THERMAL VACUUM CHAMBER REFURBISHMENT AND ANALYSIS

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Adrian Williams

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COMMITTEE MEMBERSHIP

TITLE: Thermal Vacuum Chamber Refurbishment
and Analysis

AUTHOR: Adrian Williams

DATE SUBMITTED: June 2018

COMMITTEE CHAIR: Kira Abercromby, Ph.D.
Associate Professor of Aerospace Engineering

COMMITTEE MEMBER: Amelia Greig, Ph.D.
Assistant Professor of Aerospace Engineering

COMMITTEE MEMBER: Jordi Puig-Suari, Ph.D.
Professor of Aerospace Engineering

COMMITTEE MEMBER: Roland Coelho
VP Launch Services, Tyvak NanoSatellite Systems

ABSTRACT

Thermal Vacuum Chamber Refurbishment and Analysis

Adrian Williams

Spacecraft are subject to different environments while on orbit around the Earth and beyond. One of the most critical of these environments that must be counteracted is the thermal environment. Each spacecraft has an operating temperature that is specified in the mission requirements. The requirement stems from internal component operating temperatures that are critical to mission success. Prior to placing the spacecraft in orbit, engineers must be sure that the spacecraft will survive or risk losing the mission entirely.

The primary way to mitigate this risk is to use a thermal vacuum chamber (TVAC). The chamber is designed to resemble a space environment by reducing the pressure within the chamber to $1\text{e-}6$ Torr. The differentiating factor between a vacuum chamber and a thermal vacuum chamber is the ability for the TVAC to complete a process known as thermal cycling using a temperature controller. Thermal cycling begins at a set temperature and increases within the chamber to a designated hot temperature expected to be seen on orbit. After the maximum temperature is reached, it remains there for a specified amount of time in what is called a soak. The controller then reduces the temperature to a specified cold temperature where a second soak takes place. Finally, the temperature is returned to the initial temperature and the process is repeated for a number of cycles until testing is complete.

For the purpose of this thesis, only the initial temperature increase and the first soak are being investigated. The chamber being used to run these experiments was graciously donated by MDA US Systems, however, no additional documentation was provided with the chamber. The Two identical black coated aluminum and brass cylinders have been chosen to be run with three different temperature profiles. The

profiles are manually designed in the temperature controller on the chamber and vary by final soak temperature. To supplement the testing, simulations have been created for each test case in order to verify the computer model of the chamber. The simulations utilize AutoCad and Thermal Desktop to provide the results for comparison.

Each of the tests were completed successfully and produced good results that corresponded well to the simulation. The largest difference between the simulation cylinder temperature and the experimental cylinder temperature was 1.9 °C. The effectiveness and efficiency of the blue chamber was compared to the other thermal vacuum chamber in the Space Environments lab. Overall, the Blue Chamber proved to be more robust and much easier to operate than the HVEC thermal vacuum chamber.

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Chapter 1

INTRODUCTION

1.1 Thesis Statement

The thermal environment of space can be very damaging to spacecraft and the payloads those spacecraft carry. Therefore, thermal engineers must be able to determine whether the spacecraft will be able to operate properly under the known temperature constraints. In order to ensure that the satellite will perform in extreme temperature conditions, each of the satellite subsystems, and the satellite as a whole, is cycled through expected temperatures in thermal vacuum chamber testing.

This thesis will be used to demonstrate some of the capabilities of the new thermal vacuum chamber donated by MDA US Systems to the Space Environments Laboratory located on the California Polytechnic State University campus. It is intended to show that the "blue chamber" can be run more effectively with fewer complexities than the High Vacuum Equipment Corporation (HVEC) vacuum chamber already present in the lab and used for thermal vacuum testing. Additionally, a thermal model will be created to simulate the testing outcomes and compare the accuracy of the chamber readouts.

1.2 Space Environment

The environment in which spacecraft operate is drastically different from the environment on Earth. First and foremost, there is little to no atmosphere, meaning the spacecraft must operate where no air exists. For reference, the pressure at sea level on Earth is 760 Torr, whereas in Low Earth Orbit (LEO), the pressure is on

the order of 10^{-6} Torr.[9] Second, the temperature that spacecraft must survive in is not constant. As the satellite orbits the Earth, it will pass in and out of Earth's shadow, or eclipse, many times. The difference in temperature when in and out of eclipse can be dramatic and must be properly prepared for. On Earth, heat can be transferred through the atmosphere with convection. The lack of atmosphere on orbit means there is no convection and the primary mode of heat transfer shifts to radiation and conduction. Radiative heat transfer is a process by which electromagnetic (EM) waves are emitted from one source and absorbed by another. The EM waves cause the absorber to heat up or the emitter to cool down, depending on the temperature differential between the two objects.

A few radiation sources include: direct solar radiation from the sun, planetary albedo radiation (reflected off a planet), radiation from celestial bodies, and deep space temperatures (approximately 4 Kelvin).[16] Depending on where the spacecraft is flying, there is generally a dominant source of radiation heating. For example, in LEO, the direct solar and Earth albedo radiation will be much more prevalent than radiation from other celestial bodies. But for spacecraft such as Voyager, which has left our solar system, the deep space temperature will have the largest effect and direct solar radiation will have very little, if any, effect at all.

Conduction heat transfer for spacecraft occurs within materials and through contact points. This heat is either collected from radiation or created by on board heat sources such as electronics boxes, operational payloads, and heaters. In order to remove excess heat, spacecraft are designed to radiate that heat out to space or store it to be used later when the spacecraft may need to heat up once again.

1.3 Thermal Vacuum Chambers

Thermal vacuum chambers (TVAC) are used to demonstrate the capability for components and satellites to survive in space. The air within the chamber is pumped out creating a low-pressure environment. Then, the environment is then cycled through high and low temperature regimes to simulate the satellite passing in and out of Earth's shadow. The temperature that the chamber runs its tests depends entirely on the orbit at which the satellite will fly. This testing is critical to each mission because it mitigates risk prior to launch. Every TVAC is fairly unique in its setup and capabilities and customized based on the desired outcomes of the testing. They all have some kind of mechanical pump to pull an initial vacuum, but once that is complete, chambers can have many different functions. Most chambers have feed-through ports on the side of the chamber that allows for electrical wiring, fluid lines, etc. to have access to the testing area. Depending on the design of the chamber, the number of ports can range from zero to more than fifteen for smaller lab size chambers. In addition to varying numbers of feed-through ports, chambers can also possess more pumps that allow the pressure to drop to lower levels. For example, the chamber used for this thesis has a turbo pump that can lower the pressure from 10^{-3} Torr to 10^{-6} Torr. TVACs fill an important role in the design and verification process for all spacecraft, regardless of size or mission, and understanding their purpose is essential to using them efficiently.

1.4 NASA General Environmental Verification Standard

Satellites are tested according to the NASA General Environmental Verification Standard (GEVS) based on the temperatures they will encounter in space.[7] This document outlines many different environmental testing constraints and provides am-

ple descriptions of why those constraints are necessary. There are different types of testing that the satellite must go through in order to be approved for launch. The first is qualification testing, which is the most rigorous test, as it requires the temperature to vary ± 10 °C above or below expected maximum and minimum flight temperatures. This test is only completed on non-flight hardware in an effort to preserve the integrity of the satellite so it is not over tested. Next in rigor is flight acceptance testing, which is less strenuous and is completed on components that will be part of the finished product. This testing procedure requires that the temperature vary ± 5 °C above or below expected flight temperatures. The testing duration depends on how low of a pressure can be attained. The standard states that below 1×10^{-5} Torr, a dwell time of 4 hours is required for component testing. If the testing is completed at ambient pressures, the dwell time must be increased to 6 hours. Therefore, any testing completed between 1×10^{-5} Torr and ambient pressure will require a dwell time between 4 and 6 hours.

1.5 Motivation

Completing the refurbishment of the blue thermal vacuum chamber will provide ample opportunities for graduate research projects as well as undergraduate education. The current TVAC that exists in the Space Environments laboratory is not ideal for properly teaching students about vacuum chamber functions because there are many nuances and complexities involved. The blue chamber is simple to understand and operate and has easy access for maintenance. The thermal modeling completed in Thermal Desktop can also provide a deeper understanding of how the chamber operates and what to expect when running a new test.

Chapter 2

BACKGROUND

2.1 Vacuum Heat Transfer

Thermal heat transfer occurs in one of three methods: convection, conduction, and radiation. Due to the lack of air pressure, convection does not affect the temperature of the spacecraft in any way because there is no fluid for the heat to move through. Therefore, radiation and conduction are the only methods of heat transfer spacecraft design must take into consideration.

The amount of radiation a spacecraft will face varies based on the occupied orbit and location within that orbit. Radiation is a result of electromagnetic (EM) waves being absorbed by or emitted from different surfaces.[2] Every material used to design a spacecraft has an associated absorptivity and emissivity value, both ranging from 0.0 to 1.0. Absorptivity refers to the percentage of total radiation energy that strikes the surface of the material that will be absorbed as heat. Therefore, higher absorptivity materials or coatings, such as black paint, will get much hotter than low absorptivity materials or coatings, such as white paint. Emissivity is the percentage of total energy that will be radiated out of a body. There are times when spacecraft will be too hot in their environment and they need to be cooled to maintain their optimal operating temperature; the emissivity of the materials on board will play a large role in the efficiency of that cooling process. The Stefan-Boltzmann Law is used to determine the radiative energy, Q , that is emitted from a surface using the emissivity of the material, ϵ , the Stefan-Boltzmann constant, σ , the surface area of emittance, A , and the absolute temperature, T_{abs} in Kelvin or Rankin depending on the other units.[15] Equation 2.1 shows the relationship between those variables.

$$Q = \epsilon \sigma A T_{abs}^4 \quad (2.1)$$

Another important part of radiation heat transfer is that heat energy out is equivalent to the heat energy in. Therefore, incoming radiation energy, from the sun for example, can be calculated and adequately designed for. EM waves also travel in a straight path, so when surfaces are at an angle to one another, the percentage of the total energy can be calculated using a view factor.

The EM waves mentioned above can have different wavelengths depending on the type of radiation. Shorter wavelengths encompass gamma rays and X rays and longer wavelengths include radio waves. The radiation for each of these wavelengths is different because the frequency of the radiation depends on the wavelength. Thermal radiation, which is the focus for satellite thermal analysis, is encompassed in a wavelength range of approximately $0.3 \mu\text{m}$ to $50 \mu\text{m}$. This range contains infrared, visible light, and part of the ultraviolet regime as seen in Figure 2.1. The second law of thermodynamics demonstrates that a maximum radiant energy exists for a given temperature at a given wavelength.[3]

Figure 2.1: Thermal Radiation Wavelength[3]

At any given wavelength, according to Kirchoff's law, the spectral emittance and absorptance are equal. It is most common to refer to these two values in the solar

band (0.3 μm to 3 μm) as absorptance, α , and in the infrared band (3 μm to 8 μm) as emittance, ϵ . The first law of thermodynamics states that energy in must equal energy out during heat transfer. So, the maximum amount of energy a test article inside a vacuum chamber will receive is determined by Equation 2.1 where T_{abs} is the temperature difference between the hot and cold (relatively) surfaces with each temperature raised to the fourth power.[16]

The final source of thermal heat transfer is conduction, which occurs at the physical interfaces of the spacecraft. It occurs as a result of on-board heat loads as well as heat that is collected from radiation. The process that occurs in space is the same as on Earth. When one surface gets hot, it will transfer heat to any colder surface it is in contact with. Conduction is a time varying energy transfer based on Fourier's Law.[16] The equation for a steady state, one dimensional heat transfer is shown in Equation 2.2 where Q_x is the energy per second that is transferred, k is the thermal conductivity of the material, A is the cross sectional area where the conduction is taking place, and $\frac{dT}{dx}$ is the temperature change in the x direction.

$$Q_x = -kA \frac{dT}{dx} \quad (2.2)$$

As mentioned in the previous paragraph, there are times when the spacecraft must radiate heat to space. To get heat to the proper side of the spacecraft to complete that cooling process, conduction through the body of the spacecraft is required. More detailed analysis can be done to look at conduction across multiple dimensions or even transient conduction that occurs over a set period of time.

2.2 Previous TVAC Work at Cal Poly

Prior to this thesis, there were only two TVACs on Cal Poly's campus located in the Cal Poly CubeSat lab and in the Spacecraft Environments lab. The HVEC TVAC, mentioned in Section 1.1 and seen in Figure 2.2, was worked on by Lauren Glenn for her thesis project.[11] The blue chamber is being evaluated as a replacement for HVEC TVAC for undergraduate and graduate research because of multiple complexities that are associated with the HVEC chamber.

Figure 2.2: HVEC Thermal Vacuum Chamber

The procedures to run and maintain the HVEC chamber are fairly intensive. With more steps, switches, and valves involved in the procedures, the risk of operator error increases dramatically. In addition, the ATS chiller cooling system for the chamber

is an external system to the chamber itself and has its own complex procedures for operation and maintenance. Should the chamber break while being used for an educational lab, it will not be simple to fix the problem and resume the lab quickly. With the blue chamber, the procedures for operating it are very simple and very easy to follow. Since most of the refurbishment work has been completed, no maintenance has been required over the past four months.

Another major issue with the HVEC and ATS chiller system are the problems they have had with leaks. The main source of leaking from the chamber takes place at the electrical feed-throughs. BNC cables were attached to mitigate a majority of those leaks, however, the problem seems to still occur at times. Leaking from the chamber is bad for testing because it does not allow the chamber to reach the lowest possible pressure, which is always desired. Even the smallest of leaks can prevent a chamber from dropping in pressure from 1×10^{-4} Torr to 1×10^{-6} Torr. The ATS chiller, on the other hand, has had a different leaking issue. The purpose of the chiller is to pump cold fluid through the chamber to reduce the internal temperature, thus simulating the colder regions of on orbit travel. The fluid that is pumped through the chiller is Galden HT-110, and it is very expensive to purchase. When the monetary cost is coupled with leaking issues, the problem becomes more serious. The fluid would leak out of the chiller rendering it unable to be reused and recycled. So far, the blue chamber has shown no signs of major leaks. The o-ring on the door of the chamber seems highly susceptible to leaking in its current state, however, a replacement is in the process of being obtained. Even with deteriorated door o-ring, the chamber can reach pressures as low as $10 \mu\text{Torr}$. As for the cooling system, it is entirely internal to the chamber except for the liquid nitrogen tank. Without having tested the cooling system, it is not certain whether there are leaks in the plumbing, but the system shows no visible signs of deterioration.

Finally, there is an electrical wiring issue with the lid of the HVEC chamber. The

lid is operated by a set of buttons, however, only one of the buttons works properly. A switch had to be put in place to change the direction the button will make the lid move. When bringing the lid down for testing, it is not perfectly aligned with the bottom of the chamber so it must be manually placed in the right spot. If it is not placed in the right spot, the chamber will leak and not be able to pull a vacuum properly. Since the blue chamber has been plugged in, there has only been one electrical issue, which is discussed in the refurbishment appendix. The fix was simple and there have been no issues since. The door of the blue chamber is opened and closed manually and uses a metal latch to ensure it is closed in the correct location every time.

Overall, the HVEC TVAC is much more complex procedurally and operationally than the blue chamber. Though it does accomplish its testing requirements, the blue chamber can complete similar requirements without the unnecessary complications.

2.3 Thermal Desktop

Thermal Desktop (TD) is a program created by C&R Technologies that allows engineers get an idea of what thermal loads the satellite or component being tested is likely to see on orbit. This work is critical to mitigating risk for the mission because it allows the engineers to analyze the spacecraft design prior to and following testing. The program will be utilized in this thesis to validate testing results from the blue TVAC.

The main design program behind TD is AutoCad. AutoCad can be used to create parts, drawings, and models in both 2D and 3D. Thermal Desktop runs on top of the AutoCad software by taking a part from AutoCad and analyzing it based on given thermal constraints. There are two major subset modules that TD incorporates in its analysis. RadCAD, which calculates all of the radiation exchanges between surfaces

and orbital heating, and FloCAD, which creates the flow networks and calculates convection rates. All of the data from RadCAD, FloCAD, and TD are passed into a solver also created by C&R Technologies called SINDA/FLUINT. This solver is the industry standard for thermal and fluid analysis.[1]

SINDA is the only solver required for TVAC analysis and it uses finite difference methods to analyze the data it receives. This method is much faster than using finite element models and takes much less time to iterate to a solution. The program relies on thermal "nodes" that lie on the model to complete the calculations. The location, quantity, and type of node is defined by the user based on what information is desired. There are three different types of nodes that can be used in TD: diffusion nodes, arithmetic nodes, and boundary nodes. Each node has a different purpose and must be used appropriately. The diffusion node represents any normal material that changes temperature based on its surrounding environment or contacts. This is the most common node used in TD for this thesis. Arithmetic nodes represent zero thermal mass, meaning the node will respond instantaneously to any change in energy balance. Boundary nodes have infinite capacitance and will remain at a constant user defined temperature or time-varying temperature depending on the input.[1]

When all of the nodes are defined, the program relies on contactors to determine where the heat transfer will take place. This is done between the physical connections of the chamber model and the test article. All radiative heating is calculated automatically by RadCAD and SINDA. Heat loads can be identified in the model to represent heat sources, such as strip heaters or an operational payload.

TD also has the ability to program an orbit if the testing is meant to verify the thermal environment at a specific location. However, for this thesis, the orbit parameters were not investigated as no payload or component testing needed to be completed.

Chapter 3

EXPERIMENTAL APPARATUS

3.1 Overview

All experiments conducted for the purpose of this thesis were completed inside the blue thermal vacuum chamber. The chamber was donated to Cal Poly by MDA US Systems. A plaque on the side of one of the chamber panels reads, "This chamber was used in the development of the Mars exploration rovers[sic] robotic arm. The two rovers, Spirit and Opportunity landed on Mars on Jan. 4 and 25, 2004 respectively." Documentation about the chamber's test history or operational procedures was not provided. Each of the parts described in this section are either internal to the chamber or were an external feature required for experimentation. External components required for the data collection included convectron gauges, an ion gauge, a Granville-Phillips 307 Vacuum Gauge Controller, and an Omega HH501BJK Type K thermocouple reader and thermocouple wires.

3.2 Thermal Vacuum Chamber

The blue thermal vacuum chamber has many different components. This section outlines each of those components and how they impact the experimental apparatus.

The chamber itself has been around for a while and some of its parts were outdated either technologically or just due to deterioration. Section 3.5 covers all of the refurbishment work completed on the chamber to date. If issues arise in the future, that section might be a helpful guide to solving the problem. A few of the fixes that were made were small and could easily be forgotten after a period of time.

Figure 3.1, below, is the schematic for the chamber that lays out the connections for each part of the chamber.

Figure 3.1: Chamber Schematic

3.2.1 Mechanical Pump

The mechanical pump for this chamber is a Galiso Inc. single phase induction motor. These motors are made up of a rotor, a capacitor, and two windings: a main winding and an auxiliary winding usually made of copper and placed perpendicularly to each other. When AC current passes through main winding of the motor, two oppositely rotating magnetic fields are created. A single magnetic field in one direction will cause the rotor to spin, however the two magnetic fields cancel out. To combat this, a capacitor is used to offset the current of the auxiliary winding and main winding by 90 degrees. This forces one of the magnetic fields created by the auxiliary winding to cancel out one of the magnetic fields for the main winding and the other auxiliary winding field to add to the other main winding field. This allows the rotor to begin

turning and the motor to start.[12]

The motor, seen in the Figure 3.2, is the main feature for reducing pressure inside the chamber. It can run for hours, or even days, with no harm to it or the chamber, so there is no need to worry about leaving it on for an extended period of time. This feature is extremely useful for testing because it allows the chamber to pump down to a fairly low steady state pressure before activating the turbo pump, if that is desired. It was found that after pumping down for eight to ten hours, the chamber was often at a pressure of about 3-5 mTorr. It is not required to pump down for this long in order to run the chamber, though. The chamber will reach pressures around 40 mTorr after 30 minutes and 20 mTorr after two hours.

Figure 3.2: Mechanical Pump

3.2.2 Turbo Pump

The Leybold Turbovac 151 turbo pump, or turbomolecular pump, is activated only when the mechanical pump has brought the chamber pressure below 20 mTorr.[13]

This pump is designed solely for low pressure use and can easily break if it is not operated properly. Turbos are comprised of multiple stacks of rotor blades and stator, or stationary, blades. The pump works similar to a compressor by capturing gas and successively compressing the gas as it moves through the pump until it reaches the pressure in the roughing line. When the pump is running at full speed for a couple hours, the chamber will reach pressures around 30 μ Torr, but has been seen as low as 10 μ Torr. After testing is complete and the turbo pump is turned off, the mechanical pump must run for 15-20 minutes to let the turbo pump completely stop. The turbo runs at extremely high RPMs and higher pressures will create heat friction and break the blades. An external view of the turbo pump is shown in Figure 3.3.

Figure 3.3: Turbo Pump

The turbo pump is controlled by a Turbotronik NT 20 controller, pictured in

Figure 3.4 on the main control panel of the chamber. The controller is equipped with buttons to start, stop, and heat the turbo pump. All other displays on the controller are indicators for how the pump is performing. When the turbo pump is started, the load indicator lights will flash green starting from the bottom and represent increasing load as more lights turn on toward the top of the panel. It is normal for the pump to reach a very high loading when it is turned on. When the pump starts to pull a lower vacuum in the chamber, the load lights will progress back down toward the lowest load level. The heating button is for baking out the pump in an effort to obtain very low temperatures. Water cooling must be active during the heating process.[14]

Figure 3.4: Turbo Pump Controller [14]

3.2.3 Platen

Crafted out of aluminum, this metal plate is used as the test section for all experiments. It is located in the center of the chamber and plays the largest role for the heating system via the heat strips underneath. There are also tubes running through the platen for the cooling system, however the exact routing of those tubes could not be determined without removing the plate itself.

The rectangular plate is approximately fourteen inches wide, one and a half inches

thick, and extends two feet deep into the chamber. There are three cut outs in the bottom of the platen approximately every six inches towards the back of the chamber for the heat strips. More detailed dimensions of the platen in metric units can be seen in the Figures 3.5 and 3.6 below.

Figure 3.5: Platen Dimensions

Figure 3.6: Underside of Platen

3.2.4 Shroud

The shroud for this chamber is a half cylinder sheet made of copper that sits above the platen. The purpose of the shroud is to contain the thermal environment around the test article. In addition, tubing runs along the top of the shroud for the cooling system that is discussed later in this section. The shroud increases the efficiency of the chamber to heat and cool the test section, which ultimately reduces the overall testing time. These tests will last many hours, so any time that can be saved is useful.

The shroud is 18.42 cm tall providing a total test volume of approximately $121 \times 10^3 \text{ cm}^3$ (0.121 m^3) In Figure 3.7, the shroud is the copper sheet seen above the platen.

Figure 3.7: Chamber Shroud (arching copper sheet) and Platen (flat aluminum plate)

3.2.5 Control Panel

The chamber controller is a series F4S/D Ramping Controller designed by Watlow Winona for temperature control in industrial applications.[17] Pictured in Figure 3.8, it provides ample capability for the experiments run in this vacuum chamber as it allows the user to specify the desired temperature profile based on ramp time, ramp rate, and soak duration.

Figure 3.8: F4S/D Ramping Controller

A profile can be designed with six different step types that include autostart, ramp time, ramp rate, soak, jump, and end. Autostart specifies a time and date at which to begin the profile. Ramp time changes the temperature set point over a specified amount of time. Ramp rate alters the temperature at a specified unit/minute rate. Soak maintains the temperature set point for a period of time that is defined by the

user. Jump allows the user to jump to another profile or step and repeat that jump multiple times. Finally, end terminates the profile and returns the user to the main page.

For additional help with profile programming beyond the procedure in Appendix B, "Chapter 4: Profile Programming" of the controller user's manual is very helpful.[17]

3.2.6 Heating System

The chamber is heated using three Ogden 475 Watt (240 Volt) strip heaters underneath the platen. They are equally spaced along the length of the platen in order to evenly apply heat to the system. The heat strips transfer heat through conduction to the platen, which then radiates to the test section. The chamber controller determines how much power to apply to the heat strips based on the desired heating set point. Additionally, there is a PID controller that can be tuned manually or automatically depending on the desired profile. For this thesis, all experiments were run with an autotuned PID controller. This resulted in a slight overshoot of the desired platen temperature before returning to the set point and reaching steady state. The controller is only able to control the platen temperature, not the chamber temperature, which is a very important distinction when conducting tests.

3.2.7 Cooling System

The active cooling system for this chamber uses liquid Nitrogen (LN_2). The coolant moves through the plumbing, shown in Figure 3.9, to reduce the internal temperature of the chamber.

Figure 3.9: LN₂ Chamber Plumbing

LN₂ enters the chamber plumbing through the green line where it reaches the solenoids. Solenoids are electric coils of wire that, when connected to a battery, create a magnetic field that activates a valve. When the battery is disconnected, the valve is closed. The chamber controller sends an electrical signal to these solenoids to allow the LN₂ to pass into the chamber. The green line on the left sends the LN₂ to the door shroud, shown in Figure 3.10, that provides additional cooling to the test section of the chamber. The green line on the right enters the platen and the shroud. As mentioned previously, the internal plumbing of the platen is unknown, and therefore is not shown here. The white line is the tubing on the top side of the shroud, as seen in Figure 3.7. Once the LN₂ has reached the end of the white line, it merges with the red venting line to leave the chamber from the platen. The LN₂

leaving the door shroud also merges with this red line and all of the residual coolant is vented out of the top of the chamber.

Figure 3.10: Door Shroud Plumbing

As in the first plumbing figure, the LN_2 will enter the door at the green inlet mark and exit at the red outlet. The white barriers are approximations of the path through the door.

3.3 Convectron and Ion Gauge Controller

The gauge controller for this chamber is a Granville-Phillips 307 Vacuum Gauge Controller. Pictured in Figure 3.11 on the side of the chamber, this controller displays the pressure data for the chamber, roughing line, and the ion gauge when it is turned on.

Figure 3.11: Convectron and Ion Gauge Controller

3.3.1 Convectron Gauges

Operation of the gauge controller is very simple. When the main chamber power is on, turning the controller on will show the pressure readings from the two convectron gauges, shown in Figure 3.12, located on top of the chamber (left image) and before the turbo pump on the roughing line (right image). The readings are in Torr, so atmospheric readings should show a value near $7.60 + 02$ on the display. The convectron gauges and digital controller that are currently on the chamber replaced the old gauges and analog control boxes that came with the chamber. The masking tape above the controller in Figure 3.11 shows to what pressure display each convectron gauge is connected.

Figure 3.12: Convector Gauges

3.3.2 Ion Gauge

When the mechanical and turbo pumps are both activated and the convector gauge showing the pressure reading for the chamber bottoms out (displays all zeros), the ion gauge can be turned on. After ensuring the wiring to the gauge is correct, turn on the gauge labeled "IG1" (assuming the gauge is connected to that output). The ion gauge will light up and after a few seconds, a pressure reading will display allowing the user to see pressures below 1×10^{-3} Torr. The ion gauge that arrived with the chamber has also been replaced by a new ion gauge. An image of the new ion gauge when it is on can be seen in Figure 3.13.

Figure 3.13: Active Ion Gauge

3.4 Thermocouple Controller

Internal temperature readings from the chamber are completed using an Omega HH501BJK Type K thermocouple reader. There is a known error of ± 1 °C associated with this reader, which is taken into account in the analysis of the results. The reader, displayed in Figure 3.14, uses standard thermocouple plug-ins to display the data.

Figure 3.14: Omega HH501BJK Type K Thermocouple Reader

In order to get temperature readings from inside the chamber, two thermocouples had to be rewired. The chamber has external ports that require a male thermocouple end to connect to it, the same connections required for the thermocouple reader. This process was completed for only two ports because the necessary temperature data to be collected was for the test article and the chamber. However, up to six thermocouples could be active at once with a DAQ system or multiple readers to display the outputs. Figures 3.15 and 3.16 below, show the external ports of the chamber and the double-sided male wires required to connect the reader to the ports.

Figure 3.15: External Thermocouple Ports

Figure 3.16: Double-Sided Male Thermocouple

The external ports are numbered and lead to more numbered ports inside the chamber. By connecting to the same numbered port, the temperature data transfer is complete. The internal ports, pictured in Figure 3.17, have an additional six ports, numbered seven through twelve, however, it is unclear at this time how to obtain data from them. Standard one-sided male thermocouples are attached to these ports for use inside the chamber. Ports one through six have all been tested and work properly.

Figure 3.17: Internal Thermocouple Ports

3.5 Blue Chamber Refurbishment

When the blue chamber was delivered to Cal Poly, it came with no installation or user's manual of any kind. The entirety of the refurbishment process was completed by the author with the help of the committee members and Cal Poly technical staff.

The chamber was moved into the Space Environments Lab at Cal Poly where no electrical system existed to match the current and voltage requirements for the chamber. The first thing that needed to be tested was whether or not the chamber could hold a sufficient vacuum for testing. However, the mechanical pump on the chamber could not be turned on until the chamber was plugged in. The only other option to run this test was to use an external pump to test the chamber's capabilities. After removing all exterior panels on the chamber, a mechanical pump was taken from one of the Student Vacuum chambers in the lab and connected to the blue chamber. The hose was removed from the blue chamber's internal pump connected to the external pump with a convectron gauge to read the pressures. A Granville-Phillips 316 Vacuum Gauge Controller was used to display the pressures received from the convectron gauge. There were initial issues with the convectron gauges and controller readouts, but this was solved by attaching all new devices to the chamber.

The external pump was started and the chamber pressure began to drop. After about an hour, the chamber pressure had dropped from 792 Torr to 3.1 Torr (much too high for testing purposes, but a vacuum nonetheless). Initial assumptions were that there was a leak somewhere or that there was some internal function of the chamber that required power to hold lower vacuums.

In order to combat the possibility of a leak, the o-rings in the chamber were greased with DOW Corning High Vacuum Grease. During that process, there was noticeable deterioration on the front door o-ring, which required replacement.

Wiring in the lab was completed in order to accommodate the electrical system of the chamber and the internal pump was reconnected. The main power was turned on, however, there was an issue with the electrical panel door causing the chamber to not switch on entirely. There is a safety switch that engages when the door is closed and if the door does not properly hit the switch, the chamber will not turn on.

Once the safety switch is engaged, there is a noticeable pressure in the main power switch that is felt when turning on the chamber. It is believed that the switch causes an internal valve to close allowing to the chamber to hold pressure. The mechanical pump was turned on and after three hours, the chamber reached a pressure of 16.9 mTorr.

Chapter 4

TESTING

4.1 Experimental Testing

The focus of this thesis lies in the experimental testing. There are two main goals: prove that the chamber can pull a test level vacuum according to the NASA GEVS standards and prove that the heating components of the chamber work properly and can be analyzed.

Six tests were completed to display the capabilities of the chamber and the controller. Three heating profiles were created and run once each for two different materials, black coated aluminum and black coated brass. The reasoning for using two different materials is to ensure that the computer model is truly an accurate representation of any material put in the chamber, not just for one test. The profiles attempted to reach steady state chamber temperatures of 40 °C, 60 °C, and 80 °C. However, the chamber controller is only able to set the temperature of the platen, so the final chamber temperature had to be approximated. With the help of the testing data, a better understanding of the relationship between platen temperature and chamber temperature has been developed, but a more accurate model will need to be created over time with more data points.

It is important to note that there was no background data for this chamber showing past run times, experimental data, or issues that arose. Therefore, most of the chamber had to be checked before and after each test to ensure nothing was broken or failing in a way that could result in the chamber being out of commission for a period of time. As more tests were completed, and the robustness of the chamber became more well known, these checks were not as necessary. Initially, a majority

of the checks were simply looking for leaks in the system and ensuring that the lines to the pump were connected soundly. Near the end of the testing period, checks revolved more so around the convectron gauges and thermocouple connections. No major issues arose during this time causing delays in testing.

4.1.1 Test Setup

For each test, a small polymethyl methacrylate (PMMA or Plexiglas) plate was placed on the center of the platen. The test article was set on the top of the Plexiglas plate to help isolate it from conduction through the platen. The goal of this setup was to create an environment where the temperature of the test article was affected solely by radiation, as is the case in space. A thermocouple was attached to the center of the test article to gather data throughout the test. Another thermocouple was placed to measure the temperature inside the chamber.

The test articles are small cylinders made of aluminum and brass and coated with a black finish. Both cylinders measured 1.5 inches tall and 0.75 inches in diameter. The external coating is important to note as the optical properties of the cylinder are the main drivers in radiation heating and cooling. The only difference between the test articles is the conductivity, specific heat, and density of the materials, which affects how long the material takes to reach steady state and what its final temperature can reach in a given time period.

Figure 4.1 displays the test setup inside the chamber. The test article is sitting on the Plexiglas with a thermocouple attached to it. Plexiglas has a melting temperature of about 160 °C, so there is no risk of melting for these tests. The other thermocouple is the wire to the left of the Plexiglas that is extended into the chamber from the platen and used to collect the chamber temperature data.

Figure 4.1: Experimental Test Setup

The door and manual vent valve are then sealed and the mechanical pump is turned on. Usually, the pump is left on overnight to ensure the turbo pump could be activated without any issues. Generally, turbo pumps should not be started until the chamber pressure has reached around 20 mTorr or so, however, it is safer to let the chamber continue to pump down to lower pressures. After an overnight pump down, the chamber is generally around 3 or 4 mTorr and there have been no problems starting up the turbo pump. When the convectron gauge reading the chamber pressure shows all zeros, the ion gauge can be activated to continue observing the pressure.

Most of the time, the turbo pump would be left running for a couple hours to reach somewhat of a "steady state" before starting a test. But, no real steady state was found as the chamber was seen to go as low as 10 μ Torr and most tests began around 30 μ Torr.

Recall that the NASA GEVS state that a pressure less than 10 μ Torr is required to run this test appropriately and a temperature soak at that pressure must last for at least four hours. The time requirement to run adequate temperature profiles at ambient pressure is a six hour soak.[7] Since there is only a two hour difference between the soak times required for a 10 μ Torr test and an ambient pressure test, it was assumed that only 5-10 minutes would need to be added to a 30 μ Torr test. However, since no electrical or component testing was taking place, the extra 5-10 minutes was disregarded as it was insignificant to the final test results. Additionally, there was no indication from working with the chamber that suggested it could not complete the 6 hour soak if necessary. A simple adjustment in the chamber controller would be the only change necessary to allow the test to proceed longer.

The final step to setting up the test properly is programming the heating/cooling profile into the chamber controller. Using a variety of step types in the controller, this can be achieved and the test can be initiated. If the chamber is attempting to heat up, the switch labeled "HOT" on the right of the "BASEPLATE" label must be flipped up and vice versa for cooling. These switches can be seen in Figure 4.2. Once initial data measurements are made and the profile is started on the controller, data recording can begin.

Figure 4.2: Baseplate Switches

4.2 Validation of Testing

Simulations for the chamber testing were completed in Thermal Desktop. The model, shown in Figure 4.3, represents the test setup for the chamber. The clear cylinder surrounding the platen and shroud represents the chamber walls. Without this in place, heat in the simulation would radiate out to "space" continually resulting in little to no temperature increase on the test article. The platen is the silver plate containing three red strip heaters along its length. The shroud can be seen in yellow covering the platen and test article. Finally, the small blue plate represents the thermally isolating Plexiglas and the black cylinder is the test article. Small spheres

seen mounted on various surfaces are the nodes that the program uses for its finite difference method to determine the temperature at those locations. Increasing the number of nodes results in better temperature accuracy for the simulation, however, it takes more computing power and longer to run each simulation. Higher mesh accuracy is not required for this test as the test article should see uniform heat distribution regardless of the number of nodes. More nodes is more desirable when there is a large temperature gradient across a surface or interface.

Figure 4.3: Thermal Desktop Simulation Model

The properties of each material in the chamber were chosen from tables of known property values. The two cylinders are 6061-T6 aluminum and alloy 360 brass both powder-coated flat black. The material property values used in the simulation for each material are presented in Table 4.1.

Table 4.1: Simulation Material Properties

Material	Conductivity ($\frac{W}{m*K}$)	Density ($\frac{kg}{m^3}$)	Specific Heat ($\frac{J}{kg*K}$)	Emissivity	Absorptivity
Aluminum[5]	237	2700	921.09	0.15	0.12
Brass[6]	119.9	8470	380	0.04	0.5
Copper[6]	401	8960	0.39	0.03	0.18
Plexiglas[4][8]	0.18	1180	1450	0.86	0.5
Black Coating[10]	N/A	N/A	N/A	0.95	0.9

It was determined that the aluminum was either highly or roughly polished and, therefore, should have an emissivity from 0.09-0.18. For the final results of the simulation, an emissivity value of 0.15 for the aluminum produced the most accurate temperature results. A comparison of the simulation results for the both the 60 degree aluminum and brass tests can be seen in Figures 4.4 and 4.5, respectively. The red line in both plots is the measured experimental temperature of the cylinder that the simulation is attempting to replicate. If an emissivity value of 0.16 (blue line) was chosen, the simulation would be too high for the brass test. Equally, if an emissivity value of 0.14 (green line) was chosen, the simulation would be too low for the aluminum test. To avoid favoring one test over the other, 0.15 was chosen as the emissivity value for aluminum in the simulation. Further analysis of the testing results takes place in Chapter 5. The copper values for the shroud are values consistent with polished copper and the black coating values were determined based on a range of values for black coatings in space.

Figure 4.4: Emissivity Comparison: Aluminum 60 °C Test

Figure 4.5: Emissivity Comparison: Brass 60 °C Test

The same model was used for all tests run through the simulation. The only variable changes were the material of the cylinder, the temperature of the nodes on the heat strips, and the length of the test. The test duration change was required because the higher temperature tests took longer to reach their final soak temperature. The submodel directory in Thermal Desktop made these changes very simple to complete between runs.

This simulation serves as a means to not only validate the tests being done in the chamber, but also to help predict future tests. Once the model is fully validated, analysis can be completed prior to experimental testing to determine if the tests will be safe to run for the satellite hardware. This will allow the testing process with this chamber to be more efficient and more effective as the proper temperatures can be reached for testing.

Chapter 5

RESULTS

The results for the six tests conducted and the comparison with the simulations completed for each will be discussed in this section. The tests for both the aluminum and brass cylinders attempted to be conducted at chamber temperatures of 40 °C, 60 °C, and 80 °C. The real final temperature of the chamber will be presented as well as a relationship that has been developed for the chamber and platen temperatures.

To meet the NASA GEVS standards, the soak must be maintained for at least four hours. The experiment was considered to be in the soak phase as soon as it passed the desired set point for the platen temperature.

5.1 40 °C Aluminum Test

With very little initial data as to the relationship of chamber temperature and platen temperature, an estimate had to be made to set the platen temperature for this test and the 40 °C brass test. Figure 5.1 shows the recorded test data for the physical experiment. The red line represents the cylinder temperature, the blue line represents the chamber temperature, and the green line is the platen temperature that was displayed on the side of the chamber. The error bars are required for the ± 1 °C error for the thermocouples attached to the cylinder and the chamber. The profile for the platen temperature was set so the platen would reach a final steady state of 52 °C. The error for the platen temperature displayed on the controller is ± 0.1 °C. The soak begins around 1,200 seconds when the platen temperature rises above the steady state temperature. As the controller works to bring the platen temperature back down, the chamber and cylinder also begin to display a steady state temperature,

though still slightly increasing.

Figure 5.1: Aluminum 40 °C Experimental Test

Thermal Desktop predicted a final cylinder temperature of 37.7 °C, which ended up being lower than the experimental temperature by 1.9 °C. Figure 5.2 shows the experimental cylinder temperature, in red, and the simulation cylinder temperature, in black. The two lines generally track each other throughout the course of the four hour and fifteen minute test, which is a good sign for the accuracy of the simulation. However, the discrepancy in temperature value could be caused by the simulation material properties or by the way the simulation completes the heating process. A difference in the emissivity value of the platen could alter the final temperature and the overall plot. The heating process was modelled to achieve a constant temperature across the platen, however, this would not be the case experimentally as there would be a temperature gradient from the heaters out to the edge of the platen. Finally, Figure 5.3 is an image of the heat map generated by Thermal Desktop. This image shows how important it is to have the Plexiglas underneath the test article. Without

that piece, the conduction directly from the platen would cause the final cylinder temperature increase dramatically.

Figure 5.2: Aluminum 40 °C Test vs Simulation: Cylinder Temperature

Figure 5.3: Aluminum 40 °C Simulation Heat Map

Table 5.1 is a summary of the important values from this test.

Table 5.1: 40 °C Aluminum Cylinder Test

Total Test Time (hh:mm)	Average Chamber Pressure (μ Torr)	Final Chamber Temp. (°C)	Final Platen Temp. (°C)	Final Cylinder Temp. (°C)	Final Sim- ulation Cylinder Temp.(°C)
4:15	42.27	38.0 $\pm$ 1	52 $\pm$ 0.1	39.6 $\pm$ 1	37.7

5.2 40 °C Brass Test

Regardless of the knowledge that the 40 °C aluminum test did not produce the desired chamber temperature, the same heating profile was run for this test so the re-

sults could be adequately compared. It was also desirable to observe the repeatability of the chamber performance from test to test.

Figure 5.4 shows the experimental results from this test. The platen temperature responded nearly identically to the first test, which is a good sign for the chamber performance. The final chamber temperature, however, reached a much higher temperature than the previous test by nearly 2 °C. There was an odd pressure spike that was not seen in any of the other tests in which the pressure inside the chamber reached over 200 μ Torr at its peak. For reference, the highest peak of any other test was 100 μ Torr. Even with the additional chamber temperature, the brass cylinder did not reach the same temperature as the aluminum cylinder. Although the cylinder is made of a different material, the black coating is the main driver for the cylinder temperature. The slight difference in final temperature for the two cylinders is a result of their internal specific heats. The plots for the chamber and cylinder temperature were noticeably less smooth for this test as well. The noticeable decline in the chamber temperature that occurred around 5000 seconds corresponded to a switch in thermocouple readers during the test. The two readers were not calibrated the same, therefore, the results were slightly different.

Figure 5.4: Brass 40 °C Experimental Test

Figures 5.5 and 5.6 show the results from the brass 40 °C simulation. The simulation line tracked the experimental line extremely well at the beginning of the test until the cylinder continued to a higher steady state near the end. The final temperatures for the simulation and the experimental test were off by 1 °C. Again, the slight dip in temperature can be more clearly seen at 5000 seconds when the reader was switched. The difference in final temperature is likely due to a higher than expected chamber temperature. This is the third time a test has been run at this temperature during the course of this thesis due to a necessary rerun, and it is a clear outlier in final chamber temperature. The platen and chamber temperature relationship plot in Section 5.9 shows the three chamber temperature data points at the 52 °C platen temperature. The heat map is very similar to that of the aluminum test with the platen in the red temperature range and the cylinder thermally isolated by the Plexiglas.

Figure 5.5: Brass 40 °C Test vs Simulation: Cylinder Temperature

Figure 5.6: Brass 40 °C Simulation Heat Map

Table 5.2 is a summary of the important values from this test.

Table 5.2: 40 °C Brass Cylinder Test

Total Test Time (hh:mm)	Average Chamber Pressure (μ Torr)	Final Chamber Temp. (°C)	Final Platen Temp. (°C)	Final Cylinder Temp. (°C)	Final Sim- ulation Cylinder Temp.(°C)
4:20	68.6	39.8 $\pm$ 1	52 $\pm$ 0.1	38.6 $\pm$ 1	37.6

5.3 60 °C Aluminum Test

In the 40 °C tests, the platen temperature was set 12 °C above the desired chamber temperature. Since the desired temperature was not reached, a margin of 20 °C between the chamber and platen temperature was applied for the 60 °C tests.

Figure 5.7 shows the platen temperature, in green, settling at a steady state of 80 °C. Even with the additional margin, the chamber temperature, in blue, was unable to reach 60 °C. This is helpful information because it shows that the relationship between the two temperatures is not exactly linear. In order to reach a chamber temperature of 60 °C, based on the relationship that was created from testing, the platen temperature would have to be set around 90 °C. The final chamber temperature for this test was 54.9 $\pm$ 1 °C, which resulted in a cylinder temperature of 56.2 $\pm$ 1 °C.

Figure 5.7: Aluminum 60 °C Experimental Test

The simulation predicted a slightly lower temperature than was experimentally produced, but still within the error bounds of the thermocouple error. Figure 5.8 shows the two curves with the same general trend in the beginning of the test with a sharp increase as the chamber heats up. However, as the platen reaches a steady state, the experimental test continues at a steeper slope than the simulation. This is the result, once again, of the heating process in the simulation. The simulation heating process is much less gradual compared to the experimental test. Therefore, the simulation reaches its steady state long before the experimental temperature. The final 1800 seconds of the experimental test shows a steady state being achieved allowing the final temperatures to be compared. The heat map for this test is shown in Figure 5.9. The shroud begins to play a larger role as more heat is trapped and radiated back towards the test article.

Figure 5.8: Aluminum 60 °C Test vs Simulation: Cylinder Temperature

Figure 5.9: Aluminum 60 °C Simulation Heat Map

Table 5.3 is a summary of the important values from this test.

Table 5.3: 60 °C Aluminum Cylinder Test

Total Test Time (hh:mm)	Average Chamber Pressure (μ Torr)	Final Chamber Temp. (°C)	Final Platen Temp. (°C)	Final Cylinder Temp. (°C)	Final Sim- ulation Cylinder Temp.(°C)
4:40	46.92	54.9 $\pm$ 1	80 $\pm$ 0.1	56.2 $\pm$ 1	55.3

5.4 60 °C Brass Test

The platen profile was again set to 80 °C to see if the repeatability of the chamber improved, worsened, or stayed the same as the temperature increased. The tests also had the same run time, so the final chamber temperatures should, ideally, have come out the same. Unfortunately, this was not the case. The final chamber temperature for this test was 53.5 $\pm$ 1 °C as compared to the 54.9 $\pm$ 1 °C final chamber temperature recorded in the 60 °C aluminum test. Just like the 40 °C tests, the brass cylinder did not reach the same temperature as the aluminum cylinder due to the fact that the final chamber temperature was lower and given its internal properties. The graph of this data can be seen below in Figure 5.10.

Figure 5.10: Brass 60 °C Experimental Test

Figure 5.11 shows that the simulation data did produce a resulting temperature within four tenths of a degree of the experimental temperature, which is very accurate for test modelling. The simulation, again, reached the steady state much faster than the experiment, but the slope of the two lines in steady state appear to be nearly the same. Due to the slightly higher chamber pressure, the chamber temperature did not reach the same final temperature as the aluminum 60 °C test. This resulted in a slightly lower cylinder temperature that corresponded with the simulation well. The heat map created by the simulation is shown in Figure 5.12.

Figure 5.11: Brass 60 °C Test vs Simulation: Cylinder Temperature

Figure 5.12: Brass 60 °C Simulation Heat Map

Table 5.4 is a summary of the important values from this test.

Table 5.4: 60 °C Brass Cylinder Test

Total Test Time (hh:mm)	Average Chamber Pressure (μ Torr)	Final Chamber Temp. (°C)	Final Platen Temp. (°C)	Final Cylinder Temp. (°C)	Final Sim- ulation Cylinder Temp.(°C)
4:40	56.88	53.5 $\pm$ 1	80 $\pm$ 0.1	54.8 $\pm$ 1	55.2

5.5 80 °C Aluminum Test

The final two tests to take place attempted to reach a final chamber temperature of 80 °C. Using data from the previous tests, the simulation was run to determine what platen temperature would be required to meet the desired chamber temperature. Unfortunately, the required platen temperature was above the "Hot Limit" that is set on the chamber. The chamber has a "Hot Limit" and "Cold Limit" display on the control panel that each have separate thermocouples attributed to them. These controllers turn off heating or cooling capabilities for the chamber if the set point is at or above the limit. It is possible that the limits could be reprogrammed to different boundaries, however, to minimize risk in harming the chamber, this route was not taken. The hot limit that is currently set on the chamber is 115 °C. Therefore, the platen profile was set to reach a steady state of 115 °C, which would provide the maximum chamber temperature possible. It was discovered that the hot limit is exceeded when the platen attempts to remain at that limit. Triggering the hot limit results in the chamber turning off the heat strips and decreasing the temperature of the platen, as seen in Figure 5.13. The profile was quickly reprogrammed to a set point of 114 °C and restarted in the ramp rate phase. The platen temperature promptly reached a steady state and the test continued as planned.

Figure 5.13: Aluminum 80 °C Experimental Test

It is not certain how large of an effect the temperature decline had on the final temperature of the cylinder and the chamber. The simulation, presented in Figure 5.14, predicted the temperature of the cylinder to be slightly higher, so it is possible that there was a noticeable effect. The final simulation cylinder temperature was outside of the error bounds for the experimental temperature by 0.03 °C. At higher temperatures, the simulation does not track the initial temperature increase for the experiment. The slopes of the two lines are similar, however, the simulation temperature is less gradual at the beginning of the test. The heat map for this test is shown in Figure 5.15. By collecting more heat, the shroud plays a larger role in the final chamber and cylinder temperatures.

Figure 5.14: Aluminum 80 °C Test vs Simulation: Cylinder Temperature

Figure 5.15: Aluminum 80 °C Simulation Heat Map

Table 5.5 is a summary of the important values from this test.

Table 5.5: 80 °C Aluminum Cylinder Test

Total Test Time (hh:mm)	Average Chamber Pressure (μ Torr)	Final Chamber Temp. (°C)	Final Platen Temp. (°C)	Final Cylinder Temp. (°C)	Final Sim- ulation Cylinder Temp.(°C)
5:15	54.71	74.4 $\pm$ 1	114 $\pm$ 0.1	77.6 $\pm$ 1	78.63

5.6 80 °C Brass Test

With more knowledge about how the hot limit works, this profile was run to a platen temperature of 114 °C, the same as the reprogrammed profile from the 80 °C aluminum test. This test was the first time the platen temperature did not settle right at the set point when steady state was first achieved. After the PID controller kicked in as it normally does, the temperature was brought back down to 113 °C for over two hours of the four hour soak. It was not until this point that the platen did ultimately achieve the set point temperature of 114 °C. By observing the data in Figure 5.4, it does not appear that there were any major effects on the final temperatures of the chamber and the cylinder. In fact, the brass cylinder for this test reached a higher final temperature, at 79.2 $\pm$ 1 °C, than the aluminum cylinder.

Figure 5.16: Brass 80 °C Experimental Test

The simulation, shown in Figure 5.17, predicted a slightly lower final temperature for the brass cylinder but stayed within the error bounds. As in the aluminum simulation for this test profile, the simulation does not ascend gradually like the experiment does, but reaches the same end point. Of all of the simulation versus experimental plots, this was the closest one in terms of the overlap of the two lines. As the platen profile temperature was increased, the simulation was more accurate. It is not clear at this point why the lower temperature simulations do not correspond as well as the higher temperature simulations. This is definitely something that will need to be investigated further to create a higher fidelity model of the chamber. The heat map in Figure 5.18 also produced similar results to the 80 °C aluminum simulation.

Figure 5.17: Brass 80 °C Test vs Simulation: Cylinder Temperature

Figure 5.18: Brass 80 °C Simulation Heat Map

Table 5.6 is a summary of the important values from this test.

Table 5.6: 80 °C Brass Cylinder Test

Total Test Time (hh:mm)	Average Chamber Pressure (μ Torr)	Final Chamber Temp. (°C)	Final Platen Temp. (°C)	Final Cylinder Temp. (°C)	Final Sim- ulation Cylinder Temp.(°C)
5:10	49.56	75.2 $\pm$ 1	114 $\pm$ 0.1	79.2 $\pm$ 1	78.58

5.7 Chamber Pressure-Temperature Correlation

While looking through the data for all experiments, the tests that were conducted with lower average chamber pressures ultimately reached higher temperatures for both the cylinder and the chamber, with the exception of the chamber temperature in the brass 40 °C test . This result is not surprising as radiation is far more effective with fewer air particles in the chamber. Should this testing be repeated in the future, more emphasis on ensuring similar chamber pressures should be present.

5.8 Plexigals Thermal Isolation

For the lower temperature tests, the Plexigals plate did a fairly good job of isolating the cylinder from the platen temperature due to its low conductivity. However, as the platen was increased to higher temperatures, the Plexigals plate was not as effective. Looking at the heat maps of the higher temperature simulation models, it was clear that the Plexiglas was reaching higher temperatures than expected and imparting some of that heat to the test cylinder through conduction. The extra heat load on the cylinder caused it to reach higher a higher temperature than the chamber in most tests.

5.9 Platen-Chamber Temperature Relationship

As mentioned in the previous section, the relationship between the platen temperature and resulting chamber temperature is not perfectly linear. Figure 5.19 shows that relationship based on all of the data points collected from testing. The first data point shown at 40 °C for the platen temperature was found in initial testing when it was unclear what the temperature the control panel was displaying. Over time, as more data is collected, the best fit line for this plot will become more accurate.

Figure 5.19: Chamber and Platen Temperature Relationship

Chapter 6

CONCLUSION

Successful tests were completed to prove the heating capabilities and repeatability of the chamber. Three heating profiles were programmed into the chamber controller to test a variety of data points. For each of the profiles, two tests were run with different test articles. The two test articles are small black coated cylinders made of aluminum and brass. The black coating resulted in similar cylinder temperature results for each test of the same profile with slight variations due to the thermal properties of the cylinder. The largest difference between the two cylinder temperatures was 2.2 ± 2 °C, which occurred during the 80 °C heating profile. A relationship, based on minimal data, was plotted between the programmed platen temperature and the chamber temperature. This will allow future testing to be more accurate and conducted at the appropriate temperature.

A simulation was created in Thermal Desktop to model the heating profiles and the response each cylinder would have based on the material type. The cylinder temperature data was recorded from the simulation and plotted against the experimental results. A majority of the time, the simulation was accurate and within the error bounds of the thermocouple. When the predicted temperature from the simulation was outside of those bounds, it was never by more than 0.9 °C.

Throughout the course of the refurbishment and testing process, the chamber performed very well. There was no breakdown of major parts or testing equipment that required long downtime or extensive repairs. Compared to the HVEC TVAC, the blue chamber is much more straightforward to operate from a procedure and maintenance standpoint. There are not nearly as many problems with the blue chamber that will cause testing to be delayed. The robustness of this chamber allows it to easily be

incorporated into undergraduate learning opportunities as well as graduate research and even small satellite or satellite component testing.

Chapter 7

FUTURE WORK

Though much work has been done to refurbish the chamber, there is still a lot left to do.

7.1 Cooling System

The most important work that needs to be done is getting the cooling system up and running. The internal plumbing for the chamber looks to be in good shape, but additional hoses will need to be attached to the chamber inlet and outlet. There has been some discussion about where the LN_2 will be stored and where it will vent after passing through the chamber, but no decision has been made quite yet. LN_2 is safe enough to store and vent inside the lab if there is proper air conditioning running. At this point, since the lab does not have air conditioning, Cal Poly risk management will likely want the LN_2 stored outside and vented outside after passing through the chamber. If this is the case, hoses that are long enough to reach the chamber from the door of the lab will be required. Also, after speaking with Dave Pignatelli from Cal Poly CubeSat, it was recommended that external venting be done to the roof of the lab. This would require Cal Poly Facilities Services to get involved so that might need to get started right away. Just in case the chamber has to move around the lab, it would be ideal to have the vent to the roof be fixed and have an attachable hose to the chamber instead of fixing the chamber in one spot. The cooling system is required to run full cycle testing, the main purpose of the chamber.

After heating the chamber up and transitioning to the cold section of the profile, there will be a lot of heating energy stored in both the platen and the shroud. This

energy must be dissipated in order to reach the cold temperatures that are desired. One way to accomplish this task is to paint the inside of the shroud as well as the platen with black paint. This will cause the hot energy to radiate much faster and the cooling system will be more effective. To supplement the black paint, wrapping the outside of the shroud will aide the heating and cooling process.

7.2 Switch Controlled Venting System

When the testing procedure is complete and the chamber has returned to nominal temperatures, the venting valve can be opened to bring the chamber back to atmospheric pressures. The current valve on the chamber is controlled by manually turning the venting valve to open and close it. Since everything internal to the chamber has continued to work properly, the only reason the side panels are not on the chamber, is to have access to that valve. By implementing a venting valve that can be controlled by a switch on the control panel, it will make the chamber much simpler for students to run.

7.3 DAQ System

Lauren Glenn put together a DAQ system as part of her thesis. The system is able to take outputs from thermocouples and feed them to the computer in the lab. The thermocouple wires from the HVEC vacuum chamber are inserted directly into an electronics board. This same layout can be applied directly to the blue chamber. Instead of connecting the double male thermocouple wire that connects the blue chamber to the thermocouple reader, a single male wire can be connected to the board, and thus the computer. This will allow more accurate data to be obtained and the tester will not be required to record measurements at every time interval.

7.4 Refine Thermal Desktop Model

The model in Thermal Desktop does a good job of predicting the final temperature of the cylinder, but it can still become more accurate. The simulation does not quite track the data as it increases in temperature, so there is room for improvement there. This is likely the result of how the model had to be created. Experience in AutoCad modelling was very minimal, so the platen had to be modelled as seven separate blocks instead of one block with extrusions. Fixing the platen model should allow higher accuracy simulations. The heat strips in the simulation are blocks with very high specific heat and boundary nodes that allow the temperature of the block to be set. If there is a way to make the blocks heaters, this could improve accuracy as well. The simulation has not been run on cold cases, therefore its response to decreasing temperature is unknown. The cold cases would also require full thermal cycling to verify the simulation results. Finally, a heat map that includes all parts of the testing system, including the electrical wires, will provide more accurate results because it is likely that even the wires can affect the final outcome of the test.

7.5 Platen Temperature Gradient

In this thesis, the platen temperature was assumed to be constant across the whole surface to simplify the simulation model. This is not quite accurate as the platen should be hotter closer to the heat strips. Measuring the platen temperature at different points across the face will provide a deeper insight into how the chamber heats up and how the simulation should be altered.

7.6 Turbo Pump

After using the turbo pump and turning it off, the mechanical pump is required to run until the user can be sure the turbo has stopped spinning. This can take anywhere from 15-20 minutes to complete. Currently, there is no way to tell what the RPMs of the turbo pump are, but a display could be installed to show how fast it is moving. This is another addition that would increase the safe and responsible use by students.

Additional safeguards can be installed to cut the power to the turbo pump should anything unexpected happen. This way, if there is a leak, for example, the turbo pump will automatically turn off if the pressure gets too high and is not being monitored by the user.

7.7 Thermocouples

The chamber controller is designed to display the temperature of the platen. It could be possible that another thermocouple could be attached and displayed by the controller. This would need further investigation to see if this is possible. Furthermore, the controller manual shows that there is a 0.1 °C error on what is displayed. There may be an additional error on the thermocouple wire itself as well, but that is still unknown.

There are smaller thermocouple wires that exist and can provide more accurate data for the user. The larger wires take longer to heat and cool and can alter the results of the test.

7.8 Chamber Shroud

More investigation into the shroud temperature profile is required as well. The simulation produced temperature results for the shroud shown in Appendix E. The higher temperature tests caused the shroud to get hotter and radiate more heat to the cylinder. Whether there is conduction between the platen and the shroud could have a significant impact on testing. The view factor between the test article, the platen, and the shroud can also be looked at in order to have a better understanding of the effect of the shroud.

7.9 Test Setup

For the higher temperature tests, the Plexiglas plate was not as effective for thermally isolating the test article. A test stand that is isolated from the platen won't allow conduction to take place and better simulate the space environment. Based on the dimensions of the test section, a test stand should be acquired for the chamber.

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APPENDICES

Appendix A

CHAMBER OPERATING PROCEDURE

Operation of this chamber is very straightforward. The steps have been outlined below.

Mechanical Pump Operation

1. Ensure the chamber is plugged into the outlet on the wall.
2. Flip the main power switch "ON"
3. With the door and venting valve closed, flip the mechanical pump switch up to turn it on
4. To turn it off, flip the mechanical switch down
5. Open the vent valve to return the chamber to atmospheric pressure
6. Turn off the chamber

Turbo Pump Operation

1. Follow steps 1-3 in Mechanical Pump Operation to turn on the mechanical pump.
2. After the chamber has reached 20 mTorr or lower, press the start button on the Turbotronik NT 20 control panel
3. To turn off the turbo, press the stop button

4. Wait 15-20 minutes before turning off the mechanical pump and following steps 4-6 in the Mechanical Pump Operation

Convectron Gauge Controller

1. Ensure the chamber is plugged into the outlet on the wall.
2. Flip the main power switch "ON"
3. Press the "ON" button on the Granville-Phillips 307 Vacuum Gauge Controller
 - This will immediately show the pressure for the chamber and roughing line
4. Press the "ON" button again to turn the controller off

Ion Gauge Controller

1. Follow steps 1-3 in the Convectron Gauge Controller procedure
2. ONLY when the chamber convectron gauge readout shows all zeros after the turbo has been activated, press the "IG1" button to activate the ion gauge
 - The ion gauge should light up
3. BEFORE turning off the turbo pump, press "IG1" again to turn off the ion gauge
4. Press the "ON" button again to turn the controller off

Appendix B

CHAMBER PROFILES

The chamber arrived with profiles already programmed into the controller. These profiles were the first ones used to test the heating capabilities of the chamber. For the experimental testing, profiles were manually designed using the profiles in the chamber as reference.

The heating profiles for the experiments consisted of only three steps: Ramp Rate, Soak, and End. The following procedure requires on that the main power of the chamber be turned on. The control panel will take a second to turn on, and the chamber controller will show the "Main Page." Follow the steps below to create and run a profile. One important note: to go back to a previous prompt or page, hit the Left Arrow button.

Creating a Profile

1. Turn on the "MAIN POWER" switch
2. Use the Down Arrow button and scroll down to "Go To Profiles", then press the Right Arrow button
 - This is the main profile page where profiles can be created, edited, or deleted.
3. Select the Right Arrow on "Create Profile"
4. A prompt will come up saying "Choose to Name", scroll down and press the Right Arrow on "Yes"
5. Use the Up and Down Arrows to adjust the characters and the Right and Left Arrows to switch between characters.

- Keep pressing the Right Arrow when naming is complete until the next page comes up
6. This page is where the first step of the profile is chosen. Autostart has not been tested as the date and time in the chamber would need to be reprogrammed. Choose either "Ramp Rate" or "Ramp Time" for the first step and press the Right Arrow.
 - Ramp Rate was used for all of the experiments in this thesis and no issues arose, so that would be the recommended option and the one used in this procedure
 7. The next prompt asks whether the step should wait for a specific event or not, choose "Step does not wait" and press the Right Arrow button
 8. Enter a Ramp Rate of 5 °C/minute and press the Right Arrow button
 - 5 °C/minute was used for all of the experiments, a different ramp rate can be used if desired
 - The chamber did not heat up at exactly 5 °C/minute, but that value made the heat strips operate at 100%
 9. Enter the set point that desired for the final PLATEN TEMPERATURE and press the Right Arrow button
 10. Choose PID Set 1 and press the Right Arrow Button
 11. A prompt will come up to "Choose Guar. Soak 1", select "Yes" and press the Right Arrow button
 12. The next step can be established in the same manner following the prompts on screen. The experiments in this thesis used "Soak" as step number 2.

13. When all desired steps have been input, select the last step as "End" and press the Right Arrow button and then select "All Off" and press the Right Arrow button again
14. Hit the Left Arrow Button and then make sure to "Save" the profile with the Up Arrow Button
 - The Down Arrow button allows all changes to be cancelled and the previous profiles restored

The profile has now been created and can be run using the following procedure.

Running a Profile

1. Turn on the "MAIN POWER" switch
2. On the bottom left side of the controller, there is a green profile button, press that button
3. Press the Up Arrow button to select "Yes" to start a profile
4. Scroll down to the desired profile and press the Right Arrow button
5. Select the step in the profile at which the controller should begin (Usually step 1)
6. The selected profile is now running
 - For HEATING profiles, flip the "Hot" baseplate switch ON (located underneath the controller)
 - For COOLING profiles, flip the "Cold" baseplate switch ON (located underneath the controller)
7. The profile will run to its completion unless stopped manually

- To stop a profile manually, press the green profile button again, select "Terminate", and hit the Right Arrow button
8. Flip the operational baseplate switch off when the profile is terminated

Appendix C

CHAMBER PRESSURES DURING TESTING

The chamber pressure plots for each of the six tests as well as a table for the chamber pump down time are shown below for reference. All values in the plots are in μTorr .

C.1 Aluminum 40 °C Test

Figure C.1: Aluminum 40 °C Chamber Pressure

C.2 Brass 40 °C Test

Figure C.2: Brass 40 °C Chamber Pressure

C.3 Aluminum 60 °C Test

Figure C.3: Aluminum 60 °C Chamber Pressure

C.4 Brass 60 °C Test

Figure C.4: Brass 60 °C Chamber Pressure

C.5 Aluminum 80 °C Test

Figure C.5: Aluminum 80 °C Chamber Pressure

C.6 Brass 80 °C Test

Figure C.6: Brass 80 °C Chamber Pressure

C.7 Chamber Pump Down

The table below shows the pressure of the chamber as it pumps down. The turbo pump was activated at the 4 hour mark. Pressure readings were recorded when possible so the tester should have an idea of what the order of magnitude of the pressure should be. The chamber has been seen reaching a pressure of 10 μTorr , however it did not accomplish that during this test.

Table C.1: Chamber Pump Down Pressure vs. Time

Time (hr:min)	Chamber Pressure (Torr)
0:00	7.6×10^2
1:00	2.1×10^{-2}
2:00	1.5×10^{-2}
3:00	1.2×10^{-2}
4:00	1.0×10^{-2}
7:00	4.9×10^{-5}
23:00	2.5×10^{-5}
32:00	2.2×10^{-5}

Appendix D

CHAMBER TROUBLESHOOTING

This appendix serves as a quick guide to fix any small issues that occur while working with the chamber.

In the event that the mechanical pump does not start, the first place that should be checked is the electrical panel. There is a small electrical safety switch that has to be engaged before the mechanical pump will start. When that switch is engaged, there is a noticeable pressure difference on the main power switch when turning on the chamber. Cody helped fix this issue the first time and it has not happened again during any of the testing that was completed.

If the profile on the controller is set to reach a steady state at or above the hot limit, the controller will turn off. The hot limit can be reprogrammed if a higher temperature is desired. The same is true if the cold limit is exceeded by a lower steady state temperature.

These were the only two issues that were discovered that can be fixed by the user.

Appendix E

CHAMBER SHROUD TEMPERATURE PROFILES

The following plots display the temperature data for the shroud from the simulation only. No experimental data was collected.

Figure E.1: Aluminum 40 ° Simulation Shroud Temperature

Figure E.2: Brass 40 ° Simulation Shroud Temperature

Figure E.3: Aluminum 60 ° Simulation Shroud Temperature

Figure E.4: Brass 60 ° Simulation Shroud Temperature

Figure E.5: Aluminum 80 ° Simulation Shroud Temperature

Figure E.6: Brass 80 ° Simulation Shroud Temperature

Appendix F

EXPERIMENTAL DATA

Table of Contents

Experimental Data	1
40 deg C AL Test	1
40 deg C Brass Test	3
60 deg C AL Test	4
60 deg C Brass Test	6
80 deg C AL Test	8
80 deg C Brass Test	9

Experimental Data

```
% The variables used in each test are identical.
%
% t = Time of Measurement (listed in minutes and converted to seconds)
% chpr = Chamber Pressure in microTorr
% chtemp = Chamber Temperature (read from thermocouple reader)
% cyltemp = Cylinder Temperature (read from thermocouple reader)
% plttemp = Platen Temperature (Read from chamber control panel)
% err = variable used for error bar function
% tsim = Time Output from the simulation (seconds)
% cylsim = Simulation Cylinder Temperature (output in Kelvin,
    converted to
% Celsius)
```

40 deg C AL Test

```
clear
close all
clc

t = [0 5 10 15 20 25 30 45 60 75 90 105 120 135 150 165 180 195 210
    225 ...
    240 255]*60; % seconds

chpr = [30 48 51 57 54 42 39 40 41 40 41 41 41 41 41 41 40 40 41 40
    40]; % microTorr

chtemp = [26.4 25.4 27.2 29.5 33.5 35.0 35.3 36.9 36.9 36.5 36.6
    36.7 ...
    36.9 37.2 37.2 37.4 37.5 37.7 37.8 37.9 38.0 38.0]; % Celsius

cyltemp = [26.2 25.1 26.0 27.7 30.5 31.7 32.4 35.2 35.7 36.7 37.4 ...
    37.6 38.1 38.4 38.6 38.7 38.9 38.9 39.2 39.4 39.5 39.6]; % Celsius

plttemp = [25 30 36 44 53 56 56 55 54 53 52 52 52 52 52 52 52 52 52
    52 ...
    52 52]; % Celsius
```

```

err = 1*ones(size(t));

figure
plot(t,chpr,'LineWidth',2)
xlabel('Time (seconds)')
ylabel('Pressure (\muTorr)')

figure
hold on
errorbar(t,chttemp,err,'LineWidth',2)
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(t,plttemp,'g','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Chamber Temperature','Cylinder Temperature','Platen
Temperature','Location','SouthEast')
hold off

tsim = [0 156 312 468 624 780 936 1092 1248 1404 1560 1716 ...
1872 2028 2184 2340 2496 2652 2808 2964 3120 ...
3276 3432 3588 3744 3900 4056 4212 4368 4524 ...
4680 4836 4992 5148 5304 5460 5616 5772 5928 ...
6084 6240 6396 6552 6708 6864 7020 7176 7332 ...
7488 7644 7800 7956 8112 8268 8424 8580 8736 ...
8892 9048 9204 9360 9516 9672 9828 9984 10140 ...
10296 10452 10608 10764 10920 11076 11232 11388 11544 ...
11700 11856 12012 12168 12324 12480 12636 12792 12948 ...
13104 13260 13416 13572 13728 13884 14040 14196 14352 ...
14508 14664 14820 14976 15132 15288 15444 15600];
cylsim = [293.15 294.1375738 295.3351625 296.4548722 297.4944411 ...
298.4588123 299.3529814 300.1816175 300.9490876 301.6595858
302.3170549 ...
302.9252354 303.4876378 304.0075716 304.4881326 304.9322268
305.3425639 ...
305.721679 306.0719285 306.3955123 306.6944693 306.9706984
307.2259561 ...
307.4618754 307.6799637 307.8816209 308.0681366 308.2407069
308.4004324 ...
308.548333 308.6853455 308.8123379 308.9301063 309.0393879
309.1408582 ...
309.2351426 309.3228133 309.4044003 309.4803878 309.5512244
309.6173196 ...
309.6790527 309.7367696 309.7907911 309.8414091 309.8888946
309.9334939 ...
309.9754358 310.0149282 310.0521641 310.0873188 310.1205553
310.1520212 ...
310.1818542 310.2101786 310.2371106 310.262755 310.2872098
310.3105633 ...
310.3328984 310.3542893 310.374806 310.3945111 310.4134638
310.4317167 ...
310.4493198 310.4663176 310.4827523 310.4986614 310.5140807
310.5290417 ...
310.5435748 310.5577066 310.5714629 310.584866 310.5979379
310.6106976 ...

```

```

310.6926303 310.7034374 310.7140526 310.7244841 310.7347406
310.7448291 ...
310.7547569 310.76453 310.774155 310.7836368 310.7929811
310.8021922 ...
310.8112751 310.8202336 310.8290718 310.8377931 310.8464012
310.854899]-273.15;

```

```

figure
hold on
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(tsim,cylsim,'k','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Experimental Temperature','Simulation
Temperature','Location','SouthEast')
hold off

```

40 deg C Brass Test RERUN

```

clear
close all
clc

t = [0 5 10 15 20 25 30 45 60 75 90 105 120 135 150 165 180 195 210
225 ...
240 255 260]*60; % seconds

chpr = [35 210 150 120 100 68 55 51 53 54 54 54 54 54 53 53 52 52
51 ...
51 50 50]; % microTorr

chtemp = [22.8 23.8 26.1 29.3 32.8 36.0 37.5 38.8 39.1 39.2 38.2
38.4 ...
38.6 38.8 39.0 39.1 39.3 39.4 39.5 39.6 39.6 39.7 39.8]; % Celsius

cyltemp = [23.1 23.4 24.1 25.2 26.5 28.1 29.1 31.5 33.5 34.9 34.8
35.6 ...
36.1 36.7 37.1 37.6 37.8 38.1 38.1 38.4 38.4 38.6 38.6]; % Celsius

plttemp = [21 25 32 40 48 55 56 55 54 53 52 52 52 52 52 52 52 52
52 ...
52 52 52]; % Celsius

err = 1*ones(size(t));
errpl = 0.1*ones(size(t));

figure
plot(t,chpr,'LineWidth',2)
xlabel('Time (seconds)')
ylabel('Pressure (\muTorr)')

figure
hold on

```

```

errorbar(t, chtemp, err, 'LineWidth', 2)
errorbar(t, cyltemp, err, 'r', 'LineWidth', 2)
errorbar(t, plttemp, errpl, 'g', 'LineWidth', 2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Chamber Temperature', 'Cylinder Temperature', 'Platen
Temperature', 'Location', 'SouthEast')
hold off

tsim = [0 156 312 468 624 780 936 1092 1248 1404 1560 1716 1872 2028
2184 2340 2496 2652 2808 2964 3120 3276 3432 3588 3744 3900 4056 4212
4368 4524 4680 4836 4992 5148 5304 5460 5616 5772 5928 6084 6240 6396
6552 6708 6864 7020 7176 7332 7488 7644 7800 7956 8112 8268 8424 8580
8736 8892 9048 9204 9360 9516 9672 9828 9984 10140 10296 10452 10608
10764 10920 11076 11232 11388 11544 11700 11856 12012 12168 12324
12480 12636 12792 12948 13104 13260 13416 13572 13728 13884 14040
14196 14352 14508 14664 14820 14976 15132 15288 15444 15600];
cylsim = [293.15 293.9186611 294.8640487 295.7632354 296.6128319
297.4151337 298.1725683 298.8873795 299.5617289 300.1977032
300.7973097 301.3624761 301.8950514 302.3968051 302.8694296
303.3145397 303.7336757 304.1283036 304.4998187 304.849546
305.1787417 305.4886016 305.7802561 306.0547755 306.3131725
306.5564043 306.7853755 307.0009399 307.2039032 307.3950257
307.5750238 307.7445724 307.9043073 308.0548267 308.1966938
308.3304382 308.456558 308.5755214 308.6877683 308.7937121
308.8937411 308.9882198 309.0774905 309.1618743 309.2416728
309.3171687 309.3886275 309.4562979 309.5204133 309.5811926
309.6388409 309.6935506 309.7455018 309.7948636 309.8417944
309.8864425 309.9289469 309.9694379 310.0080377 310.0448605
310.0800134 310.1135969 310.145705 310.1764257 310.2058414
310.2340296 310.2610625 310.287008 310.3119296 310.3358868
310.3589353 310.3811273 310.4025118 310.4231346 310.4430385
310.462264 310.4808486 310.4988276 310.5162342 310.5330994
310.5494524 310.5653202 310.5807286 310.5957015 310.6102613
310.6244292 310.6382249 310.6516669 310.6647728 310.6775587
310.6900401 310.7022314 310.714146 310.7257967 310.7371954
310.7483533 310.759281 310.7699883 310.7804847 310.7907788
310.8008789]-273.15;

figure
hold on
errorbar(t, cyltemp, err, 'r', 'LineWidth', 2)
plot(tsim, cylsim, 'k', 'LineWidth', 2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Experimental Temperature', 'Simulation
Temperature', 'Location', 'SouthEast')
hold off

```

60 deg C AL Test

```

clear
close all

```

```

clc

t = [0 5 10 15 20 25 30 35 40 45 60 75 90 105 120 135 150 165 180 195
    210 225 ...
    240 255 270 280]*60; % seconds

chpr = [34 50 46 46 49 53 57 62 56 44 41 42 44 45 46 46 46 47 46 ...
    46 46 46 46 46 45 45]; % microTorr

chtemp = [24.5 25.2 27.2 29.8 32.6 35.9 39.3 42.7 46.2 48.4 50.1
    50.5...
    51.4 52.1 52.7 53.1 53.4 53.6 53.9 54.2 54.4 54.5 54.7 54.8 55.0
    54.9]; % Celsius

cyltemp = [24.8 25.2 26.1 27.7 29.4 31.5 33.8 36.0 39.0 40.9 44.8 ...
    47.3 49.6 51.2 52.4 53.3 54.0 54.4 54.8 55.2 55.5 55.7 55.9 ...
    56.1 56.1 56.2]; % Celsius

plttemp = [24 28 35 44 51 60 69 74 82 84 82 80 80 80 80 80 80 80
    80 ...
    80 80 80 80 80 80 80]; % Celsius

err = 1*ones(size(t));

figure
plot(t,chpr,'LineWidth',2)
xlabel('Time (seconds)')
ylabel('Pressure (\muTorr)')

figure
hold on
errorbar(t,chtemp,err,'LineWidth',2)
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(t,plttemp,'g','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Chamber Temperature','Cylinder Temperature','Platen
    Temperature','Location','SouthEast')
hold off

tsim = [0 168 336 504 672 840 1008 1176 1344 1512 1680 1848 2016 2184
    2352 2520 2688 2856 3024 3192 3360 3528 3696 3864 4032 4200 4368 4536
    4704 4872 5040 5208 5376 5544 5712 5880 6048 6216 6384 6552 6720 6888
    7056 7224 7392 7560 7728 7896 8064 8232 8400 8568 8736 8904 9072 9240
    9408 9576 9744 9912 10080 10248 10416 10584 10752 10920 11088 11256
    11424 11592 11760 11928 12096 12264 12432 12600 12768 12936 13104
    13272 13440 13608 13776 13944 14112 14280 14448 14616 14784 14952
    15120 15288 15456 15624 15792 15960 16128 16296 16464 16632 16800];
cylsim = [293.15 295.4502654 298.2138496 300.7735628 303.1276745
    305.2882378 307.2687985 309.0815659 310.7382623 312.2503787
    313.6288815 314.8842806 316.0265124 317.064964 318.0084251
    318.8651153 319.6426666 320.3481608 320.9881274 321.5685882
    322.0950641 322.5726214 323.0058836 323.3990769 323.7560435

```

```

324.0802845 324.3749727 324.6429926 324.886951 325.1092135
325.3119131 325.4969827 325.6661619 325.8210254 325.9629882
326.0933301 326.2131992 326.3236339 326.4255642 326.5198312
326.6071872 326.6883125 326.7638151 326.8342448 326.9000923
326.9618018 327.0197691 327.0743526 327.1258715 327.1746152
327.2208408 327.2647818 327.3066453 327.3466199 327.3848723
327.4215549 327.4568019 327.4907364 327.5234667 327.5550921
327.5856999 327.6153706 327.6441747 327.6721773 327.6994353
327.7260016 327.7519222 327.7772402 327.8019928 327.8262157
327.8499388 327.8731905 327.8959956 327.9183775 327.9403565
327.961952 327.9831806 328.0040584 328.0245995 328.0448169 328.064722
328.0843261 328.1036386 328.1226694 328.1414261 328.1599173
328.1781494 328.1961299 328.2138644 328.2313592 328.2486192 328.26565
328.282456 328.2990422 328.3154123 328.3315709 328.3475215 328.363268
328.3788136 328.3941621 328.4093164]-273.15;

```

```

figure
hold on
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(tsim,cylsim,'k','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Experimental Temperature','Simulation
Temperature','Location','SouthEast')
hold off

```

60 deg C Brass Test

```

clear
close all
clc

t = [0 5 10 15 20 25 30 35 40 45 60 75 90 105 120 135 150 165 180 195
210 225 ...
240 255 270 280]*60; % seconds

chpr = [25 100 71 63 61 62 63 66 72 54 51 53 55 56 56 56 55 54 54 53
52 ...
51 50 49 49 48]; % microTorr

chtemp = [21.9 22.3 24.2 26.7 29.7 32.5 35.8 39.4 43.3 46.2 48.4
48.9 ...
49.8 50.5 50.9 51.4 51.8 52.1 52.4 52.6 52.9 53.1 53.2 53.3 ...
53.4 53.5]; % Celsius

cyltemp = [22.1 22.4 23.3 24.6 26.1 27.9 29.8 32.2 34.8 37.1 41.2 ...
44.0 46.6 48.4 50.0 51.1 52.0 52.7 53.3 53.6 54.0 54.3 54.5
54.6 ...
54.8 54.8]; % Celsius

plttemp = [21 24 32 40 48 56 64 71 79 83 82 80 80 80 80 80 80 80 80
80 ...
80 80 80 80 80 80 ]; % Celsius

```

```

err = 1*ones(size(t));

figure
plot(t,chpr,'LineWidth',2)
xlabel('Time (seconds)')
ylabel('Pressure (\muTorr)')

figure
hold on
errorbar(t,chttemp,err,'LineWidth',2)
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(t,plttemp,'g','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Chamber Temperature','Cylinder Temperature','Platen
Temperature','Location','SouthEast')
hold off

tsim = [0 168 336 504 672 840 1008 1176 1344 1512 1680 1848 2016 2184
2352 2520 2688 2856 3024 3192 3360 3528 3696 3864 4032 4200 4368 4536
4704 4872 5040 5208 5376 5544 5712 5880 6048 6216 6384 6552 6720 6888
7056 7224 7392 7560 7728 7896 8064 8232 8400 8568 8736 8904 9072 9240
9408 9576 9744 9912 10080 10248 10416 10584 10752 10920 11088 11256
11424 11592 11760 11928 12096 12264 12432 12600 12768 12936 13104
13272 13440 13608 13776 13944 14112 14280 14448 14616 14784 14952
15120 15288 15456 15624 15792 15960 16128 16296 16464 16632 16800];
cylsim = [293.15 294.9416467 297.1281291 299.1929245 301.1305029
302.9468626 304.6481579 306.2400442 307.7281243 309.1179032
310.4148 311.6240876 312.7508978 313.8001816 314.7767136 315.6850671
316.5296193 317.314537 318.0437835 318.7211119 319.3500737
319.9340166 320.4760948 320.9792704 321.4463239 321.879858
322.2823082 322.6559481 323.0028995 323.3251389 323.6245063
323.9027123 324.1613468 324.4018849 324.6256957 324.8340477
325.0281162 325.2089893 325.3776738 325.5351008 325.6821311
325.8195599 325.948122 326.0684956 326.1813068 326.2871334
326.3865082 326.4799228 326.5678304 326.6506488 326.7287632
326.8025283 326.8722712 326.9382932 327.0008716 327.0602623
327.1167005 327.1704031 327.2215698 327.2703844 327.3170163
327.3616215 327.4043434 327.4453143 327.484656 327.5224806
327.5588915 327.5939837 327.627845 327.6605563 327.6921927
327.7228216 327.7525065 327.7813054 327.8092723 327.8364566
327.8629043 327.8886574 327.9137551 327.9382336 327.962126
327.9854627 328.0082724 328.0305811 328.0524135 328.0737919
328.0947374 328.1152693 328.1354056 328.155163 328.1745571
328.1936022 328.2123119 328.2306986 328.2487741 328.2665492
328.2840342 328.3012386 328.3181714 328.3348409 328.3512549]-273.15;

figure
hold on
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(tsim,cylsim,'k','LineWidth',2)
xlabel('Time (seconds)')

```

```

ylabel('Temperature (°C)')
legend('Experimental Temperature','Simulation
Temperature','Location','SouthEast')
hold off

```

80 deg C AL Test

```

clear
close all
clc

t = [0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 90 105 120 135
150 ...
165 180 195 210 225 240 255 270 285 300 315]*60; % seconds

chpr = [10 36 33 32 33 35 37 40 43 48 55 62 71 82 61 54 55 57 64
64 ...
66 66 66 66 66 65 65 65 64 64 63 63]; % microTorr

chtemp = [21.6 22.1 23.9 26.3 29.3 32.3 35.6 39.0 42.8 46.5 50.3 ...
54.3 58.3 62.5 66.0 67.2 67.8 67.6 71.3 71.2 71.9 72.3 72.7
73.0 ...
73.1 73.5 73.6 73.8 74.0 74.2 74.3 74.4]; % Celsius

cyltemp = [21.8 22.1 23.1 24.4 26.1 28.1 30.2 32.6 35.5 38.4 41.6 ...
44.9 48.5 52.3 55.8 58.3 63.4 66.9 70.7 72.4 73.7 74.6 75.3
75.8 ...
76.1 76.5 76.7 76.9 77.1 77.3 77.4 77.6]; % Celsius

plttemp = [21 24 32 40 48 55 63 70 78 86 93 100 107 113 118 117 114
110 ...
116 114 114 114 114 114 114 114 114 114 114 114 114]; %
Celsius

err = 1*ones(size(t));

figure
plot(t,chpr,'LineWidth',2)
xlabel('Time (seconds)')
ylabel('Pressure (\muTorr)')

figure
hold on
errorbar(t,chtemp,err,'LineWidth',2)
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(t,plttemp,'g','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Chamber Temperature','Cylinder Temperature','Platen
Temperature','Location','SouthEast')
hold off

```

```

tsim = [0 189 378 567 756 945 1134 1323 1512 1701 1890 2079 2268 2457
2646 2835 3024 3213 3402 3591 3780 3969 4158 4347 4536 4725 4914 5103
5292 5481 5670 5859 6048 6237 6426 6615 6804 6993 7182 7371 7560 7749
7938 8127 8316 8505 8694 8883 9072 9261 9450 9639 9828 10017 10206
10395 10584 10773 10962 11151 11340 11529 11718 11907 12096 12285
12474 12663 12852 13041 13230 13419 13608 13797 13986 14175 14364
14553 14742 14931 15120 15309 15498 15687 15876 16065 16254 16443
16632 16821 17010 17199 17388 17577 17766 17955 18144 18333 18522
18711 18900];
cylsim = [293.15 297.9832069 303.6443888 308.7959512 313.4467248
317.6280056 321.3733699 324.7168848 327.6888332 330.3247224
332.6563088 334.713967 336.5263437 338.1201212 339.5198888
340.7481004 341.8250992 342.7691915 343.5967537 344.3223622
344.9589341 345.5178726 346.0092116 346.4417548 346.8232071
347.1602981 347.4588935 347.7240985 347.9603499 348.1714986
348.3608838 348.5313979 348.6855444 348.8254886 348.9531021
349.0700032 349.1775862 349.2770542 349.3694472 349.4556624
349.5364736 349.6125478 349.6844599 349.7527056 349.8177118
349.8798466 349.9394274 349.9967276 350.0519829 350.1053966
350.1571441 350.2073769 350.2562257 350.3038033 350.3502077
350.3955235 350.4398241 350.4831732 350.5256264 350.5672321
350.6080325 350.6480647 350.6873615 350.7259516 350.7638605
350.8011111 350.8377236 350.8737164 350.909106 350.9439076 350.978135
351.0118008 351.0449169 351.0774944 351.1095436 351.1410742
351.1720955 351.2026166 351.2326457 351.2621913 351.2912612
351.3198632 351.3480047 351.3756933 351.402936 351.42974 351.4561122
351.4820596 351.5075888 351.5327066 351.5574197 351.5817344
351.6056574 351.6291949 351.6523534 351.675139 351.697558 351.7196166
351.7413208 351.7626767 351.7836901]-273.15;

figure
hold on
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(tsim,cylsim,'k','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Experimental Temperature','Simulation
Temperature','Location','SouthEast')
hold off

```

80 deg C Brass Test

```

clear
close all
clc

t = [0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 90 105 120 135
150 ...
165 180 195 210 225 240 255 270 285 300 310]*60; % seconds

chpr = [40 50 43 40 38 38 39 40 42 45 48 54 61 57 48 47 51 53 54
55 ...
55 55 55 54 54 54 53 53 53 53 52 52]; % microTorr

```

```

chtemp = [22.4 23.1 24.9 27.6 30.4 33.5 36.9 40.5 44.2 47.7 51.9
55.9 ...
60.0 64.3 66.4 67.2 68.1 69.5 70.8 71.5 72.1 72.8 73.2 73.6
73.7 ...
74.1 74.3 74.9 74.8 74.8 75.0 75.2]; % Celsius

cyltemp = [22.7 23.2 24.6 26.6 28.7 31.3 34.0 37.0 40.3 43.6 47.3
51.2 ...
55.2 59.4 61.9 63.6 66.8 69.9 72.2 73.9 75.1 76.0 76.7 77.3
77.6 ...
78.1 78.3 78.6 78.6 78.8 79.0 79.2]; % Celsius

plttemp = [22 25 33 41 49 57 65 72 80 87 95 102 109 115 117 116 ...
112 113 113 113 113 113 113 113 114 114 114 114 114 114 ...
114 114]; % Celsius

err = 1*ones(size(t));

figure
plot(t,chpr,'LineWidth',2)
xlabel('Time (seconds)')
ylabel('Pressure (\muTorr)')

figure
hold on
errorbar(t,chtemp,err,'LineWidth',2)
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(t,plttemp,'g','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Chamber Temperature','Cylinder Temperature','Platen
Temperature','Location','SouthEast')
hold off

tsim = [0 189 378 567 756 945 1134 1323 1512 1701 1890 2079 2268 2457
2646 2835 3024 3213 3402 3591 3780 3969 4158 4347 4536 4725 4914 5103
5292 5481 5670 5859 6048 6237 6426 6615 6804 6993 7182 7371 7560 7749
7938 8127 8316 8505 8694 8883 9072 9261 9450 9639 9828 10017 10206
10395 10584 10773 10962 11151 11340 11529 11718 11907 12096 12285
12474 12663 12852 13041 13230 13419 13608 13797 13986 14175 14364
14553 14742 14931 15120 15309 15498 15687 15876 16065 16254 16443
16632 16821 17010 17199 17388 17577 17766 17955 18144 18333 18522
18711 18900];
cylsim = [293.15 296.9187356 301.416599 305.6094484 309.4938632
313.0831133 316.3923809 319.4376107 322.2306906 324.7866514
327.1226149 329.2537596 331.1949056 332.960453 334.5642605
336.0195543 337.338864 338.5339817 339.6159404 340.5950102
341.4807063 342.2818087 343.0063891 343.6618435 344.2549292
344.7918035 345.2780637 345.7187877 346.1185732 346.4815762
346.8115476 347.1118684 347.3855822 347.6354258 347.8638583
348.0730864 348.2650975 348.441655 348.6043482 348.7545998
348.8936829 349.022736 349.1427768 349.2547149 349.359363 349.4574469

```

```
349.5496146 349.6364449 349.7184543 349.7961038 349.8698051
349.9399253 350.0067925 350.0706991 350.1319064 350.1906477
350.2471311 350.3015428 350.354049 350.4047982 350.4539234
350.5015434 350.5477647 350.5926826 350.6363826 350.6789416
350.7204285 350.7609051 350.8004275 350.839046 350.876806 350.9137487
350.9499114 350.985328 351.0200292 351.0540433 351.087396 351.1201108
351.1522094 351.1837118 351.2146365 351.2450006 351.2748201
351.3041099 351.332884 351.3611553 351.3889364 351.4162388
351.4430736 351.4694514 351.4953821 351.5208755 351.5459407
351.5705866 351.5948216 351.6186542 351.6420921 351.6651432
351.6878151 351.7101149 351.7320498]-273.15;
```

```
figure
hold on
errorbar(t,cyltemp,err,'r','LineWidth',2)
plot(tsim,cylsim,'k','LineWidth',2)
xlabel('Time (seconds)')
ylabel('Temperature (°C)')
legend('Experimental Temperature','Simulation
Temperature','Location','SouthEast')
hold off
```

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