Demonstration of ice extraction and ice collection system for Lunar Ice Miners

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Mining water-ice in the permanent shadow region of the moon opens opportunities for In Situ Resource Utilization (ISRU) since it is a valuable resource for lunar exploration activities. To realize an efficient water-ice mining system, Advanced Cooling Technologies, Inc. in collaboration with Honeybee Robotics, is developing an advanced thermal management system under an ongoing SBIR Phase II funded by NASA. The thermal management system consists of two-principal components: 1. thermal corer and 2. volatile cold trap tank. The thermal corer is an improved drill auger developed by Honeybee Robotics incorporating mini-channels to facilitate regolith heating for ice sublimation. Volatile cold trap tank is a chamber with multiple variable conductance heat pipes (VCHPs) integrated to three radiator panels. The VCHPs aid in effectively collecting frost and subsequently defrosting. A prototype thermal corer, 17.3 cm long and with a 5 cm internal diameter was 3D printed with stainless steel. Ice extraction demonstration experiments were performed to determine the performance of the thermal corer with the heat transfer fluid flowing through the thermal corer at different temperatures for certain times. During the experiments, the concentration of the ice in the regolith was 5%. Likewise, a VCHP-based cold trap tank was designed and fabricated. Currently, thermal characterization of the cold trap tank is being performed to determine the performance of the ice collection by modulating the heat transfer modes of the VCHP from fully active adiabatic and condenser for 100% heat rejection to diode mode.

Nomenclature

dt	=	Time Step
$\dot{E}$	=	Rate of Energy
FOM	=	Figure of Merit
H	=	Capillary Height
HX	=	Heat Exchanger
L_s	=	Latent Heat of Sublimation
P_{sat}	=	Saturation Pressure
Q	=	Heat Pipe Power
$\dot{Q}$	=	Heat Transfer Per Unit Time
T	=	Temperature
TC	=	Thermocouple

I. Introduction

Detection of water-ice and many other trapped volatiles opened up possibilities for sustaining future space exploration missions. The plume at the Lunar Crater Observation and Sensing Satellite (LCROSS) impact zone

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detected by the Lyman Alpha Mapping Project (LAMP) Ultraviolet spectrograph onboard the Lunar Reconnaissance Orbiter (LRO) estimated water-ice concentration to be 5.6±2.9% by mass.[1,2] Water is a valuable resource that can be extracted at the sites for habitat and space exploration utilization. Water is trapped in the lunar regolith in the form of ice, especially in the Permanent Shadow Region (PSR) moon. The mean PSR temperature is about 85 K but varies between 40 K at the lowest to 120 K at the highest.[3] The sky radiative temperature is only at 4 K. The lunar surface pressure is as low as 2E-12 Torr.[4] Under such conditions, water-ice extraction is possible by sublimation of ice. One stated reference In-Situ Resource Utilizaiton (ISRU) objective is to mine water-ice at a rate of 15 metric tons annually[5] and the cost associated with in-situ mining and utilization is significantly lower than launching from earth.[6] Water-ice can be thermally mined by sublimating the frozen ice captured within the regolith and collecting the condensed/ sublimated vapor back in ice form in a collection tank. From preliminary estimations, it was determined that about 2.3 kWh of thermal energy is required to sublimate ice at a target rate of 0.278 kg/hr.[7] Several thermal ice mining methods explored predominantly use heating drill rods/augers[8-10] over a wide range of temperatures, typically below -15°C, and at low pressures (1 mBar or lower). On the collection side, a low temperature and low-pressure capture tank is typically employed to capture vapor and re-sublimate as ice.

A. System under Development

Under an ongoing NASA Small Business Innovation Research (SBIR) Phase II program, an energy efficient Thermal Management System (TMS) for water-ice mining is being developed. The TMS consists of an innovative thermal corer based on the Planetary Volatiles Extractor (PVEx) drills[8] for ice extraction by thermal sublimation and a Variable Conductance Heat Pipes (VCHPs)[11] integrated cold trap tank for selectively and efficiently collecting ice and rejecting heat to deep space. The thermal corer is a representative PVEx drill auger with mini-channels to provide a heat transfer pathway to sublimate ice. The heating is provided by making use of waste heat produced by an onboard power source like a Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs). A mechanically pumped fluid extracted the waste heat and transported it to the icy-regolith captured within the thermal corer volume by circulating through the mini-channels. This liquid transport between the stationary power source and the rotating drill was facilitated by a rotary union (also called swivel joint). Schematic of the TMS for ice mining is shown in Figure 1.

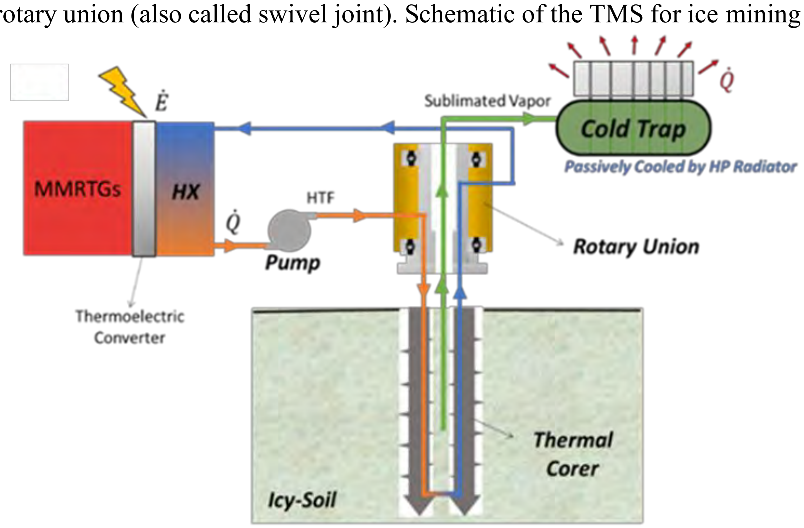

Figure 1. Schematic of the ice extraction and collection system.[5]

In the following sections, the development of the key TMS components, 1. Thermal corer, and 2. VCHP cold trap tank is described. The majority of the manuscript will focus on the developmental activities of the thermal corer. The design, analysis, and fabrication status of the VCHP cold trap tank is presented. Additionally, ACT has tested an improved Commercial Off-The-Shelf (COTS) rotary union developed by a commercial partner to determine fluid leak rates under extreme low vacuum as part of the programmatic objectives.

II. Development of Thermal Corer

A. Thermal Corer

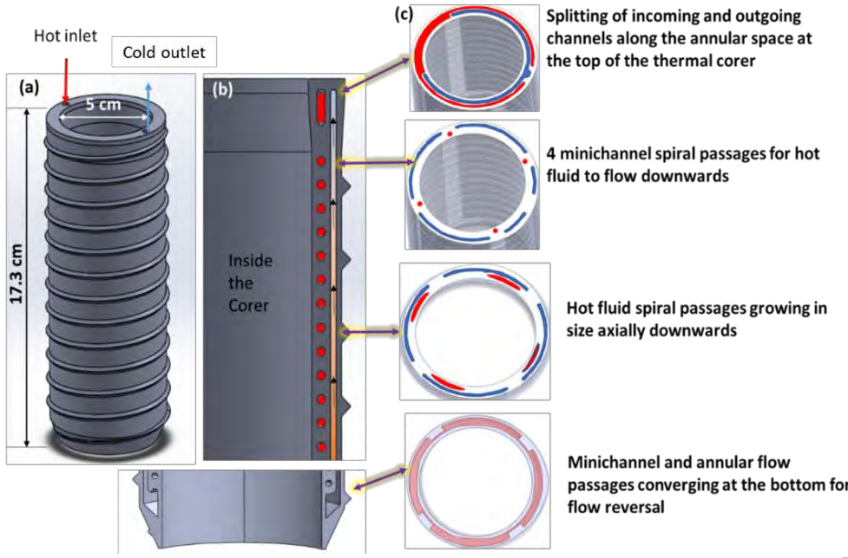

Figure 2. Schematic of the thermal corer investigated in this manuscript.[5]

The thermal corer is a drill auger with integrated mini-channels to provide a heat transfer pathway for ice sublimation using heat from a waste-heat source. Figure 2 shows the schematic of the Heat transfer fluid (HTF) flow through the thermal corer with representative thermal markers for HTF temperatures, red being hot and blue being cold. The thermal corer has two manifolds at the top for hot HTF inflow and cold HTF outflow. The incoming fluid manifold is split into four different mini-channel pathways whose size expands as it follows the thermal corer axially downwards. These ports are present closer to the inside wall of the drill. The mini-channels converge at the bottom and the flow reverses through the annular passage by the outer wall of the drill.

B. Experimental System for Ice Extraction Performance of the Thermal Corer

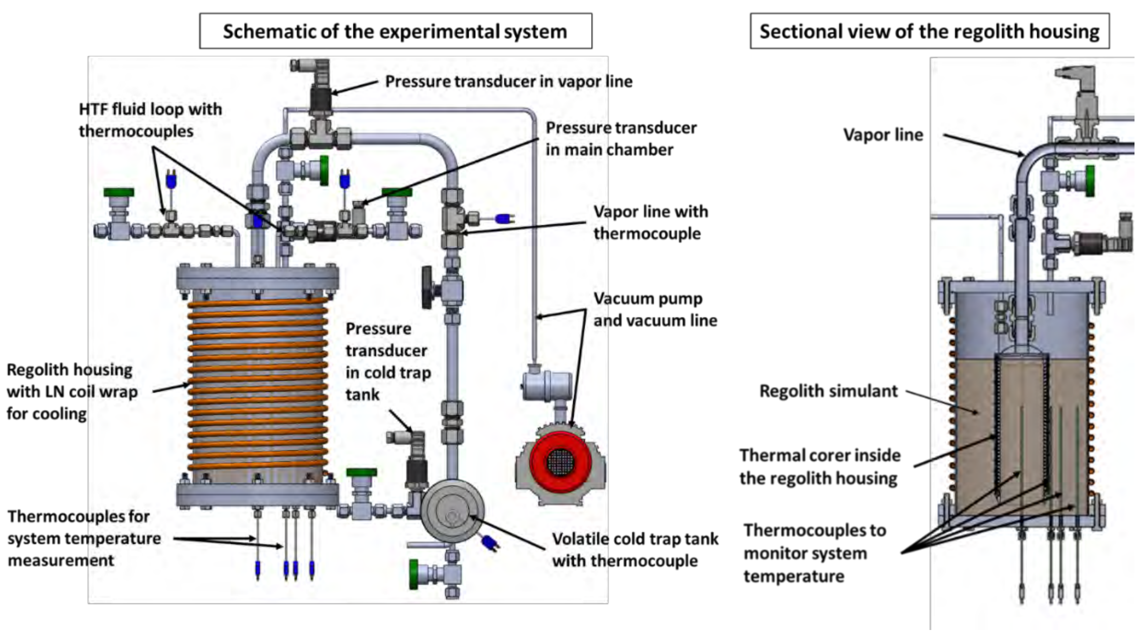

Figure 3. Schematic of the experimental system for ice extraction performance testing.

The schematic of the ice extraction performance testing is shown in Figure 3. The thermal corer was placed in a regolith chamber which was prepacked with the wet regolith (5% by weight). The regolith chamber is a cylindrical container with leak tight top and bottom covers enabled by copper gaskets. The regolith chamber simulates a low temperature and pressure environment by means of liquid nitrogen coil wraps and provision for vacuum. The icy-regolith was prepared by pouring de-ionized water on the dry-regolith and mixing them using a hand drill attached to a mechanical mixer arrangement for even distribution. The vapor sublimated from the regolith flows into the cold trap tank through the vapor line. The cold trap tank is kept at a low temperature by circulating liquid nitrogen through liquid nitrogen coils where vapor deposits as ice. A sight glass was provided to visualize ice deposition on the cold trap tank. The system test components are shown in Figure 4. The prototype thermal corer, 5 cm inner diameter and 17.3 cm long, was fabricated by 3D printing with stainless steel. The size of the mini-channels was 1.5 mm. Liquid lines were welded onto the liquid ports. A cap with central vapor line of diameter 6.3 mm (0.25 in) was welded to facilitate sublimated vapor transport onto the proxy cold trap tank. To measure system conditions, thermocouples, and pressure transducers were placed as needed.

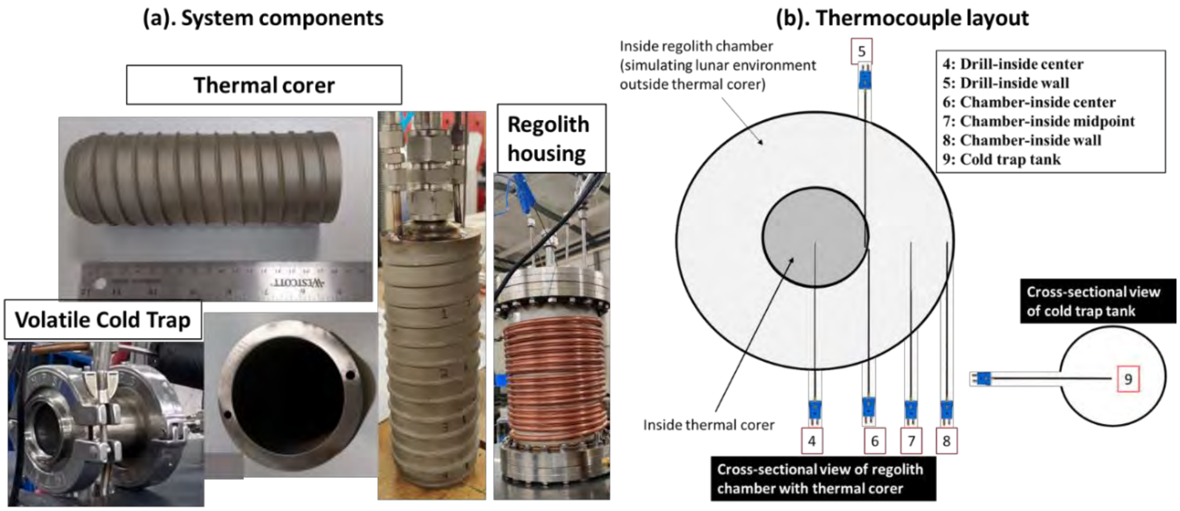

Figure 4. (a) System components for characterizing ice extraction performance of the thermal corer; (b). Thermocouple layout for systematic temperature measurements.

Thermocouples were placed radially inside the regolith chamber and the notation is shown in Figure 4. The captured regolith volume of interest is denoted with dark gray markers with thermocouples TC4 (at the center of volume) and TC5 (inside wall of the thermal corer). The regolith chamber was kept at a constant temperature by regulating liquid nitrogen flow through the coil wraps around the regolith chamber by TC8. Likewise, another thermocouple (TC9) was kept in the cold trap tank to regulate liquid nitrogen driven cooling to keep the cold trap tank at a constant temperature. During performance testing, the regolith chamber was kept at a temperature of -30°C to -20°C, and the cold trap tank was maintained at -50°C. The regolith chamber cold temperature was chosen given the freezing limitations of the HTF (ethylene glycol 50% by volume) at low temperatures. Frozen HTF in the thermal corer during the test preparation stage might destroy the mini-channels due to expansion. The system was vacuumed to a level of ~ 7E-3 Torr, measured by the vacuum meter display connected to the turbo pump. However, the pressure transducers used in the regolith chamber and the cold trap tank had the lowest value of ~ 100 Pa and on the vapor line had the lowest value of ~ 600 Pa.

C. Ice extraction Performance Testing of the Thermal Corer

Performance testing of the thermal corer to determine the ice extraction performance was undertaken with HTF flowing through the thermal corer at 75°C. Figure 5 shows the system temperature and pressure curves during ice extraction. HTF circulation started at ~ 150 s. It must be noted that the thermocouples recording the fluid temperatures were outside the chamber and so during the preparation stage, they read higher temperature values than the system. The vapor line and cold trap tank pressure increase gradually as the system temperature increases. The rate of sublimation was likely low during this time. As the system temperature increased, the ice in the regolith melted and the vapor was generated due to liquid-vapor phase change instead of sublimation. Around 185 s, about 3 minutes after the beginning of the experiment, significant pulsations on the pressure transducer and the cold trap tank thermocouple

(TC9) were noticed. This indicates that the ice deposition rate was increasing as more vapor was extracted from the captured regolith. Shortly after, the TC4 and TC5 curves diverge, possibly indicating that the vaporization occurred first along the wall and so the poor diffusivity of dry regolith results in larger temperature differences. However, vaporization still occurred as there was sufficient vapor pressure differential as measured from the vapor pressure and the cold trap tank pressure. After ~ 970 s, about 16 minutes after the start of the experiment, the system pressure reaches a maximum value and then gradually decreases from 1970 s, about 33 minutes after the experiment was started. After this point, the ice deposition rate decreases. This can be attributed to depleting ice/water fraction in the captured wet regolith, coupled with poor thermal diffusivity of dry regolith, and increasing pressure in the cold trap tank which increases the resistance to incoming vapor.

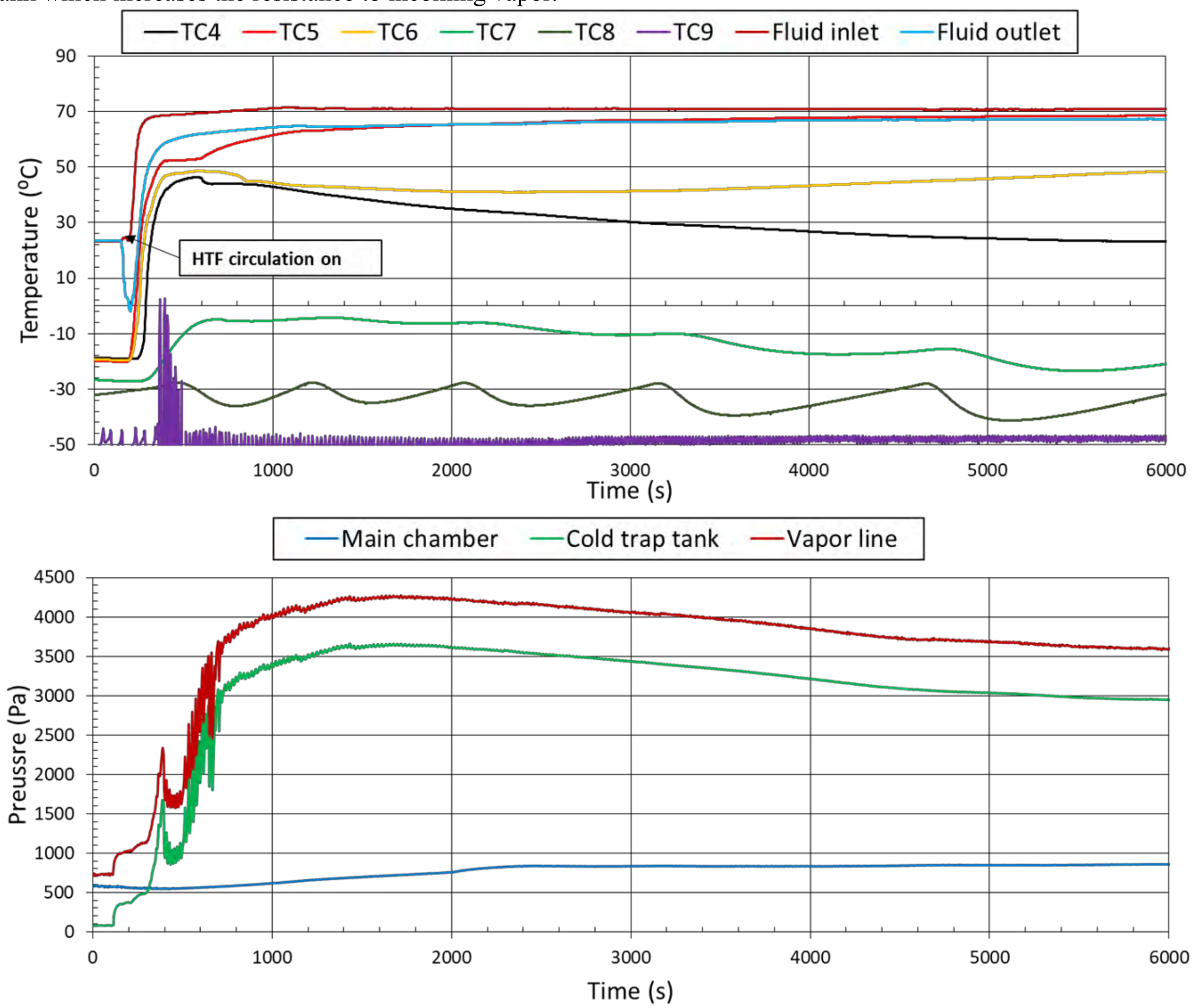

Figure 5. System temperature and pressure curves during ice extraction.

Figure 6 shows ice deposition on the cold trap tank. From the ice deposition pattern, it is evident that the ice extraction and collection rate is maximum in the first 20-30 minutes. After this point, the rate of extraction/deposition decreases. During this test, the vapor line was insulated but no heating was provided, so there is some tendency for sublimating vapor to condense along the vapor line wall. The test was repeated three times for reproducibility of the data.

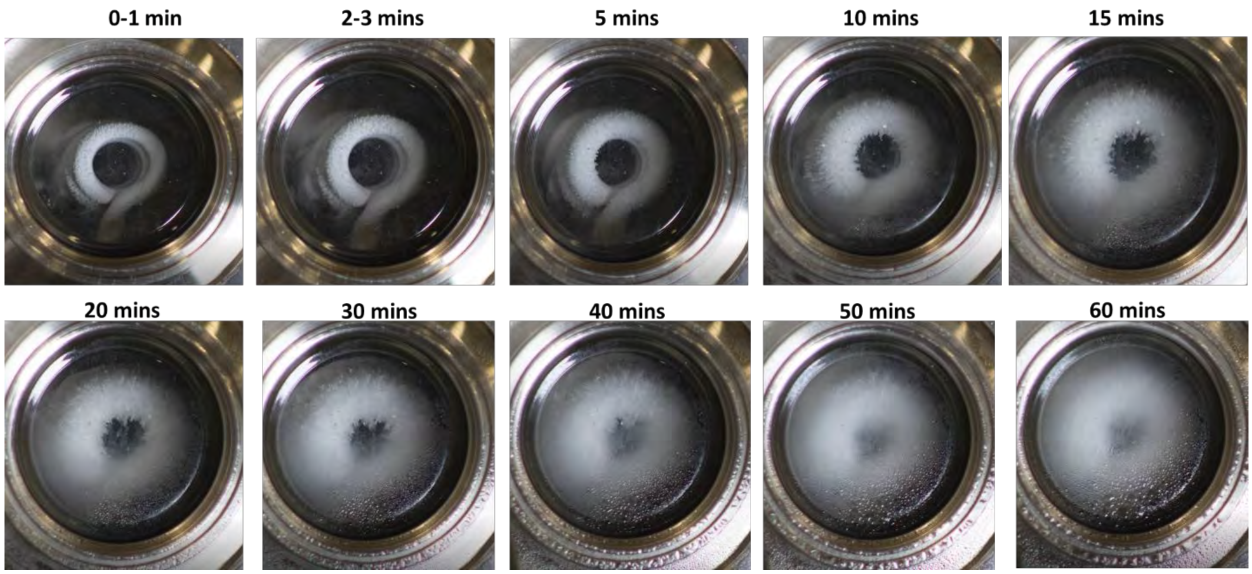

Figure 6. Visualizing ice deposition on the cold trap tank.

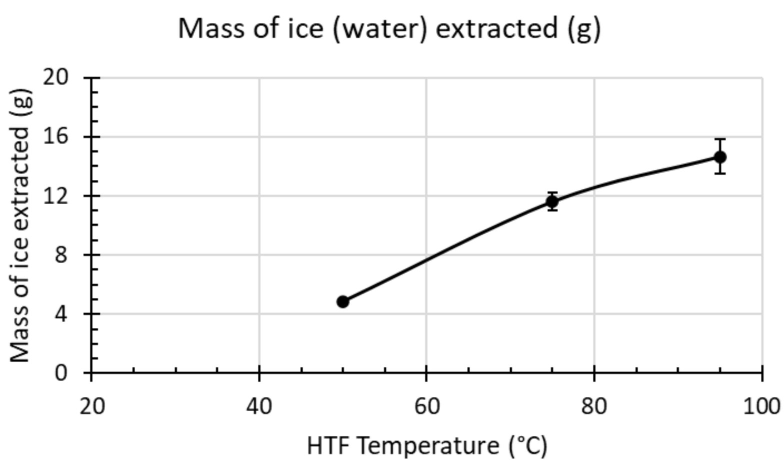

Figure 7. Cumulative ice extracted by the thermal corer with varying heat transfer fluid (HTF) temperature.

After the ice extraction experiment, the system was allowed to reach room temperature. The now liquid water in the cold trap tank was drained in a glass flask and weighed. Figure 7 shows total mass of ice extracted by the thermal corer with varying HTF temperatures. At low HTF temperature of 50°C, only 4.8 to 5 g of water was extracted. As the HTF temperature increased to 75°C, the total mass of ice extracted was between 11 to 12.2 g of water. Further increasing the HTF temperature to 95°C increased the total mass of ice extraction to between 13.5 to 15.8 g. At higher HTF temperatures, the available temperature gradient allows for more heat transfer for sublimation, so the mass of extracted ice increases. But at the highest temperature, the slope of ice extraction curve declines. This is similar to the measurements described in.[12]

D. Ice Extraction Performance Testing of the Thermal Corer with a Larger Volatile Cold Trap Tank

In the above described experiments, the volume of the cold trap tank used was only 111 cm^3. Such a small volume tank would result in a fast increase in the cold trap tank pressure which negatively influenced the ice extraction rate. So, the previous smaller cold trap tank was replaced with a larger cold trap tank with 19 times more internal volume (Figure 8). The inflow vapor line was divided into three tubes to uniformly spread the ice deposition on the LN coils. Consequently, the rate of increase in pressure will reduce allowing for greater ice extraction. The larger tank also facilitates incorporating more LN coil turns so the surface area available for ice deposition also increases. With more available areas for ice deposition, the thickness of ice decreases which will decrease the thermal resistance barrier for the incoming vapor.

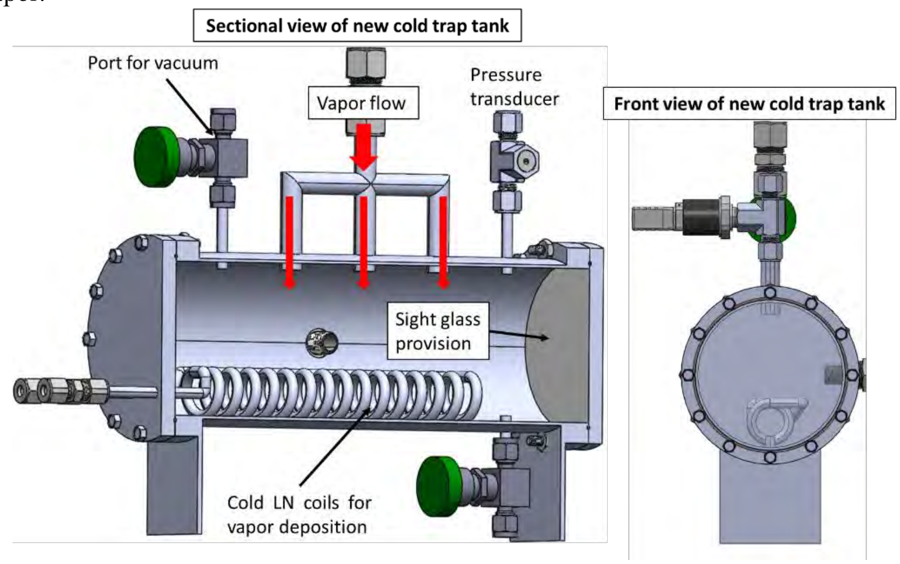

Figure 8. Schematic of improved larger cold trap tank.

Ice extraction testing of the prototype thermal corer was performed with the new cold trap tank with the HTF circulation at 75°C. Figure 9 shows the temperature and the pressure curves during the ice extraction test with the larger cold trap tank. During this test, the vapor line was maintained at 90°C to avoid condensation of the flowing vapor. This is another distinction in the performance testing compared to the results shown above. The HTF circulation started at ~ 230 s. TC5 immediately responds to the HTF circulation and TC4 increases shortly after. The vapor temperature gradually increases, possibly showing some sublimation (vaporization) of the ice (water). At around 4980 s, about 2-3 minutes after the start of the test, the vapor pressure in the vapor line suddenly increases and the corresponding changes in the vapor line temperatures are noticed. The ice extraction and deposition rate increased in the cold trap tank beyond this point. However, there is a transient period of ice extraction and deposition that ensues as the system temperature and the pressure in the regolith chamber increase while the LN circulation rate increases in the cold trap tank to regulate the temperature. The temporal ice extraction rate is also the highest around this point. After 1100 s, 18 min from the start of the experiment, a steadier ice extraction is achieved as corroborated by the resulting system temperatures and consistent gradually increasing vapor line and cold trap tank pressures. The ice extraction test was stopped after 1 hour of testing.

Figure 10 shows the ice deposition in the larger cold trap tank. As mentioned, the ice deposition rate increases after the first 3 minutes and continues throughout the test. It was noted that the ice bridging happened between the LN coil and the cold trap tank surface as the coil was almost in contact with the tank wall, as an additional ice deposition surface. This indicates that a careful cold trap tank design can realize higher ice deposition. Since the vapor inlet was at the top of the cold trap tank, more ice deposition was noticed there. About 32 g of water was extracted during this test. Assuming compact density of 1600 kg/m^3 for the wet regolith (from in-house measurements), available mass of water in the captured regolith was 28 g, yielding >100% ice extraction efficiency in this test. The overestimation in ice extraction rate is attributed to: some uneven distribution in the water concentration in the icy-regolith during the preparation, initial condensation of the trapped air in the cold trap tank during the preparation stage (cooling period), and some migration of wet moisture in the nearby regolith below the captured volume or outside of the thermal corer due to the heat transfer by the thermal corer.

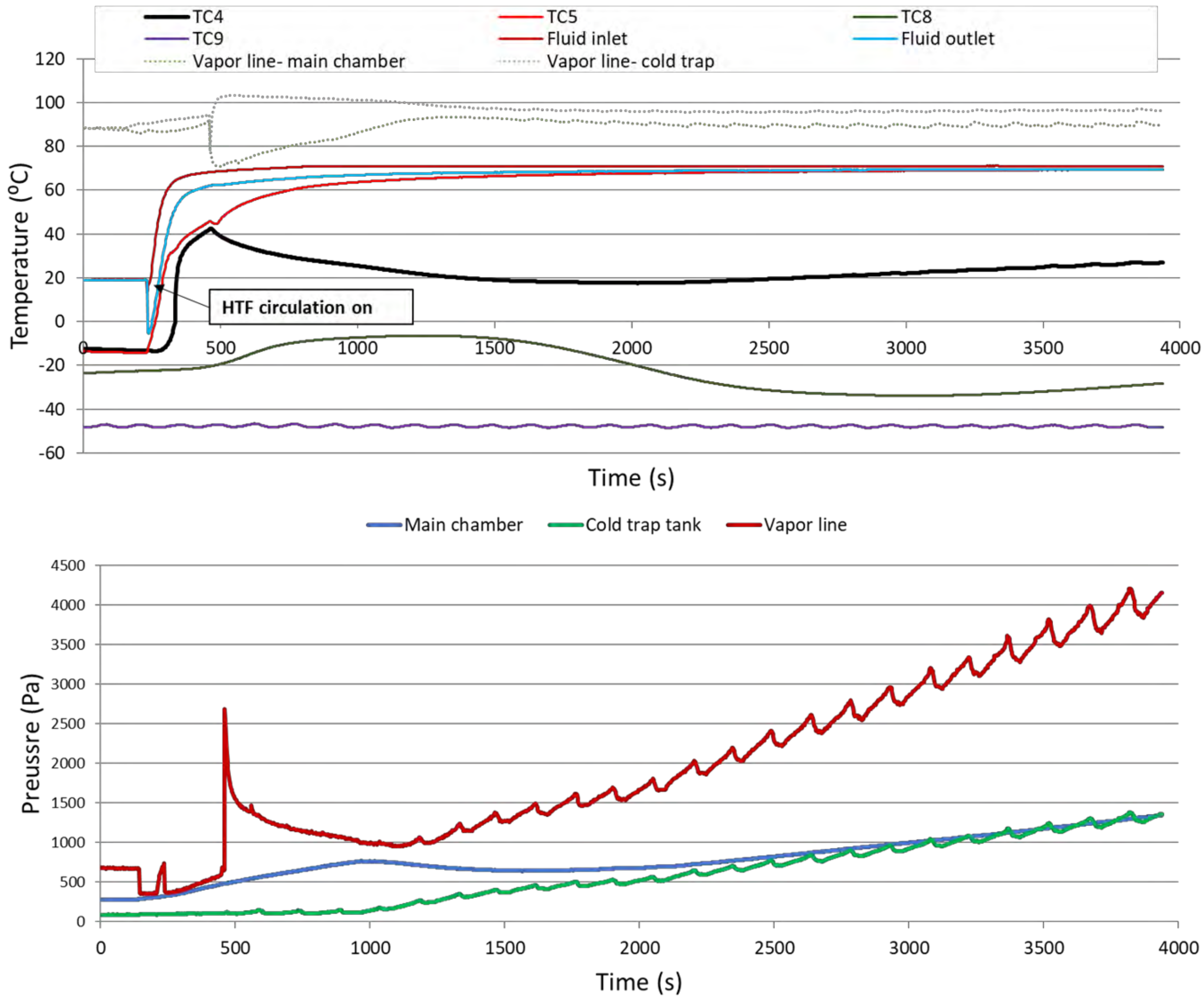

Figure 9. System temperature and pressure curves during ice extraction with larger cold trap tank.

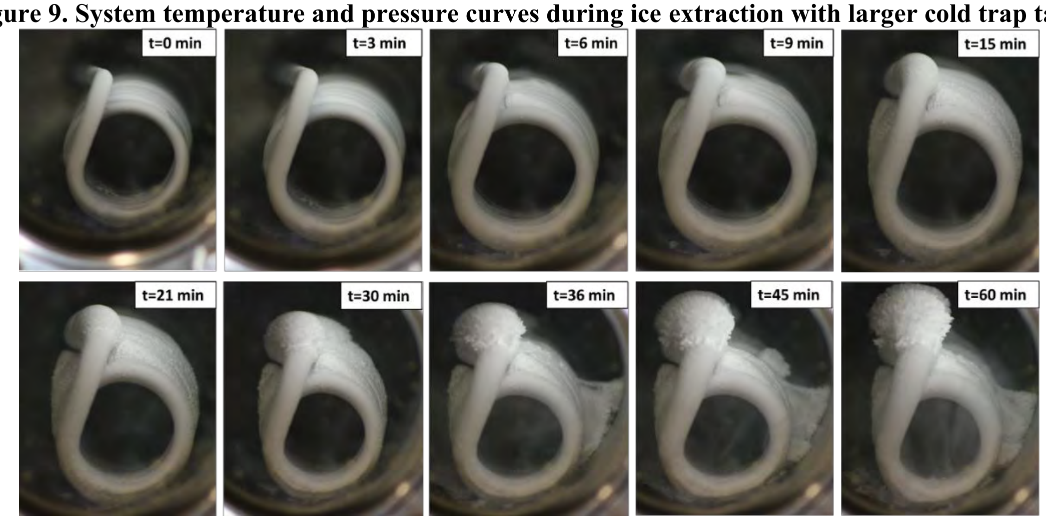

Figure 10. Visualizing ice deposition in the larger cold trap tank.

E. Prediction of Thermal Performance of the Thermal Corer

In previous work[7,13], a 2D transient FEA-based thermal model was developed through ANSYS Fluent to investigate heat and mass transfer aspects during a thermal extraction process. Thermo-physical properties of ice and regolith such as thermal conductivity, specific heat, latent heat, vapor pressure, etc. were based on Metzger et. Al[14], and Feistel et al[15], and specified by User Defined Functions (UDF). During simulation, FLUENT will use the equations in UDFs to calculate icy-soil properties based on current temperature, and use those properties to solve the energy equation to update temperature for the next time step, as shown in Figure 11. The model was validated against experimental water extraction of Mars regolith and Lunar regolith[13], and was used to obtain the optimal corer size.

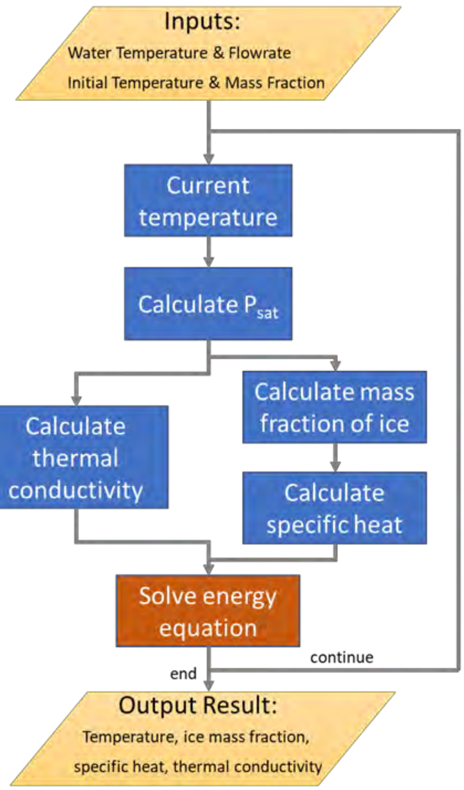

Figure 11. Schematic of FLUENT's solver with UDFs. Based on current temperature, P_{sat} will be calculated and used to obtain conductivity, mass fraction of ice, and specific heat. Then, the energy equation will be solved using the new thermal properties to obtain the new temperature in the next time step.

In order to reduce the complexity of the ice extraction system, a moderately larger corer is preferred over multiple small sized corers. However, a larger corer is expected to experience less heat diffusion toward the center, and reduces ice extraction rate. Thus, numerical analysis was performed to determine and compare the ice extraction performance of thermal corers with internal diameters of 2 in (5.1 cm) and 4 in (10.2 cm). As a result of doubling the diameter, the volume and the mass of regolith was 4 times higher with 4 in ID thermal corer compared to 2 in ID. The length of both thermal corers was 17.3 cm in this simulation. A 2-D transient model in ANSYS Fluent was constructed with model parameters defined as user defined functions. Both thermal corers were set under the same operating condition with HTF temperature of 50°C and back pressure of 5 Pa. The low back pressure was applied to simulate operation in actual lunar environments. Assuming the initial mass fraction of ice inside the regolith is 5%, the maximum amount of ice that can be extracted from using 2 in corer is 28.3 g, while using 4 in corer is 113.2 g. The 2 in corer completely sublimated all ice inside its volume in 11 minutes, while the 4in corer could not complete. As a result, the 2 in corer sublimated 28.3 g (100% extraction), while the 4 in corer could only extract 90 g of ice, below its corresponding maximum value of 113.2 g (~ 80%). The 4 in corer experienced more heat leak to the bottom, causing more sublimation of ice outside of the corer's volume. In conclusion, HTF temperature of 50°C is not high enough to completely extract ice inside a 4 in corer.

The HTF temperature was set at a higher value of 85°C, so as to determine whether full sublimation can be achieved in the 4 in thermal corer. Figure 12 shows the mass fraction of ice over time using 4 in thermal corer and HTF temperature of 85°C. The red-color represents 5% ice mass fraction, the blue-color represents 0% ice mass fraction.

Over time, the heat from the corer sublimated the ice and reduced the ice mass fraction inside the corer from 5% to 0%, as the blue region grew inward. As a result, the higher temperature of HTF helped the 4 in corer to completely sublimate the ice inside in 6.5 hours, as shown in. The layer of ice near the 4 in corer's wall quickly sublimated 22 g in 12 minutes, similarly to the 2 in corer. After that, the extraction rate decreased significantly as the heat traveled into the center of the corer. In conclusion, complete ice sublimation is possible with a 4 in corer, however, at a higher temperature of 85°C. In addition, the extraction rate of a 4 in corer is 30 times slower than of a 2 in corer, while the amount of ice extracted is only 4 times. Further improvement to the corer design is necessary to maintain the heat diffusion toward the center.

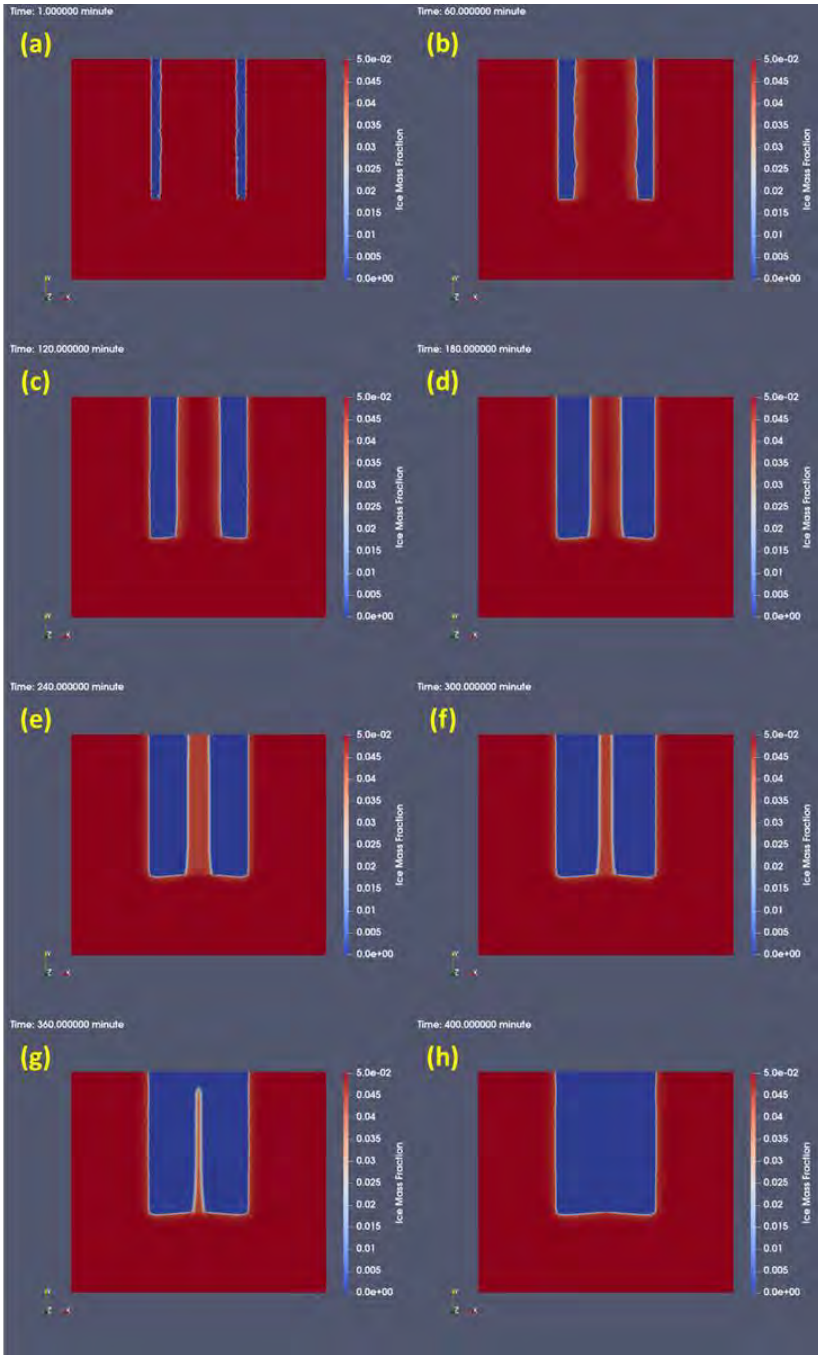

Figure 12. Cumulative ice extraction using 4 in corer and HTF at 85°C: The corer completely sublimated the ice inside (113.2 g) in 6.5 hours. For comparison, cumulative ice extraction with 2 in corer is shown with orange curve.

III. Development of VCHP Cold Trap Tank

To facilitate efficient ice collection, a VCHP cold trap tank was designed. The VCHP cold trap tank operates in two modes:

- **Ice collection mode:** the vapor deposits as frost in this mode. The heat extracted by the heat pipe is rejected to deep space. In this case, the non-condensable gas (NCG) is in the reservoir section and the heat pipe connected to the radiator is fully active.
- **Ice removal mode:** a thick layer of ice forms a thermal barrier and suppresses frost deposition. So, in this mode, NCG blocks the heat pipe portion in the radiator by external heating (HTF). Simultaneously, the common VCHP working fluid reservoir at the bottom of the device (see Figure 13) is heated by the HTF, so the heat is transferred from the HTF to melt the deposited frost. As ice melts and gets collected in the bottom, fresh vapor can then be deposited as frost in the subsequent frost-extraction cycles.

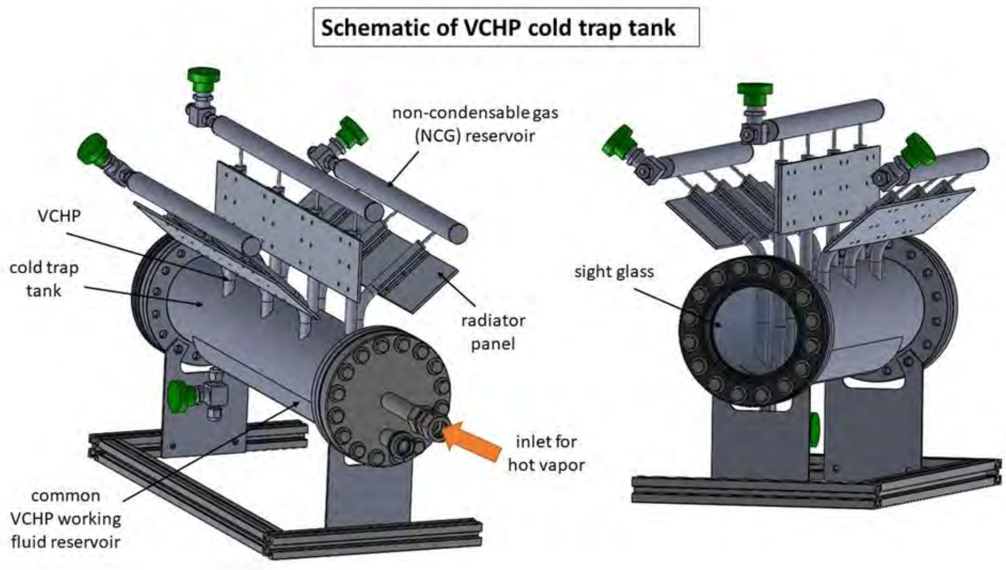

Figure 13. Schematic of the VCHP cold trap tank.

Figure 13 shows the schematic of the VCHP cold trap tank that is being currently fabricated. The cold trap tank consists of 10 heat pipes in 3 rows. Each heat pipe will consist of a mechanical structure to hold additional working fluid to avoid dry-out during the operation. Each row of heat pipes is connected to radiator panels of size 40 cm x 6.2 cm. A three radiator panels arrangement was considered to reduce the size of the system and facilitate easy testing. Also, if one row fails, the other two rows of heat pipe radiator panel system will be operational. The NCG reservoirs of 133 ml (for 3 heat pipe rows) and 172 ml (for middle row with 4 heat pipes) will be attached to the heat pipes above the radiator panels. Likewise, a heat pipe working fluid reservoir will be placed below the cold trap tank. During frost-removal mode, both working fluid reservoir and the NCG reservoir will be heated to melt the frost inside the cold trap tank. The calculations pertaining to the design of the VCHP cold trap tank is explained below.

The on-going developmental effort is classified into four stages of (i) energy, (ii) heat pipe sizing, (iii) reservoir sizing, and (iv) fabrication. The first stage requires calculating the heat rejection power to determine the size of the radiator panels, and also to determine whether the heat pipe can carry the heat. From conservative methods assuming 75% mass extraction within 30 minutes, it was determined that 50 W heat must be carried by heat pipes and rejected by the radiators. As a design option, 10 heat pipes were considered to facilitate sufficient surface area for frost-deposition. So, in parallel network, each heat pipe must carry 5 W. In the heat pipe sizing calculations, a trade study was performed to determine the proper VCHP working fluid with operating temperatures ranged from 200 to 350 K. Table 1 compares four different possible working fluids with which the lunar ice miner VCHPs can operate. Although ammonia is the best working fluid with high power transport capability and capillary height, it is a toxic liquid which makes it difficult to handle and work with. Propylene has low capillary height, making four balconies to be installed inside each individual VCHP to completely transport the liquid across each VCHP evaporator. Methanol is not a suitable working fluid as its critical temperature is low around 190 K. Among these four working fluids, Acetone is the only working fluid which can transport enough power with moderate capillary height, requiring only two balconies to be embedded within each VCHP. Therefore, acetone was down selected as the heat pipe working fluid to simplify the design analysis. Then in-house models were leveraged to determine the heat transfer limits and the capillary transport of the working fluid to ensure uninterrupted VCHP operation in both frost-collection and frost-removal modes. The specifications of the heat pipes are summarized in Table 2.

A. Ice Collection Mode

The heat pipe operates at a temperature below 0°C as vapor deposits on the heat pipe surface as ice. Analysis was performed considering a temperature range of -70°C to 0°C to determine the heat transfer operating limits of the heat pipe and the capillary rise of the liquid.

Table 1: Characteristics and advantages/disadvantages of different VCHP working fluids at 273.15 K.

Fluid	FOM	$H_{capillary}$ (cm)	Q (W)	Disadvantages
Acetone	3.04E+10	7.68	314	Low surface tension, causing to install 2 balconies
Propylene	1.71E+10	3.53	1177	Insufficient capillary height which would cause in installing 4 balconies
Methanol	2.91E+10	7	363	Low critical temperature (~ 190 K), low surface tension, causing to install 2 balconies
Ammonia	1.6E+11	14.4	2525	Toxic, high pressure liquid, difficult to work with

Table 2. Specifications of heat pipe for VCHP cold trap tank sizing.

Dimensions		Wick structure	
Evaporator length	9.83 cm	Material	Stainless-Steel
Adiabatic length	4.45 cm	Mesh number	180
Condenser length	6.43 cm	Number of wraps	4
Outer diameter (OD)	1.27 cm	Porosity	0.63
Inner diameter (ID)	1.1 cm	Wrap thickness	0.162 mm

In the ice collection mode, the heat pipe surface inside the cold trap tank serves as the evaporator since it removes heat from the vapor. The heat pipe connected to the radiator panel serves as the condenser in this mode of operation. Figure 14 shows the heat transfer operating limits of the heat pipes with acetone as the working fluid. It was observed that the heat pipe can easily carry the required heat power of 5 W to reject to the heat sink. The heat pipe length in the cold trap tank is 9.83 cm. At extreme operating temperatures, it was determined that the working fluid can rise through the wick structures up to 7.2 cm. To ensure that the liquid can climb and saturate the full evaporator length in the cold trap tank, a mechanical structure called "*liquid balcony*" to withhold some working must be installed in the heat pipe. The representative schematic and an example of such a mechanical structure that will be installed midway of the heat pipe is shown in Figure 15.

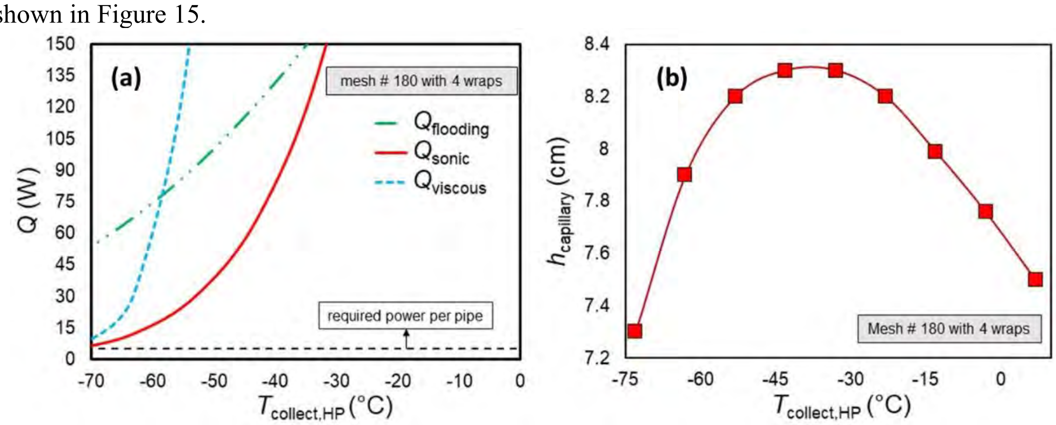

Figure 14. (a) Heat transfer operating limits of the heat pipe; (b) capillary rise of the working fluid.

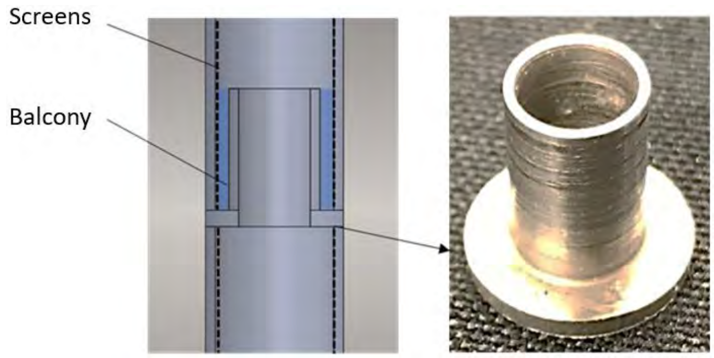

Figure 15. Mechanical structure to hold liquid pool in the heat pipe.

B. Ice removal mode:

The calculation here will yield the NCG reservoir sizing and heating condition. In frost-removal mode, the NCG blocks the actual adiabatic and condenser sections. The common working fluid reservoir on the bottom of the cold trap tank will be partitioned to add redundancy and heated by the HTF to remove the frost from the heat pipe surface inside the cold trap tank, which now serves as the condenser. In the limiting case, the NCG reservoir must be sized to match the total volume that the gas must fill to fully block the heat rejection to the radiator panel. The overall NCG reservoir volume was determined to be 400 cc.

IV. Near Term Plans

Ongoing and near-term activities include developing the VCHP cold trap tank to characterize the ice collection (deposition) performance. The layout of the VCHP cold trap tank has been explained above. After the tank fabrication, thermocouples and pressure transducer will be strategically placed in the tank for measuring operational conditions during the deposition tests. Ice deposition tests will be performed using by flowing the hot water vapor at known temperature into the tank. The tank will be maintained cold. Currently, the VCHP cold trap tank is under fabrication. The performance characterization tests including mass and thickness of ice being accumulated onto the VCHPs, Transient bi-modal response of the VCHP will be demonstrated. Additionally, the thermal performance of the VCHP cold trap tank will be determined by varying the heat sink and heat pipe temperatures. On the other hand, a scale-up thermal corer of length 34.5 cm was fabricated with aluminum for ice extraction. The existing regolith chamber shown in this manuscript is being modified to incorporate the scale-up drill and to characterize the performance. Inherently, the HTF must travel a longer distance for ice extraction, and the total amount of icy regolith captured for processing is two times more than the current prototype thermal corer. Then, the ice extraction and ice collection system will be assembled to characterize the full ice extraction & collection cycle. The performance of the assembled thermal management system consisting of the thermal corer and the VCHP cold trap tank connected to the radiator will be determined by series of tests at more relevant conditions (preferably low temperature ~ -50 °C and very low pressure) at Honeybee Robotics lunar chamber.

V. Conclusion

The developmental status of the thermal system components for ice extraction system and the ice collection system was described. The ice extraction is facilitated by a thermal corer, which is a drill auger with mini-channels. A prototype 17.3 cm long and 5 cm ID thermal corer was fabricated 3D printing of stainless steel 316L. Ice extraction performance tests were performed with a lab-scale thermal corer with simulated regolith environment between -30°C to -20°C and vacuum level ~ 7E-3 Torr. Following takeaways were noted:

- The total mass of ice extraction increased with increasing HTF circulation temperature through the mini-channels of the thermal corer. When HTF temperature increased from 50°C to 75°C, the mass of ice extracted increased from 5 g to more than 11-12.2 g. However, further increasing the HTF temperature to 95°C resulted in increasing ice extraction to around 13.5-15.8 g only.
- With a small cold trap tank, the ice extraction rate was high initially (up to 30 minutes) which then decreased, due to increase in collection side pressure and increasing ice layer thickness on the deposition surface.

- With above mentioned observations, a larger cold trap tank with 19 times more available volume was integrated into the experimental system. Ice extraction performance testing with HTF circulation at 75°C yielded about 32 g of ice extraction in one hour, which was a little above > 100% total available ice mass in the captured volume. The higher value is attributed to potential migration of vapor from the vicinity of the captured volume which is also heated by the thermal core. During the testing, it was also noticed that there was some ice condensation during the preparation stage. Appropriate steps will be undertaken to mitigate them.
- Numerical analysis was performed to assess the comparative performance between 2 in ID and a 4 in ID thermal corer drill for ice extraction. It was determined that the performance of the drill was influenced by HTF flow temperature. However, sublimating the available ice mass fraction required longer time due to potentially poor diffusivity of the regolith.

On the ice collection side, a VCHP integrated radiator panel based cold trap tank was designed and analyzed. The design consisted of 10 heat pipes for vapor-ice deposition and to reject heat to the ultimate heat sink. From recursive in-house modeling, appropriate heat pipe geometry and specifications were chosen along with down selection of acetone as the working fluid. Currently, the VCHP cold trap tank is being fabricated and testing will commence soon.

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References

[1]Colaprete, A., Schultz, P., Heldmann, J., Wooden, D., Shirley, M., and Ennico, K., "Detection of Water in the LCROSS Ejecta Plume," *Science*, Vol. 330, 2010, pp. 463.

[2]Gladstone, G.R., Hurley, D.M., Retherford, K.D., Feldman, P.D., Pryor, W.R. , Chaufray, J.Y., Versteeg, M., Greathouse, T.K., Steffl, A.J. , Throop, H., Parker, J.W., Kaufmann, D.E., Egan, A.F., Davis, M.W., Slater, D.C., Mukherjee, J., Miles, P.F., Hendrix, A.R., Colaprete, A., and Stern, S.A., "LRO-LAMP Observations of the LCROSS Impact Plume," *Science*, Vol. 330, 2010, pp. 472-476.

[3]Kleinhenz, J.E., and Paz, A., "Case Studies for Lunar ISRU Systems Utilizing Polar Water," *ASCEND*, 2020, pp. 4042.

[4]https://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html

[5]Sanders, G., "NASA Lunar ISRU Strategy," 2019.

[6]Kornuta, D., Abbud-Madrid, A., Atkinson, J., Barr, J., Barnhard, G., Bienhoff, D., Blair, B., Clark, V., Cyrus, J., DeWitt, B., Dreyer, C., Finger, B., Goff, J., Ho, K., Kelsey, L., Keravala, J., Kutter, B., Metzger, P, Montgomery, L., Morrison, P., Neal, C., Otto, E., Roesler, G., Schier, J., Seifert, B., Sowers, G., Spudis, P., Sundahl, M., Zacny, K., and Zhu, G., "Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production," *Reach*, Vol. 13, 2019, pp. 100026.

[7]Lee, K.L., Truong, Q., Hota, S.K., and Zacny, K., "Waste Heat-Based Thermal Corer for Lunar Ice Extraction," *51st International Conference on Environmental Systems (ICES)*, St. Paul, MN, 2022.

[8]Song, H., Zhang, J., Ni, D., Sun, Y., Zheng, Y., Kou, J., Zhang, X., and Li, Z., "Investigation on In-Situ Water Ice Recovery Considering Energy Efficiency at the Lunar Pole," *Applied Energy*, Vol. 298, 2021, pp. 117136.

[9]Liu, Y., Wang, C., Pang, Y., Wang, Q., Zhao, Z., Lin, T., Wang, Z., Shen, T., Liu, S., Song, J., Lai, X., Quan, X., Yao, W., "Water Extraction from Icy Lunar Regolith by Drilling-Based Thermal Method in a Pilot-Scale Unit," *Acta Astronautica*, Vol. 202, 2023, pp. 386-399.

[10]Zacny, K., Luczek, K., Paz, A., and Hedlund, M., "Planetary Volatiles Extractor (PVEx) for In Situ Resource Utilization (ISRU)," *Earth and Space: Engineering for Extreme Environments*, Reston, VA, 2016, pp. 378-390.

[11]*https://www.1-act.com/resources/heat-pipe-fundamentals/different-types-of-heat-pipes/*

[12]He, L., Wang, C., Zhang, G., Pang, Y., Yao, W., "A Novel Auger-Based System for Extraterrestrial In-Situ Water Resource Extraction," *Icarus*, Vol. 367, 2021, pp. 114552.

[13]Lee, K.L, Tarau, C., Truong, Q., and Rokkam, S., "Thermal Management System for Lunar Ice Miners," *50th International Conference on Environmental Systems*, 2021.

[14]Metzger, W., Kris Z., and Phillip, M., "Thermal Extraction of Volatiles from Lunar and Asteroid Regolith in Axisymmetric Crank-Nicolson Modeling," *Journal of Aerospace Engineering*, Vol. 33, No. 6, 2020, pp. 04020075.

[15]Feistel R., and Wagner, W., "Sublimation Pressure and Sublimation Enthalpy of H_2O Ice Between 0 and 273.16K," *Geochimica et Cosmochimica Acta*, Vol. 71, No. 1, 2007, pp. 36-45.