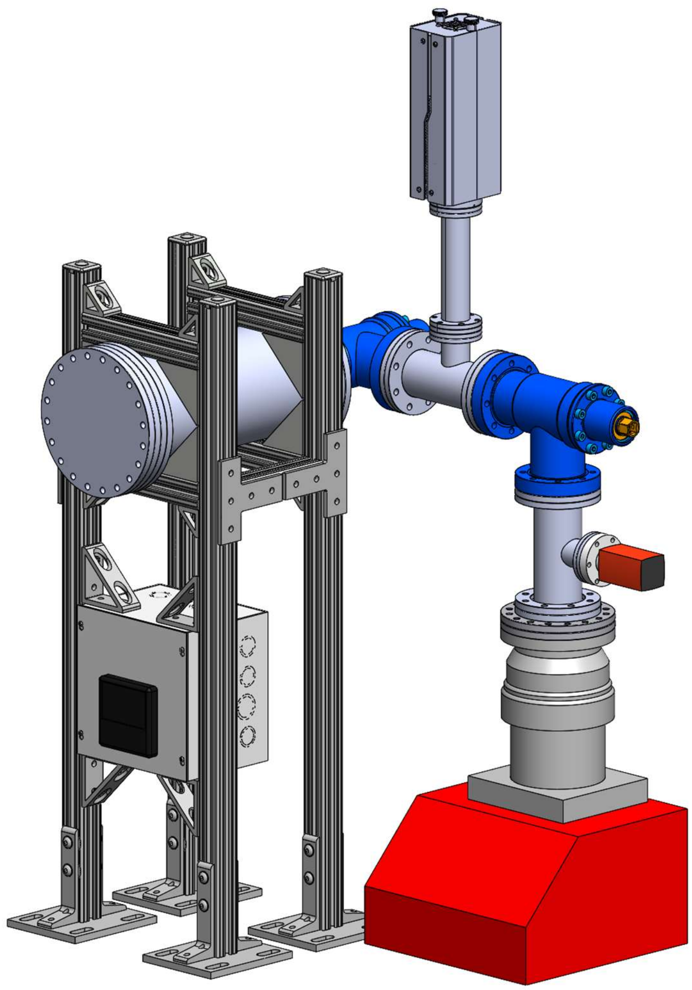
Optimizing Outgassing Test-Stand to Increase Testing Throughput and Accelerate Quantum Computing



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Executive Summary

Quantum computing is quickly emerging as a groundbreaking new technology that promises unprecedented development in countless different fields. The efforts being taken to advance quantum computing are motivated by the idea of solving complex optimization problems, increasing cybersecurity through cryptography, discovering new drugs, creating more robust financial models, and more with this unparalleled technology. One emerging type of quantum computing utilizes individual ions trapped in electromagnetic fields to perform logic operations. Our client, Quantinuum, is advancing this cutting-edge field.

The individual ions being manipulated to solve algorithms are prone to many sources of error. To avoid interference from stray particles, the trapped ions must be held at Ultra-High Vacuum (UHV), around 10^{-8} Pascals. To maintain this environment, all components used in the computing system must not release any particles that would contaminate the space. This process of materials releasing particles under vacuum is called outgassing, and the system we have built for our project will test samples for their outgassing characteristics.

Our client wanted a system that could test the outgassing rates of as many samples per year as possible and gave us size and pressure requirements compatible with the components they will be testing. The system we designed and built is optimized for quick testing turnover by having a large overall vacuum conductance determined through simulation. After researching vacuum conductance in the molecular flow regime, we were able to come up with a series of design options that we simulated to determine their overall vacuum conductances and pump-down times. Our final optimized system includes a chamber large enough to test parts and small assemblies that will be installed in the quantum computer. It also includes a heating system which can dictate a precise temperature profile of the entire system to ensure quick pumping times. To secure the safety of our system we designed a rigorous support structure, along with implementing runaway heating shutoffs. To test the integrity of our system, we tested the temperature profile generated by the heating system, and performed a helium leak test to verify the level of vacuum the system is able to achieve. The finished system will be shipped to our client along with assembly and testing procedures and documentation of the entire system and its working components.

This report outlines the research that went into our design concepts, as well as the calculations and simulations used to determine our final design choice. Our assembly and testing processes are discussed in detail, and included in the appendices is all of the documentation we will be delivering to our client along with our system.

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Introduction

With the opportunity to perform complex calculations unachievable by classical computers, quantum computing is accelerating us into an era of unprecedented computing power. Quantum computing will lead us to new drug and materials discovery, climate change solutions, advanced financial modeling and encryption systems, and many other advancements in fields that impact a major portion of our society. However, with the impressive computing power of quantum computing comes the equally difficult challenge of developing the systems. One of the many difficulties in producing a quantum computer is finding compatible hardware. Our senior design project focuses on combating this issue, as our goal is to make the testing and characterization of the components going into quantum computers more efficient.

Our client for this project is a company called Quantinuum based in Boulder, Colorado that is working towards the development of one specific type of quantum computer called a trapped-ion quantum computer. In this type of system, the material selection for the hardware is particularly important, as the whole system operates at ultra-high vacuum (UHV) conditions. In order to test how different materials will behave in this unique environment, Quantinuum currently uses outgas-test chambers to detect the rate at which their intended components emit molecules under UHV conditions. They currently have three of these test-stands, but they are not entirely adequate for the desired scale of their testing. Their current stands are small, a 6 inch diameter by 6 inch long cylinder, and take roughly two weeks to complete one testing cycle. The goal of this project is to increase the size of the chamber so that it can hold a sample that fits into a 5 in by 5 in by 12 in space, while minimizing the impact this increase in chamber size will have on the cycle time, as larger volumes take longer to evacuate. There are certain complications that arise when designing for UHV conditions, which force the design to utilize different strategies to optimize the time it takes to evacuate the larger chamber. Additionally, a heating system for the test chamber is necessary to the test process. The heating system needs to steadily ramp the temperature of the chamber to 150°C over a period of time in order to aid in the preparation of the sample by decreasing its outgassing rate. This new test-stand will allow the client to test large assemblies at a time, and perform an optimized number of tests per year to increase their efficiency.

The first half of this year-long project focused on meticulously researching, designing, and simulating system design options in order to optimize the design strategy for this test stand. After determining a series of design options based on researched methods of increasing vacuum conductance and minimizing chamber evacuation time, our team performed several simulations on vacuum simulation software to compare each of these designs based on their vacuum conductance, which is essentially how readily particles can escape the system, and the time it takes the system to pump down to operating pressure. Following this comparison, we presented our proposed design solution to our client which is shown in Figure 1 below.

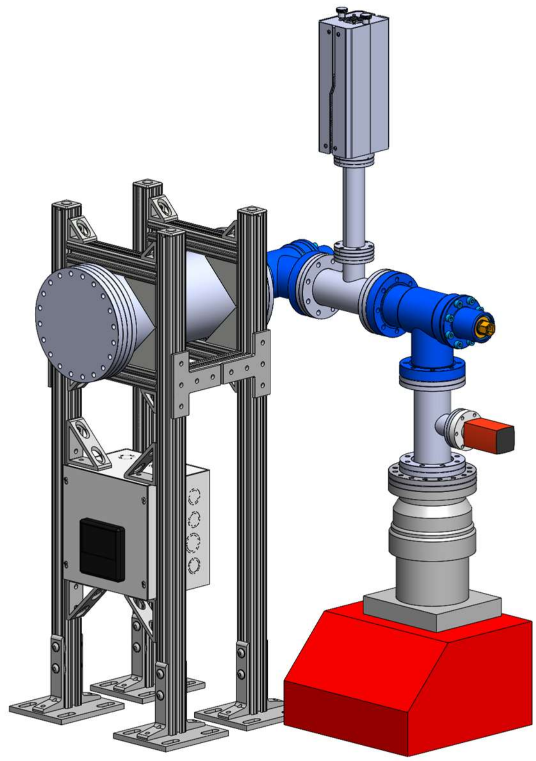

Figure 1: Finalized Outgas-Test Stand Design

This stand has a chamber almost double the previous size, increased piping diameter in order to increase pumping speed, and utilizes right angle valves already owned by Quantinuum in order to save money on expensive components. After their approval we moved on to determining all the necessary components for assembly, as well as the design for the heating system.

The second half of this project involved the assembly and testing process. Assembling the vacuum components was an intensive process that involved the installation of copper gaskets and methodical tightening of bolts to ensure a proper seal. Once all components were assembled. The system was pumped down to pressure and a helium leak test was performed to validate the level of vacuum achieved. Similarly, once the wiring and programming of the heating system was completed, the heating system was tested to confirm the temperature profile.

To deliver our completed system to our client we generated detailed documentation of all assembly and testing procedures, as well as documentation of all CAD and electrical components. The complete package is a readily functional system that will allow our client to test samples significantly more efficiently than they were previously able to and will aid them in developing this groundbreaking new technology.

Background Information

With the main goal of this updated design being efficiency, certain considerations must be made in order to design this successful vacuum system. Vacuum design is complex and requires an optimization of geometry, materials, component capabilities, and time. Working off of the system previously utilized by Quantinuum, it is clear that the main area of improvement will be the capacity of the chamber, and a major focus will be to not excessively increase the time required of this testing process even with the added chamber volume. In order to do this, we will need to assess the conductance of our pipeline, the possible presence of virtual leaks in our system, and a heating method to decrease the outgas rate of both the sample and our system.

Previous Solution

Quantinuum currently has an outgassing test stand setup that uses a chamber that is six inches in diameter and six inches in length. This system has been identified by Quantinuum as an area for improvement, as test throughput can be increased by increasing available chamber volume and maintaining current test cycle time. The previous setup utilizes a residual gas analyzer (RGA) which measures minute traces of impurities in a high vacuum environment. The system also implements a Pirani gauge to monitor the pressure inside the system. The stand currently occupies a 20.103” x 14.325” footprint which is under the stated goal of 24” x 24”. The current test stand’s CAD geometry can be seen in Figure 2 below.

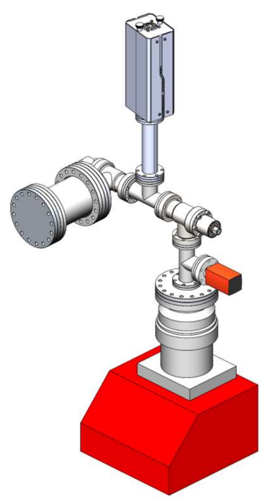

Figure 2: CAD Geometry of Current Outgassing Stand Assembly

This model includes the chamber, Residual Gas Analyzer (RGA), Pirani gauge, valves, and turbo pump. The pump we will be using is a Pfeiffer HiCube 300 ECO. The current process to test samples takes about 14 days for a full test cycle. First, a roughing pump runs for approximately 30 seconds to bring the vacuum pressure to approximately 10 torr, or around 10%

of atmospheric pressure. After this, the system switches over to a turbo pump, which brings the internal pressure to E-7 torr, which is approximately one ten-billionth of atmospheric pressure.

After the system reaches UHV levels, there is a heating time over a one day period. During the heating time, the sample is slowly brought from room temperature to 150 °C using manual controls and monitoring. This bake temp is then held for a 10 day period, which helps to speed up the release impurities from both the chamber and testing sample. After this, the chamber is cooled to 90 °C which takes another day to complete. The sample can then be tested and data can be collected from the RGA, which concludes the testing process.

Design Requirements and Specifications

The overall objective of the newly designed test stand is to increase the number of samples the client can test per year by designing a highly efficient outgas-test stand. The new design must achieve this objective while conforming to additional requirements set by Quantinuum. These design requirements can be seen below in Table 1.

Table 1: Design requirements set by Quantinuum for updated design

No.	Description	Requirement	Units	Value
1	The sample chamber shall have working test volume of 5”x5”x12”	Volume	in3	300
2	The chamber shall be heated	Temperature	°C	150
3	The test stand shall be compatible with a Pirani Gauge	Functional	NA	NA
4	The test stand shall be compatible with RGA	Functional	NA	NA
5	The test stand shall have a footprint of no more than 24” x 24”.	Area	in2	576
6	The test stand shall be able to achieve vacuum levels of’ 10-11 mbar	Pressure	mbar	10-10 to 10-11

This table is not exhaustive of the goals for the final design, but highlights the most important needs for our client. One additional requirement outlined by Quantinuum was to automate the chamber heating system by implementing closed-loop controls, which will replace the existing manually controlled heating method. This controller will be able to heat the chamber to 150°C at a steady rate of 1°C every 5 minutes without requiring an operator to be present. Our budget for this project is $15K, which allots money for vacuum valves, and custom parts.

Design Analysis

Designing UHV systems is complex and requires the consideration of many different factors. Therefore, in order to develop an optimized design for this outgas-test stand, each proposed system design will need to incorporate concepts of vacuum conductance, virtual leak minimization, and chamber evacuation trends. Our design analysis consists of conceptual design considerations, calculations, and design simulations in order to qualitatively and quantitatively compare our proposed designs and select the optimal design solution.

Vacuum Theory

When designing for UHV conditions, there are certain concerns that are not present in the average environment. At such low pressures, flow is in the molecular regime which means that the flow through the system is determined by the random motion of the particles within the system. How readily a chamber and piping system allows particles to flow through it is called the system's vacuum conductance. In order to maximize flow through the system, and minimize the time it takes to pump down to the desired pressure, the system's conductance must be maximized.

Each design variable we manipulated attempted to increase the conductance of the system in some way, and the effect of each variable would be assessed through simulation. Upon first consideration, we asserted that reducing the number of bends on the piping system of the test stand design would increase the vacuum conductance through the system. Our understanding was that 90° bends in the system inhibit the conductance of particles through the system. Especially at molecular flow levels, which is the case at the operating pressure of roughly 10^{-10} Pa, since the conductance of particles through a pipe is determined by the random bouncing of particles through the geometry, bends in the system will decrease the probability of particles making it through to the pump. Therefore, we first attempted to reduce the number of bends in the system by designing a single-bend system, and an entirely straight system to test the effect of this variable.

Similarly, the diameter of the pipe through which the particles are flowing influences the system conductance. The bigger the diameter, the easier it is for particles to successfully pass through to the pump and evacuate the chamber. Therefore, we also designed a system with an increased pipe diameter in order to attempt to increase the conductance of the system. However, the increase in volume caused by the larger piping would increase the total volume of the chamber, and possibly increase the time it takes to evacuate the chamber. Our simulations would assess the value of increasing the diameter of the pipe and whether the trade-off of conductance for pump-down time is beneficial. Lastly, in an attempt to minimize the abrupt change in pipe diameter caused by the direct attachment of the chamber to the piping system, we developed a design that included a conical reducer from the chamber to the first pipe in the system. Since there is not an off-the-shelf conical reducer that goes completely from our desired chamber flange diameter of 8” to the piping diameter of 2.75”, our design includes a conical reducer in series with a zero length reducer. If the simulation results proved the conical reducer to be beneficial, we would consider using a custom reducer to further increase the conductance through the system.

Calculations

In order to quantitatively compare our proposed designs, we wanted to calculate the conductance of each system and the time that it takes each system to evacuate to the desired pressure. To do this, we utilized a software called VacTran, which gave us the ability to import our geometry and simulate the evacuation of our system with the insertion of a few additional parameter estimates. Each of the pipes used in our geometries are inserted by calling out their geometry, including diameter and length. VacTran calculates the conductance of these pipes based on the pressure of the system at viscous flow, and based solely on the geometry once molecular flow is reached. For each of the valves used in our systems, the conductance value from the manufacturer is inputted into VacTran. The software is then able to calculate the total conductance of the system by summing the conductance of each component in series using Equation 1.

$$\frac{1}{C_{tot}} = \sum_{i=1}^{n} \frac{1}{C_n} \qquad [1]$$

Where C_n is the conductance of each component. The conductance of the system is then used to find the effective pumping speed of the pump, which is translated to the evacuation time of the system. The effective pumping speed due to conductance is given by Equation 2.

$$\frac{1}{S_{effective}} = \frac{1}{S_{max}} + \frac{1}{C_{tot}} \qquad [2]$$

Where S_{max} is the speed of the pump based on the manufacturer specifications. The pump we will be using is a Pfeiffer HiCube 300 ECO with a backing pump speed of 1.8 m^3/s. To simulate this pump in VacTran, we were able to import a pumping speed versus curve of this pump into the software. Therefore our results are representative of not only our custom piping system, but the specifications of the pump we will be using.

Just as the samples to be tested outgas particles, so do the chamber and the components making up the test-stand. While these components are designed specifically for UHV environments, they still outgas a certain amount. For the 304L stainless steel we will be using, this is primarily hydrogen outgassing [1]. The accumulation of particles that they release is called the gas load. An accurate simulation creates the theoretical gas load produced by the chamber and piping material in order to create realistic plots of both the chamber pressure over time, and the system conductance versus pressure as it evacuates. VacTran requires some preliminary calculation and analysis in order to calculate this gas load of the system. The equation for gas load, or throughput, is shown below in Equation 3.

$$Q = \frac{q_n A}{t^{\alpha_n}} \quad [3]$$

Where q_n is the outgassing constant at time t, A is the internal surface area of the system, and α_n is the decay constant at time t. VacTran uses this equation to simulate a gas load in the system, and requires user inputs for α_n, A, and q_n. This software uses inputs of q_n and α_n for two separate times t, one for time up to 1 hour of pumping and one for a time of 10 hours or greater. As outgassing rates are logarithmic over time, VacTran can produce a rough gas load curve based on the two given these inputs. The total internal surface area for each system was calculated using SolidWorks, and values for the decay constant and outgassing constants were found through external research. The decay constant for ultra-clean metal surfaces is 1.1 to 1.2 [2]. For these calculations, a constant value of 1.2 will be used for the decay constant across all time, as this value should not change significantly in this case. For the outgassing constant at times 1 and 2, outgassing data for baked and unbaked 304L stainless steel will be used to mimic the bakeout of the chamber. Unbaked 304L SS has an experimental outgassing rate of about 1.9E-5 Pa-L/s-cm^2 [3]. This value was used for the q_1 input into VacTran. To roughly simulate the chamber after the bake, an outgassing constant of 2.7E-10 Pa-L/s-cm^2 was used for q_2. This is the experimental outgassing rate of 304L SS after 30 hours at 150°C [2]. This is not exactly representative of the test procedure used by our client, as they use a ramped bake for a longer period of time, but this will allow for a rough comparative analysis of the effects of baking on the gas load of the system and in turn the conductance of the system. Once these preliminary calculations are imported into VacTran for each design option, simulations were run to yield plots of conductance versus pressure, and chamber pressure versus time.

Simulation Analysis

Each design concept was modeled in Solidworks using a mixture of vacuum components from K.J. Lesker, VAT, and Pfieffer. Following this step, we reconstructed each system design in VacTran to calculate the total system conductance by noting the length and diameter of each pipe component used, and in the case of the vacuum valves, inputting their measured conductance directly into VacTran. We then developed a model of the pump we are going to use by importing a curve of its pumping speed as a function of pressure provided by the manufacturer. Lastly, in order to simulate the gas load that is outgassed by the chamber and other vacuum components, we used the experimental data from our research on 304L stainless steel as well as the total internal surface area of each system calculated from Solidworks. This data is configured in VacTran to produce this theoretical gas load.

A simulation was run on each proposed design as well as the original design, including the system with no bends, one with a single bend, one with an increased piping diameter, and one with a conical reducer from the chamber to the first pipe. Plots were generated for the conductance of the system as a function of the chamber pressure, as well as the chamber pressure as a function of time. The plots for the simulations run on the system with a larger piping diameter are shown in Figures 3 and 4 below.

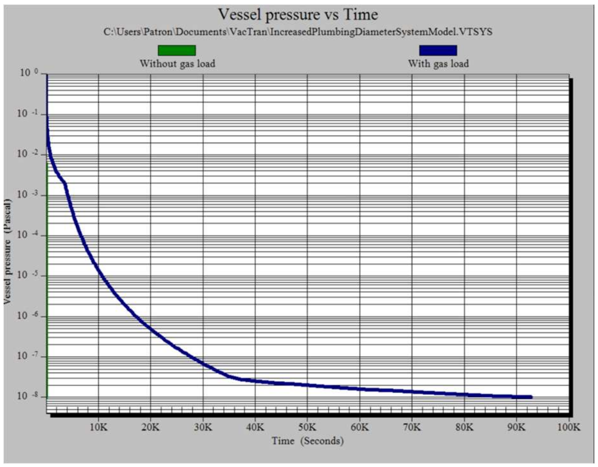

Figure 3: Increased Piping Diameter System Pump-Down Time

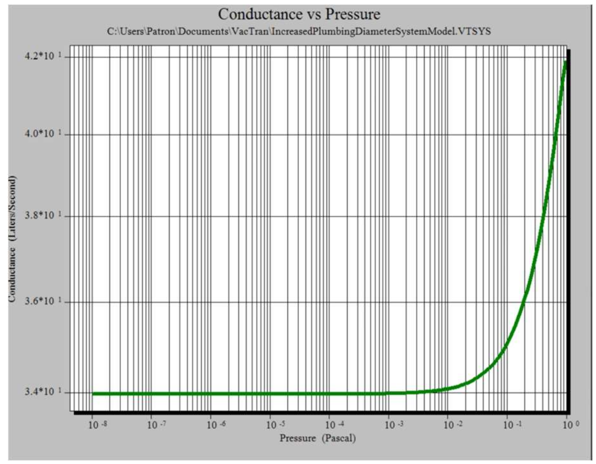

Figure 4: Increased Piping Diameter System Conductance versus Pressure

From these plots, the conductance of each system at the operating pressure of 10^{-9} Pa was determined, and the time it would take to evacuate the chamber to that pressure was also determined. The plots produced by these simulations for each of the other systems are available in Appendix A. The results from these simulations are shown in Table 2 below.

Table 2: Summary of Quantitative Analysis From Simulations

Design Version	Pump-Down Time [hr]	Conductance [L/s]
Baseline	21.0	9.991
Increased Plumbing Diameter	25.8	33.973
Conical Reducer to Chamber	48.6	9.47
Straight Plumbing	38.8	10.205
One Bend Plumbing	40.4	11.5825

From this data, it is clear that the system with the increased piping diameter outperforms the other system designs. While the reduction in bends to the system does improve the conductance slightly, it isn't significant enough to warrant the extra cost of the straight vacuum valves required of this design. Therefore, because of its high conductance and short pump-down time, we concluded that the increased piping diameter has the best effect on vacuum performance.

Final Design

Following the completion of our design work, we held a final design review with our client, in which we pitched to them our recommended design. An annotated assembly drawing is shown below in Figure 5.

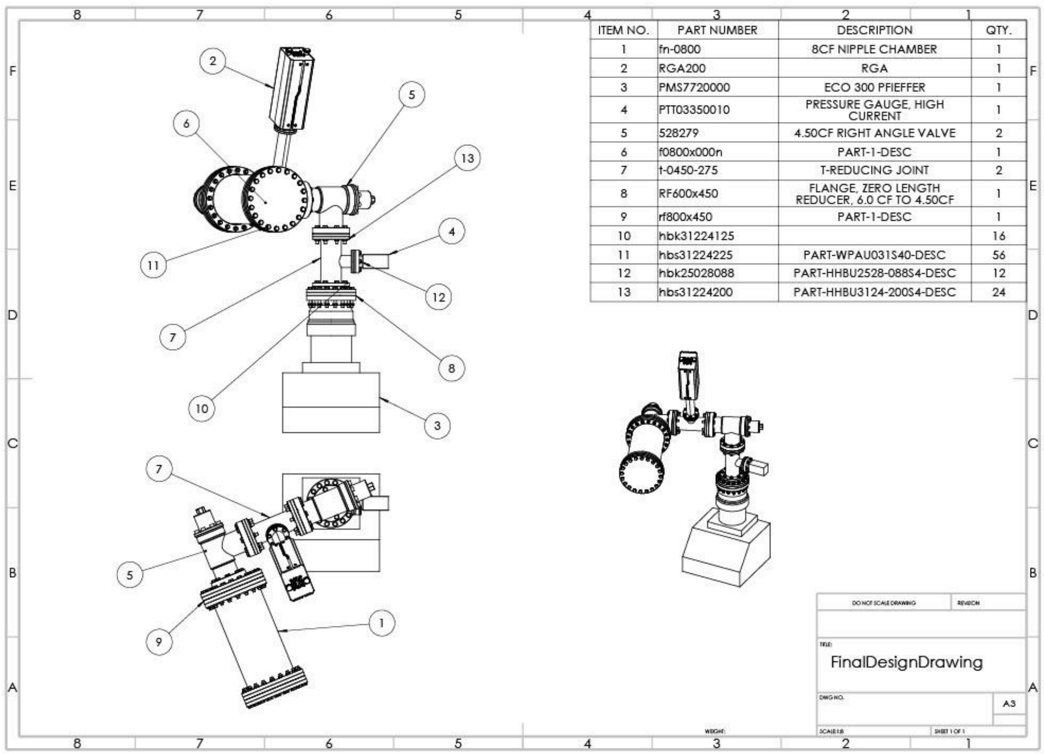

Figure 5: Final Assembly Drawing

Since our design choice was well supported with the results from our simulations, our client was happy with our design and approved it to move forward. We then put together our final bill of materials, which is included in Table B-5. Once the parts arrived we were able to begin our assembly and testing process. This involved assembling three subsystems: the vacuum components, the support structure, and the heating system. The vacuum and heating systems then underwent testing to prove their functionality.

Vacuum System Assembly

When handling vacuum components, it is important to take care to not touch any internal surfaces, as this can contaminate parts and increase the time it takes to draw down to vacuum. Due to this, the team used aluminum foil to cover any openings of the system, as well as wearing latex gloves to avoid system contamination. The team also utilized an assembly plan that included part details, bolt information, and a general order for assembly which was made prior to parts arriving. This helped in streamlining the assembly process as a whole.

Another important thing to note when assembling any UHV system such as ours is ensuring a strong gasket seal. This seal is vital to the function of the system, as the required pressure will not be achievable if even a small leak is present. Oxygen-free, high thermal conductivity, or OFHC, copper gaskets were used in assembly and all junctions except for one was found to have a leak free seal. In order to ensure proper installation of these gaskets, each flange must be tightened in what is called a “star pattern”, which ensures that each side of the flanges are being tightened simultaneously. This involves tightening opposing fasteners only 1/12th of a revolution at a time in a consistent order. The assembly of the connection between one of the valves and the chamber is shown in Figure 6 below, and the star pattern tightening is shown in Figure 7.

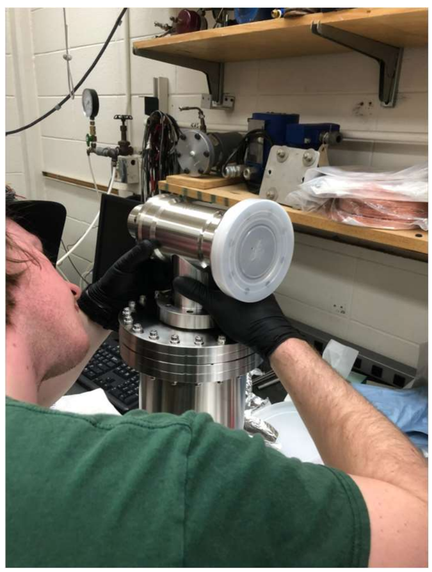

Figure 6: Aligning Valve to Chamber Flange

Figure 7: Tightening Reducing T-Flange to Valve Connection

There was only one CF connection that was not properly sealed during the initial assembly process and was found during a helium leak test which is described in the following section. This gasket was then replaced and retested, which resulted in a proper leak free seal. Installing copper gaskets in vertical CF connections proved to be non-trivial. To ensure every flange connection was assembled correctly, the team followed the procedure outlined by McNabe and Utz [7].

Support Structure Assembly

The support structure assembly was completed as specified in the assembly plan. The support structure primarily consists of 80/20 extruded aluminum and utilizes a v-clamp design to hold the chamber, which allows for easy adjustment to achieve proper leveling of the system. This leveling was important to achieve, as it ensures there are minimal residual bending moments and stresses in the system. This helps to preserve the gasket seals in the test stand and minimizes the potential for leaks. Designing the support structure using 80/20 also allowed the client to easily modify the test stand if a need arises in the future as components are widely available and standardized. The final assembly and support structure is pictured in Figure 8 at the end of this section.

Heating System Design

To achieve the heating parameters specified by the client, the team designed a robust heating control system. The system is built around an off-the-shelf ramp/soak process controller made by OMEGA. This controller is programmable to accommodate periods of ramp control where the temperature is raised at a uniform rate and soak controls where the temperature is held constant. This will allow the client to run the heating profile fully automatically with the press of a button.The controller uses an integrated relay to output 120V to the heating tape. To protect the controller from power surges, the power input is wired with an inline 120V 1A time-delay fuse.

To improve the safety of the system, there is a high limit temperature controller in series with the ramp/soak controller. This limit controller uses feedback from an independent thermocouple to prevent runaway heating. If the chamber temperature rises above a specified level, the limit controller will cut power to the heating tape until a manual reset button is pressed.

Both controllers used in this setup are rated for less than the peak current draw of the heating tape. This could lead to overheating of components, however the heating tape only draws current for a fraction of the total operation time. This makes the actual average current draw significantly lower than the nominal rating. This would likely allow for the safe operation of the system without any additional modifications. Regardless, a solution was implemented to improve the safety and longevity of the components. Instead of connecting the heating tape directly to the output of the controllers, the output of each controller is connected to the input of a 25A solid state relay. This effectively isolates the high current heating tape from the lower current controllers. See Figure 8 for a detailed wiring diagram, note that gray connections represent white wires in the actual system.

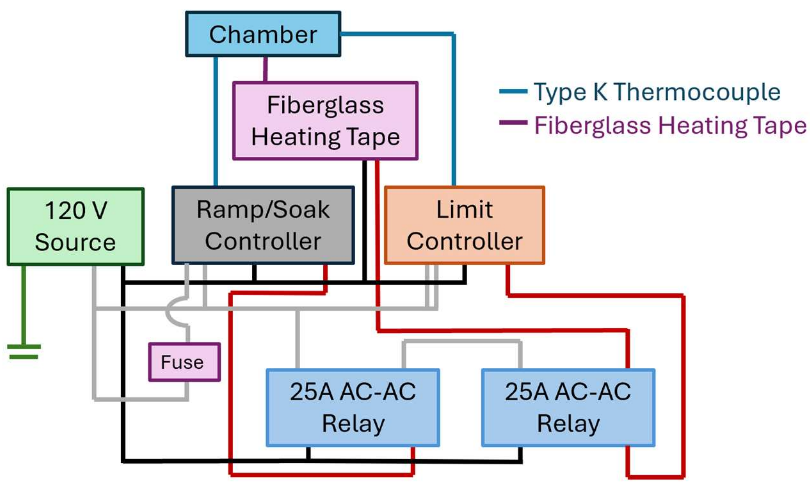

Figure 8: Schematic of the Heating Control Circuit

Once the circuit was wired and tested, all components were mounted inside the control box using 3M VHB tape. While this solution allows for mounting without drilling additional holes, the longevity of the tape remains a concern. If the tape fails over time, the box is large enough to accommodate standard DIN rails.

Pictured in Figure 8 is the final assembly including the integrated vacuum, heating, and support systems.

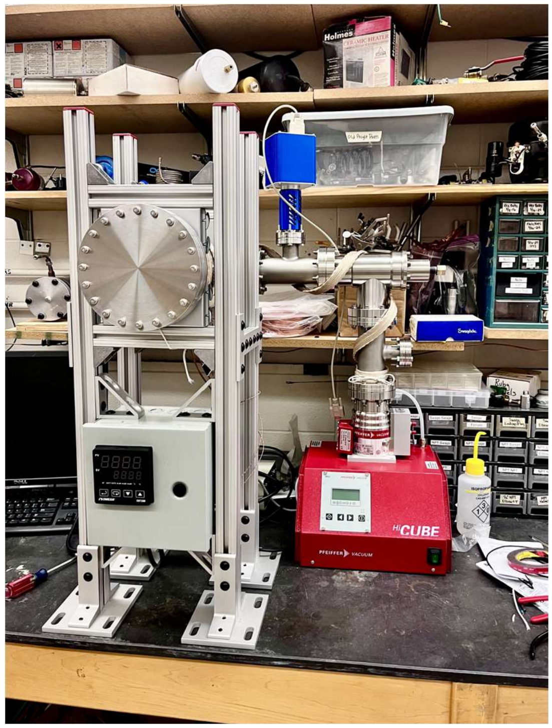

Figure 9: Completed Test Stand Assembly.

At the base of the assembly is the vacuum pump, which was lent to us for testing by Professor Nellis, and at the top is the pressure gauge also lent to us for testing by Professor Miller. Mounted to the support structure is the control box and panel which houses our heating system components. Wrapped around the chamber is the fiberglass heating tape. For the purposes of this display, we have removed the aluminum foil that is normally used to further seal and thermally insulate the system.

System Testing

Once the assembly of the system was complete, it was important to test it to ensure proper function. The team was able to borrow a pressure gauge from one of the department professors which could read the internal pressure of the test stand. Initially, the test stand was not able to achieve a pressure of 10^{-9} Pa , meaning there was a leak present in the system. The team then pivoted to conducting a helium leak test with equipment borrowed from the department. To perform this leak test, we used a CF to KF adapter flange to connect the helium leak detector to our system. While KF connections are not rated for UHV, this does not prevent KF flanges to be used for leak detection in UHV systems.

We then turned on our pump and kept it running while turning on the detector. While the detector was on, we sprayed a very light stream of helium diligently around every flange connection, and watched for spikes in pressure on the detector. The helium leak test confirmed the presence of a leak in one junction of the system. Once this leak was found, the team took corrective action to replace the gasket and test the system again. After this replacement was complete, the team was able to verify that there were no more leaks present in the system by redoing the helium leak test. Once the system was found to be leak free, a full vacuum test was performed and the system was found to be able to reach the threshold of 10^{-9} Pa.

The second subsystem of the test stand that needed to be tested was the controlled heating system. To test the heating system for proper wiring, a test program was used that heated the tape up to 50 °C and held it there for five minutes. While this proved that the system was wired properly, it was still important to test the safety features of the heating system. To do this, an additional test was performed to simulate a runaway heating scenario, which confirmed the functionality of the temperature limit controller. To do this, we set the temperature limit controller to a low limit of 50°C and ran our original test program. When the limit controller was tripped, it successfully cut power to the system and displayed the LED indicator.

Conclusion

Quantum computing shows promise to improve our lives from security to medical research. Quantinuum's trapped ion computing holds potential to lead the industry provided they disintegrate the primary roadblock: material outgassing. Outgassed particles within the trapped ion chamber can force errors in measured electric fields. These particles are most prominent at very low pressures like extreme vacuum conditions.

Quantinuum required a larger test chamber to increase the test sample dimensions yet also requested a lower cycle time. Research indicated the conductance to be the most significant variable in contributing to evacuating outgassed particles and reducing pump down time. Three design variations could improve the conductance: reducing bends, increasing diameter, involving reducers. Simulations calculated that reducing bends and involving reducers would only have a slight improvement in conductance. Additionally, new straight valves or conical reducers were terribly expensive. The best course of action was to implement larger diameter piping with the baseline configuration.

The final design of the chamber involved two additional subassemblies: a heating system and support structure. In order to properly outgas the molecules trapped in sample materials, the chamber and test must be heated. Following the stand design, the heater system required adaptation to be fully automated. The new heater tape would be controlled by a ramp soak control allowing the full procedure to be executed with a single button press. Lastly, the stand would need a support structure underneath the chamber. The support structure design incorporates the control box for the heating system and is sturdy enough to remain stalwart through accidental bumps and collisions. The full final design of the test stand, heating system, and support structure accomplishes Quantinuum's goals of increasing the chamber size while decreasing the cycle time.

Appendices

Included in the appendices are the plotted results from the simulation analysis of each proposed system design, as well as tabulated results for quantitative analysis and the decision matrix tables for the design specification. Appendix D includes the total documentation delivered to Quantinuum.

Appendix A: Simulation Results

Below are the simulation results for each proposed system design. The results, in order, are summarized for the original system, the increased piping diameter system, the system that includes a conical reducer, the entirely straight piping system and the single-bend piping system. For each system design, the plot of vessel pressure versus time is shown. This graph was used to determine the pump-down time of the system in order to achieve operating pressure. The plot of conductance versus pressure is also shown, which was used to determine the conductance of each system at operating pressure.

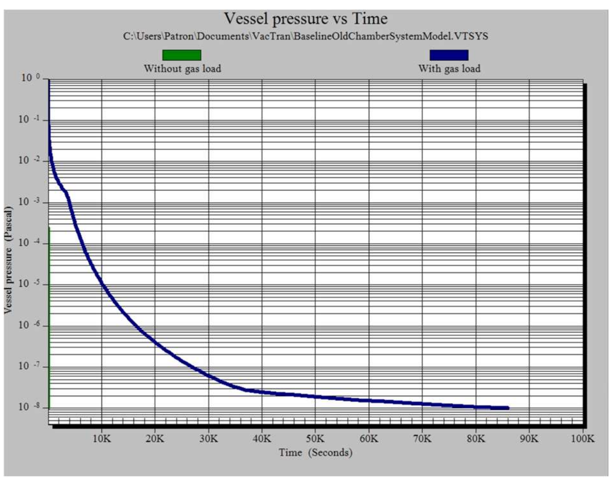

Figure 6-A: Original System Pump-Down Time

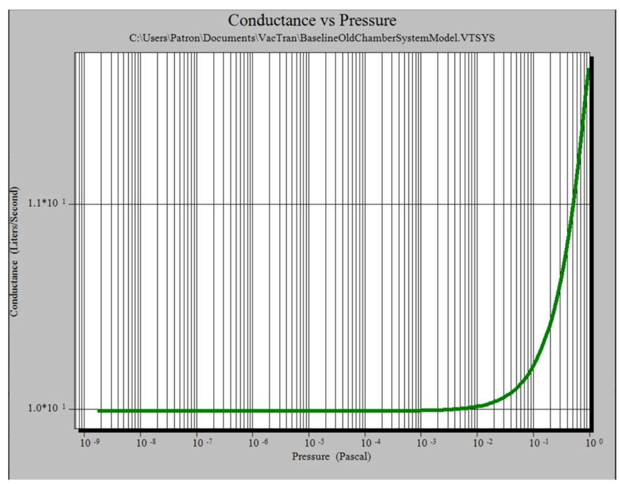

Figure 7-A: Original System Conductance versus Pressure

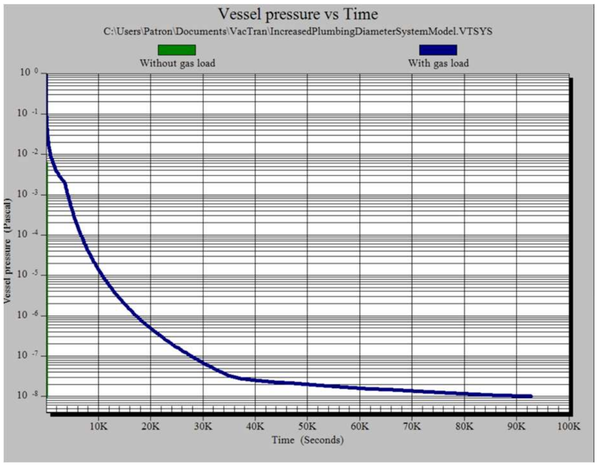

Figure 8-A: Increased Piping Diameter System Pump-Down Time

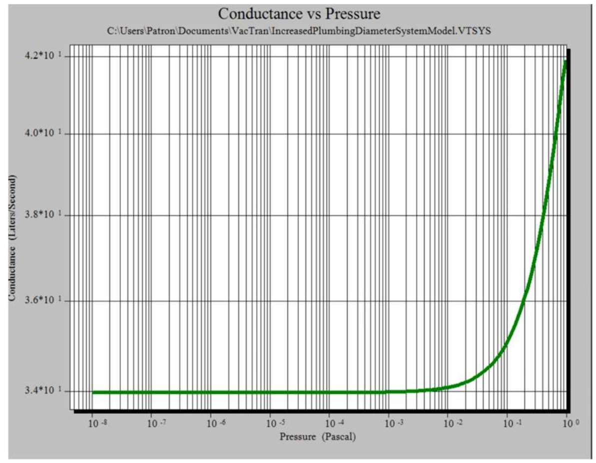

Figure 9-A: Increased Piping Diameter System Conductance versus Pressure

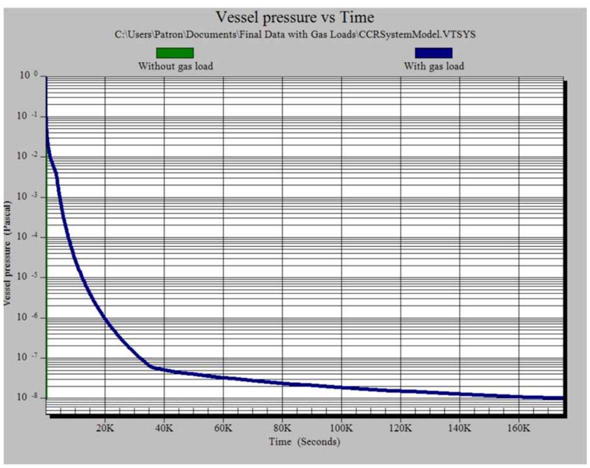

Figure 10-A: Conical Reducer System Pump-Down Time

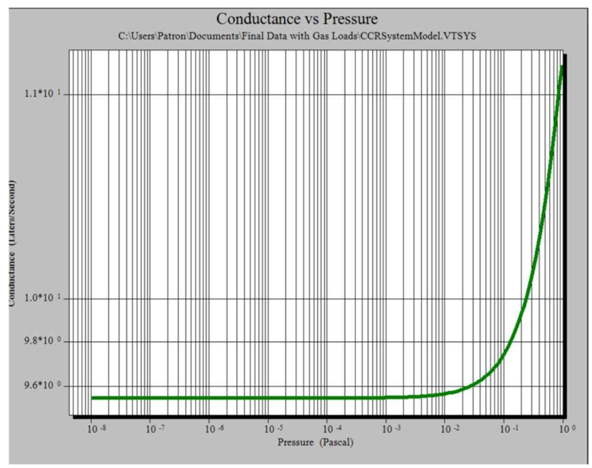

Figure 11-A: Conical Reducer System Conductance versus Pressure

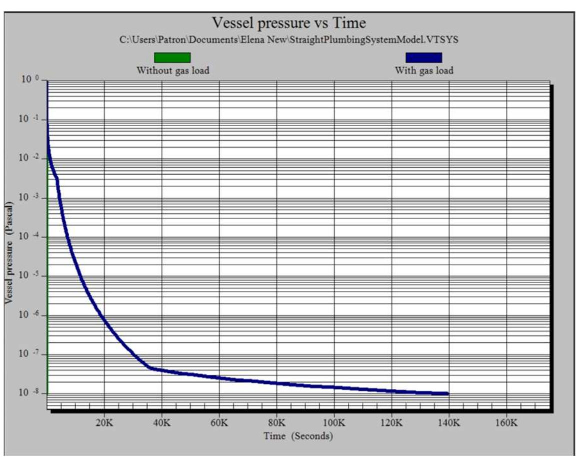

Figure 12-A: Straight Piping System Pump-Down Time

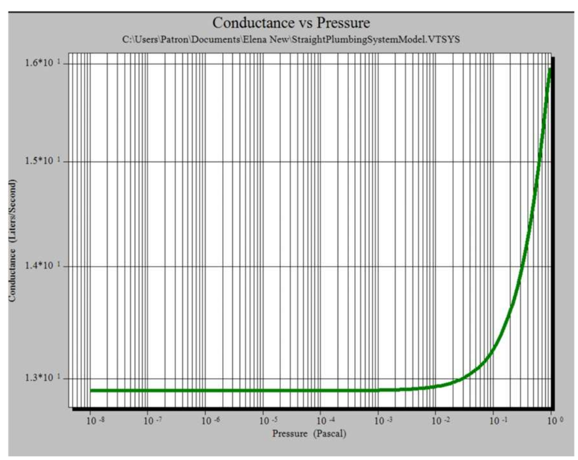

Figure 13-A: Straight Piping System Conductance vs. Pressure

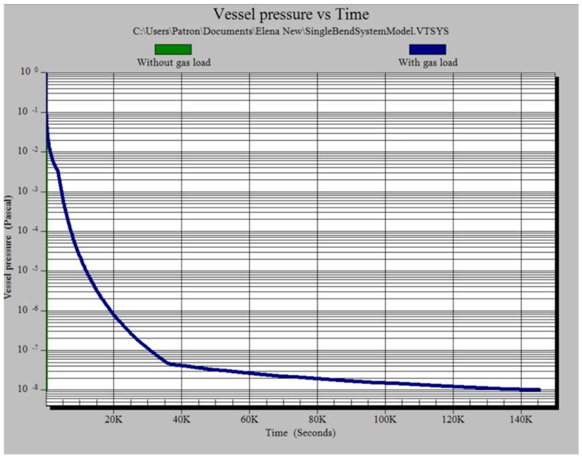

Figure 14-A: Single Bend System Pump-Down Time

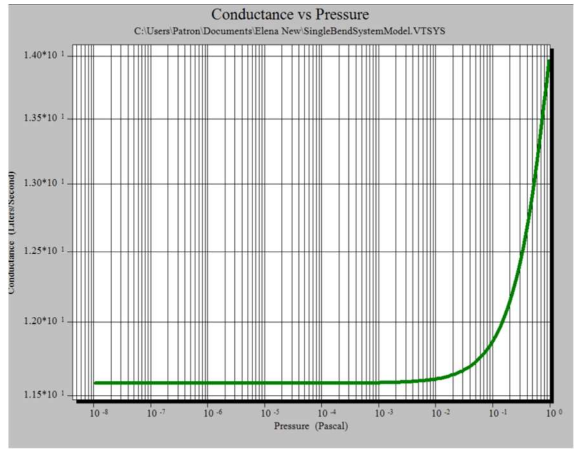

Figure 15-A: Single Bend System Conductance versus Pressure

A summary of the results from these simulations are shown in Table 3-A below. Included are the pump-down times for each system to achieve operational pressure, and the conductance of the system at operational pressure.

Table 3-A: Summary of Quantitative Analysis From Simulations

Design Version	Pump-Down Time [hr]	Conductance [L/s]
Baseline	21.0	9.991
Increased Plumbing Diameter	25.8	33.973
Conical Reducer to Chamber	48.6	9.47
Straight Plumbing	38.8	10.205
One Bend Plumbing	40.4	11.5825

Appendix B: Assembly Cost

Below is a summary of the estimated cost of each assembly in Table 4-B. These price estimates are taken from the K.J. Lesker website and summarize the cost of off-the-shelf parts that would need to be purchased if each given design was chosen. A full Bill of Materials is included in Table 5-B.

Table 4-B: Summary of Cost Analysis of Each Proposed System Design

Design Version	Assembly Cost ($)
Baseline	3,486
Increased Plumbing	2,113
Conical Reducer to Chamber	3,755
Straight Plumbing	32,112
One Bend Plumbing	17,744

Table 5-B: Bill of Materials

Call Out	Part Description	Supplier	Supplier P.N.	Quantity	Unit Price	Price
1	UHV cap for RGA and Piranni ports	KJ Lesker	F0275X000N	2	$24.50	$49.00
2	Chamber cap	KJ Lesker	F0800X000N	1	$176.30	$176.30
3	Sample chamber	KJ Lesker	FN-0800	1	$565.70	$565.70
4	10 count 2.75" copper gasket	KJ Lesker	GA-0275	1	$34.40	$34.40
5	10 count 4.5" UHV copper gasket	KJ Lesker	GA-0450LB	2	$79.30	$158.60
6	10 count 8" copper gasket	KJ Lesker	GA-0800	1	$105.30	$105.30
7	25x, 12-Point Bolts, Washers for 4.5" CF Tapped	KJ Lesker	TBK31224125	1	$28.16	$28.16
8	25x, 12-Point Bolts, Washers for 2.75" CF Tapped	KJ Lesker	TBK25028088	1	$21.13	$21.13
9	25x, 12-Point Bolts, Washers for 6"/8" CF Through	KJ Lesker	TBS31224225	3	$43.85	$131.55
10	25x, 12-Point Bolts, Washers for 4.5" CF Through	KJ Lesker	TBS31224200	2	$40.96	$81.92
11	24x, Plate Nuts for 4.5" CF	KJ Lesker	PN-0450	1	$52.90	$52.90
12	24x, Plate Nuts for 6" CF	KJ Lesker	PN-0600	1	$72.00	$72.00
13	24x, Plate Nuts for 8" CF	KJ Lesker	PN-0800	1	$52.90	$52.90
16	Zero length reducer	KJ Lesker	RF600x450	1	$261.35	$261.35
17	Zero length reducer	KJ Lesker	RF800x450	1	$285.00	$285.00
18	Reducing tee	KJ Lesker	T-0450-275	2	$500.50	$1,001.00
19	1/4 DIN Ramp/Soak Temperature/Process Controller - Relay/Relay	OMEGA	CN7233	1	$237.77	$237.77
20	High Limit Analog Temperature Controller with DIN Rail Mounting	OMEGA	CN3261-KF	1	$230.53	$230.53
21	BRISKHEAT Heating Tape: 0° to 482°, 12 ft Lg, 1 in Wd, 120 V Volt, 1,250 Watt	Grainger	13P759	1	$215.29	$215.29

22	Ready-Made Insulated Thermocouples	OMEGA	5TC-GG-K-24-36	1	$61.96	$61.96
23	GASKET, COPPER, DN100CF (6.00" OD) FLANGE, 4.743" OD,4.006" ID	KJ Lesker	GA-0600	1	$75.80	$75.80
	Total					$3,849.56

Appendix C: Decision Matrix

Below is the decision matrix table used to select the most optimal system design based on a series of weighted variables. The variables that were used to select a design include cost, volume, virtual leak potential, design complexity, footprint, pump-down time, and conductance.

Table 5-C: Decision Matrix

Decision Variable		**Orientation**			**Chamber Additions**		**Piping Diameter**
Criteria	*Weight*	*Baseline*	*Straight*	*Single-Bend*	*Conical Reducer*	*Custom Reducer*	*DN63CF*
Cost	25	3	1	1	3	1	3
Volume	5	3	4	4	2	2	1
Virtual Leak Potential	15	3	3	3	3	1	3
Design Complexity	10	3	1	2	2	2	3
Footprint	5	3	3	3	2	3	3
Pump-Down Time	5	3	4	4	1	2	5
Conductance	35	3	4	4	2	2	5
Total		300	275	285	235	165	370

Appendix D: Documentation

<u>OMEGA 1/4 DIN Ramp/Soak Temperature/Process Controller (PN: CN7533) Instructions</u>

This controller allows the user to program a set of set points and durations to guide a temperature profile. This document contains information on how the controller is currently programmed, how to run this program and interface with the controller, and how to program a different temperature profile.

Navigating The Menu Screens:

The main menu of the controller displays the process value and either the setpoint, the remaining time to setpoint, or the pattern number. To cycle through these options press the up or down arrows and then *Enter* to select. Currently the process value is shown in ℃, but this can be changed. To return to this main menu at any point, short press *Enter* and then press and hold *Enter* for 3 seconds. To cycle through screens, short press *Index*.

The first screen after the main menu is *Run/Stop*. To run or stop the current program, use the arrows and *Enter* to select. Press *Index* again to access "Temp Units", "High Temp Limit", "Low Temp Limit" and "Control Type". If Control Type is set to Program, a ramp/soak temperature profile can be programmed.

Programming a Ramp/Soak Temperature Profile:

The controller splits temperature profiles into 8 patterns which each have 8 available setpoints. Indexing through each pattern displays each setpoint and required time to reach each setpoint. After the last setpoint, the last step parameter, cycle parameter, and link parameter can be set. Each setpoint has a maximum time of 15 hours, but each pattern can be cycled through multiple times. More details about these parameters can be found in the *Program Setup* section on page 12 of the instruction manual which is included in this documentation

The current program is set up as follows:

- Pattern 0: Ramp
  - SP00: 25℃; Time: 10 minutes
  - SP1 150℃; Time 12.5 hours
- Pattern 1: Soak
  - SP10: 150℃; Time 15 hours
  - Cycle 16
- Pattern 2: Cool
  - SP20: 60℃; Time 7.5 hours

This program is set to ramp up the temperature to 150℃ at a rate of 1 degree every 5 minutes, hold for 10 days, then cool to 60℃ at a rate of 1 degree every 5 minutes.

<u>Wiring Table</u>

Note: All wires must be 14 AWG or larger

From		**To**		**Wire Color**	**Notes**
Component	Terminal	Component	Terminal		
Ramp/Soak	11	Live Bus	N/A	White	In-line 120V 1A time delay fuse
Ramp/Soak	12	Neutral Bus	N/A	Black	
Ramp/Soak	9	TC	(+)	Yellow	Mount hot junction to chamber
Ramp/Soak	10	TC	(-)	Red	
Ramp/Soak	19	SSR1	3	Red	
Ramp/Soak	20	Live Bus	N/A	White	
SSR1	4	Neutral Bus	N/A	Black	
SSR1	1	Live Bus	N/A	White	
SSR1	2	SSR2	1	White	
Limit	1	Live Bus	N/A	White	
Limit	2	Neutral Bus	N/A	Black	
Limit	4	SSR2	3	Red	
Limit	5	Live Bus	N/A	White	
Limit	6	TC	(+)	Yellow	Mount hot junction to chamber
Limit	7	TC	(-)	Red	
SSR2	2	Heater Tape	N/A	N/A	
SSR2	4	Neutral Bus	N/A	Black	
Heater Tape	N/A	Neutral Bus	N/A	N/A	
Power Cable	Live	Power Switch	OFF	White	
Power Switch	ON	Live Bus	N/A	White	
Power Cable	Neutral	Neutral Bus	N/A	Black	
Power Cable	Ground	Control Box	Ground Screw	Green	

Leak Test Procedure with Full Range Pressure Gauge

In order to use this test procedure, the stand must be equipped with a full range pressure gauge. Gauges only capable of reading low pressures can be damaged if exposed to higher pressure environments.

1. Start the vacuum pump.
2. Wait till max backing pump speed. (The Pfeiffer HiCube 300 Eco Pumping System contains a MVP 030-3 backing pump which reaches a speed of 1800 rpm.) This should only take about 5-10 min.
3. Turn on the pressure gauge.
4. Wait for the stand to reach maximum pressure. The pressure gauge will be at steady state. This can take up to 24 hours.
5. Spray helium around flanges. Use a helium tank with an attached hose and spray helium around each flange. Start at the flanges closest to the pump. Watch the pressure gauge to observe increases in pressure.

Leak Test Procedure with Helium Leak Detector

1. Replace pirani gauge with KF flange converter.
2. Use cast clamps to connect flexible tubing to KF flange converter. Connect the other side of the flexible tube to the helium leak detector (HLD).
3. Start HLD. HLD should be calibrating and measuring leaks to the magnitude of E-10 mbar-L/s.
4. Starting the vacuum pump.
5. Wait till max backing pump speed. (The Pfeiffer HiCube 300 Eco Pumping System contains a MVP 030-3 backing pump which reaches a speed of 1800 rpm.) This should only take about 5-10 min.
6. Once the pump has reached max speed, press the cycle button on the HLD to start measuring the stand leak.
7. Spray helium around flanges. Use a helium tank with an attached hose and spray helium around each flange. Start at the flanges closest to the pump. Watch the pressure gauge to observe increases in pressure.
8. Observe leak rates on the HLD. Test stand should have leak rates no higher than magnitudes of E-9 mbar-L/s.

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