack the two side panels on their edge on the bottom panel while the top panel is slid onto the ram stock. Adjust the side panels into their final position for welding and then set the top panel to rest on top of them, holding them in place. Once correctly lined up, the panels can first be tack welded together and then fully welded. In addition to welds on the inside and outside seams, instruct the welder to apply a small seam weld to the eight gaps on the front and rear face of the chamber to ensure the door sealing face has no gaps. Next, remove the ram stock and insert the finished chamber section into the HAAS CNC mill and take a face cut off the front and rear sealing faces. This should ensure a smooth sealing surface on which the door o-ring can engage. Next, on a large drill press, drill the vacuum plumbing penetration and then install the vacuum gauge and valve assembly. Finally, assemble the rest of the chamber and mount it to the tensile tester.

To test the vacuum leak rate of the chamber, first install the o-rings in the door and ram seals. Next Insert the ram stock to plug the ram bore seals and then close the doors. Connect a vacuum pump to the vacuum gauge assembly and then turn it on. Once the gauge reads a vacuum pressure of -30 inHg, turn off the vacuum pump and start a timer. Time how long it takes for the gauge to return to 0 inHg to find the vacuum leak rate.

When in operation for a material test, the vacuum pump will be run either for the duration of the test or intermittently to maintain a specified vacuum level, however knowing the rate at which air leaks into the chamber is an important metric to assess the quality of the seals. Additional vacuum quality testing may be required depending on the specified vacuum requirements of the heating element, however this would require the use of a higher precision vacuum gauge.

7.2 Cooling Flow

One of the tests that needed to be performed was a leak test with a liquid gasket. The liquid gasket was tested with the acrylic panel cover so the flow could be observed. The gasket material was spread on the outer perimeter of the panels in between the channels. After the liquid gasket was applied, the cover panel was then placed and screwed down to apply an even pressure so the gasket could fill any unwanted paths that the water could to go through. The seal was tested with a garden hose with flow rate of $0.24\,\mathrm{L\,s^{-1}}$. During the test the acrylic panels were bending due to the pressure the water was applying into the water channels. This caused the water to leak out of various areas of the seal and acrylic. The machined paths were directing the water to the desired outlet, however the test should be repeated utilizing the aluminum cover panels instead of the acrylic covers.

8 Financial Assessment

8.1 Budget

The Santa Clara University School of Engineering awarded our group $2000, $500 per person, which is going to serve as our budget. Currently, we are well below budget which gives us room to send the chamber to get welded in the future. This also gives us some leftover funds that could be passed along for future groups to use to further expand this ongoing project.

Table 4: Budget

Category	Quantity	Cost	Notes
Raw Materials	22	$838.56	Aluminum plates, steel ram, aluminum bar
Seals	13	$86.98	Door and ram o-rings, silicone sealant
Plumbing + Vacuum	28	$172.43	Plumbing fittings, vacuum valves, gauge
Mounting	314	$222.05	Bolts, turnbuckles, eyelets
Miscellaneous	2	$31.44	Acrylic display panels, cutting tools
Total		$1,382.90	

8.2 Payback Period

The cost of our 2023-2024 project is going to be about $1,600. This cost is calculated based on the requested budget. There isn't a monthly economic benefit for our project since the target device won't have been completed by the end of our project. Our project will begin to see an economic benefit once the final furnace is completed, which will be after subsequent project groups. The best estimate of the total cost of the project is at least another 1-3 thousand dollars for electrical, control, and insulation materials, and then another 2-3 thousand for the heating elements themselves. All told the final price of the project will most likely be in the range of 6-10 thousand dollars. Once the project is completed, economic benefits will vary based on usage. Research would bring in grant money, whereas offering services testing materials at high temperatures could allow the university to receive a regular income from external customers. Estimates for the cost of these types of services are not readily available, so instead of working to a payback period as the final result, we're going to work backward starting with a payback period to get a reasonable price to charge for these services.

Starting with an arbitrary payback period of 10 years, with a discount rate of 12 percent, the monthly income should be at least $109.03. Based on the price for other material testing services, this rate would relate to approximately 7 tests performed for customers per year, at a price of approximately \$250 per test [9]. Estimating the capital costs of the completed furnace, we predict the chamber will cost \$1600, the electrical supply \$1000, the control system \$1000, the insulation and shielding \$1000, and the heating element \$3000. This comes out to a total of \$7600. To determine the discount rate, we estimate a 1% per month (12% per year) discount rate for this project based on inflation and common interest rates. In order to evaluate a payback period for our project, we need to select a reasonable payback period. We decided 10 years would be reasonable, considering the intermittent usage of scientific equipment like our furnace. The amount of monthly revenue (M) required to pay back the cost is found with the equation:

$$M = \frac{Lr\left(1+r\right)^n}{\left(1+r\right)^n - 1} \tag{1}$$

Where L is the amount of initial capital: \$7600, r is the monthly discount rate: 12% yearly or 1% monthly, and n is the number of months in the payback period: 120 months. From this calculation, the university would need to make \$109.04 per month using the testing furnace to pay back the capital cost of the furnace within 10 years. We believe this is a reasonable value, as considering the cost of a material test from other vendors, a customer paying standard rates for a single test every two months would allow this payback period to be achieved.

9 Future Work

9.1 Chamber Welding and Vacuum Testing

We reached out to various welders for quotes on welding our chamber, but did not end up receiving any responses. As mentioned in Section 8.1, we have leftover funds that can go towards the cost of welding in the future. Once welded, the chamber can be tested to determine a leak rate based on the testing procedure described in Section 7.1.

9.2 Future Project Scope

There are still aspects of the project that future groups can work on over the span of a few years. While we designed the rams to be water-cooled, future groups can possibly improve the design so once the water-cooled rams are installed the water-cooling loop can be completed.

We have set up an integration plan that includes the process of mounting the chamber to the tensile tester and ensuring proper alignment and sealing. Our project was funded with a $2000 budget, which we have managed to stay within limits of *via* careful budgeting and creative cost-saving techniques. The estimated total cost of the completed project is between $6,000 and $10,000. We have considered future funding needs and potential income from offering high-temperature material testing services, ensuring the project's economic viability and sustainability.

Some areas that we left future groups to research would be the pass throughs for instrumentation and the instrumentation itself. This includes pass throughs for thermocouples and power lines for the heating element. The group working on this would also need to consider how those components are going to be insulated and cooled. Heat shielding is also a major aspect of this project that could take a significant amount of research and time to handle. This is to both prevent the heat from escaping the center of the chamber and prevent the extreme temperatures from reaching the outside of the chamber. Lastly, there's the heating element and the power supply. This is the most important, and most likely expensive, aspect of the project. Designing and building the heating element to our desired temperature, is going to determine the success of our project. Once all of those aspects have been researched, designed, and implemented, a high-temperature material test can then be conducted.

10 Conclusion

In this thesis, we have detailed the development process, design considerations, and projected outcomes of our high-temperature vacuum furnace attachment for a standard tensile tester at Santa Clara University. This multi-year, phased project aims to enhance the university's material testing capabilities, promoting sustainability and advancing research in materials science. Our project embodies several ethical considerations, including ensuring the responsible use of our equipment to prevent misuse or unsafe experimentation. We have carefully considered the environmental and societal impacts of our research, adhering to ethical guidelines from our university and professional societies. By focusing on sustainability and the advancement of knowledge, we aim to contribute positively to both the scientific community and society at large. With our product, we aim to make high-temperature material testing accessible to a wider range of institutions, emphasizing the role of universities and research institutes in advancing technological and societal welfare. We have engaged with various stakeholders to understand the requirements and constraints of similar projects, ensuring our design meets industry standards and addresses the needs of the scientific community.

The overall system consists of a low-cost, heated vacuum furnace designed to test the mechanical properties of material samples at temperatures up to 2000 °C. The primary components include a water-cooled vacuum chamber, dynamically sealed testing rams, and pass-throughs for instrumentation and power. Our initial phase focused on constructing the water-cooled vacuum chamber, setting the foundation for future integration of heating elements and sophisticated control interfaces. During our tenure, we were able to successfully machine the structural components and cooling channels, preparing the chamber for welding.

Our project represents a significant first step forward in enhancing the material testing capabilities at Santa Clara University. By developing a low-cost, high-temperature vacuum furnace attachment, we aim to make advanced materials research more accessible, contributing to technological innovation and sustainability. Through careful design, thorough analysis, and strategic planning, we have laid a strong foundation for future developments, ensuring the long-term success and scalability of the project. The completion of this furnace will not only benefit our university but also serve as a scalable model for other research institutions, fostering broader scientific advancements and collaborations.

References

[1] Song, L.-Y., Gao, X.-H., Xue, Q.-H., Sun, C., Wang, M.-M., Devesh Kumar Misra, R., Zhang, X.-L., Wu, H.-Y., and Du, L.-X., 2021, “Hot Ductility and Fracture Behavior of High-Ti Weathering Steel,” *steel research international*, 92(2000643), doi:10.1002/srin.202000643.

[2] Schwartz, N., *Design and Construction of High-Temperature, High-Vacuum Tensile Tester for Fusion Reactor Materials*, Senior Thesis, Massachusetts Institute of Technology, Cambridge, MA, 2018, http://hdl.handle.net/1721.1/119939.

[3] Johnson, R. and Killpatrick, D. H., “Evaluation of Dispersion Strengthened Nickel-Base Alloy Heat Shields for Space Shuttle Application,” Contractor Report NASA-CR-2614, McDonnell Douglas Astronautics Company, Huntington Beach, California 92647, 1976, https://ntrs.nasa.gov/citations/19760011175.

[4] Taylor, J. L., 1963, “Apparatus for Tensile Testing to 5400°F in Vacuum,” *Review of Scientific Instruments*, 34(5): pp. 500–504, doi:10.1063/1.1718417.

[5] Marks, R. A., Sugar, J. D., and Glaeser, A. M., 2001, “Ceramic Joining IV. Effects of Processing Conditions on the Properties of Alumina Joined via Cu/Nb/Cu Interlayers,” *Journal of Materials Science*, 36(23): pp. 5609–5624, doi:10.1023/A:1012565600601.

[6] Parker Hannifin Corporation, 2021, “Parker O-Ring Handbook,” https://www.parker.com/content/dam/Parker-com/Literature/O-Ring-Division-Literature/ORD-5700.pdf.

[7] Aluminum Guide, 2024, “6061 Aluminium Alloy,” https://aluminium-guide.com/alyuminiim-alloy-6061/.

[8] MatWeb LLC, “Aluminum 6061-T6; 6061-T651,” https://www.matweb.com/search/DataSheet.aspx?MatGUID=b8d536e0b9b54bd7b69e4124d8f1d20a.

[9] Gedney, R. and Smith, I., 2013, “Manage Materials Testing Costs,” *Quality Magazine*.

Appendix A: Interview Summaries

A.1 MRF Interview

Customers / Product Development

- Who do you target your product to? (Tensile testing specific)
  - National labs
  - Universities
  - navy/army
  - Government research
  - Not targeting industry so much
    - Large companies like GE and Lockheed don't do testing as much, if anything they send samples for testing elsewhere
- What jobs do you advertise your product to do?
  - Find where the money to purchase one of these devices is like through government grants
- What materials/products/industries have used your furnace?
  - Carbon fiber
- What features/functions do you find your customers requesting for your product?
  - Customers often want Reliable, repeatable machine
  - Dynamic seals are important but proprietary to MRF
  - Extensometer
    - MRF makes a chamber that incorporates the extensometer into the test space but above 2000°C most aren't willing to put in that cost

- How do you gauge your customer satisfaction with your products or receive and address their complaints? Do you do interviews, in-house use of your products, etc.

  - $\sim$ 6 months is the shortest lead between starting order process and getting final product

  - Customers come out for factory acceptance testing

  - SUMMARY: lots of direct interaction with customers

Testing Furnace Details

- How do you deal with the load cell? Is it integrated into the tensile tester, is it inside the furnace, or is the weight and effects of the furnace housing not significant to the reading of the load?

  - Usually sealed with o-rings

- Do you use fabric insulation in addition to water cooling the walls?

  - Refractory ceramics or graphite

  - 3-4 inches of carbon board and surround with felt

A.2 Dr. Marks Interview

- Need to be custom made

- Very few customers want this

- Must Haves:

  - 1200 °C to 1300 °C for testing

  - 1700 °C for sintering

  - Use as a furnace

  - Heat treating at 1800 °C

  - Vacuum or specialized atmosphere to get to temp

  - Connections for the vacuum pump fittings and argon fill tank

- Argon at 1 atm preferred over vacuum fittings for fill and vent
- Internal space minimum size
- Hot zone 4 in diameter
- The furnace must be removable from the tester
- Thermocouple (W-Re) passthrough (OMEGA.COM) with Teflon ferrule compression fitting which reaches the hot zone
- Vacuum gauge/ pressure gauge (30 psi to 0-1000 mTorr range)

- Preferred
  - Room temp, or cooling water capacity saturation
  - Ease of use, not planning to mass produce things
  - Door clearance and good seal
- WHY does the customer want this?
  - To test materials at these temperatures

Appendix B: Drawings

Drawings start on the next page.

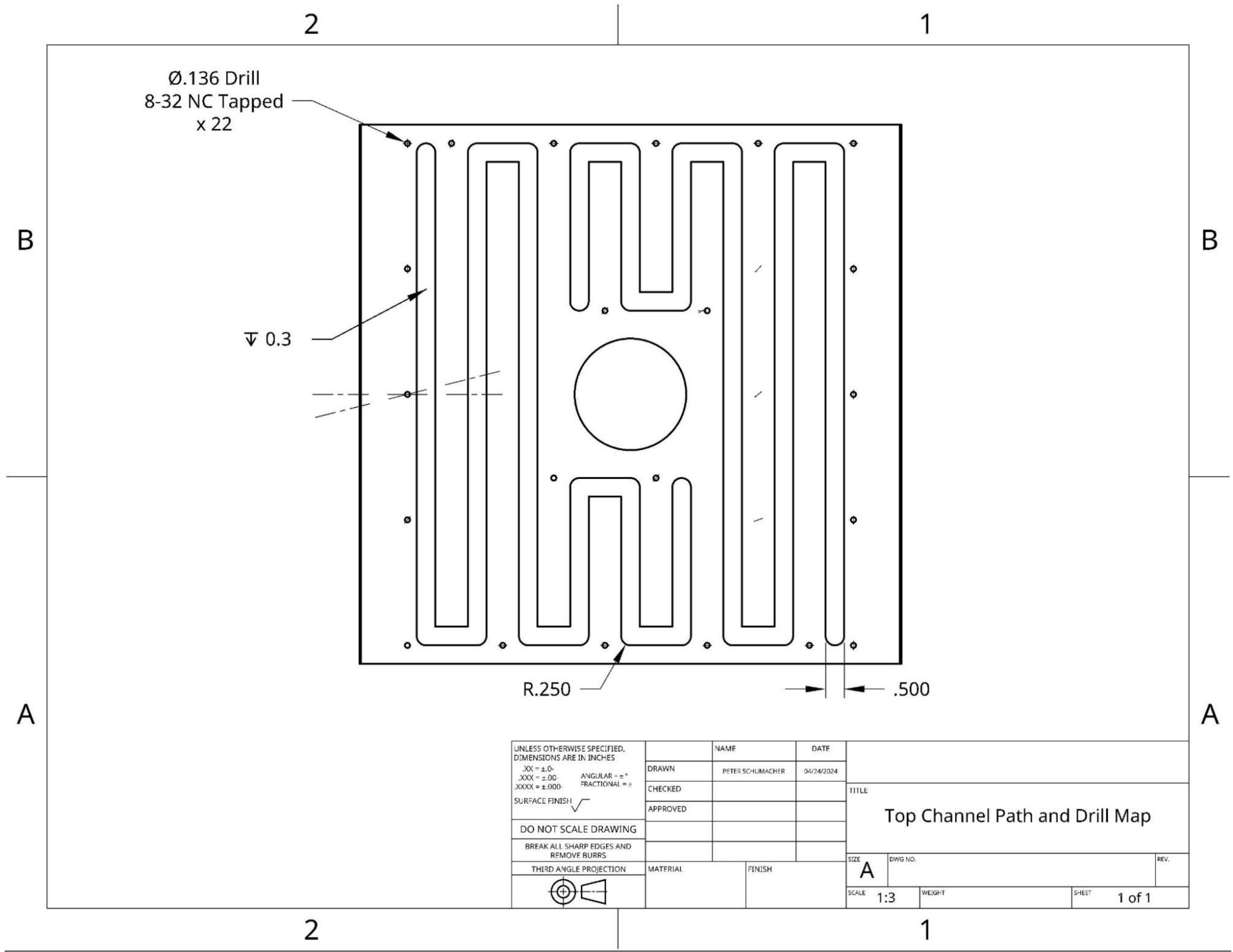

Figure 19: Drawing of the ram panels showing the cooling channels

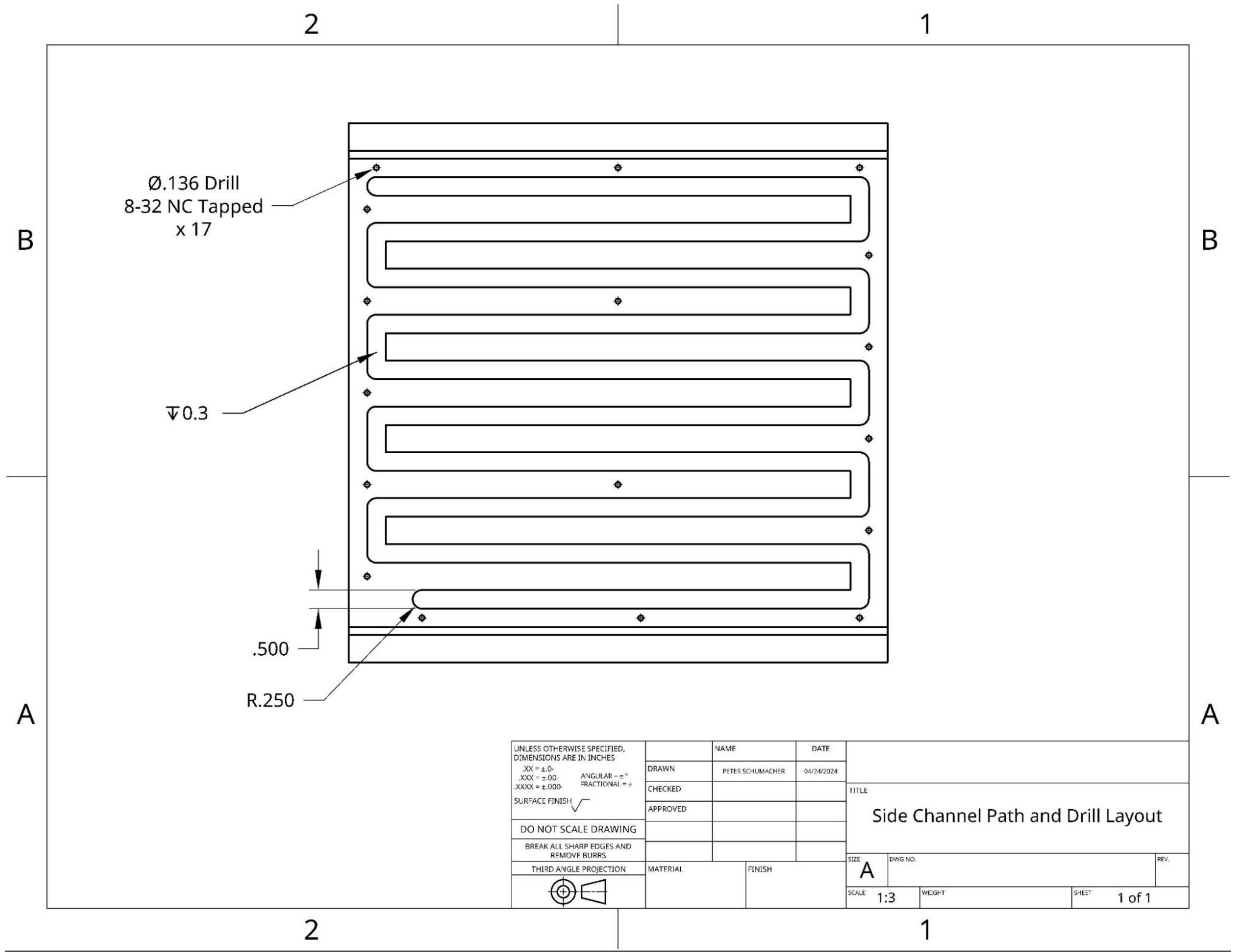

Figure 20: Drawing of the side panels showing the cooling channels

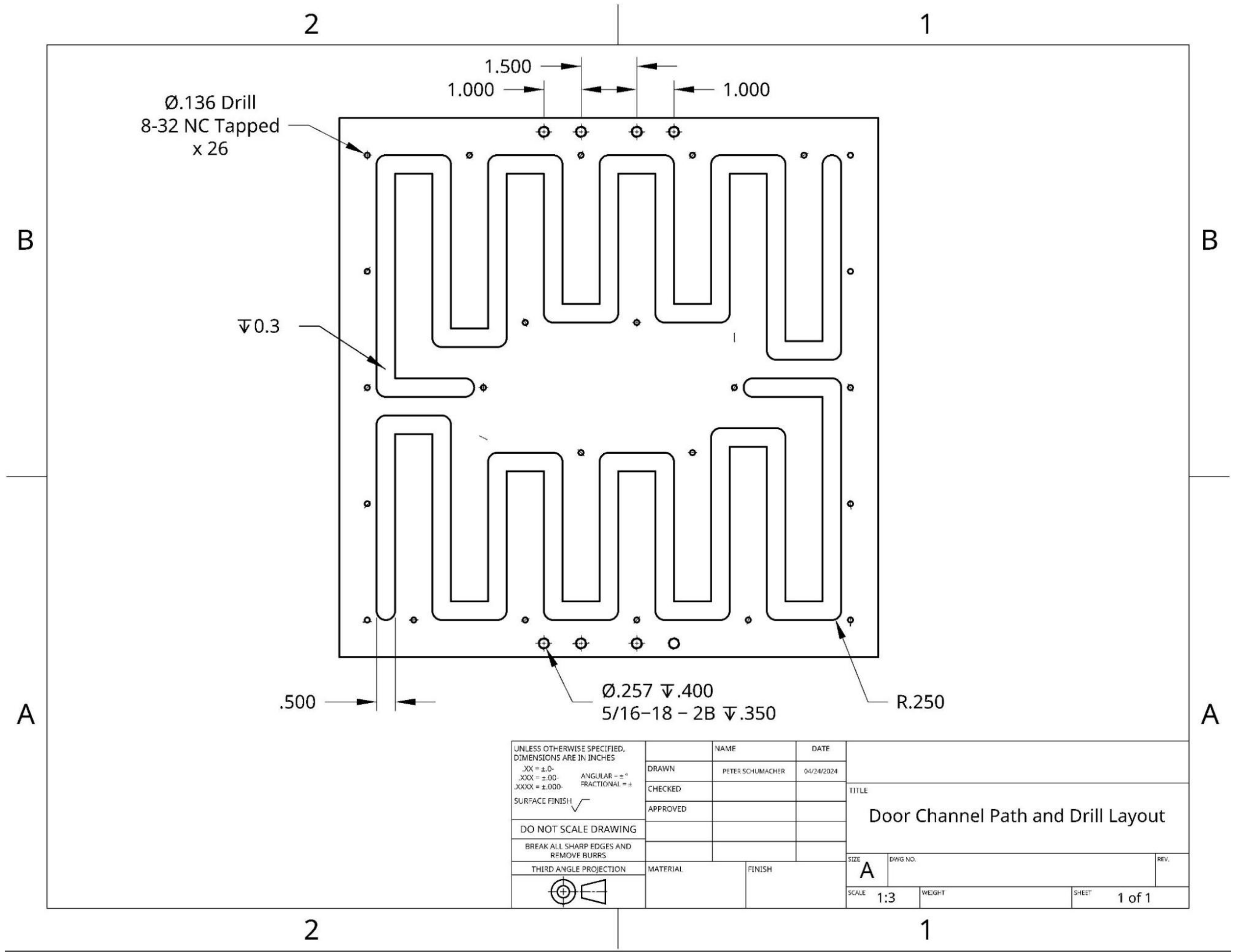

Figure 21: Drawing of the door panels showing the cooling channels

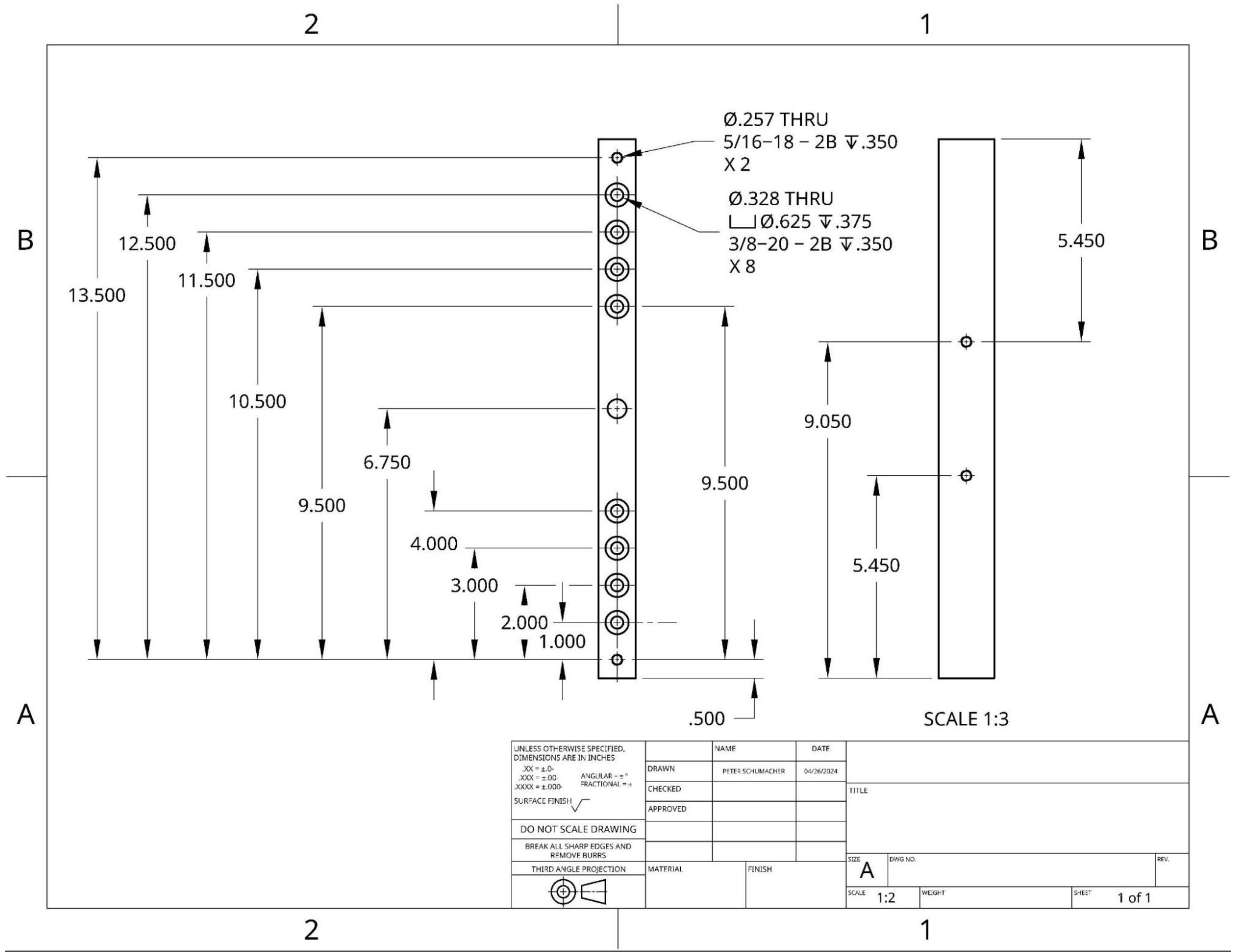

Figure 22: Drawing of the mounting bars showing hole sizes and locations.

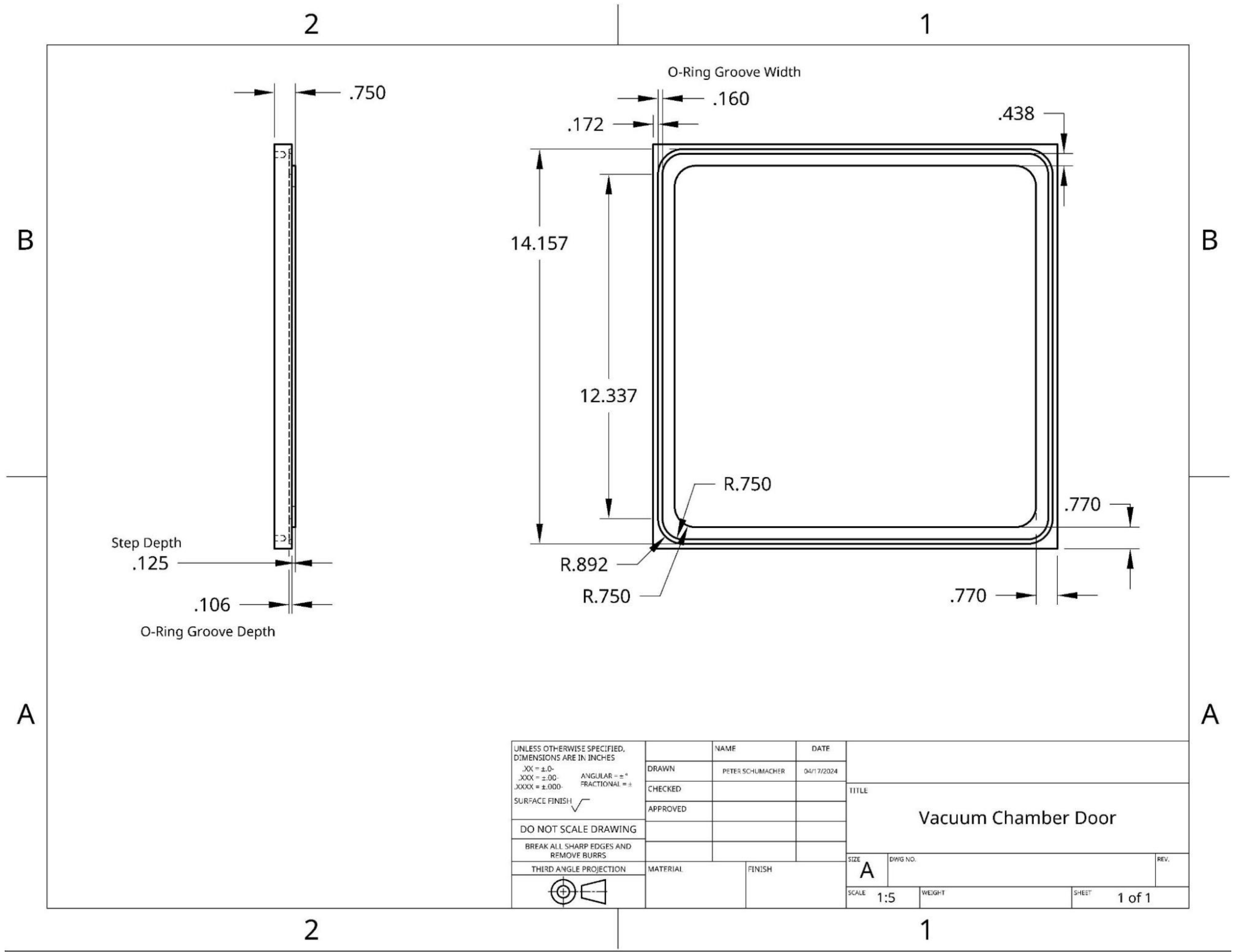

Figure 23: Drawing of the door panels showing the vacuum seal.

Appendix C: Part Specifications

C.1 Ram O-Ring Specifications

Dash Number Size: 234

Actual ID: 2.984 in

Actual OD: 3.262 in

Durometer: 70A

Specifications Met: ASTM D2000, FDA Compliant 21 CFR 177.2600, SAE AS568, SAE J200, USP VI Certified

Temperature Range: -60 °F to 400 °F

C.2 Door O-Ring Specifications

Dash Number Size: 283

Actual ID: 16.955 in

Actual OD: 17.233 in

Durometer: 70A

Specifications Met: ASTM D2000, FDA Compliant 21 CFR 177.2600, SAE AS568, SAE J200, USP VI Certified

Temperature Range: -60 °F to 400 °F

C.3 Turnbuckles

Capacity: 2200 lb

Retracted Length: 13.5 in

Max Adjustment: 6 in

Clevis Inside Width: 0.625 in

Appendix D: Bill of Materials

Table 5: Bill of Materials

Part Number	Name	Description	Quantity
1	Chamber Section	Main Vacuum Chamber Structure	1
2	Door Panel	Encloses chamber with o-ring seal	2
3	Door Hinge Mount	Attaches hinge arms to door panel	4
4	Door Hinge Arm	Allows door to hinge open	8
5	Top Mounting Rail	Mounting point for door hinge, hanging eyelet, and upright clamp	2
6	Bottom Mounting Rail	Mounting point for door hinge and upright clamp	2
7	Upright Clamp	Clamps to tensile tester upright	4
8	Side Channel Cover	Encloses side panel cooling channels	2
9	Ram Channel Cover	Encloses top and bottom panel cooling channels	2
10	Door Channel Cover	Encloses door panel cooling channels	2
11	Door Seal O-Ring	Seals door seat against vacuum	2
12	Ram Seal O-Ring	Seals ram against vacuum	4
13	M12 Eyelet	Supports the hanging load of chamber from tensile tester	4
14	Turnbuckle	Supports the hanging load of chamber from tensile tester and adjusts height	2
15	Top Mounting Block	Supports the hanging load of chamber from tensile tester	2
16	M12 Bolt		4
17	5/16-18 x 1.5 Bolt		40
18	5/16-18 x 3.5 Bolt		4
19	5/16-18 x 2.5 Bolt		4
20	5/16-18 x 8.5 Bolt		8
21	5/16-18 Nut		4
22	8-32 NC Screw	Cover panel screws	126

Appendix E: Cooling Capability Simulations

E.1 Door Panels

Not shown in this compilation is the contour plot for the door panel type for either 30 kW or 18 kW, which is included earlier as Figure 10 and Figure 11 respectively.

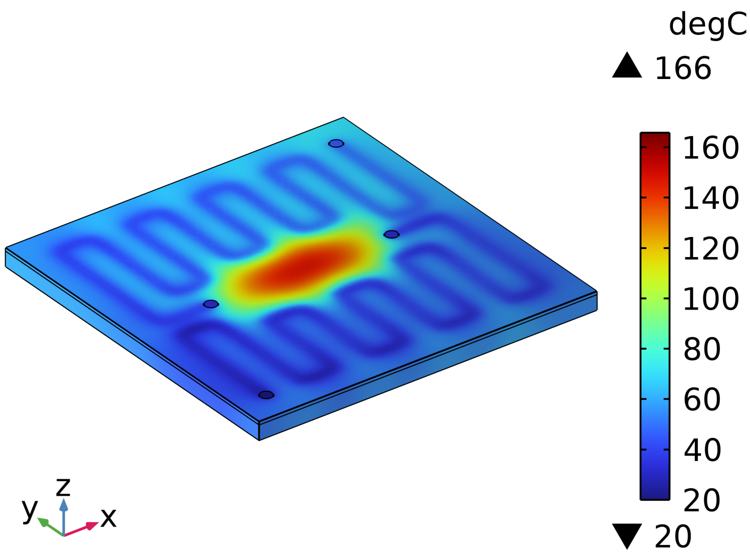

Figure 24: Temperature distribution for a door panel.

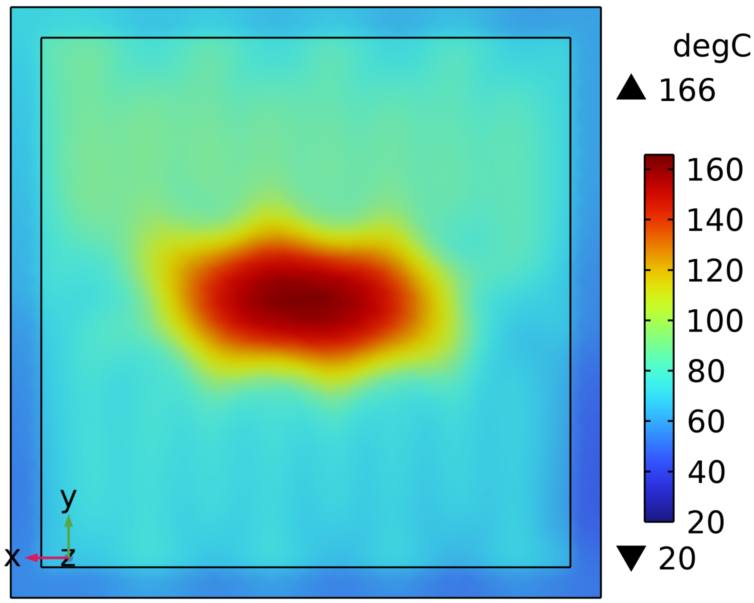

Figure 25: Backside of temperature distribution for a door panel (see Figure 24).

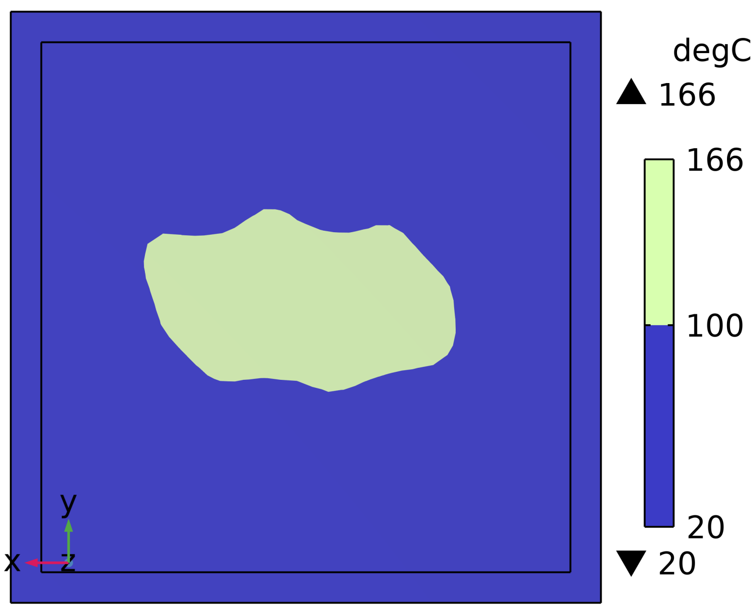

Figure 26: Backside of contour plot separating temperatures >100 °C and <100 °C for a door panel, heat flux of 30 kW (see Figure 10).

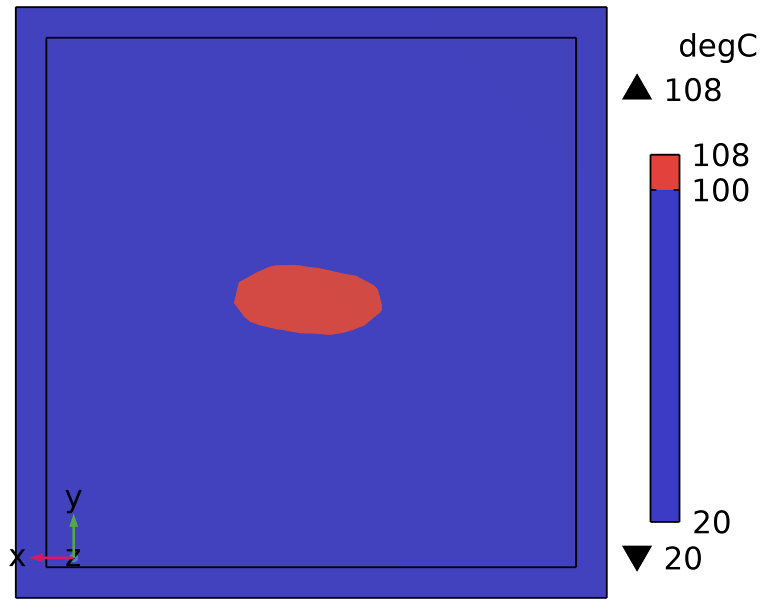

Figure 27: Backside of contour plot separating temperatures >100 °C and <100 °C for a door panel, heat flux of 18 kW (see Figure 11).

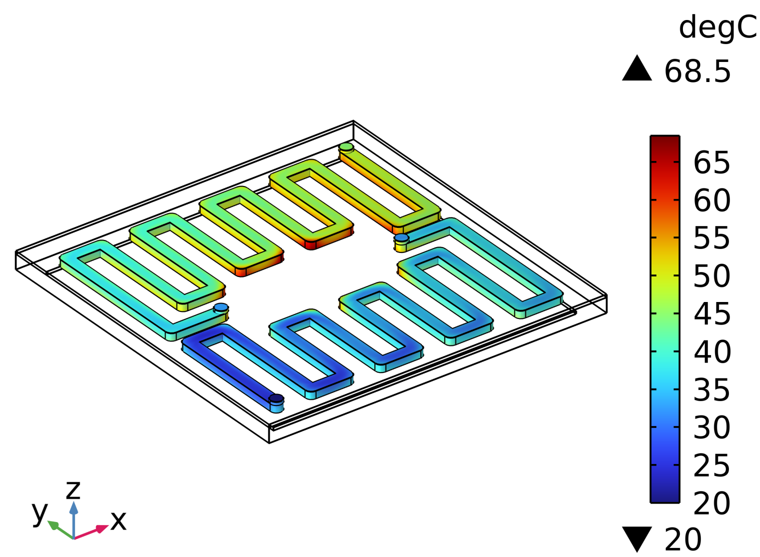

Figure 28: Temperature distribution for cooling fluid in a door panel.

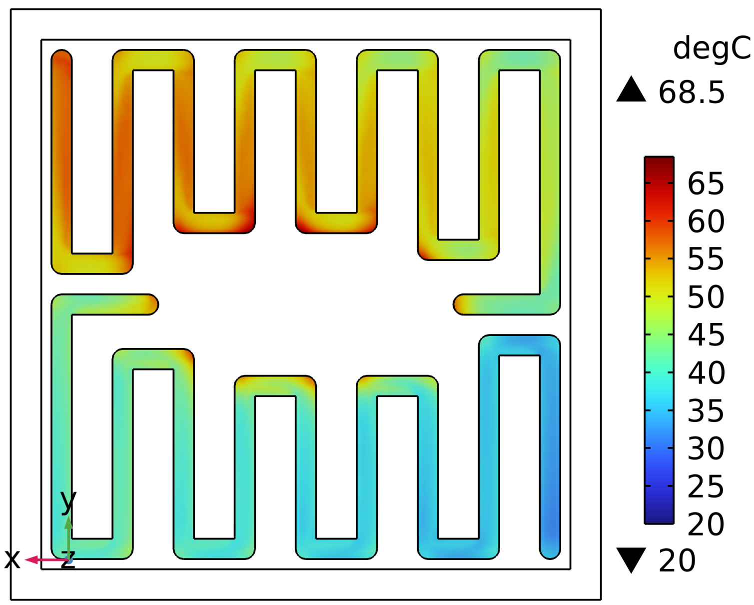

Figure 29: Backside of temperature distribution for cooling fluid in a door panel (see Figure 28).

E.2 Ram Panels

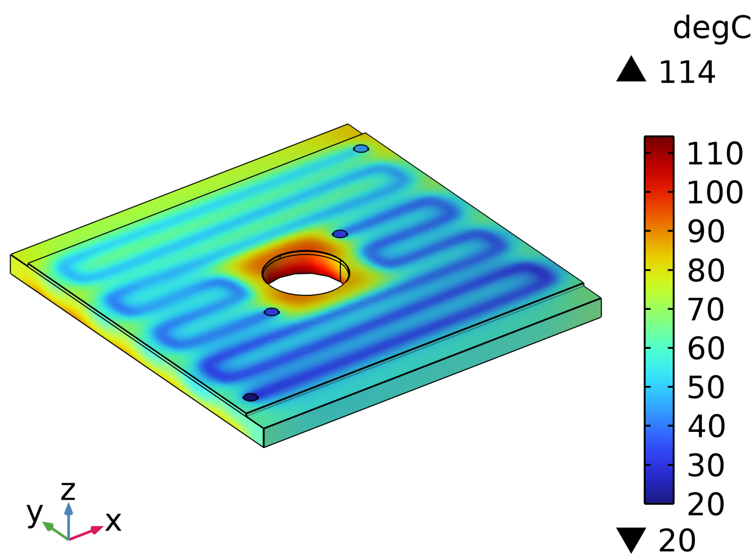

Figure 30: Temperature distribution for a ram panel.

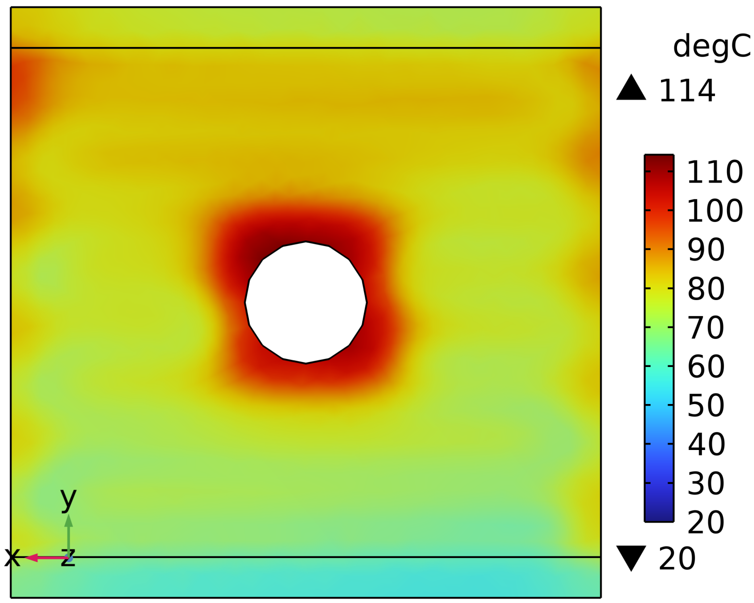

Figure 31: Backside of temperature distribution for a ram panel (see Figure 30).

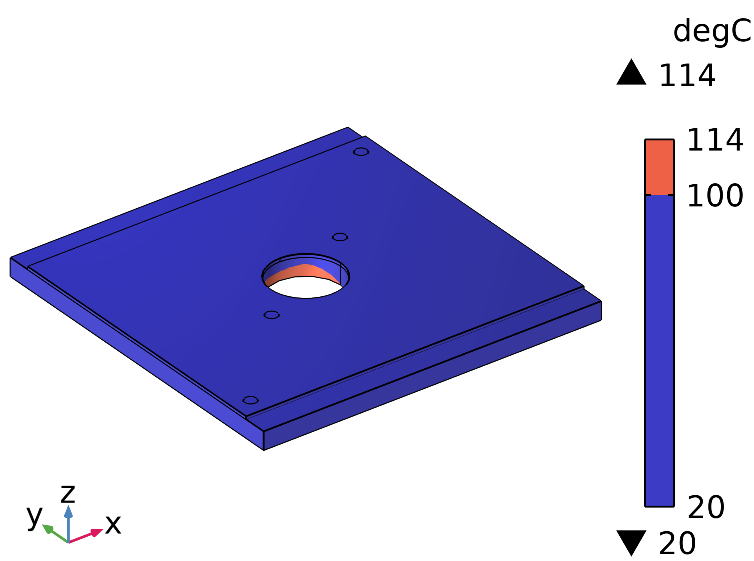

Figure 32: Contour plot separating temperatures >100 °C and <100 °C.

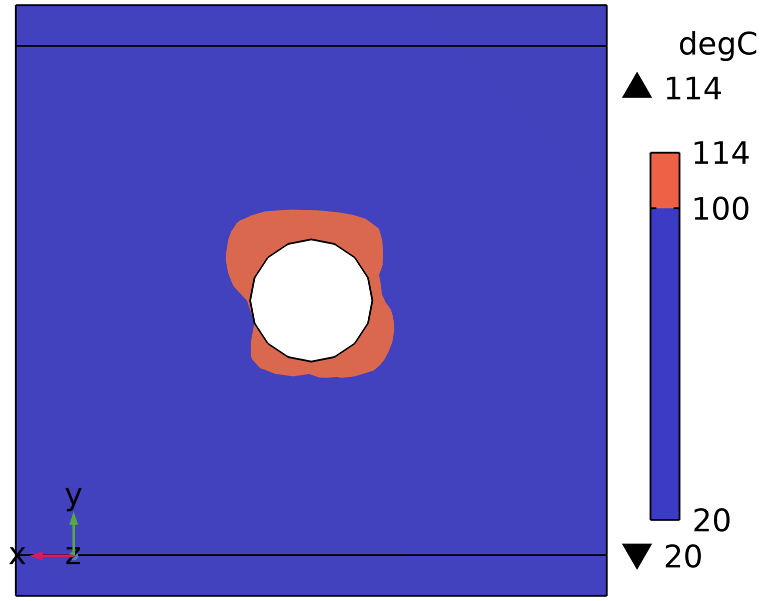

Figure 33: Backside of contour plot separating temperatures >100 °C and <100 °C for a ram panel (see Figure 32).

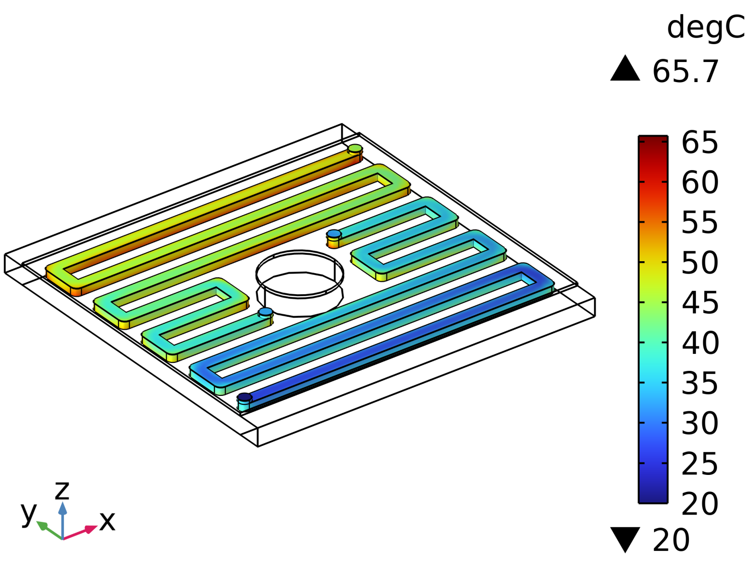

Figure 34: Temperature distribution for cooling fluid in a ram panel.

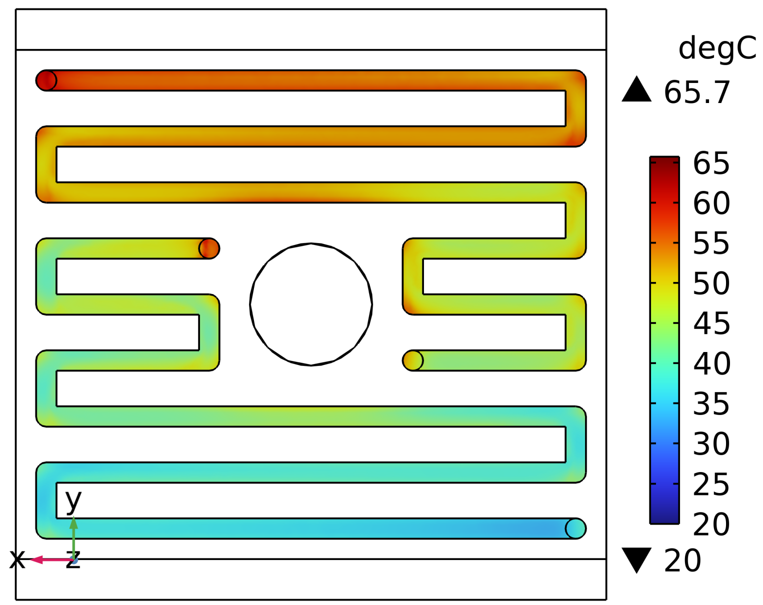

Figure 35: Backside of temperature distribution for cooling fluid in a ram panel (see Figure 34).

E.3 Side Panels

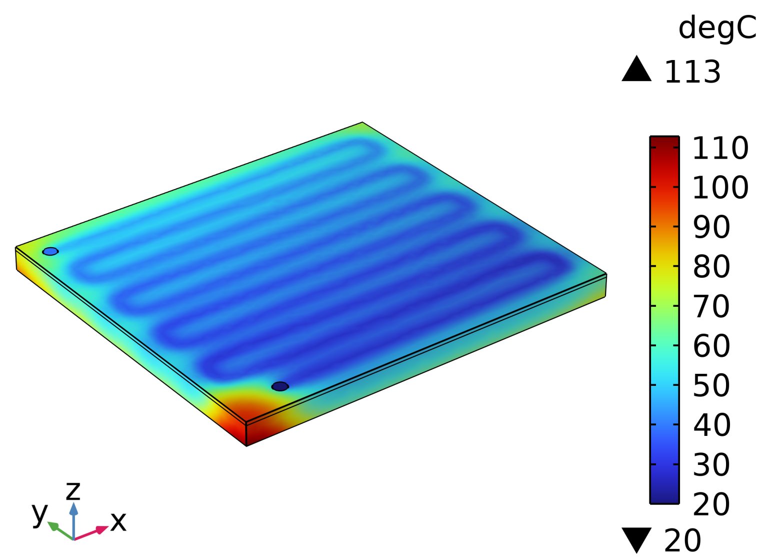

Figure 36: Temperature distribution for a side panel.

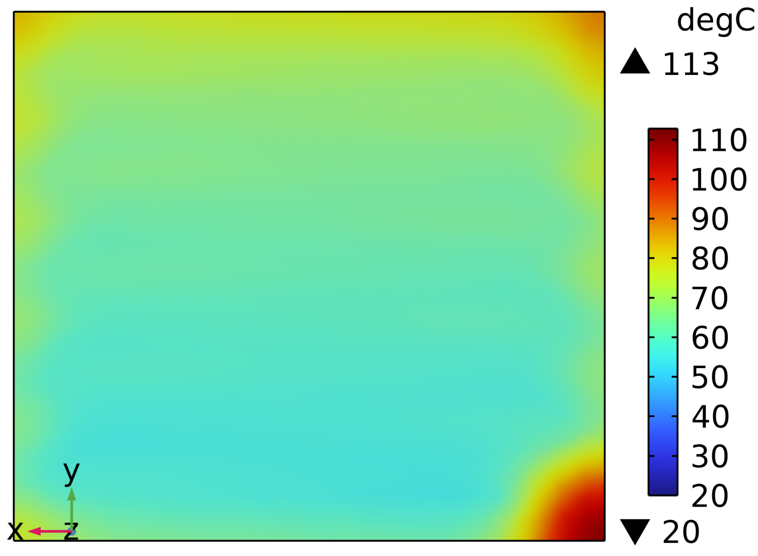

Figure 37: Backside of temperature distribution for a side panel (see Figure 36).

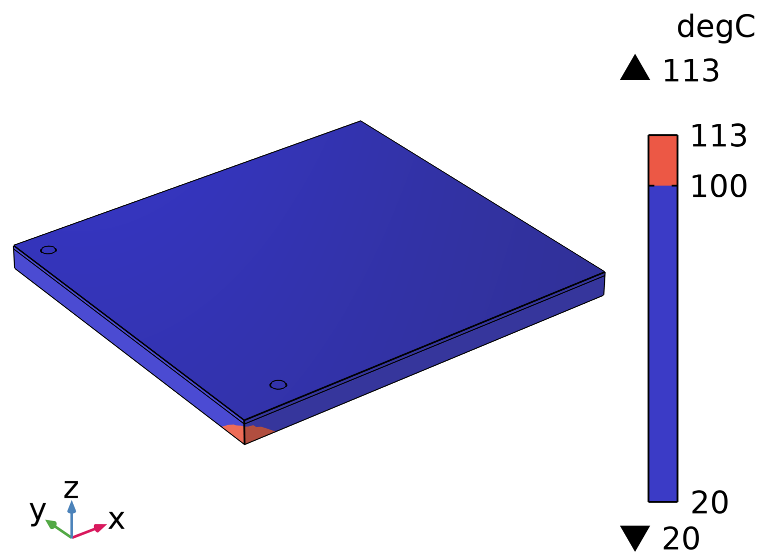

Figure 38: Contour plot separating temperatures >100 °C and <100 °C.

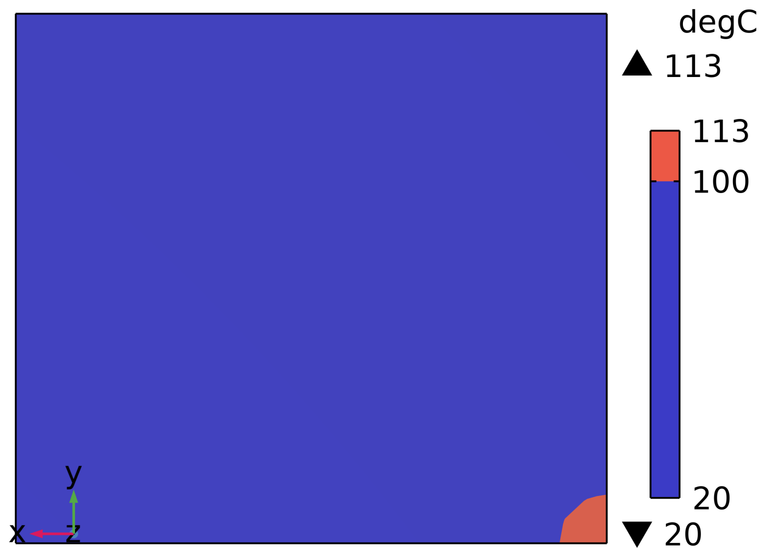

Figure 39: Backside of contour plot separating temperatures >100 °C and <100 °C for a side panel (see Figure 38).

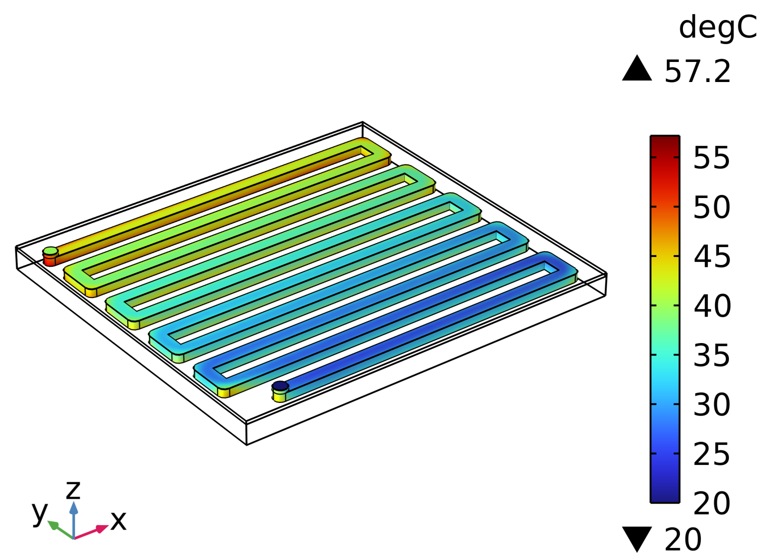

Figure 40: Temperature distribution for cooling fluid in a side panel.

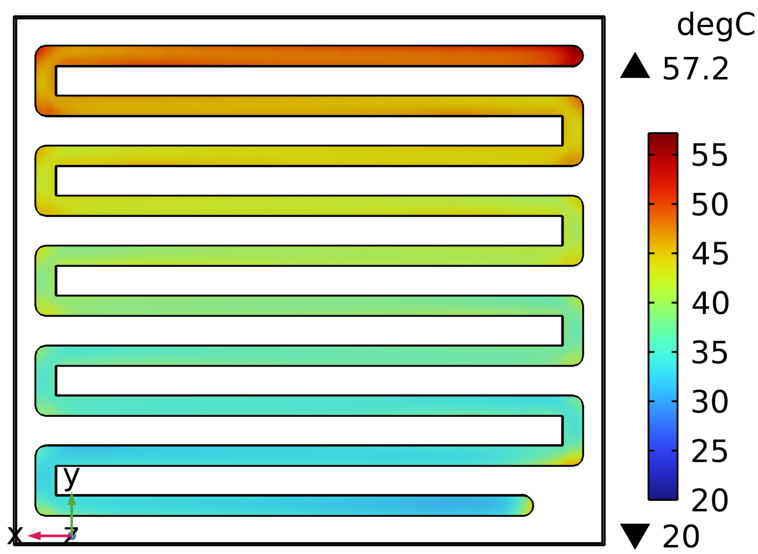

Figure 41: Backside of temperature distribution for cooling fluid in a side panel (see Figure 40).

Appendix F: Manufacturing Photos

Figure 42: All the chamber components.

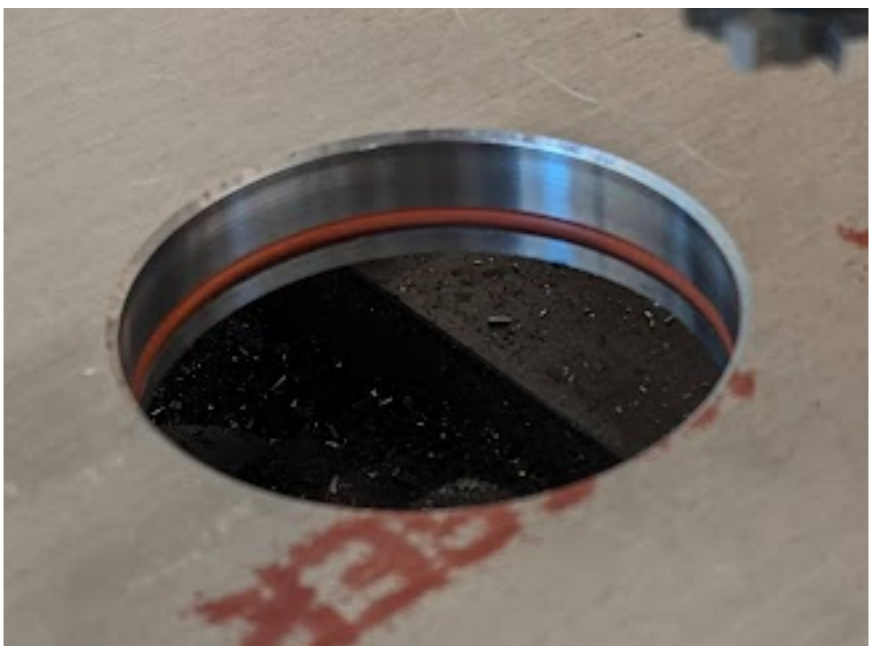

Figure 43: O-ring test fit during o-ring groove machining.

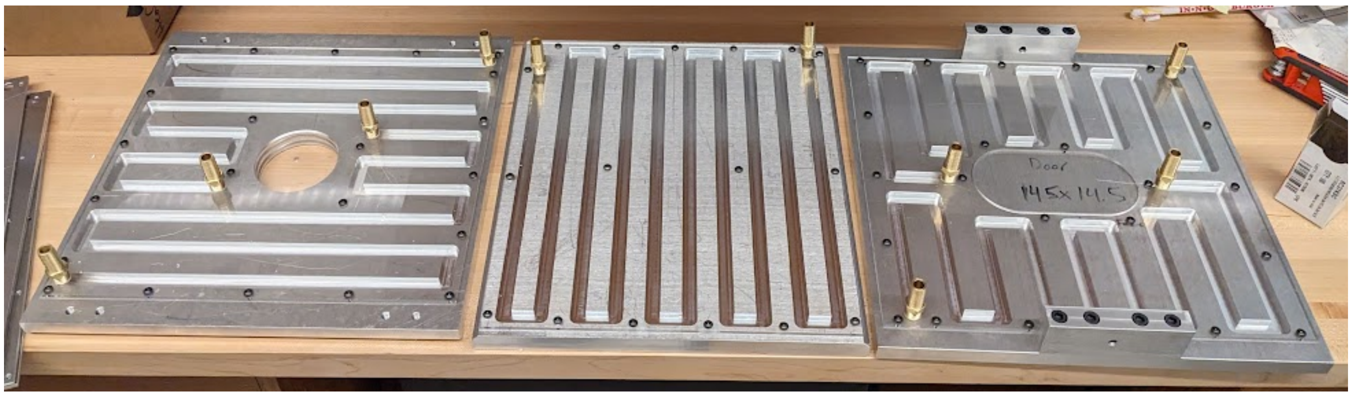

Figure 44: The three chamber panel types; Ram panel (left), side panel (Middle) and door panel (Right)