Kennedy Space Center
Fluids Test Engineer Internship Report
NE-F6 Fluids Testing and Technology Development Branch

INTERNSHIP TASKS ASSOCIATED WITH CIF ICY REGOLITH EXCAVATION AND VOLATILE CAPTURE UNDER VACUUM CONDITIONS

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Abstract:

Understanding the surface and atmosphere of Mars is critical to current and future development of exploration systems. Dealing with the Martian regolith—the top layer of soil—remains a significant challenge, and much research is still needed. Addressing this need, the Cryogenics Test Lab and Granular Mechanics and Regolith Operations Lab at NASA's Kennedy Space Center are partnering to develop an apparatus that utilizes simulated Martian regolith in an analogous atmospheric environment to gather data about how the material behaves when exposed to water vapor. Martian surface temperatures range from 128 K (-145°C) to 308 K (35°C), and the average pressure is approximately 4.5 Torr; which presents an environment where water can potentially exist in vapor, solid or liquid form. And based on prior Mars missions such as the Phoenix Lander, it is known that water-ice exists just below the surface. This test apparatus will attempt to recreate the conditions that contributed to the Martian ice deposits by exposing a sample to water vapor at low pressure and temperature; thereby forming ice inside the simulant via diffusion. From this, we can better understand the properties and behavior of the regolith, and have more knowledge concerning its ability to store water—and subsequently, how to dig up and extract that water—which will be crucial to sample gathering when the first manned Mars mission takes place.

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LISTING OF NOMENCLATURE

T — Temperature, *Kelvin (K)*

H — Distance between two blackbodies, *meters (m)*

X— Geometric configuration constant

σ — Stephen-Boltzmann constant = 56.69 x $10^{-9}\frac{W}{[(m)^2 - K^4)}$

R_1—Radius of sample surface, *meters (m)*

R_2—Radius of heater plate, *meters (m)*

A_1—Area of sample surface, *meters squared (*m^2)

Q—Heat, *Watts (*W *)*

F_e—Emissivity Factor

F_{12}—Radiation Configuration Factor

e_1—Emissivity of heater plate

e_2—Emissivity of sample surface

1. INTRODUCTION

During Spring semester 2014, I was privileged to work side-by-side with scientists and engineers of the Cryogenics Test Laboratory (CTL). I worked on a wide variety of projects that ranged from pipe insulation to nano-fabric material wicking experiments. One of these projects was called *CIF Icy Regolith Excavation and Volatile Capture under Vacuum Conditions* or *Icy Regolith* for short. The objective of this project was to expose cold (cryogenic) regolith simulant to water vapor in a vacuum chamber under analogous Martian atmospheric pressure and composition, thereby causing ice to form inside the granular material. From there, the regolith must be extracted from the testing apparatus and analyzed to determine the density and location of the ice. Once the process is understood, and can be predictably repeated, excavation technologies will be tested under vacuum conditions to further understand the mechanical properties of the simulated icy regolith. The initial simulated regolith will be 500-600 µm glass spheres due to the ease of its analytical modeling and to compare to previous work.

Figure 1.1 — Evidence of water-ice uncovered from Mars Phoenix lander in 2008[4]

Both the Cryogenics Test Laboratory (CTL) and the Granular Mechanics and Regolith Operations Laboratory (GMRO) were involved in the construction and operation of this apparatus. Initial testing and procedure development was performed at the CTL, while larger scale mechanical testing was handled at the GMRO.

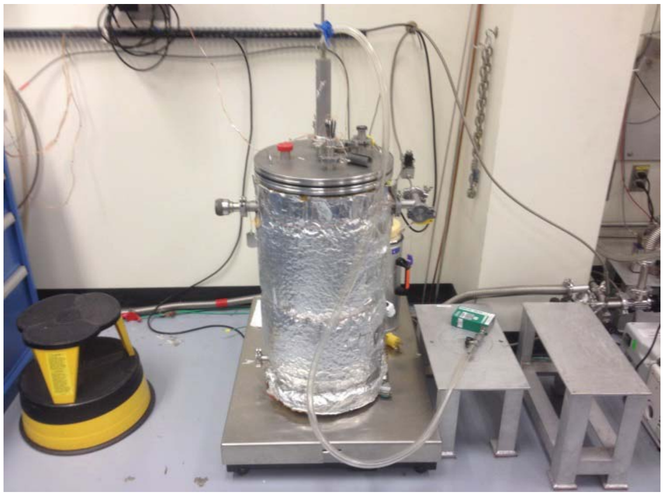

Figure 1.2 — Similar cryostat vacuum chamber used for CTL testing operations[1]

The main components of the CTL testing apparatus consist of a 12” diameter by 3’ tall vacuum chamber (see figure 1.2), an 8” diameter by 12” tall regolith sample holder, liquid nitrogen (LN_2) heat exchanger, radiative heater plate, and vacuum-jacketed LN_2 feed/return lines.
Alongside this initial, smaller testing apparatus, a second and significantly larger chamber was necessary to simulate excavation under vacuum conditions. A custom built, large-scale chamber will be fabricated by an outside vendor and then configured by the GMRO laboratory to suit the needs of the experiment.

The Icy Regolith project aims to build upon a previous study performed by researchers at Caltech. The end goal in terms of construction is to replicate this former testing apparatus in scaled-up versions for a cryostat style and a large vacuum chamber to allow for mechanical property data acquisition.

2. PROJECT TASKS

Finding the maximum gap size between the regolith sample surface and radiative heater plate

One of my duties as an intern was to help figure out the maximum gap size at which the heat required to maintain the temperature at the sample surface would potentially overpower the radiative heater plate. To do this the equations of radiation heat transfer are utilized.[2]

$$X = 1+\frac{H^2 + R_2^2}{R_1^2} \qquad (2.1)$$

$$Q = F_e F_{1-2} \sigma A_1 (T_1^4 - T_2^4) \qquad (2.2)$$

$$F_{12} = \frac{1}{2\left(X - \left[X^2 - 4\left(\frac{R_2}{R_1}\right)^2\right]^{(1/2)}\right)} \qquad (2.3)$$

$$\frac{1}{F_\varepsilon} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \qquad (2.4)$$

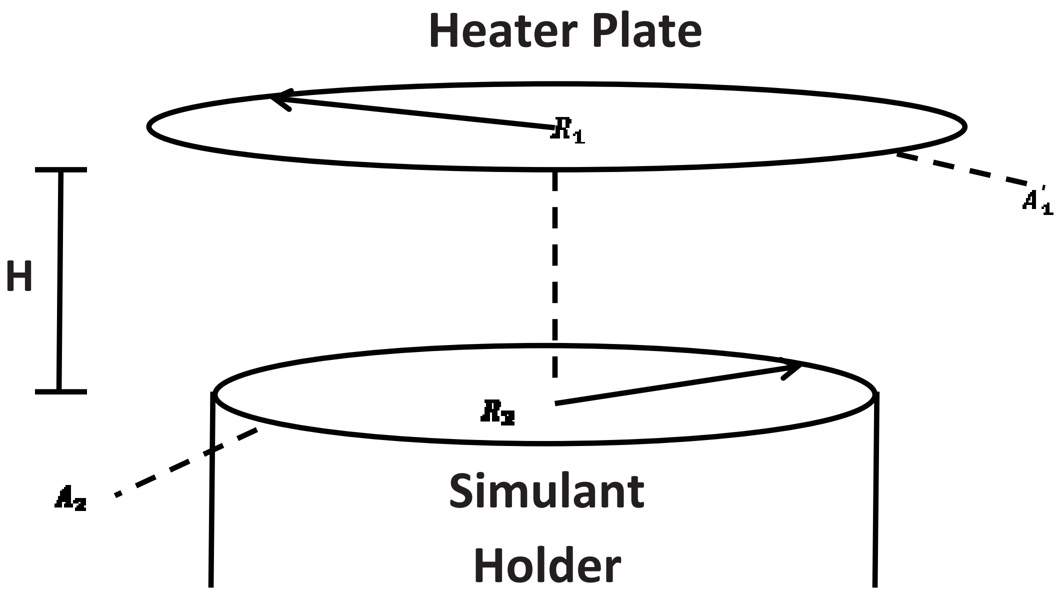

Figure 2.1 — Radiation configuration factor geometric representation

The radii for each surface is known, R_1 = 0.114 m and R_2 = 0.101 m. The emissivity for both the regolith and the black paint that will cover the heater plate is .7 and .86 respectively. Now, using equations 2.1, 2.2, 2.3, and 2.4; the heat transfer rate as a function of gap size (H) can be calculated.

The boundary conditions specify that the maximum heater plate temperature is 473 K (200°C) and the minimum sample surface temperature is 250 K (-23°C).

To start, the geometric configuration constant (X) must be found. To do this, the geometric case of the testing apparatus must be analyzed (Figure 2.1). Knowing R_1, R_2, and H, X can be found using equation 2.1. Once X is found, applying it to equation 2.3 will generate the radiation configuration factor F_{12}, or the emissivity of the heater plate onto the regolith surface.

To find the emissivity factor F_ϵ, equation 2.4 must be used. Both ϵ_1 and ϵ_2 are known by prior analysis of both the regolith and black paint. A simple application of these known values will yield F_ϵ.

As a final step, to find the heat that is being transferred between the heater plate and regolith by means of radiation, equation 2.2 is applied. By this point all variables associated with equation 2.2 are known. With the given constraints and boundary conditions, a plot was generated showing the heat transfer rate as a function of gap size. This information was then used by the design team to determine what gap size to use for the experiment.

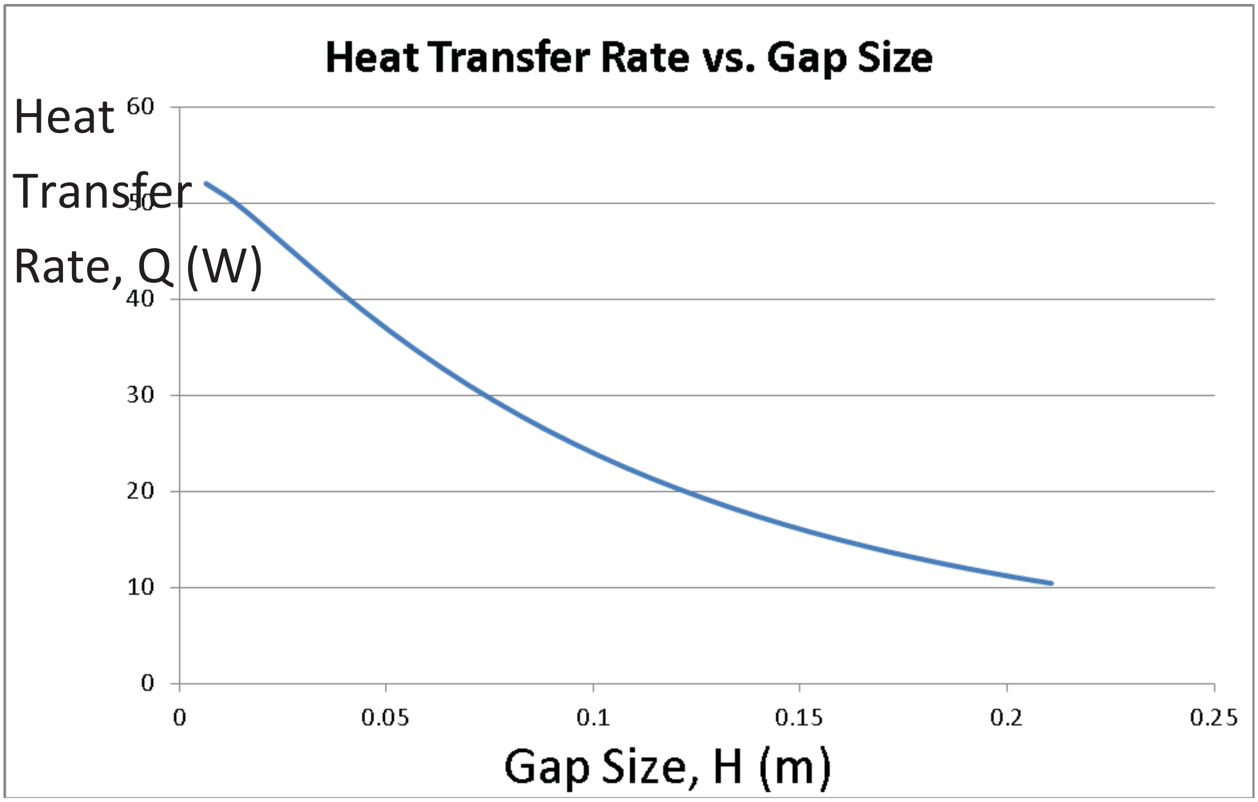

Figure 2.2 — Plot of Heat Transfer Rate vs. Gap Size

Constructing the schematic for the testing configuration

I was also given the responsibility to draft a system mechanical schematic (SMS) of the entire testing configuration. This diagram summarized all the major system components and laid out the fluid flow paths. I used the drawing tool on Pro-E/ Creo Parametric to develop the schematic, seen in Figure 2.2.

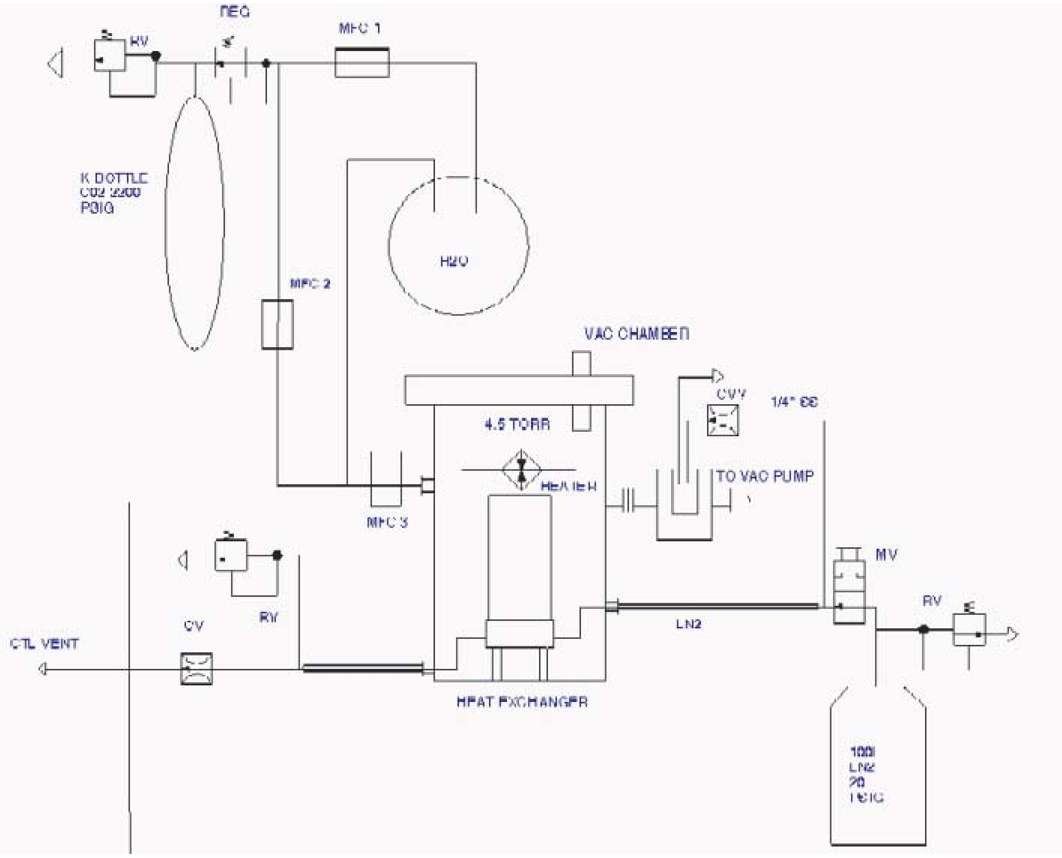

Figure 2.2 — Schematic of testing configuration

Design of alternative specimen holder

As the construction process proceeded, it was decided that a second sample holder was needed that could be broken apart into three pieces (one half, two quarters) to help with regolith excavation. I interfaced with technicians from the NASA Prototype Development Laboratory (PDL) to elaborate on this additional work request for fabrication.

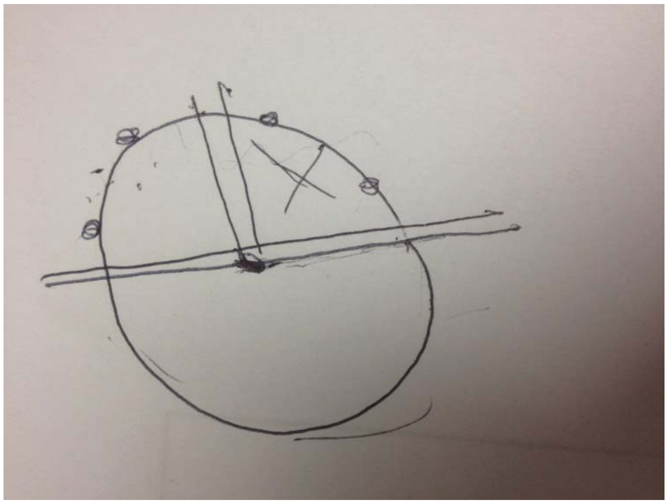

Figure 2.4 — Rough sketch of G10 cutout depiction

As depicted in Figure 2.4, the edge of the saw blade will cut across the G10 tube so that the edge of the blade will meet precisely with the center, hence making one complete 180° piece of G10. This is to accommodate for the loss of material from the saw blade. After the half piece is cut out, the shorter, non-180° piece will have the process repeated, but for a 90°, quarter piece. The remaining piece will be set aside and a second G10 tube will be cut to fill the second quarter slot.

Figure 2.5 — 8” G10 specimen holder

The 8” diameter regolith holder will also be configured to hold several “smaller” samples. This will be done by fabricating several small regolith holders at a diameter of roughly 2”. The advantage of this configuration is that various samples can be tested under the exact same testing conditions.

3. TESTING AND RESULTS/ DISCUSSION

Before beginning the testing phase of the project, the sample holder will be installed into the vacuum chamber and secured. Once the chamber is sealed, a vacuum pump is used to lower the internal pressure and carbon dioxide is fed in at a rate that maintains a 4.5 Torr environment. To chill the simulant to Martian temperatures, LN2 is fed into the chamber and through a flat-plate heat exchanger from a 100 liter dewar; target surface temperatures at the base of the regolith sample are ≈ 250K (-23°C). Once chilled, water vapor is injected into the CO2 environment and is frozen inside the regolith due to vapor diffusion.

This process is driven by the large temperature gradient between the top and bottom of the sample and should allow for various degrees of icy regolith to form at different levels inside the simulant. The simulant will also be compacted at different degrees across various levels of depth.

Figure 3.1a — CTL personnel pouring LN2

Figure 3.1b — CTL personnel checking LN2 levels

As a control, the simulant will be measured for mechanical properties prior to being exposed to the simulated Martian environment.

Once the vapor diffusion stage of operations is completed, the vacuum chamber will be opened and the simulant holder removed. The simulant will then be extracted from the holder and examined by a variety of methods. This is done to determine the ice formation process inside the simulant.

One method of examination involves splitting open the simulant holder into a half section and two quarter sections. If the simulant should hold its geometry, a razor blade can be used to split apart the sections. From there, thermocouples will be inserted into the chilled regolith where thermal and granular properties can be determined for testing procedure verification.

Another examination method involves leaving the G10 wall intact, and after exposure, a scaled-down shovel or related tool will be used to lift out small samples of the regolith that will test its mechanical properties.

A third method involves installing thermocouples into the regolith prior to exposure. From there, frequently monitoring of the change in thermal and granular properties can be made.

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusion

At the time of finalizing this report, the construction and certification of the vacuum chamber was still ongoing. Hence, initial testing data is unavailable.

However, based on the analysis of previous experiments, the understanding of the Martian surface and atmosphere, and on the granular and thermo-mechanical properties of lunar regolith (Table 4.1), which is known from acquisition of Apollo regolith samples, a theoretical conclusion can be made to be later verified.

Table 4.1 — List of simulants to be tested

Simulant	Description
JSC-1A	Lunar regolith simulant manufactured at NASA JSC. Similar to lunar regolith both chemically and mechanically.
BP-1	Discovered at the Black Point lava flow near Flagstaff, AZ. Has similar mechanical properties to lunar regolith.
FJS-3	Developed in Japan from Mount Fuji area basalts. Has similar mechanical properties to lunar regolith.

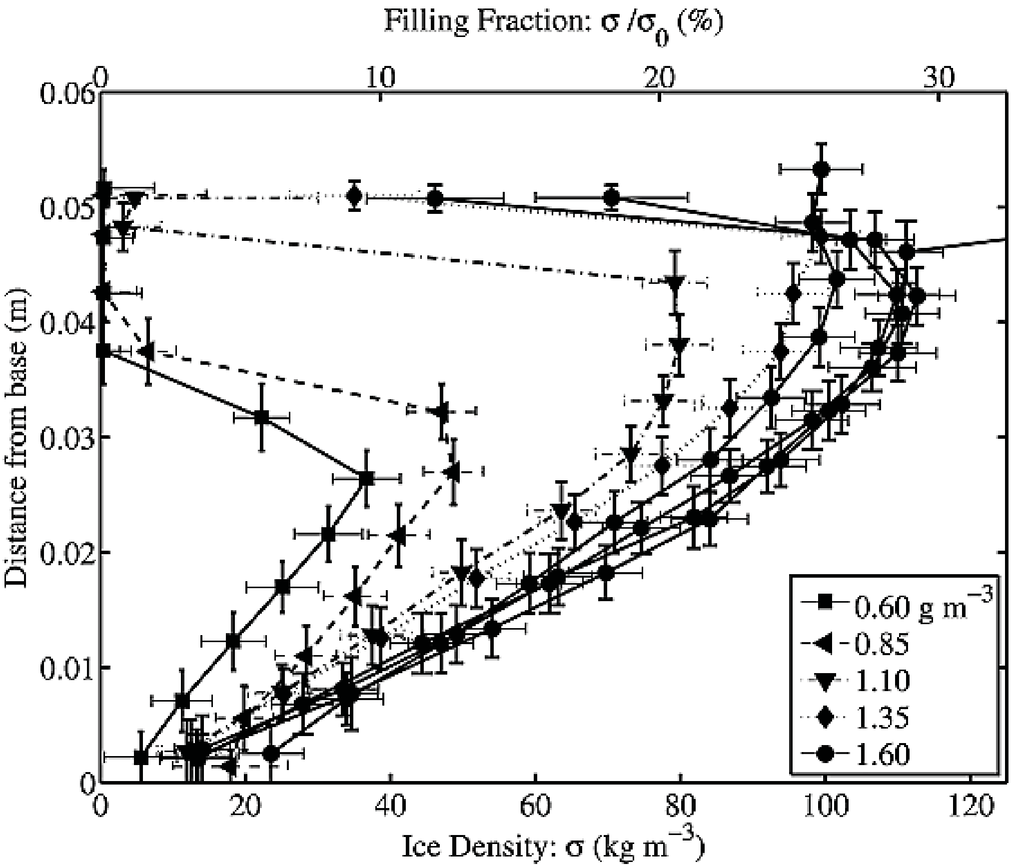

Figure 4.1 —Ice content data for experiments run for 24 hours at various vapor densities. (Previous Experiment)[3]

Based on Figure 4.1, the simulated regolith will generate the iciest regolith at a depth of roughly .005m and gradually decrease towards 0 as the depth reaches the heat exchanger at the bottom of the regolith holder. From previous work it is known that "low humidity or short-duration experiments give rise to an ice table beneath an ice-free layer, while other conditions (e.g., longer durations, higher vapor densities) produce stable surface ice.[3]" It is reasonable to assume that the Icy Regolith test setup will behave in a similar manner only on a larger scale.

The icy regolith will form in a "flake" like fashion due to the solidification of water from its vapor state, and will be concentrated at a particular depth. However, due to the nature of vapor diffusion, there will be inconsistencies throughout the specimen. This may create issues when attempting to excavate, and could require unique excavation techniques in order to successfully dig up actual Martian regolith either by unmanned rovers or humans themselves.

Final Comments

Despite the fact that I am only one and a half years into my college career, I learned several new concepts in cryogenics, thermodynamics, fluid dynamics, solids, and granular mechanics. I had the opportunity to work and think alongside engineers and scientists at the NASA Kennedy

Space Center. All of these new concepts that I have learned will undoubtedly aid in my future coursework as I traverse through my college career.

Coming into the Cryogenics Test Lab team back in January, I initially thought that cryogenics involved placing people into cryogenic hibernation and preserving bodies, a most intriguing misconception. However, after learning and gaining experience with cryogenics, I now understand that it involves far more. Cryogenics has been around in existence for the longest time. Without it, human life today would not be the same. Cryogenics involves taking ordinary and common elements, like that of hydrogen and oxygen; and chilling them below their critical points to make invaluable propellants that are critical to space systems and a host of other technologies.

From this internship, I have gained an immersive insight on not just spacecraft engineering involving rocket propellants, but also industrial and commercial applications.

The intriguing field of cryogenic should continue to be researched and understood. This discipline of engineering will continue to help pioneer the never-ending quest to understand the universe that encompasses us.

6. APPENDIX

Sample calculations for heat transfer rate between regolith and heater:

$$A_1 = .114^2 \ x \ \pi = .041 \ m^2$$

$$X = 1 + \frac{.0026 + .0103}{.0131} = 1.98$$

$$F_{12} = \frac{1}{2\left(1.98(3.92 - 4(.89)^2)^{\frac{1}{2}}\right)} = .61$$

$$\frac{1}{F_\varepsilon} = \frac{1}{.86} + \frac{1}{.70} - 1 = \frac{1}{1.59} = .63 = F_\varepsilon$$

$$Q = .63(.61)(56.69 \text{ x } 10^{-9} \frac{W}{m^2 - K^4})(.041 \ m^2)(473K^4 - 250K^4) = 4122 \ W$$

5. REFERENCES

1 ASTM. *Standard Guide for Thermal Performance Testing of Cryogenic Insulation Systems*. Publication no. C1774. N.p.: ASTM, 2013. Print.

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3 Hudson, Troy L., Oded Aharonson, and Norbert Schorghofer. "Laboratory experiments and models of diffusive." *Journal of Geophysical Research* 114 (2009): Print.

4 Swanger, Adam, James Mantovani, Ph.D., and Ivan Townsend. "Challenges in Characterizing Low-Temperature Regolith Properties." 4th International Workshop on Lunar Superconductor Applications. Cocoa Beach. 11 Apr. 2014. Lecture.