2021

COMMISSIONING AND TESTING OF A NEW DUSTY THERMAL VACUUM CHAMBER

Ben Wiegand
Michigan Technological University, bdwiegan@mtu.edu

COMMISSIONING AND TESTING OF A NEW DUSTY THERMAL VACUUM CHAMBER

By

Benjamin D. Wiegand

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2021

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

Department of Mechanical Engineering-Engineering Mechanics

Report Advisor:	*Dr. Paul van Sustante*
Committee Member:	*Dr. Ye Sun*
Committee Member:	*Dr. Sajjad Bigham*
Department Chair:	*Dr. William Predebon*

Table of Contents

List of Figures

List of Tables

Acknowledgements

Thank you, Dr. Paul van Susante, for giving me the opportunity to work on something that is new and exciting, as well as the guidance and support you have provided me. I would like to thank the PSTDL and its members for being open and friendly, and providing me with the resources and facilities to conduct interesting research. Lastly, thank you Dr. Sajjad Bigham and Dr. Ye Sun for taking the time to act as committee members in my defense.

Abstract

The Dusty Thermal Vacuum Chamber (DTVAC) is a new facility purchased by the Planetary Surface Technology Development Lab (PSTDL) that will be used to test the Technology Readiness Level (TRL) of extraplanetary devices and systems. With the use of vacuum pumps and simulated regolith the DTVAC can create extraplanetary environments such as those found on the Moon and Mars. This report details the actions that were taken to prepare the DTVAC for TRL testing, including the development of a Data Acquisition Center (DAC) and test fixtures, along with the findings of baseline tests that were performed to understand the behavior of the DTVAC. In the future, the DTVAC will be used to test devices designed for use in the lunar polar regions with the help of the PSTDL icy regolith creation facilities.

1 Introduction

Before systems or devices, such as lunar rovers, can perform extraplanetary expeditions, their viability must first be tested in a relevant environment on Earth. The Dusty Thermal Vacuum Chamber (DTVAC) (Figure 1.1) is a new facility in the Planetary Surface Technology Development Lab (PSTDL) and is used to determine if a system is capable of operating in a simulated relevant environment. By use of various vacuum pumps, thermal shrouds, and simulated regolith, the DTVAC can produce an environment similar to what an extraplanetary device would experience during its operation. The performance of the system is then observed with the use of a data acquisition system and videography/photography devices.

To create the simulated environments that the PSTDL requires for testing devices, facilities surrounding the DTVAC needed to be created and upgraded. This report details the actions, tests, and procedures that were done to prepare the DTVAC for use.

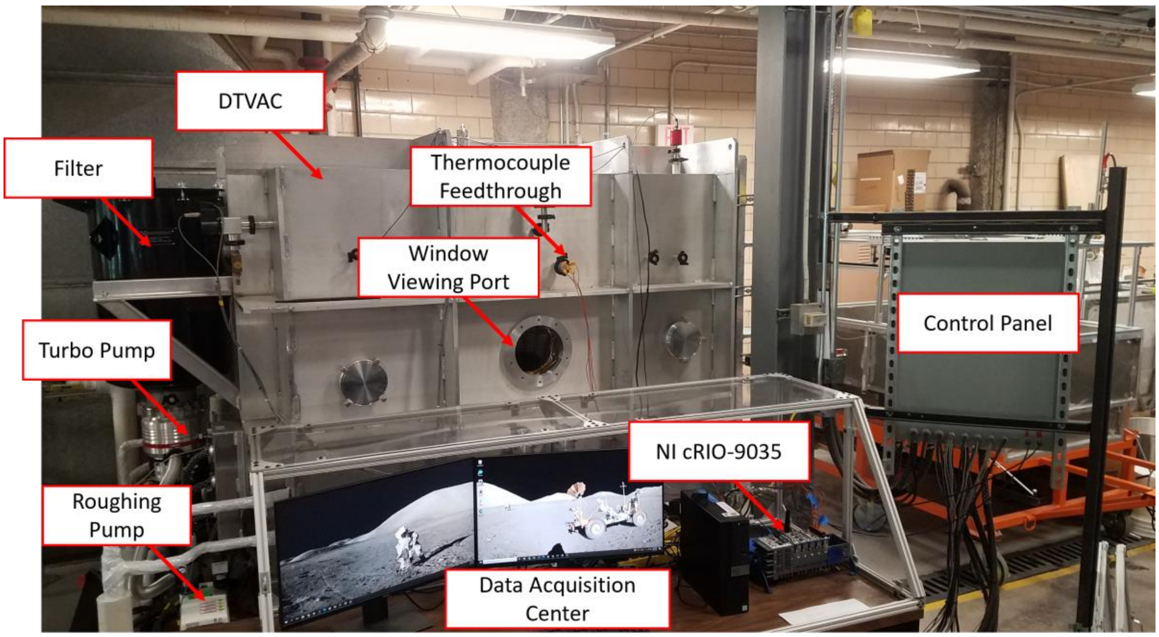

Figure 1.1 PSTDL DTVAC Facility with Relevant Labels

1.1 Other DTVAC Facilities

Several DTVAC facilities have been created by other labs for the purpose of testing in simulated environments. The scope of use for these facilities varies, with some focusing on observing the effects of charged dust particles on equipment, or the in-situ volatiles that arise from putting simulants in a vacuum. These other DTVACs are often equipped with instruments for measuring specific phenomena.

1.1.1 Lunar Environment Test System

One example of another DTVAC facility is the Lunar Environment Test System (LETS) developed by the Marshall Space Flight Center and seen in Figure 1.2. This cylindrical chamber, 0.8 m in diameter and 1.2 m, long can maintain high vacuum test conditions with use of a Cryo-pump. The system uses a cryo-shroud and quartz lamp array to reach temperatures from -150 to 130 degrees Celsius and has a lunar simulant bed capable of holding 75 kg of simulant. Additionally, solar radiation and solar wind can be simulated inside the chamber with the use of ultraviolet lamps, an electron flood gun and a low energy proton source. A LabView data acquisition system is used to acquire signals and control the chamber [1]. The LETS system has been used to study the effects of a charge on dust particles. Charged particles are subject to changes in adhesion and attraction properties and are capable of levitating and migrating [2].

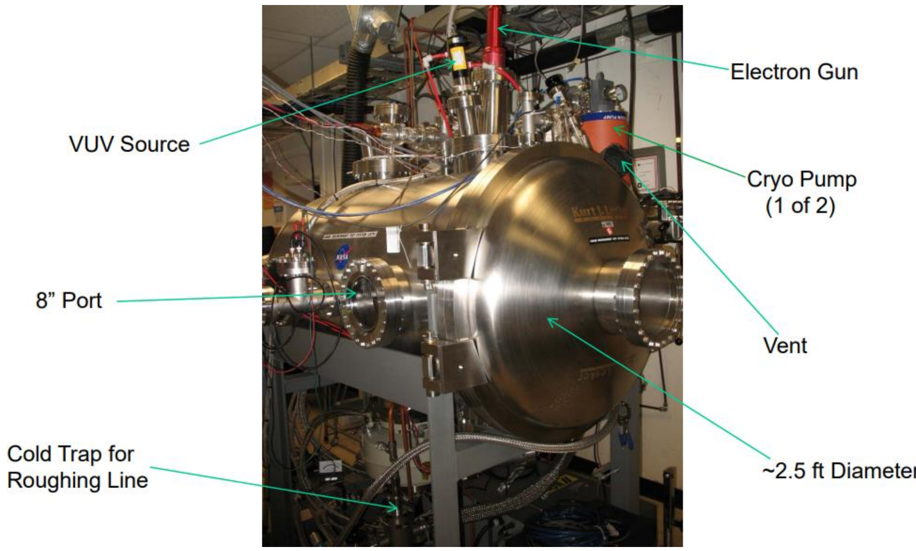

Figure 1.2 LETS DTVAC Developed by the Marshall Space Flight Center [1]

1.1.2 MPB and The Canadian Space Agency DTVAC

Another example is the DTVAC developed by MPB and the Canadian Space Agency seen in Figure 1.3. This is a cylindrical chamber that can test devices with a size up to 1x1x0.9 m. The chamber operates in high vacuum, and its thermal shroud reaches temperatures between -183 to 60 degrees Celsius [3]. A regolith simulant bed of 500 kg can be placed within the chamber, and a programmable dust dispenser can be used to drop simulant from the top of the chamber to the simulant bed. With the use of a metal halide lamp, the DTVAC can simulate the solar spectral irradiance on the simulant bed. A data acquisition system is used to log data from pressure gauges, thermocouples, valves, dust dispenser, and power consumption of the device being tested while also controlling the chamber's pressure [4].

The Canadian Space Agency intends to use the DTVAC for studying in-situ lunar volatiles with the use of a residual gas analyzer (RGA). An RGA can be used to identify

the molecular composition of particles that have been outgassed from articles within the chamber [3].

Figure 1.3 MPD and Canadian Space Agency DTVAC [5]

1.2 PSTDL DTVAC Requirements

With the PSTDL DTVAC, the Technology Readiness Level (TRL) of a device that is destined for use in space can be assessed. The TRL is an indicator of a system or device's maturity and is used to regulate whether a technology is ready for use in space. There are nine levels, with each level corresponding to a different degree of readiness [6]. The DTVAC is used to evaluate the readiness of systems, prototypes, and devices that the PSTDL, or others, create. To reach a TRL of six, device testing must be done in realistic simulated environments. For a device destined for operation on the moon, this would include tolerating temperatures within the range of -173 to 127 degrees Celsius, existing in a vacuum, and interacting with lunar regolith [7]. For a Martian environment, a device would have to withstand an absolute pressures near 5 Torr and temperatures ranging from -125 to 20 degrees Celsius [8], [9].

To test the TRL of devices, these conditions should be achieved within the DTVAC. The internal thermal shroud was designed for cooling or heating between temperatures of -196 to 150 degrees Celsius. With use of a roughing pump and turbomolecular pump, pressures down to a high vacuum (<1.33E-3 to 1.33E-6 Torr) should be maintained [10]. With a rectangular prism thermal shroud the size of 127x127x177.8 cm a lunar regolith simulant bin can be placed inside the chamber and be used to replicate the interactions between a device and simulated lunar regolith. Data can be measured from within the chamber via the ports and the feedthroughs listed in Table 1.1 and Table 1.2, respectively.

Table 1.1 PSTDL DTVAC Ports

Port name	**Quantity**
ISO-LF DN160 (NW160)	2
ISO-LF DN63 (NW63)	4
KF/QF40-100-LF (NW40)	4
KF/QF25-100-LF (NW25)	2
KF/QF16-100-LF (NW16)	4

Table 1.2 PSTDL DTVAC Currently Available Feedthroughs

Description	**Size**	**Quantity**
MS High Current Series, Multipin Feedthrough, 4 Pins, 700 Volts, 28 Amps per Pin, 0.094″ Moly Conductors, 1.18″ QF / KF Flange	KF 16	1
SMA double ended	KF 16	1
Thermocouple, single ended, type K, M, 5 ports	KF 40	2

The TRL level of two ongoing PSTDL projects can be assessed with the use of the DTVAC. The Tethered permanently shadowed Region EXplorer (T-REX), seen in Figure 1.4, is a lunar rover that was developed by the PSTDL to bring power and communications to the permanently shaded regions of the lunar surface. The TRL of the power-electronics system for the rover can be verified in the DTVAC by creating similar conditions to that of the moon. For the Extraction of Water from Hard Extraterrestrial Soils project, associated with NASA's Early Stage Innovations Grant (ESI), the slurry suction setup, which is part of a system to obtain water from gypsum on Mars, was tested in the DTVAC. The TRL of the project was increased by verifying the pressure differential needed to provide suction for the apparatus.

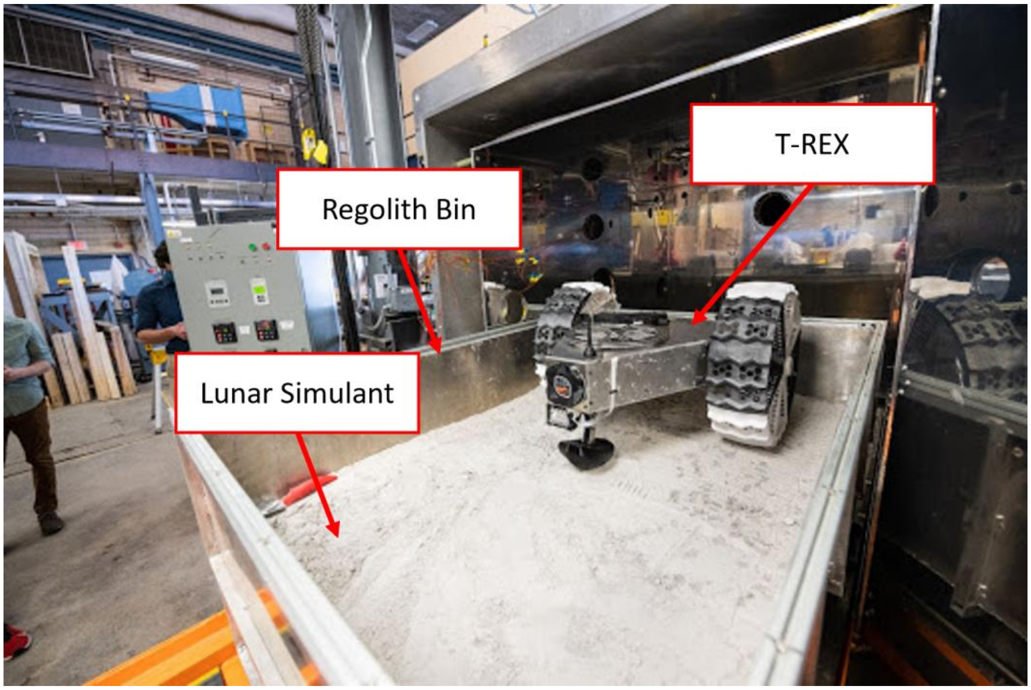

Figure 1.4 PSTDL T-REX Lunar Rover on Simulant Bed inside DTVAC

In the future, the PSTDL DTVAC will be used to assess the TRL of TransAstra's water extraction device which will use microwaves to thaw and extract water trapped as ice in lunar regolith. To prepare for the upcoming tests, a low reflectance foil for the interior surface of the DTVAC was considered, and fixtures were created to ensure that microwaves could safely be produced within the DTVAC without leakage to the outside. Furthermore, A bed of lunar simulant with 10% by weight shaved ice was created and tested within the vacuum chamber to establish a baseline for the behavior of icy regolith under a vacuum.

1.3 Project Scope

The purpose of the work conducted was to prepare the DTVAC for the testing of devices or systems while also ensuring that the chamber was operated safely and effectively. The DTVAC was prepared for testing by producing data acquisitions systems, safe operating procedures, documentation, and test fixtures and beds. Importance was placed on the ability to test systems within the chamber accurately and reliably, while also creating documentation to detail the tests that were performed and the characteristics of the operation of the DTVAC.

2 Data Acquisition

For testing any device or system and ensuring that the design requirements have been met, it is essential to collect data that can be used to illustrate the tested system's performance. In the case of a system that is to be used for extraplanetary explorations, measured data of the simulated environment is also critical to ensure that the tested device is proved in a relevant environment before increasing TRL.

To accurately create simulated environments a data acquisition system (DAQ) that accurately and timely measures the conditions within the vacuum chamber is needed. To meet this requirement, the PSTDL purchased a DAQ and developed surrounding hardware and software to create a data acquisition center (DAC) in which operators could effectively monitor and collect data from the vacuum chamber and any device being tested within. The first component of the DAC is the DAQ. The DAQ includes systems used to obtain numerical data as well as visual data from within the chamber. The second component is a computer used to communicate with, store, and illustrate the data being observed by the DAQ. Lastly, an enclosure that is used to protect the DAQ and computer from tampering and a dusty lab environment.

2.1 Data Acquisition Center Enclosure

The DTVAC and subsequently the DAC are located in a shared lab space that is subdivided into portions dedicated to the PSTDL and other labs. The DAC was susceptible to tampering and dust since the shared lab space also contains metal and woodworking tools. To mitigate the risk of exposure for the DAQ and computer a lockable enclosure (seen in Figure 2.1) was created that prohibited the intrusion of dust or unwanted tampering.

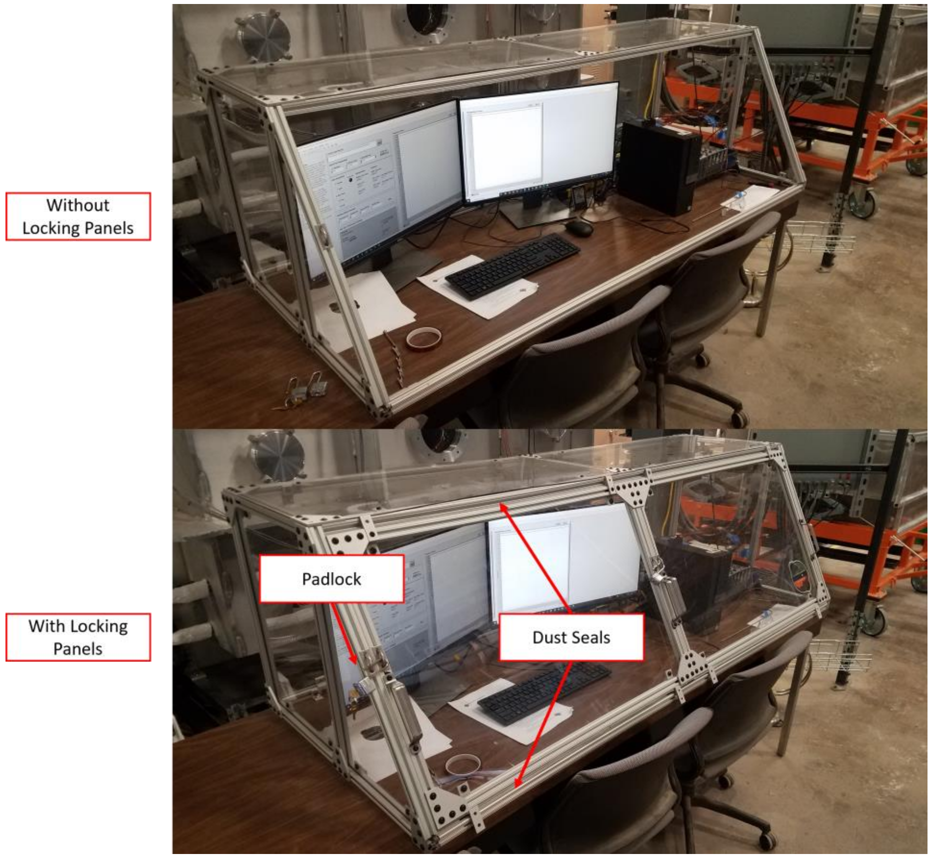

Figure 2.1 DAC Enclosure

The requirements for the enclosure included being dust and tamper resistant and large enough to house the DAQ and computer while also allowing the DAC user to comfortably use the enclosed systems. Measurements were taken of the enclosed systems and the enclosure was designed in CAD to accommodate their size as seen in Figure 2.2. Once the enclosure was designed, CAD models of the enclosed systems were created to confirm that the enclosure was adequate in size. An angled design for the removable panels was incorporated so that the enclosure did not block the user's view of the computer monitors and allowed for a top-down view of the DAQ.

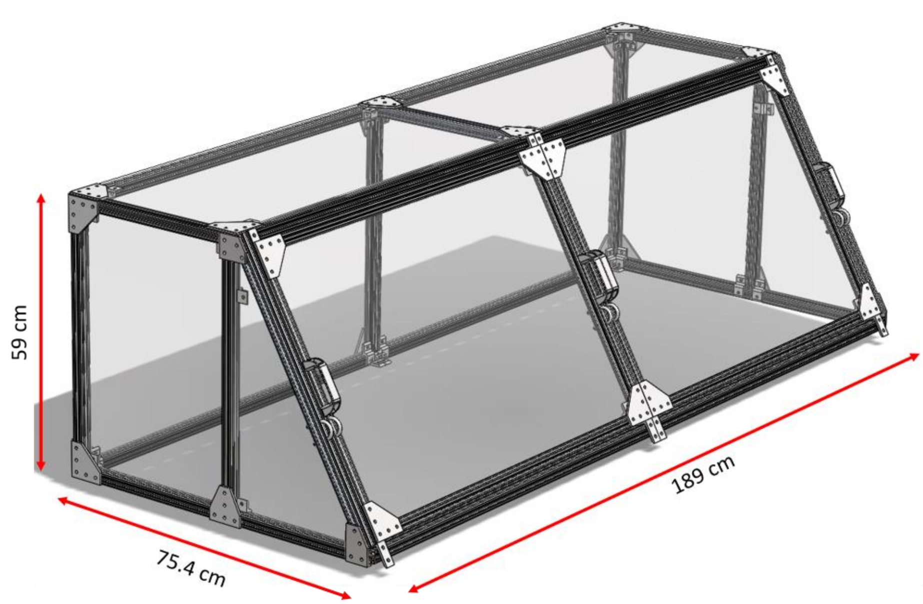

Figure 2.2 CAD Model of DAC Enclosure with Dimensions

Once the CAD model was completed and verified, the necessary parts and T-slot extruded aluminum pieces were purchased. The enclosure was then built, and the computer and DAQ system were placed inside.

2.2 Data Acquisition Systems

2.2.1 National Instruments DAQ

The National Instruments cRIO-9035 DAQ system, shown in Figure 2.3, was chosen to interface with sensors and record data from the vacuum chamber. The cRIO is a National Instruments chassis that incorporates a real-time Linux based processor that allows users to install custom programs capable of monitoring or controlling applications. Modules are added to the chassis and are selected based on the type of sensors that data is to be recorded from [11].

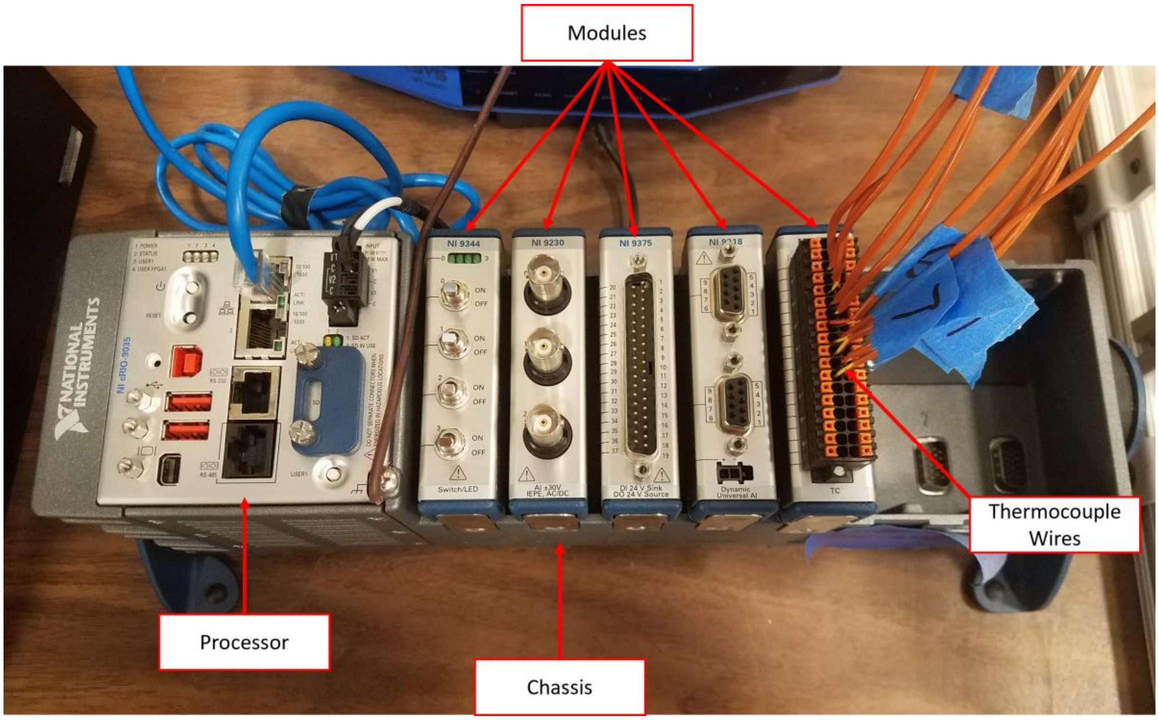

Figure 2.3 NI cRIO-9035 DAQ

For collecting data from the DTVAC four modules were chosen that represent a range of different data collection capabilities. These modules and capabilities are listed in Table 2.1, and others can be added and customized as needed.

Table 2.1 NI DAQ Modules

Module	**Purpose**
NI 9344	4-Channel C Series Digital User Interface Module
NI 9230	3-Channel, 12.8 kS/s/channel, ±30 V C Series Sound and Vibration Input Module
NI 9375	30 V, 32-Channel (Sinking Input, Sourcing Output), 7 µs (Input)/500 µs (Output) C Series Digital Module
NI 9218	51.2 kS/s/ch, 2-Channel C Series Universal Analog Input Module
NI 9213	16-Channel, 75 S/s Aggregate, ±78 mV C Series Temperature Input Module

To measure temperature from within the chamber, ten k-type thermocouples were installed using k-type feedthrough ports mounted to the chamber walls that allow the thermocouple signals to pass and connect to the DAQ system thermocouple module. Once connected, the module was programmed to interpret k-type thermocouple signals. K-type thermocouples have a range between -270 to 1260 degrees and a tolerance of +-1.5 degrees Celsius [12].

Initially, large amounts of noise were seen in the temperature signals, with temperature values sometimes spiking to thousands of degrees. After troubleshooting, it was found that the thermocouple connections to the feedthrough on the inside of the vacuum chamber were coming into contact with the chamber walls. A thick insulative tape was added to the feedthrough connections, and the problem was resolved.

To validate the accuracy of the thermocouples, two tests were performed. In the first test, the thermocouples were submerged in ice water. The ice water was confirmed to be at 0 degrees Celsius via the use of an external thermometer. Thermocouple values were recorded, and the temperature for each thermocouple was found to fluctuate between 0 degrees and to within 1 degree of 0 degrees Celsius during steady-state conditions. In the second experiment, the thermocouples were submerged in boiling water that was verified to be at 100 degrees Celsius. Values from the test were recorded, and the temperature for each thermocouple was found to fluctuate between 100 degrees and to within 1 degree of 100 degrees Celsius during steady-state conditions. These results were expected considering the temperature ranges that the thermocouples were verified at are well within the permissible range of k-type thermocouples. These tests confirmed that the thermocouples and DAQ system were working properly for temperature readings and were within the tolerance needed for testing in the DTVAC.

2.2.2 LabView Virtual Instruments for Data Collection

LabView is a visual coding language developed by National Instruments that is used to interface with systems such as DAQs. Users can visually develop programs, or Virtual Instruments (VIs), by grabbing and assembling premade code blocks, or subVIs, and connecting them with lines that represent signals. Once the architecture of a VI is complete the program can be deployed on a host processor where it can execute functions, record and monitor data, or control systems.

2.2.2.1 Thermocouple Data

For obtaining data concerning the DTVAC, two VIs were created. The first VI, seen in Figure 2.4, was produced to observe and record data from the thermocouple module. This VI was produced by creating a while loop that executes at a rate of 1 Hz. When the VI is deployed, with every execution of the loop analog signals from the thermocouples are filtered and converted to digital signals in the thermocouple module. The digital data is then sent to the processor where the VI acquires the thermocouple values, displays them on a chart for the user to see, and then stores them in a text file for later data analysis. Once the user is done testing, a stop button is pressed, and the program exits the while loop.

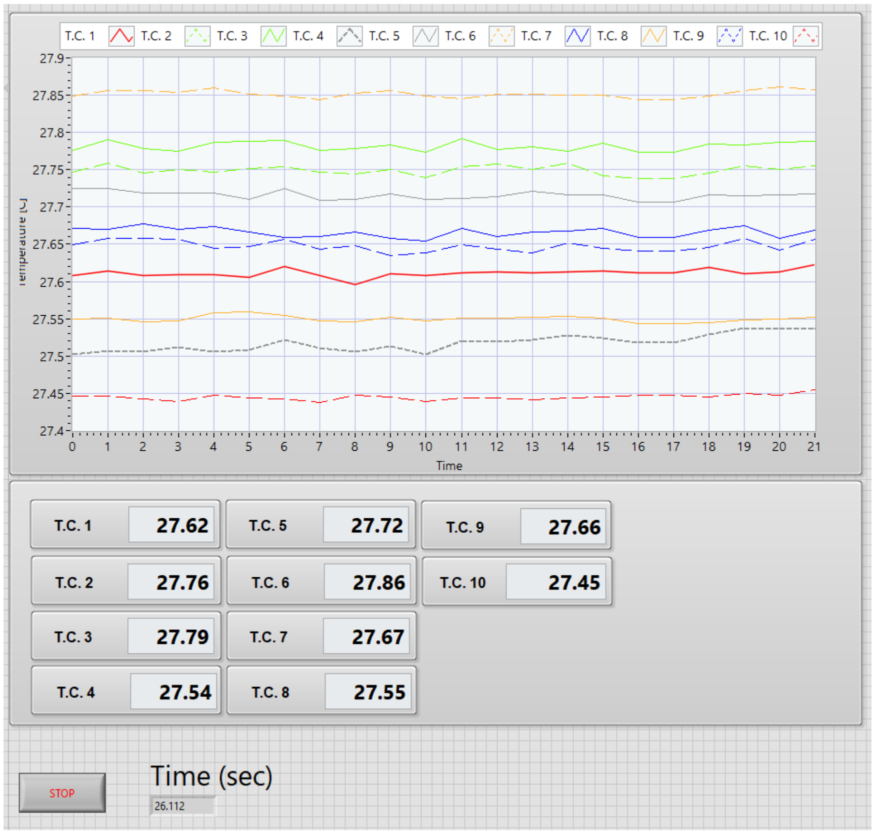

Figure 2.4 Control Panel of VI for Capturing Thermocouple Data

2.2.2.2 Pressure and Thermal Shroud Temperature Data

The next VI, seen in Figure 2.5, was created to obtain data from the pressure and temperature sensors built into the DTVAC pressure monitoring system and thermal shroud temperature control system. The developed VI was able to obtain data from these systems using serial communication and the appropriate third party LabView Libraries.

For better usability, a state-machine was used for the VI's architecture. A state-machine is a programming architecture that allows a program to execute different states depending on the previous state's or user's input. A state is defined as a function or series of functions that only execute when the proper input is given [13]. For the state machine created for the VI, there are six states, each designed for executing a specific task detailed in Table 2.2. The program transitions between states based on the user's input to the VI's control panel.

Table 2.2 State Machine States for Pressure and Thermal Shroud Data Acquisition VI

State	**Functionality**
Initialize	Initiates serial communication channels for DTVAC monitoring systems
Read	Begins data acquisition, displays values to chart, and stores data to a text file
Stop Read	Stops data acquisition
Write	Used to send commands to the thermal shroud temperature control system
Close	Closes serial communication channels
Exit	Exits VI

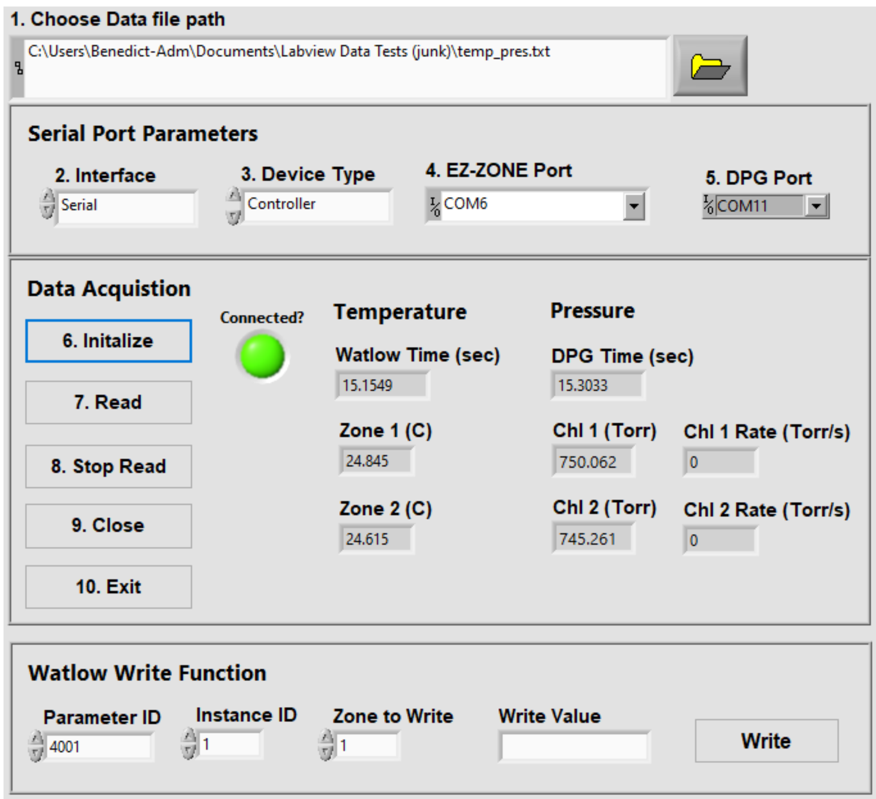

Figure 2.5 Control Panel of Pressure and Thermal Shroud Data Acquisition VI. Used to enter serial communication parameters, see values acquired, choose recorded data file path, and select actions for the program to perform. Charts of pressure and temperature recorded are not pictured but are present to the right of the selection shown.

While producing the VI, it was noticed that the control panel was reacting slowly to user inputs while the program was running. To help combat this, a producer/consumer loop design was added to the VI's architecture and is shown in Figure 2.6. The producer/consumer design pattern allows the state-machine and user input monitoring portions of the program to perform at different speeds [14]. For this VI, the loop polling for user inputs is the producer because it sends commands to the loop housing the state-

machine, the consumer. With the implementation of this design, the VI control panel became more responsive to user inputs.

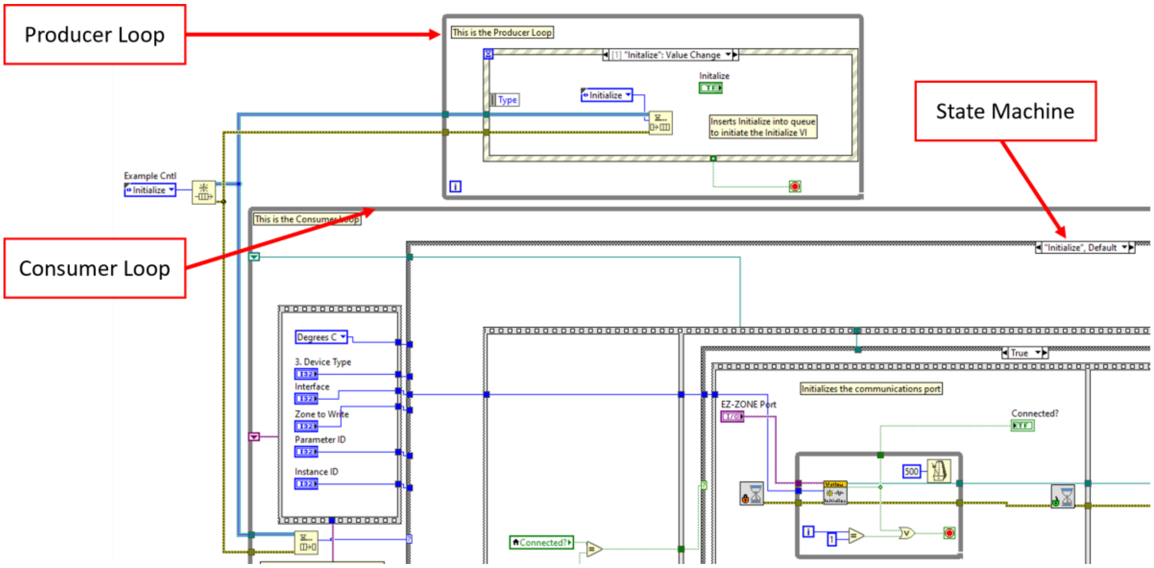

Figure 2.6 Pressure and Thermal Shroud Data Acquisition VI Program Architecture

2.2.2.3 Data Acquisition Inaccuracies

An inaccuracy occurred in the initial procurement of thermocouple temperature data. Before the accuracy of the thermocouple probes were checked they were used for the testing of small ice and regolith samples within the chamber. It was noticed that the temperature readings were not consistent with those from the external probe. When the VI for recording thermocouple values was created, it was assumed that the type of thermocouple was only inputted into the program. After investigating, this assumption was not true, and the thermocouple type also needed to be entered into the module settings in the project's device folder. The resulting data for the first initial tests were measured with K-type thermocouples and J-type settings. This mistake was repeated when the cRIO system had to be reintroduced to the project file which caused the system to default to J-type settings. During a DTVAC test, the thermocouple measurements were not consistent with the thermal shroud control system measurements. The VI was stopped, the setting was corrected, and when the VI was executed, the observed temperatures were more consistent with what was expected, as seen in Figure 2.7.

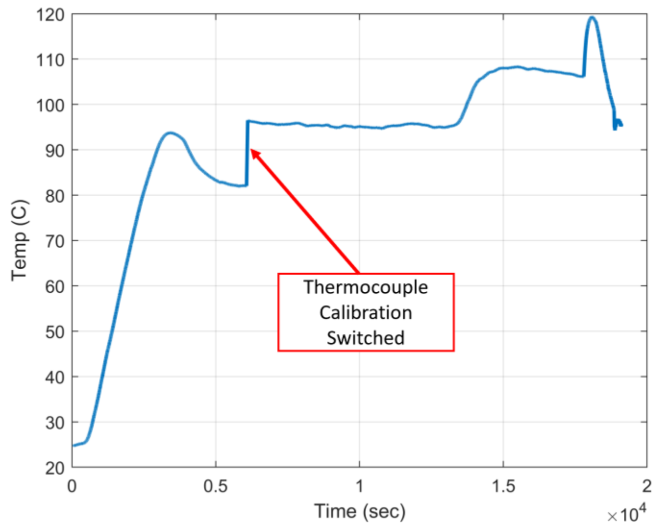

Figure 2.7 Step in Measurement due to Calibration Switched to Proper Thermocouple Type during Testing

A second inaccuracy occurred in the initial measurements of pressure data. When creating the VI for measuring and recording the pressure of the vacuum chamber the incorrect number of places after the decimal to record data was entered. For the first initial tests of the vacuum chamber the pressures observed were much lower than the program was able to record. This error was not apparent since the chart used during the tests displayed the data correctly. This resulted in data sets where the pressure was measured as 0.000 instead of the actual values nearing 1E-7 Torr, as shown in Figure 2.8. This error was fixed by adjusting the VI to record pressures down to 1E-9 Torr.

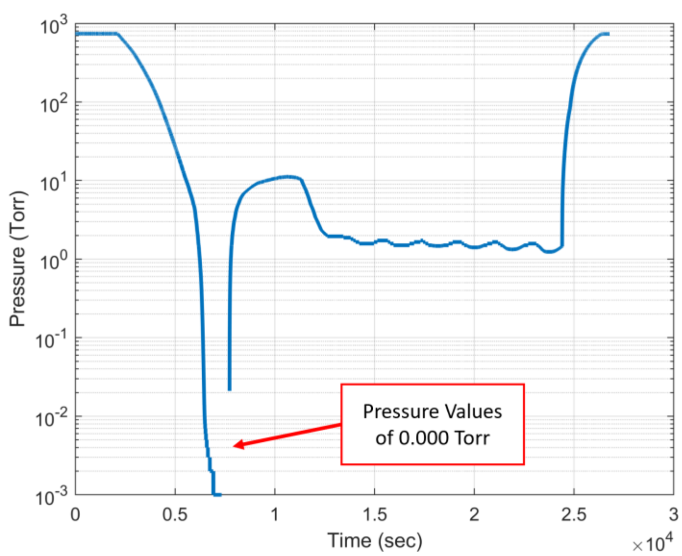

Figure 2.8 Missing Pressure Values due to Improper Data Recording

2.2.3 ESP32 Camera DAQ

Aside from obtaining numerical data, a system for obtaining visual data from within the DTVAC was needed. The camera system to be used had to be low cost and easily replaceable, as DTVAC tests involve extreme temperatures that can ruin electronics. Additionally, a system that could stream data over WI-FI to the external DTVAC computer would be ideal since it would eliminate the need for an additional feedthrough or signal connections to the cameras. Lastly, the camera system could not use batteries since they are not vacuum rated.

From the requirements set forth, two options were found and considered. The first option was a Raspberry Pi with a camera attachment. A Raspberry Pi is an open source Linux based microprocessor with WI-FI capabilities. The second option was the ESP32 Camera. This open-source camera module is programmed using an Arduino IDE and was designed for capturing and recording visual data. Table 2.3 shows the advantages and disadvantages considered for each camera. The ESP32 camera was chosen for the task as it exhibited two important advantages over the Raspberry Pi. The ESP32 camera was 80% more affordable compared to the Raspberry Pi and was more user friendly. With the use of the Arduino IDE, an ESP32 camera could easily be programmed to create a web server capable of streaming live video over WI-FI. This would allow for the cameras to be easily and affordably replaced in the event that they are rendered inoperable.

Table 2.3 Advantages and Disadvantages of Considered Cameras

Raspberry Pi		**ESP32 Cam**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
5 MB Camera	Higher Expense	Lower Expense	2 MB Camera
60 fps at 1080p	Less User Friendly	More User Friendly	1 fps at 1080p
Capability for Expanded Use	Temperature Range of 0 to 70C	Easier to Mount	
		Temperature Range of -20 to 80C	

ESP32 Cameras were purchased, and fixtures were 3D printed that allowed for mounting on aluminum T-slot (Figure 2.9 a)). Using the Arduino library for the ESP32 Camera, an example web-server script was altered to allow for the use of the camera's flash function while recording video. The altered script with the Wi-Fi credentials was uploaded to the cameras. The cameras were placed inside the DTVAC, and their functionality was tested (Figure 2.9 b)). It was found that the cameras operated as expected, and video was able to be streamed to the DAC computer and recorded. Documentation detailing how to use and format the cameras was created and can be found on the DAC computer.

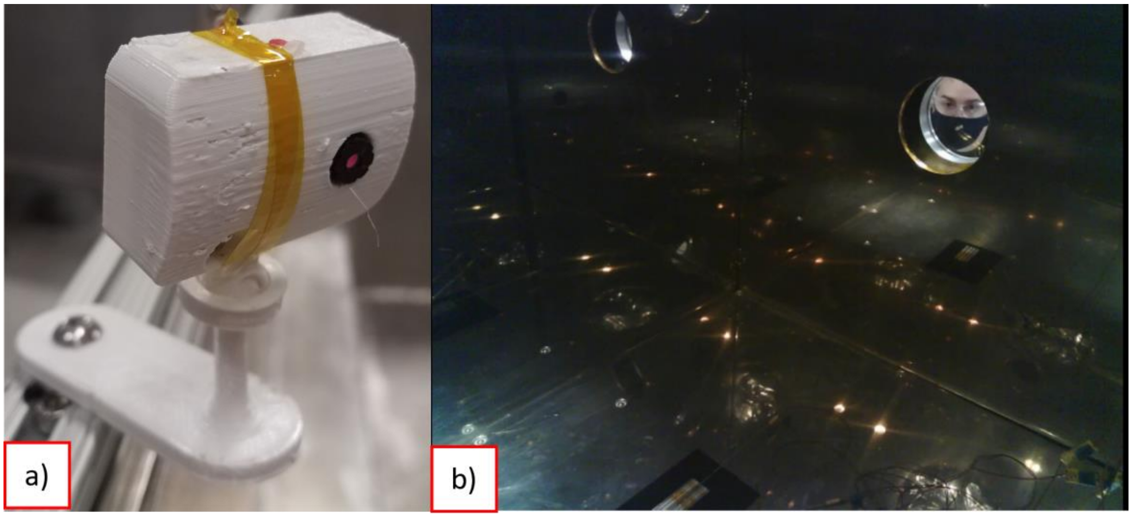

Figure 2.9 a) ESP32 Camera in Mounting Fixture b) Picture Taken by Cam in DTVAC

A test in the DTVAC with the installed cameras was then conducted to determine their ability to withstand a vacuum and extreme temperatures. A pressure of 4E-2 Torr was obtained within the chamber and the thermal shroud was set to -50 degrees Celsius. The cameras' temperature dropped from 50 degrees Celsius and then achieved steady-state at 20 degrees Celsius (Figure 2.10). The thermal shroud was then set to 100 degrees Celsius. The cameras' temperature increased rapidly and before the shroud could reach the setpoint the cameras started to exhibit green filtered images, as seen in Figure 2.11. The power to the cameras was disconnected out of fear that the increased temperature would permanently affect their image. It was thus concluded that the cameras could operate between -50 to 80 degrees Celsius.

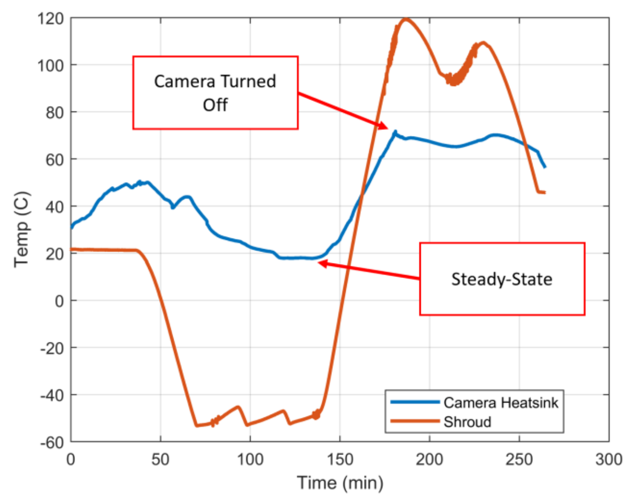

Figure 2.10 Temperature of ESP32 Cam compared to Thermal Shroud

Figure 2.11 Overheating of ESP32 Cam produces Green Color Effect

In the event of long duration testing with temperatures nearing -196 degrees Celsius, MLI and/or electric surface heaters will be added to the rear of the cameras to prevent their temperature from falling below -20 degrees Celsius.

3 DTVAC Characterization

The DTVAC was designed and purchased to help the PSTDL increase the TRL of devices and systems by simulating extraplanetary environments such as the Moon and Mars. Accomplishing this goal requires that the vacuum chamber be able to produce conditions similar to these environments which include extreme temperatures and a high vacuum. Using the DAC, the performance of the vacuum chamber was analyzed to determine if the design requirements were met.

The ability for the DTVAC to maintain low pressures at extreme temperatures was tested, and the results can be seen in Figure 3.1and Figure 3.2. The chamber was able to maintain temperatures up to 150 degrees Celsius, with pressures remaining below 1E-5 Torr. Furthermore, the chamber was able to achieve pressures less than 1E-5 Torr while maintaining temperatures near -180 degrees Celsius. Once the chamber reached temperatures nearing -175 degrees Celsius the liquid nitrogen (LN2) supply had to be throttled to prevent the LN2 from exiting the exhaust pipe at the lab’s roof line without evaporating. Although -196 degrees Celsius was not observed in this short duration test, it is possible that temperatures nearing the value could be seen in long duration tests with proper LN2 valve throttling.

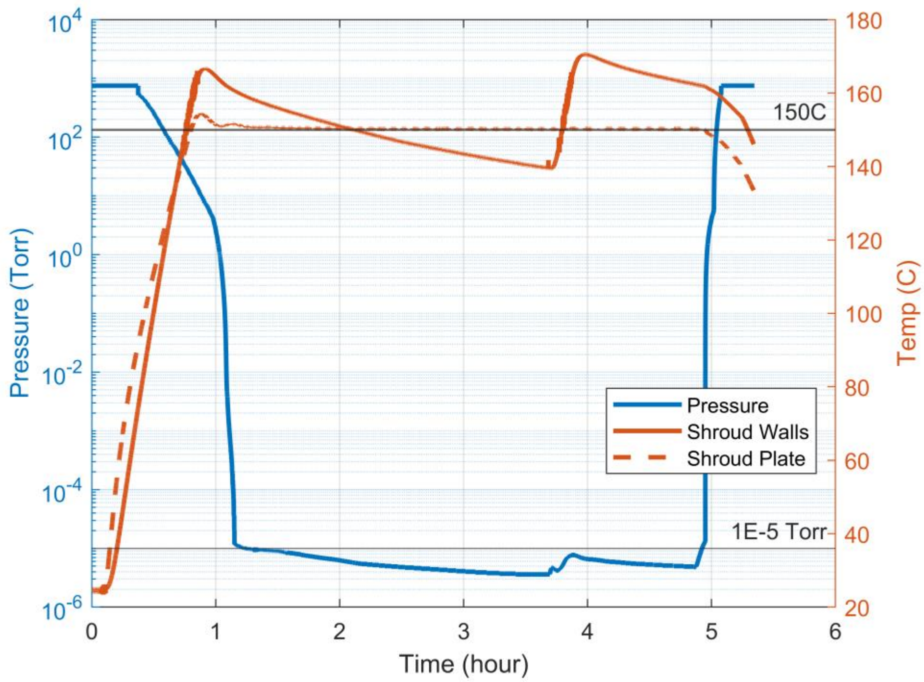

Figure 3.1 Pressure and Temperature Profiles for Heating of Empty DTVAC to 150 C

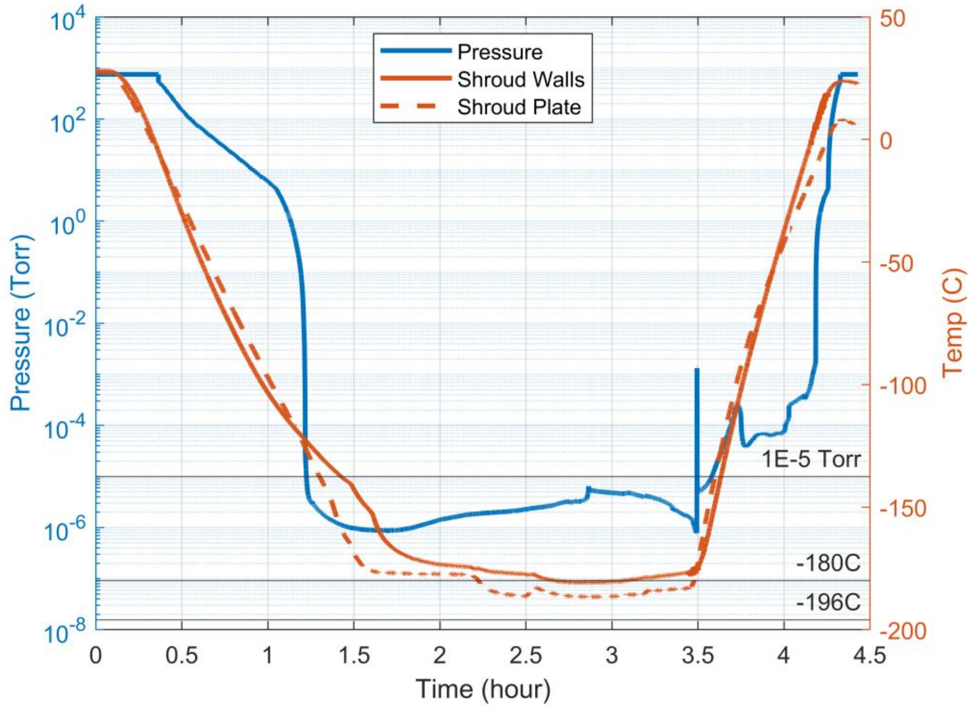

Figure 3.2 Pressure and Temperature Profiles for Attempting to Cool the DTVAC to -196C

It was concluded that the design requirements for the DTVAC set forth by the PSTDL were met. The capabilities of the DTVAC are adequate to perform TRL testing for devices designed for use in areas on the Moon and Mars. An SOP was created to allow for safe use of the DTVAC and can be seen in Appendix A.

4 Setup for TransAstra Testing

The PSTDL has been contracted through the TransAstra Corporation for testing a device essential for their lunar polar mining operation [15]. The device, otherwise known as the Beetle, uses a combination of radio frequency, microwaves, and infrared radiation to heat ice deposits and then collect the resulting volatiles [16]. Facilities and testing hardware were created in preparation for testing the Beetle. This included facilities to create an icy regolith test bed, fixtures to prevent microwave radiation from exiting the DTVAC while testing, and the potential application of low reflectance foil to the test bed for better thermal performance.

4.1 Creating Icy Regolith

To test the ability of the Beetle to heat ice deposits on the moon, an icy regolith test bed that can be placed within the vacuum chamber is needed. A procedure for icy regolith creation was developed and a 770kg test batch of icy regolith was created and then tested in the DTVAC. The goal of the test was to determine the time required for creating the icy regolith and taking it down to a high vacuum and a temperature of -196 degrees Celsius in the DTVAC.

Creating icy regolith involves acquiring simulated lunar regolith and ice. The PSTDL has developed its own lunar regolith (MTU-LHT-1A) for use in previous projects, and 860 kg of dry regolith was available for use. For the ice, 230 kg of cubed ice was procured from a local supplier. Tools that were acquired included ice shavers, an HDPE concrete mixer, a scale, and hand scoops. This test was conducted during the winter, and a canvas enclosure was erected outside to shield the tools, simulant, and ice from precipitation. The 770 kg batch of icy regolith was prepared on a day where external temperatures were below freezing so that the icy regolith did not thaw before it could be put into the vacuum chamber. Using the procedure found in Appendix B, the batch of icy regolith was created in eight hours.

The icy regolith bed, shown in Figure 4.1, was transported into the DTVAC where thermocouples were placed in each corner and in the center of the regolith bin at depths of 5 cm and 30 cm from the regolith's surface. A schematic of the thermocouple locations can be seen in Figure 4.2. Temperature data was recorded from the thermocouples and the thermal shroud temperature controllers. Pressure data was recorded from the DTVAC pressure monitoring system. The thermal shroud controllers were set to -196 degrees Celsius, as seen in Figure 4.3. The chamber was pumped down to 5 Torr with the roughing pump, and the turbo pump was activated and pumped the chamber down to a pressure below 1E-3 Torr. The turbo pump operated for 30 minutes before an oil deficiency error occurred and the pump was deactivated. The pressure profile can be seen in Figure 2.8. The thermal shroud controllers were set to 0 degrees Celsius and the test was conducted for another 4.6 hours.

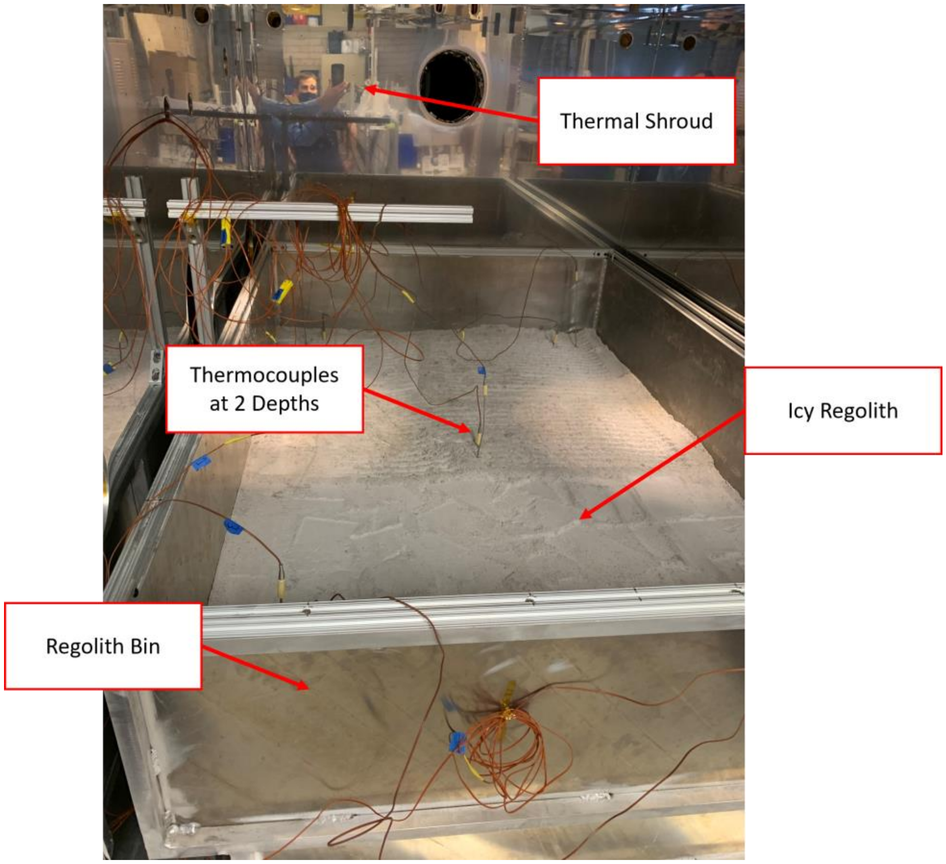

Figure 4.1 Icy Regolith Test Bed with Installed Thermocouples at Two depths (5 cm and 30 cm) in Regolith Bin Corners and Center

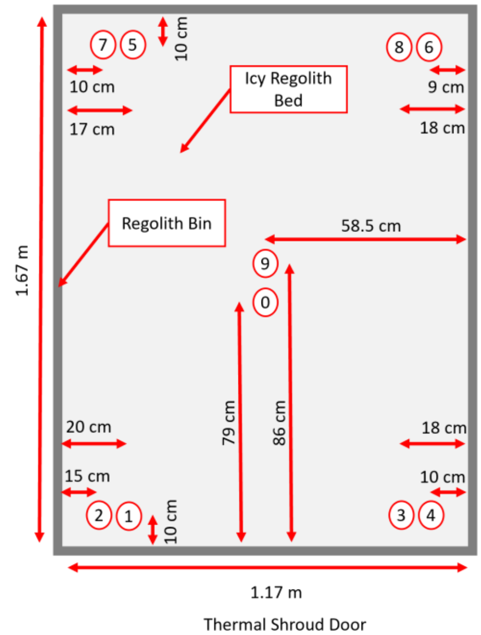

Figure 4.2 Placement of Thermocouples Channels (Ch) in the Icy Regolith Bed. Channels 1,3,5,8, and 9 are located 30 cm below the surface, the remaining thermocouples are 5 cm from the surface.

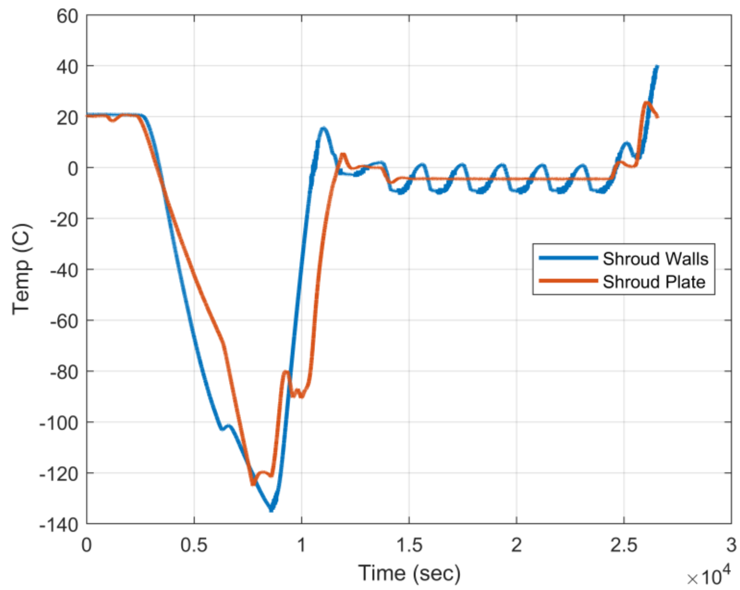

Figure 4.3 DTVAC Thermal Shroud Temperatures for Icy Regolith Test

Using the temperature profiles obtained from the experiment, shown in Figure 4.4, an average of the probe temperatures from when the thermal shroud was being cooled was taken. Using a linear fit of the averaged data, as seen in Figure 4.5, a minimum time of

13.25 hours was computed to be necessary for the average temperature of the simulant bed to reach -196 degrees Celsius. The fit that was created was based on a limited amount of data, and the thermodynamic properties of the icy regolith in the vacuum chamber are not expected to be linear in nature. However, the value found is useful insight into future tests.

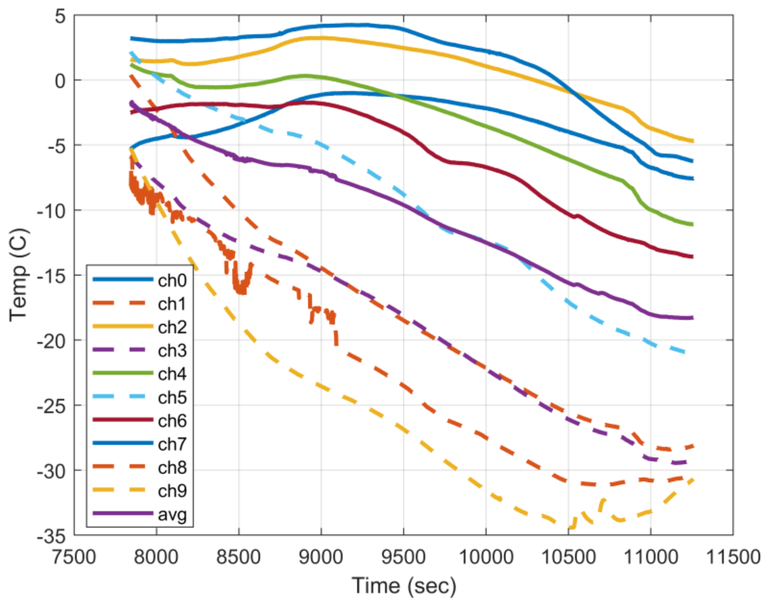

Figure 4.4 Thermocouple Data of 770kg Icy Regolith Test during Thermal Shroud Cooling. Dashed lines are for 30 cm depth, Solid lines are for 5 cm depth. Average (avg) of all profiles shown.

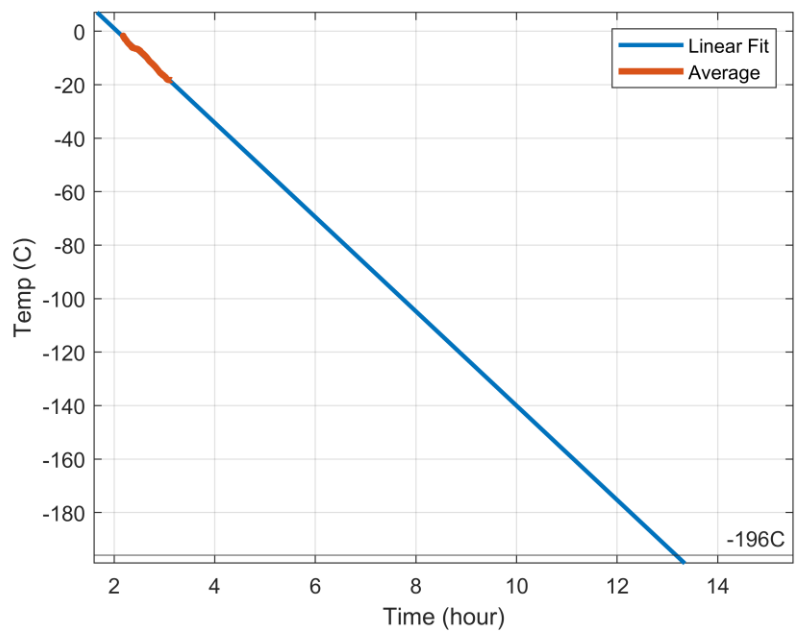

Figure 4.5 Approximation of Time Required for 770kg Icy Regolith Batch to Reach -196C Using Linear Fit of Averaged Thermocouple Data

4.2 Microwave Leakage Prevention Fixtures

When tested in the DTVAC, TransAstra's Beetle device will emit microwave radiation. In order to prevent leakage to outside of the DTVAC that could harm individuals, fixtures were created to ensure that the vacuum chamber functions as a Faraday Cage. The viewing ports were the only areas identified in need of retrofitting, as they are made of glass and allow microwaves to pass through. If needed, aluminum tape can be used to seal the door and ports of the DTVAC against leakage.

The fixtures created for the viewing ports, seen in Figure 4.6, were designed based on the screens that are found in household microwave appliances. A perforated steel panel with the same diameter hole size as microwave appliance screens was purchased and laser cut into viewing port sized pieces. The pieces were then fitted into place with the utilization of aluminum tape to ensure there is no leakage.

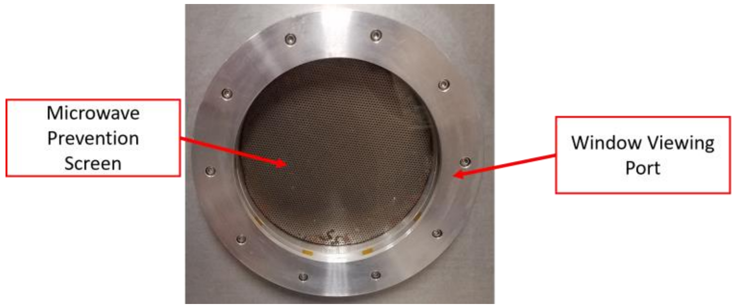

Figure 4.6 Microwave Prevention Fixture Mounted in DTVAC Window View Port

4.3 Testing of Metal Velvet for use in the DTVAC

Metal Velvet (MV), produced by Acktar, is an adhesive backed foil that has an ultralow reflective coating applied to its surface. Due to the interior of the DTVAC and exterior of the regolith bin being polished and brushed aluminum, the amount of heat transfer due to radiation is minimal. The heat transfer due radiation was sought to be improved with the application of MV which would approximate a black body, allowing for a higher absorption and lower reflectance. The goal of the MV application was to decrease the time necessary for lowering the icy regolith's temperature by increasing the radiative heat flux. A series of experiments were conducted to quantify the difference in temperature for areas where the MV was applied and to areas where it was not applied. Additionally, the ruggedness of the coating and performance of the adhesive in extreme temperatures was tested.

The first set of experiments sought to characterize the heat transfer between the DTVAC's thermal shroud with MV applied and the unmodified regolith bin. This was accomplished by creating the test fixture seen in Figure 4.7 that suspended two identical aluminum sheet metal squares over the thermal shroud with and without the MV. A diagram of the fixture can be seen in Figure 4.8.

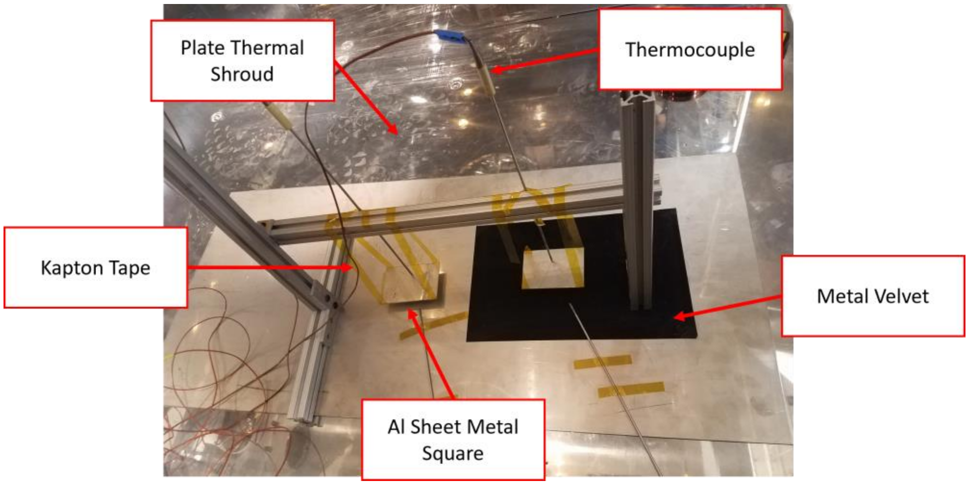

Figure 4.7 Suspended Identical Aluminum Sheet Metal Squares to Simulate With and Without MV on Thermal Shroud. Squares are suspended using Kapton tape to limit conduction.

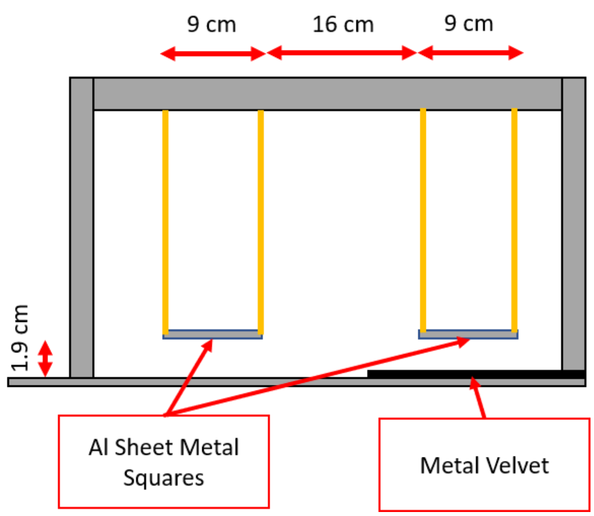

Figure 4.8 Diagram of Test Fixture used in Simulating MV on Thermal Shroud

Thermocouples were placed at areas shown in Figure 4.7 to help illustrate the effects of the difference in heat flux between the two test samples. Figure 4.9 shows the difference between the sheet metal squares' temperature and the temperature of the surface below them. The difference between the surface with the MV applied and the sheet metal square directly above it is lower overall compared to the test sample without the MV. This implies that the heat transfer between surfaces is greater with the MV than without.

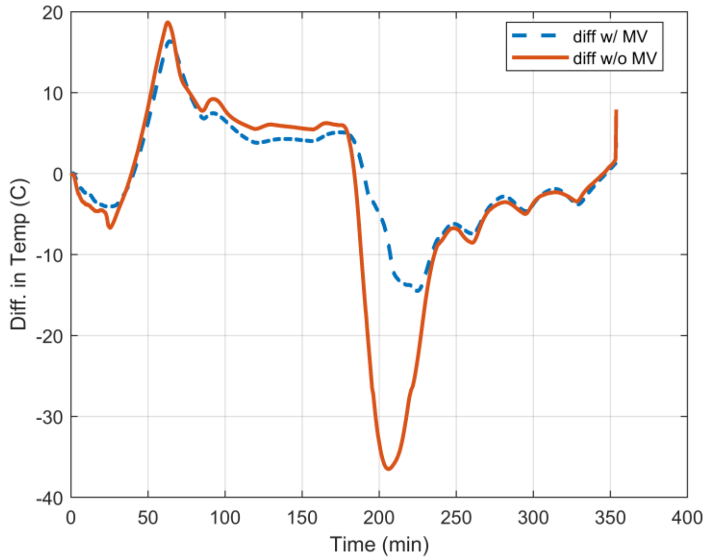

Figure 4.9 Difference in Temperature between Plate Thermal Shroud and Aluminum Squares with and without MV. Thermal Shroud was cooled to -50C then heated to 100 C. Values close to zero are desired which correlates to more heat transfer between surfaces.

The second set of experiments were performed to characterize the heat transfer between the regolith bin with the MV applied and the unmodified DTVAC thermal shroud. Initially, the same test fixture used in the previous experiments was to be used, but it was found that the MV adhesive was too strong to remove. Thus, the sheet metal that it was applied to was suspended as seen in Figure 4.10. A diagram of the test sheet metal suspended can be seen in Figure 4.11.

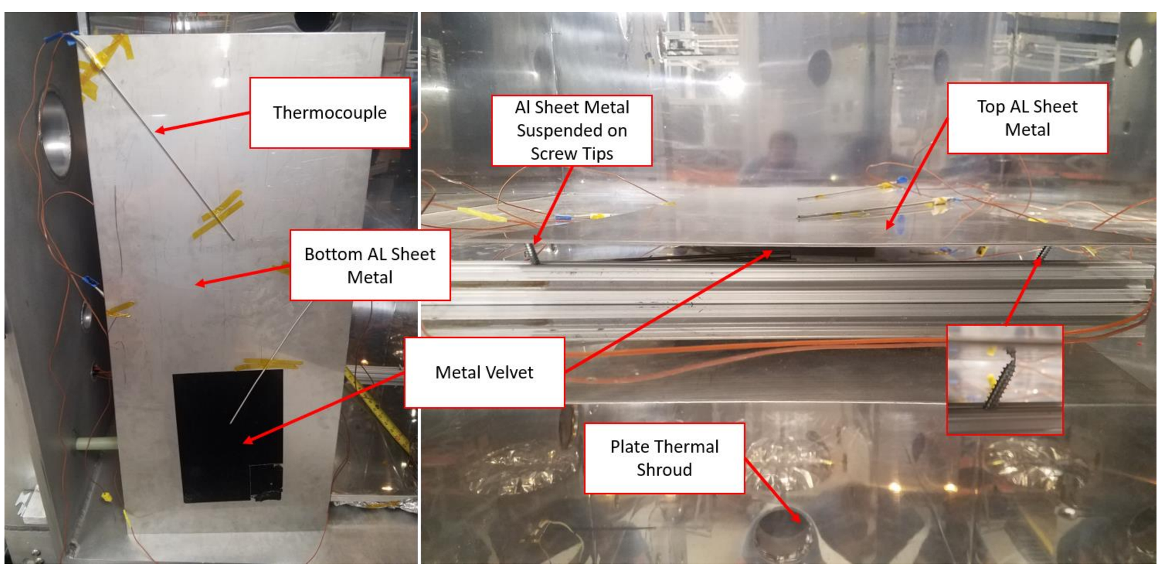

Figure 4.10 Aluminum Sheet Metal Test Fixture to Simulate MV on Regolith Bin Suspended on Screw Tips to Limit Conduction

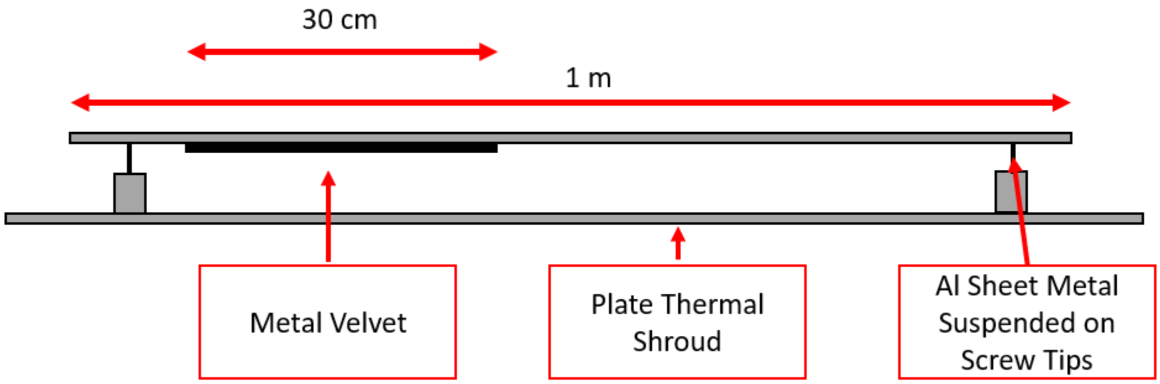

Figure 4.11 Diagram of Test Fixture used in Simulating MV on Regolith Bin

Figure 4.12 shows the difference in temperature between the areas with and without the MV and the thermal shroud below them. The results are similar to the experiment before, showing that with the MV the temperature difference between the two surfaces is less, indicating a better thermal coupling between the surfaces.

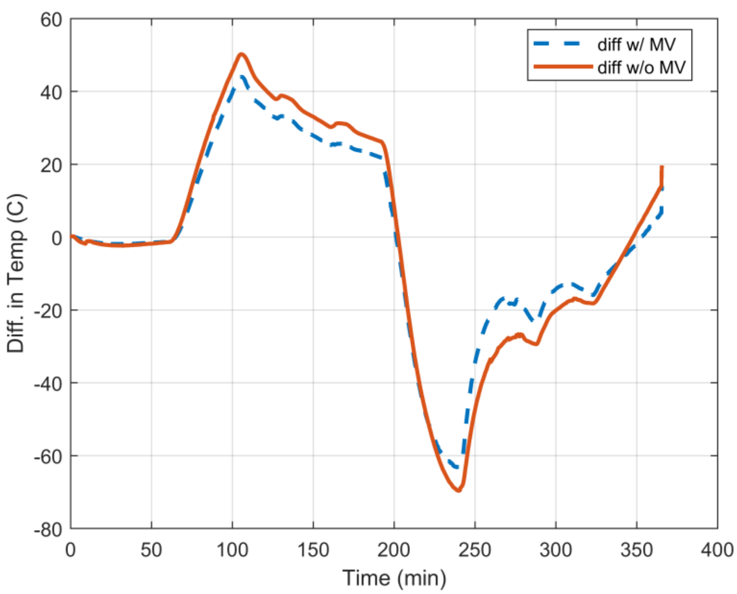

Figure 4.12 Difference in Temperature between Plate Thermal Shroud and Aluminum Sheet with and without MV. Thermal Shroud was cooled to -50C then heated to 100 C.

Although the results of the thermal analysis were favorable, the PSTDL chose not to purchase MV for the entire DTVAC thermal shroud. From doing the experiments listed, the black coating on the MV started to wear and was easily scratched. Although the adhesive was proven to function at extreme temperatures, it was incredibly difficult to remove. If the MV were to be purchased for the entire chamber, it would eventually have to be replaced and the adhesive used would make the task extremely difficult. These

factors, along with the cost of $4400, proved that the MV was not suitable for use at this time.

5 Early Stage Innovations Gantry Crane

The ESI project involves a pressure differential pumping system that is used to pump deposited gypsum slurry into a reservoir. The PSTDL raised the TRL of this system by testing it in the DTVAC. A gantry crane, shown in Figure 5.1, was designed, built, and mounted on the regolith bin, allowing for the suction of slurry in two dimensions within the depressurized DTVAC. A stepper motor control system was created to allow users to maneuver the crane and suction device to the areas desired.

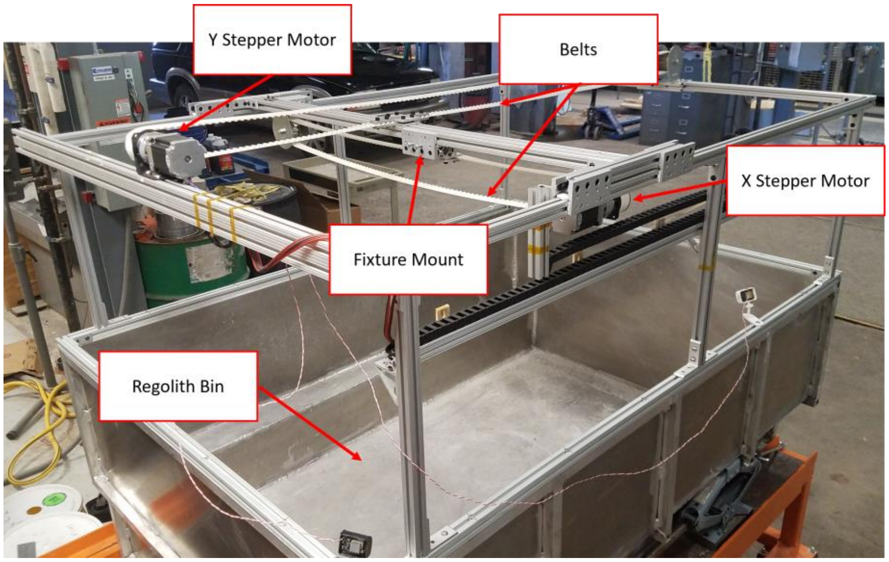

Figure 5.1 Gantry Crane mounted on Regolith Bin

The appropriate stepper motor drivers were purchased based on the stepper motors voltage and current requirements [17]. Inputs to the drivers are as seen in Table 5.1, and the connections were made with a common anode arrangement to an Arduino Mega ADK.

Table 5.1 Gantry Stepper Motor Driver Connections to Arduino Mega for X and Y Motors

Input	**Purpose**	**X Motor Connection**	**Y Motor Connection**
PUL+	Square Pulse directing Stepper Speed	Arduino +5V	Arduino +5V
PUL-	Square Pulse directing Stepper Speed	Arduino D11	Arduino D9
DIR+	Step Signal representing direction	Arduino +5V	Arduino +5V
DIR-	Step Signal representing direction	Arduino D36	Arduino D43
ENA+	Step Signal Enabling Motor	N/A	N/A
ENA-	Step Signal Enabling Motor	N/A	N/A

To control the speed and direction of the stepper motors, a joystick potentiometer provided input to the Arduino. This was done by reading the X and Y positions of the potentiometer, and then mapping the values to the speeds for the X and Y stepper motors. The AccelStepper Arduino Library was used to generate the PUL and DIR signals with the inputted speeds. Two buttons were connected to digital pins on the Arduino with anti-bounce coding. The speed of the motors is set to zero if the first button is not pressed, and the second button transitions stepping speed from low to high. LEDs were added to the controller, shown in Figure 5.2, to indicate when a button was pressed, and a mechanical switch was used to control power to the Arduino controller. The connections made can be found in the script developed for the controller found in Appendix C.

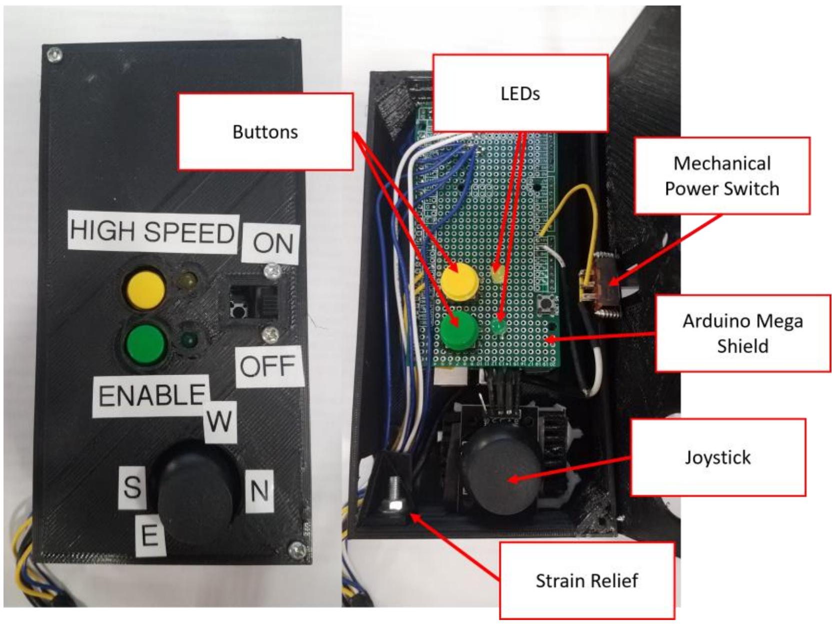

Figure 5.2 Gantry Stepper Motor Controller in 3D Printed Box

With the purchased stepper motor drivers, Arduino controller, and power supply located outside of the DTVAC, the gantry crane can be remotely operated while the DTVAC is depressurized. The crane can move the fixture in an area 1.32 m long and 1.17 m wide, at speeds of 3 cm/sec and 6 cm/sec for low and high-speed selections, respectively.

6 Future Work

Improvements to the DTVAC and surrounding facilities continue to be made. Projects that are currently underway include installation of a non-adhesive MV, freezing and heating shipping containers, and tests to find the characteristics of large samples of regolith.

6.1 Freezing and Heating Insulated Shipping Containers

Two retrofitted insulated 40 ft. shipping containers have been acquired by the PSTDL and will be installed on the MTU grounds. One container will be able to maintain temperatures below freezing and will be used to create icy regolith and perform frozen regolith tests in atmospheric conditions. The other container produces heated air currents that will be used to dry and recycle the used icy regolith. Projects concerning these containers will include procedures and documentation on use, as well as fixtures for performing regolith handling.

6.2 Testing of Large Icy and Dry Regolith Samples

To date, only one large (>=770 kg) sample of regolith has been tested in the DTVAC. If the PSTDL is to routinely test devices with large simulant beds, then the characteristics of the simulant beds alone in a vacuum chamber at extreme temperatures must be found. Future simulant tests will seek to see the effects of large icy and dry regolith beds in the vacuum chamber such as pump down time and time required for the regolith to reach the desired temperature.

7 Conclusion

The DTVAC is a facility that will create extraplanetary environments, such as those found on the Moon and Mars, with the use of vacuum pumps and simulated regolith. The simulated environments will be used to test the TRL of systems and devices created for use in space. Two other DTVAC facilities were explored, including the LETS system and the MPD and Canadian Space Agency DTVAC. These DTVACs are being used to examine the effects of charged regolith particles on exploration vehicles.

For preparing the DTVAC for TRL testing, facilities and fixtures were created and tested. This includes a DAC where users can record data from within the vacuum chamber with the use of open-source cameras and a National Instruments DAQ that are protected from dust and tampering with a lockable sealed enclosure. The behavior of the vacuum chamber at the higher and lower temperature operating conditions of 150 and near -196 degrees Celsius was observed. It was found that the chamber could exhibit temperatures sufficient for Moon and Mars testing, while being able to remain at an absolute pressure below 1E-5 Torr.

Fixtures and a test bed were created and tested in preparation for the testing of TransAstra’s Beetle device. Fixtures for preventing microwave radiation leakage to outside of the DTVAC were created and installed. A 770 kg batch of icy regolith was produced and tested in the DTVAC to understand its characteristics in the chamber while be cooled and depressurized. MV was tested in the DTVAC to determine if it was appropriate for use and was found to generate better heat transfer characteristics but was not durable enough. Other products similar to MV are being explored.

A gantry crane stepper motor controller was created using an Arduino Microcontroller that will allow users to operate the crane from the outside of the DTVAC. This system has been and will be used to move devices or fixtures within the chamber during testing.

Lastly, future work concerning the setup of facilities to create icy regolith year-round is underway. An insulated freezer container will be used to create icy regolith that will be tested in the DTVAC. The thawed icy regolith will then be dried in an insulated heating container for reclamation. Fixtures and procedures are to be developed for the PSTDL icy regolith creation facilities.

8 Works Cited

[1] P. Craven, J. Vaughn, T. Schneider, J. Norwood, M. Abbas, and R. Alexander, "MSFC Lunar Environment Test System (LETS) System Development," p. 20, 2009.

[2] "20090002581.pdf." Accessed: Jun. 28, 2021. [Online]. Available: https://ntrs.nasa.gov/api/citations/20090002581/downloads/20090002581.pdf

[3] R. V. Kruzelecky *et al.*, "Dusty Thermal Vacuum (DTVAC) Facility Payloads Operations under Simulated Lunar Environment," pp. 1012–1026, Apr. 2021, doi: 10.1061/9780784483374.093.

[4] R. Kruzelecky *et al.*, "DTVAC Dusty Planetary Thermo-VACuum Simulator Commissioning and LN2 Upgrade," Jul. 2018, Accessed: Feb. 16, 2021. [Online]. Available: https://ttu-ir.tdl.org/handle/2346/74179

[5] R. V. Kruzelecky *et al.*, "Dusty Thermal Vacuum (DTVAC) Facility Integration," pp. 1189–1202, Nov. 2018, doi: 10.1061/9780784481899.112.

[6] I. Tzinis, "Technology Readiness Level," *NASA*, May 06, 2015. http://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level (accessed Jun. 28, 2021).

[7] T. Sharp, "What is the Temperature on the Moon?," *Space.com*. https://www.space.com/18175-moon-temperature.html (accessed Jun. 28, 2021).

[8] "What is the Temperature of Mars?," *Space.com*. https://www.space.com/16907-what-is-the-temperature-of-mars.html (accessed Jun. 28, 2021).

[9] "Mars." https://mars.nasa.gov/MPF/mpf/realtime/mars2.html (accessed Jun. 28, 2021).

[10] "What is the Purpose of a Vacuum Pump," *Vacaero*, Sep. 07, 2015. https://vacaero.com/information-resources/vacuum-pump-technology-education-and-training/1009-what-is-the-purpose-of-a-vacuum-pump.html (accessed Jul. 08, 2021).

[11] "CompactRIO Systems." https://www.ni.com/en-us/shop/compactrio.html (accessed Jun. 29, 2021).

[12] "K Type Thermocouple - Introduction,Usage and its Composition." https://tempsens.com/blog/k-type-thermocouple (accessed Jun. 29, 2021).

[13] "Application Design Patterns: State Machines." https://www.ni.com/en-us/support/documentation/supplemental/16/simple-state-machine-template-documentation.html (accessed Jul. 01, 2021).

[14] "Producer/Consumer Architecture in LabVIEW." https://www.ni.com/en-us/support/documentation/supplemental/21/producer-consumer-architecture-in-labview0.html (accessed Jul. 01, 2021).

[15] "Lunar Polar Mining Operations," *TransAstra Corporation*. https://www.transastracorp.com/lunar-polar-mining (accessed Jul. 08, 2021).

[16] "Radiant Gas Dynamic Mining™," *TransAstra Corporation*. https://www.transastracorp.com/rgd-mining (accessed Jul. 01, 2021).

[17] "M542T.pdf." Accessed: Jul. 03, 2021. [Online]. Available: https://www.omc-stepperonline.com/download/M542T.pdf

A DTVAC SOP

Additional information available in DTVAC ring binder in the filing cabinet.

1. Operations for **pump down** process for **every operating condition**
    a. Ensure that the door seal is clear of debris, grease, or any other substance.
    b. Ensure the door gasket is free of cracks, tears, or any other imperfections.
    c. Remove guards/safety lockout and close the chamber door.
    d. Check feedthrough ports for disturbance, ensure all are installed properly.
    e. Check coupling points for turbopump and roughing pump, ensure all are installed properly.
    f. Ensure that the LN2 exhaust valve for the DTVAC is open, and the exhaust valve for the small vacuum chamber is closed.
    g. Check turbopump oil level.
        i. Meniscus should be out of sight, above the top of the viewport.
    h. Ensure the roughing pump gas ballast valve is closed.
        i. Exception – Water Vapor Operating Condition
    i. Ensure the roughing pump silencer is emptied of condensed moisture.
        i. Silencer is located on the exit of the roughing pump. Detach clamp and remove.
    j. If using the turbo-pump, turn on the turbo-pump water supply.
        i. Located on the I-beam in front of the mini vacuum chamber.
        ii. Turn the handle roughly 30 degrees counterclockwise.
    k. Turn on the control panel (main power switch), ensure no errors present on DPG and DCU LCD screens.
        i. If using the turbo-pump, turn on the turbo-pump switch (Turbo).
    l. Turn on/setup data acquisition system.
        i. PC_Watlow_DPG_measurements_5w.vi for capturing data from the vacuum chamber controllers.
        ii. NICRIO_thermocouples_measurements.vi for recording thermocouple values
    m. Begin to pump down by pressing the big green button.
2. Operations for **venting** process for **every operating condition**
    a. Ensure manual valve venting knobs are in the desired position.
    b. Hit the vent button.
    c. Ensure Turbo has spooled down to below 10000 RPM before solenoid valves open.
    d. Turn off Turbo water 5 minutes after 0 RPM has been reached.
    e. Let the chamber come to ambient pressure by hitting the big red button.
        i. Usually, 750 Torr
        ii. Read from channel 2 on DPG.
            1. Channel 1 is not accurate at higher pressures.
    f. Stop data recording.

g. Turn off the control panel (main power switch).
h. If the chamber is wet, leave it open. If dry, close the chamber to prevent contamination.

3. Operations for **pump down and venting** process for a **Hot Test** operating condition
    a. Ensure no items inside the chamber that will melt at 200 deg C are touching the walls or plate.
    b. Turn on the liquid nitrogen (LN2) manual valve slowly.
    c. Begin pumping down after completing items in section 1.
    d. Adjust temperature controllers to desired positions.
    e. Once 5 Torr is reached (turbopump starting pressure) increase temperature at a slower rate to ensure pressure does not exceed 5 Torr.
        i. If pressure starts to rise and exceeds 5 Torr ensure turbo shuts down, or the turbo bearing temperature does not exceed its normal range of 57-65 deg C. (Turbo has overheating failsafe)
        ii. Pressure rise is due to materials off gassing at higher rates due to high temperatures.
    f. When ending the test, adjust temperature controllers to ambient conditions.
    g. Vent when shroud and plate temperatures are within 5 degrees of ambient conditions.
    h. Ensure that one or both of the LN2 control valves are open, then turn off the LN2 manual valve.
    i. Once ambient pressure is reached, open.
        i. Be careful, as Thermal shroud walls, plate, and door will still be warm/hot.
4. Operations for **pump down and venting** process for **Wet Hot Test**
    a. Follow directions for Hot Test operating condition (section 3) with additional following instructions.
    b. One hour before pump down, ensure the inlet solenoid valve on the roughing pump is closed. Open gas ballast valve on roughing pump. Let the roughing pump operate for one hour before pump down.
    c. Before pumping down, remove the roughing pump silencer.
    d. While pumping down, if there is a lot of water vapor being produced, open the gas ballast valve until the amount of vapor has decreased. (see page 31/32 in the ACP40 manual).
        i. Ensure the gas ballast valve is closed if the turbo pump is on.
5. Operations for **pump down and venting** process for a **Cold Test** operating condition
    a. Turn on the liquid nitrogen (LN2) valve slowly.
    b. Begin pumping down after completing items in section 1.
    c. Adjust temperature controllers to desired positions.

            i. **If the desired temperatures are low (-150 to -196) ensure that LN2 is not coming out of the exhaust pipe outside (pipe going to roof level). If LN2 droplets are coming out, then partially close the manual shutoff valve inside.**

   d. When ending the test, adjust temperature controllers to ambient conditions.
   e. Vent when shroud and plate temperatures are within 5 degrees of ambient conditions.
   f. Ensure that one or both of the LN2 control valves are open, then turn off the LN2 manual valve.
   g. Once ambient pressure is reached, open the chamber.
      i. Be careful, as Thermal shroud walls, plate, and door will still be cold.

6. Operations for **pump down and venting** process for **Wet Cold Test**
   a. Follow directions for Cold Test operating condition (section 5) with additional following instructions.
   b. One hour before pump down, ensure the inlet solenoid valve on the roughing pump is closed. Open gas ballast valve on roughing pump. Let the roughing pump operate for one hour before pump down.
   c. Before pumping down, remove the roughing pump silencer.
   d. While pumping down, if there is a lot of water vapor being produced, open the gas ballast valve until the amount of vapor has decreased. (see page 31/32 in the ACP40 manual).
      i. Ensure the gas ballast valve is closed if the turbo pump is on.

B Icy Regolith Making Procedure

1. Shave ice at the ice shaving station using the procured ice in bags. Use a 5-gallon bucket to collect the shaved ice.
2. Open a sealed 5-gallon bucket containing dried regolith. **Weigh the bucket**, then pour the regolith into the concrete mixer slowly and cautiously to ensure little dust is produced. A scoop can be used to assist the pouring of the regolith, and if too much dust is being produced, then it is recommended to scoop the regolith from the bucket to the mixer.
3. Weigh the empty bucket and subtract the weight of the regolith and bucket from the weight of the bucket to obtain the weight of the regolith. For a 10% water to regolith mixture, multiply the regolith's weight by 0.10 and measure out a sample of shaved ice whose weight is equal to the product found.
4. Place the measured shaved ice sample into the mixer. Use a scoop to roughly mix the regolith and ice. Ensure that no ice is in contact with the mixer walls or paddles, otherwise it will stick and not mix properly.
5. Cover the mixer opening using the supplied plastic sheet and bungy strap. Place the plastic sheet over the opening, then secure it by running the bungy strap around the lip of the mixer and hooking the ends together.
6. Turn on the mixer and let run for up to 5 minutes. The time needed will have to be adjusted depending on the conditions observed. More or less time may be optimal. While the mixer is running, use the transport handles to tilt the mixer back and forth along the axle axis. This action enhances mixing**. Ensure not to over tilt the mixer to where the regolith hits the plastic sheet around the opening.** This will cause regolith mixture to be stuck in the crevice between the lip and sheet, resulting in lost material.
7. When the regolith mixture is being mixed, prepare then next batch of dried regolith and shaved ice. Use the determined bucket weight from the previous batch so that the next batch can be prepared without emptying the regolith bucket.
8. After an appropriate amount of time has elapsed, turn off the mixer, and let sit as is for 2-5 minutes, or until the dust inside has settled.
9. Remove the plastic sheet and bungy strap.
10. Ensure that the regolith and ice mixture is completely mixed by using a scoop to move the mixture around inside the mixture. Look to see if any large clumps remain, or if ice has stuck to a surface of the mixer. If clumps are seen, use the scoop to break them apart as much as possible. Then proceed to repeat steps e-j, it is likely less time will be needed to mix, adjust based on your observations.
11. Once the regolith and ice are properly mixed, wheel the mixer to the icy regolith sandbox. Use a scoop to empty the contents from the mixer to the sandbox.
12. Repeat steps c-k for the remaining available dried regolith buckets, or until the desired amount of icy regolith is reached.
13. While mixing is in progress, use the scoops to spread the mixture evenly inside the sandbox. Pack the mixture lightly after each layer is added.

C Arduino Script for Gantry Crane Controller

```
/*
 * DTVAC Gantry Crane Steppers Control
 * Ben Wiegand
 * version 3.0
 * 4/2/21
 */
//code with only one enable, just controls speed input

 //arduino mega adk interrupt pins  2, 3, 18, 19, 20, 21

//PINS IN USE
int x_mot_enb_but_pin=2; // x motor enable button input pin
int x_pot_pin=A8; // x motor joystick input pin
int x_mot_enb_led_pin=23; // x motor led output pin
int x_mot_pul_pin=8; // x motor pulse output pin
int x_mot_dir_pin=24; // x motor direction output pin
int x_mot_enb_pin=26; // x motor enable output pin

int y_mot_enb_but_pin=20; // x motor enable button input pin
int y_pot_pin=A7; // x motor joystick input pin
int y_mot_enb_led_pin=28; // x motor led output pin
int y_mot_pul_pin=9; // x motor pulse output pin
int y_mot_dir_pin=40; // x motor direction output pin
int y_mot_enb_pin=32; // x motor enable output pin

int hl_speed_pin=3; // high-low speed interrupt pin

//ACCEL STEPPER
#include <AccelStepper.h>
//setup accel stepper objects
AccelStepper x_stepper(1,x_mot_pul_pin,x_mot_dir_pin); //1 indicates
mode
AccelStepper y_stepper(1,y_mot_pul_pin,y_mot_dir_pin); //1 indicates
mode
//stepper max speed, min speed, accel
float step_max_spd=2000; // maximum stepping speed
float step_min_spd=1.00; // min steppping speed
float step_accel=20.00; // stepping acceleration

//JOYSTICK GBs
int x_pot_speed=0; //speed mapped from pot to stepper
int x_pot_cent=502; // center of joystick analog value
int y_pot_speed=0; //speed mapped from pot to stepper
int y_pot_cent=509; // center of joystick analog value

//BUTTON GBs
bool x_enb=LOW; // boolean for x enable button
unsigned long x_enb_t=0; //time since last execution
bool y_enb=LOW; // boolean for x enable button
unsigned long y_enb_t=0; //time since last execution
bool hl_speed_state=HIGH;
unsigned long hl_enb_t=0;
int hl_speed_mltp=2;
```

```
int z_speed=0;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(115200);
  Serial.println("Setup Initiated");

  //DEFINE PIN INPUTS/OUTPUTS
  //inputs
  pinMode(x_mot_enb_but_pin,INPUT_PULLUP);
  pinMode(x_pot_pin,INPUT);
  pinMode(y_mot_enb_but_pin,INPUT_PULLUP);
  pinMode(y_pot_pin,INPUT);
  pinMode(hl_speed_pin,INPUT);
  //outputs
  pinMode(x_mot_enb_led_pin,OUTPUT);
  pinMode(x_mot_pul_pin,OUTPUT);
  pinMode(x_mot_dir_pin,OUTPUT);
  pinMode(x_mot_enb_pin,OUTPUT);
  pinMode(y_mot_enb_led_pin,OUTPUT);
  pinMode(y_mot_pul_pin,OUTPUT);
  pinMode(y_mot_dir_pin,OUTPUT);
  pinMode(y_mot_enb_pin,OUTPUT);

  //ATTACH INTERRUPTS FOR BUTTONS
  attachInterrupt(digitalPinToInterrupt(x_mot_enb_but_pin), x_mot_enb,
CHANGE);
//  attachInterrupt(digitalPinToInterrupt(y_mot_enb_but_pin),
y_mot_enb, CHANGE);
  attachInterrupt(digitalPinToInterrupt(hl_speed_pin), hl_speed,
CHANGE);

  //SET STEPPER DEFAULT SETTINGS
  x_stepper.setMaxSpeed(step_max_spd);
  x_stepper.setAcceleration(step_accel);
  y_stepper.setMaxSpeed(step_max_spd);
  y_stepper.setAcceleration(step_accel);

  Serial.println("Setup Complete");
}//END SETUP

void loop() {
  // put your main code here, to run repeatedly:
  x_stepper.runSpeed(); //needs to be executed continuously, tells
motor to step
  y_stepper.runSpeed();

  //ANALOG JOYSTICK/POT INPUT
  int x_pot=analogRead(x_pot_pin);
  int y_pot=analogRead(y_pot_pin);

  x_stepper.runSpeed();
  y_stepper.runSpeed();

  //MAP JOYSTICK TO +/- SPEED X direction
```

```
  if(x_pot<x_pot_cent-2){ // for joystick off center
    //map pot min max input to stepper min max spd, *-1 for ccw
    x_pot_speed=map(x_pot,x_pot_cent,0,step_min_spd,step_max_spd);
    x_pot_speed=x_pot_speed*-1;
  }
  else if(x_pot>x_pot_cent+2){
    //map pot min max input to stepper min max spd, *1 for cw
    x_pot_speed=map(x_pot,x_pot_cent,1023,step_min_spd,step_max_spd);
    x_pot_speed=x_pot_speed*1;
  }
  else{
    x_pot_speed=0;
  }

  x_stepper.runSpeed();
  y_stepper.runSpeed();

  //MAP JOYSTICK TO +/- SPEED Y direction
  if(y_pot<y_pot_cent-2){ // for joystick off center
    //map pot min max input to stepper min max spd, *-1 for ccw
    y_pot_speed=map(y_pot,y_pot_cent,0,step_min_spd,step_max_spd);
    y_pot_speed=y_pot_speed*-1;
  }
  else if(y_pot>y_pot_cent+2){
    //map pot min max input to stepper min max spd, *1 for cw
    y_pot_speed=map(y_pot,y_pot_cent,1023,step_min_spd,step_max_spd);
    y_pot_speed=y_pot_speed*1;
  }
  else{
    y_pot_speed=0;
  }

  x_stepper.runSpeed();
  y_stepper.runSpeed();

  //SET AND RUN STEPPER AT DETERMINED SPEED
  x_stepper.setSpeed(z_speed*x_pot_speed/hl_speed_mltp);
  y_stepper.setSpeed(z_speed*y_pot_speed/hl_speed_mltp);
  //WHILE LOOP IF NO CHANGE IN INPUT FROM POT
  //do this to increase speed of stepper
  while(x_pot==analogRead(x_pot_pin) && y_pot==analogRead(y_pot_pin)){
    x_stepper.runSpeed();
    y_stepper.runSpeed();
  }
  x_stepper.runSpeed();
  y_stepper.runSpeed();

} //END LOOP

// Interrupt function to enable/disable both motors
void x_mot_enb(){
  unsigned long cur_t_x=millis();
  if(cur_t_x-x_enb_t>500){
    x_enb_t=cur_t_x;
    x_enb=!x_enb;
```

```
    if(x_enb==HIGH){
      z_speed=1;
      Serial.println("motors enabled");
      digitalWrite(x_mot_enb_led_pin,HIGH);
    }
    else if(x_enb==LOW){
      z_speed=0;
      Serial.println("motors disabled");
      digitalWrite(x_mot_enb_led_pin,LOW);
    }
  }
} //END X_MOT_ENB

//Interrupt function to switch btw high and low speed
void hl_speed(){
  unsigned long cur_t_hl=millis();
  if(cur_t_hl-hl_enb_t>500){
    hl_enb_t=cur_t_hl;
    hl_speed_state=!hl_speed_state;
    if(hl_speed_state==LOW){
      hl_speed_mltp=2;
      Serial.println("Low Speed");
      digitalWrite(y_mot_enb_led_pin,LOW);
    }
    else if(hl_speed_state==HIGH){
      hl_speed_mltp=1;
      Serial.println("High Speed");
      digitalWrite(y_mot_enb_led_pin,HIGH);
    }
  }
}
```