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Thermal Management System for Lunar Ice Miners

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Million tons of ice water discovered by the Lunar Crater Observation and Sensing Satellite (LCROSS) mission is considered to be the most valuable resource on the moon. Extracting these water ice from the Lunar regolith would require very high thermal energy input and inversely, capturing these water vapor in the near-vacuum environment also requests significant cooling capacity. Therefore, it is necessary to develop a dedicated thermal management system (TMS) for future Lunar Ice Mining Rovers that are powered by the radioisotope. Under an SBIR Phase I program, Advanced Cooling Technologies, Inc (ACT) in collaboration with Honeybee Robotics (HBR) is developing a thermal management system that can strategically use the waste heat of nuclear power sources to sublimate water vapor from icy-soil on the moon and use the Lunar environment temperature as the heat sink to refreeze the sublimated vapor within the cold trap container. In such a way that the required electric energy for both ice extraction and vapor collection can be minimized with lower system mass and footprint. A preliminary trade study was performed to design multiple thermal components of TMS including a waste heat-based thermal corer and a heat pipe radiator cold trap tank. Proof-of-concept prototypes were developed and tested. A preliminary full-scale system that can potentially meet NASA's mining goals was designed and the mining efficiency, system mass/volume, and power consumption (both electrical and thermal) were estimated.

Nomenclature

A_{core} = surface area of icy-soil core created by a thermal corer
C_p = specific heat of icy-soil mixture
L_s = latent heat of sublimation
m_v = mass vapor being released by ice sublimation
M_w = molecular weight of water
P_{sat} = saturation pressure of water
P = back pressure
$\hat{R}$ = gas constant
w = mass fraction

I. Introduction

In 2009, the Lunar CRater Observation and Sensing Satellite (LCROSS) mission confirmed the existence of water ice in the craters of the polar regions on the moon. Based on their data, the concentration of water ice mixed with the dry regolith was estimated to be ~5.6%wt (Ref.1). The water ice accumulated in the Permanently Shadow Regions (PSR) are considered to be the most valuable resource on the moon since they can be processed to generate Oxygen

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for life-supporting and converted into LH_2 and LO_2 for satellite and spacecraft refueling. The long-term goal of Lunar In-situ Resource Utilization (ISRU) is to mine water from the polar crater at a rate of 15 metric Tons per year (2.78 kg per hour) (Ref.2).

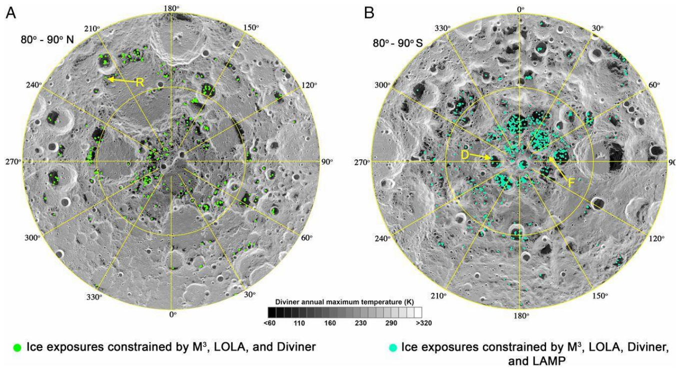

Figure 1. Presence of surface water ice in PSRs at the North and South polar regions of the Moon (Ref. 1)

Many planetary mining architectures have been proposed and developed, some of them are based upon proven approaches employed in the mining industry on earth, which involve excavating fluid-rich soil, transporting material to processing sites, crushing material to reduce particle sizes, and extracting the volatiles from the material. These terrestrial mining processes require intensive involvement of robotics and consume a great amount of electricity, which are not suitable for planetary mining applications, especially in PSR where solar energy is limited. Other emerging concepts for water extraction from icy-soil include microwave mining (Ref.3) and solar thermal mining (Ref.4). One of the most promising Lunar ice mining architectures, developed by Honeybee Robotics (HBR), is the "Planetary Volatiles Extractor (PVEx)", which is a drilled-based excavation system with integrated Volatile capturing system (Ref.5). The PVEx is mounted on a rover as the conceptual design shown in Figure 2(a), which significantly simplifies the conventional mining efforts with an all-in-one system of water extraction, vapor collection, and ice transportation. The system is powered by two onboard MMRTGs. A coring drilling design also referred to as "the corer" shown in Figures 2(b) and (c) is used for ground penetration and volatile extraction. After the corer penetrates the icy-soil and creates a core, electric heaters attached to the inner surface of the corer will be turned on to sublimate volatiles within the core. Sublimated volatiles will travel through the annular space between the inner and outer cylinders. Then the volatiles will flow into the cold trap container and refreeze.

The required thermal power to sublimate water ice from Regolith under the ground with the rate of 2.78 kg/hour is estimated based on the following assumptions and conditions:

- The initial temperature of water-bearing regolith is 40K
- The latent heat of sublimation is around 2,800 kJ/kg (Ref.6).

Depending on the concentration of water in the regolith, the required heating power to satisfy the 2.78 kg/hr extraction rate is around 2.5 – 3.2 kW as the figure shows. Inversely, the energy that needs to be removed by either active or passive cooling systems at the collector (i.e. condenser) can also be estimated, which is the product of the required water collection rate and latent heat of deposition (~2,800 kJ/kg). This value is around 2.2kW. To meet this large thermal power requirement for ice mining, the most energy-economical solution is to utilize the waste heat of on-board MMRTGs (each will generate 2kW of thermal power) for extraction and using the extremely low environmental temperature (~40K) as the heat sink for ice refreezing within the cold trap tank. To do so, it is critical to come up with a dedicated thermal management architecture for next-generation Lunar ice mining vehicles (Lunar Ice Miners) that can strategically handle the waste heat of the nuclear power sources and passively reject the heat into the environment for ice collection.

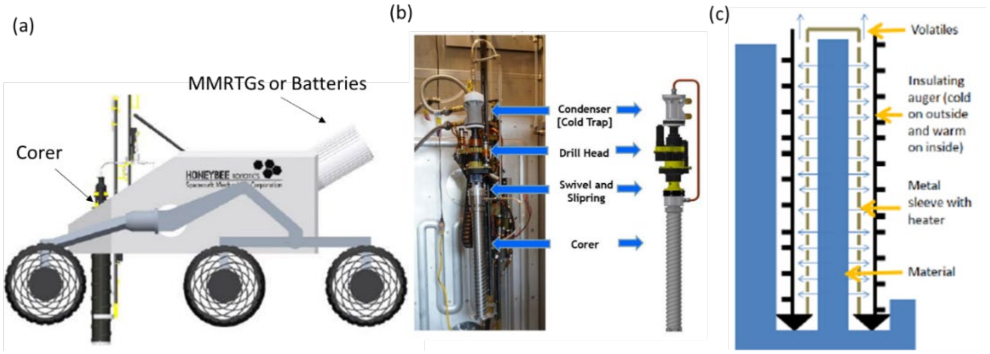

Figure 2. (a) Planetary Volatiles Extractor (PVEx) integrated on a rover for Lunar ISRU applications (b) the prototype corer fabricated by HBR (c) schematic of electric heated thermal corer (Ref. 5)

II. Thermal Management System for Lunar Ice Miners

Under an SBIR Phase I program, ACT in collaboration with Honeybee Robotics (HBR) proposes to develop a Thermal Management System (TMS) for Lunar Ice Miners which can directly use the waste heat of power sources (e.g. MMRTGs) for ice extraction and uses the Lunar environment as the heat sink for ice collection. The system consists of the following key components:

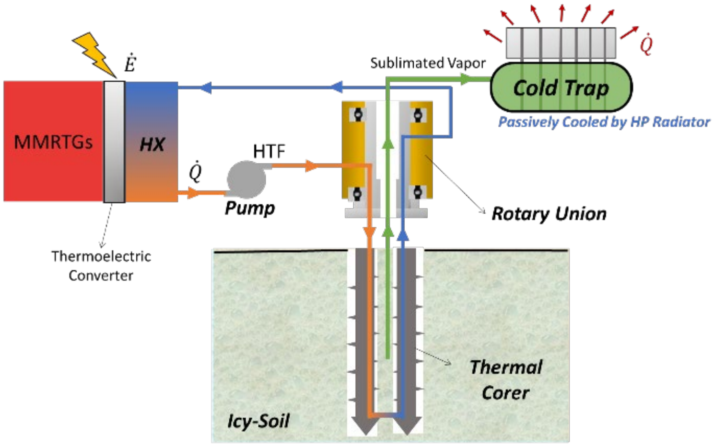

Figure 3. The Thermal Management System for Lunar Ice Miners, consisting of a pumped fluid loop, a waste heat-based thermal coring drill and a passively cooled cold trap container (HTF: Heat Transfer Fluid).

1. (1) A mechanically pumped fluid loop (MPFL) is a "thermal bus" to deliver and distribute the waste heat from an MMRTG to components that required thermal energy. The majority of the waste heat will be used for ice extraction.
2. (2) One or multiple coring drills (i.e. thermal corers) with embedded miniature flow channels. Heat delivered by the pumped loop will travel through the drills via mini-channels and directly warm up and sublimate the ice within the regolith
3. (3) A cold trap tank with integrated variable conductance heat pipes (VCHPs) that can switch between two modes of operation (ice collection and ice removal modes) without using any electricity and moving parts.
4. (4) Rotary unions that couple the pumped fluid loop, thermal corer, and the cold trap

The major advantages of the proposed thermal management system are as follows:

- Minimized electricity usage for ice extraction: The electricity output from the MMRTGs will be only used for drilling, pumping HTF, and providing power to rover and instrument.
- No electricity consumption for ice collection: heat rejection from the cold trap is fully passive.
- Smaller and lighter cold trap vessel: the integration of heat pipe radiator will increase both internal and external heat transfer surface, which will allow a smaller and light tank design. This statement will be further addressed in the next section.

This paper reports the concept feasibility study performed during the Phase I program, including the development of two proof-of-concept prototypes (waste heat-based thermal corer and VCHP cold trap), a numerical study of thermal extraction, and a full-scale TMS preliminary design and analysis.

III. Waste Heat-based Thermal Corer Development

One of the key components for the TMS is a thermal corer that can be heated directly using heat transfer fluid. ACT designs the thermal corer based on HBR's coring drill for Planetary Volatile Extractor (PVEx) system. As the CAD drawing (Figure 4a) shows, the total length of the coring drill is 50 cm, ID is 5cm and the wall thickness is around 0.7 cm. The flow channel pattern and channel size are determined based on the following design considerations:

1. (1) Liquid pressure through mini-channels and pumping power must be minimized
2. (2) Heat transfer between HTF and the wall material should be reasonably high
3. (3) Can be fabricated by additive manufacturing

A. Mini- channel design

A mini-channel design is illustrated in the right figure of Figure 4b. A hot HTF will enter the drill from the top and flow into a top ring-shaped manifold, which divides the flow into 4 parallel, spiral channels as the blue lines shown in the figure. The hot fluid will travel down through the spiral channels and transfer heat into the drill. These spiral channels will be closed to the inner wall of the corer to improve heat transfer into the center. Four channels will meet at the bottom manifold and the cold fluid will travel back to the top via four straight return lines.

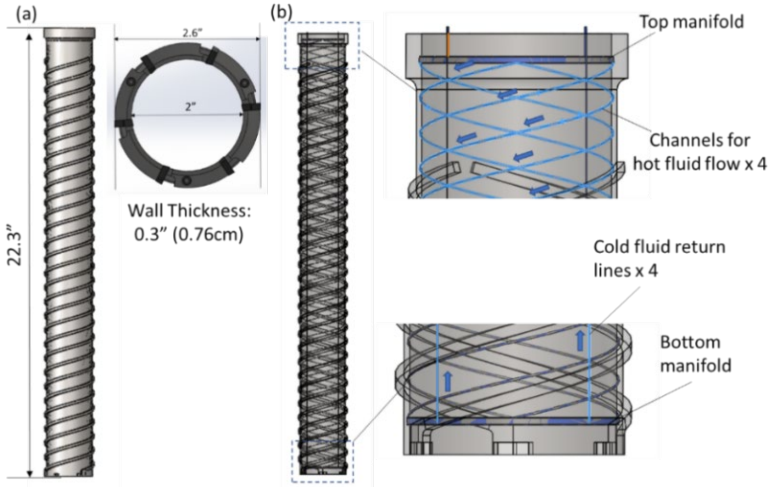

Figure 4. (a) PVEx coring auger CAD drawing (b) spiral mini-channel design embedded within the corer wall

The size of the mini-channels and the number of turns (pitches) are determined by calculating the pressure drop, pumping power, and the heat transfer coefficient under different flow rates. It was found that the required pumping power to deliver HTF through designed mini-channels is very small because the flow rate is very low. For example: with a channel size of 0.75 mm, to deliver 2 cm^3/s flow rate through a thermal corer would consume ~ $0.03W_e$ and the resulting heat transfer coefficient between the fluid and the wall is 1.6E4 W/m^2K. The analysis shows that heating the corer by circulating warm HTF is an electricity economical solution.

B. Sub-scale Prototype Development and Proof-of-Concept Testing

For concept demonstration purposes, a reduced-scale thermal corer prototype is fabricated via additive manufacturing as shown in Figure 5. This prototype has a dimension of 6 inches long and 0.6 inch ID. Four parallel spiral mini-channel (with 2mm channel size) is embedded within the wall material as the radiography photo shows. The drill prototype is tested on an ice extraction system depicted in Figure 6. The system consists of a chiller cup filled with an icy-soil surrogate and cooled by LN, a bell jar to simulate low-pressure environment, a volatile collection vessel to refreeze extracted volatile, and a constant temperature bath to circulate warm HTF into the sub-scale corer prototype. Instead of drilling into an icy-soil surrogate, the sub-scale corer was preloaded into the chiller cup and then frozen with the water-soil mixture. The icy-soil surrogate is prepared by mixing a certain % wt of water with LHS-1 simulant. Multiple TCs are used to monitor temperatures of icy-soil at two different spots (in the center and outside the corer), HTF inlet and outlet, thermal corer inner and outer surfaces, etc. One pressure transducer is placed inside the bell jar and another one is placed in the volatile transport line to monitor volatile pressure.

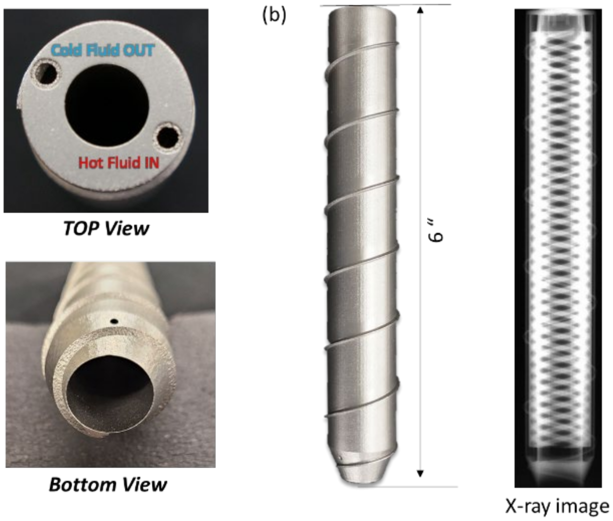

Figure 5. 3D printed thermal corer with embedded mini-channels (a) top and bottom views (b) front view (c) x-ray shows the mini-channels

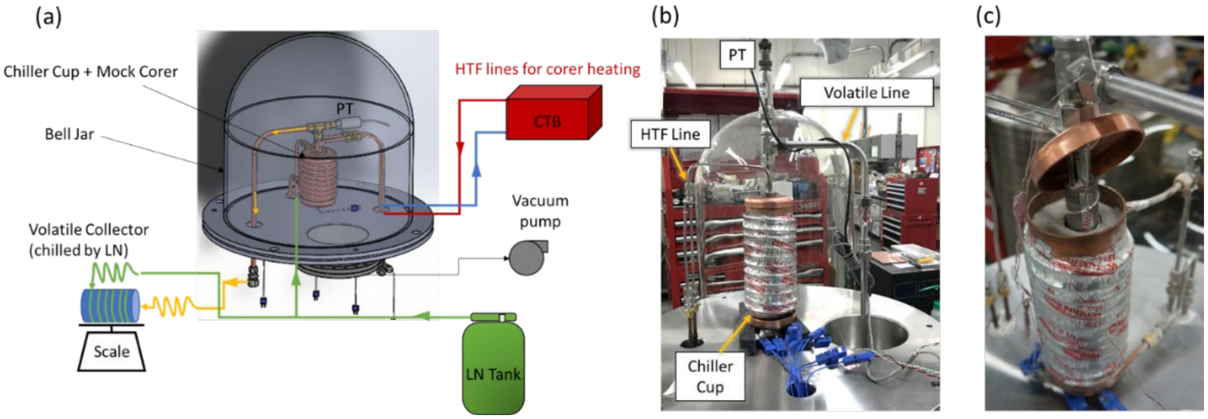

Figure 6. Ice extraction system setup for thermal corer testing (a) system diagram (b) actual apparatus (c) thermal corer inserted into a chiller cup filled with icy-soil surrogate

One of the test results is shown in Figure 7. In this test, water concentration is 10%wt, the HTF set point is 50°C and the HTF volumetric flow rate is 3 gallons per hour (~3.15 cm^3/s). At the beginning of the test, the chiller cup, icy-soil, and the mock corer are chilled by LN until everything reaches -20°C in a steady-state. At t=600 seconds, a by-pass valve is closed and the warm HTF (at 50°C) starts flowing through the corer mini-channels. It can be seen that the temperature of icy-soil inside the core (the brown line) responds very quickly. At t = 900s, the core temperature starts flattening, indicating that water starts vaporizing. This phase change completes after 9 mins of operation when the temperature rises again and eventually reaches a steady-state with other TCs. It can be seen that the temperature of the icy-soil inside the corer increases much faster than outside the core. This is mainly due to the nature of radial heat flux going into the center is higher than the heat flux going outward. After the test, water collected by the volatile collection container is weighed. The sub-scale corer successfully extracted water of 1.52 grams, which is around 44% of the total extractable water mass inside the core (i.e. extraction efficiency).

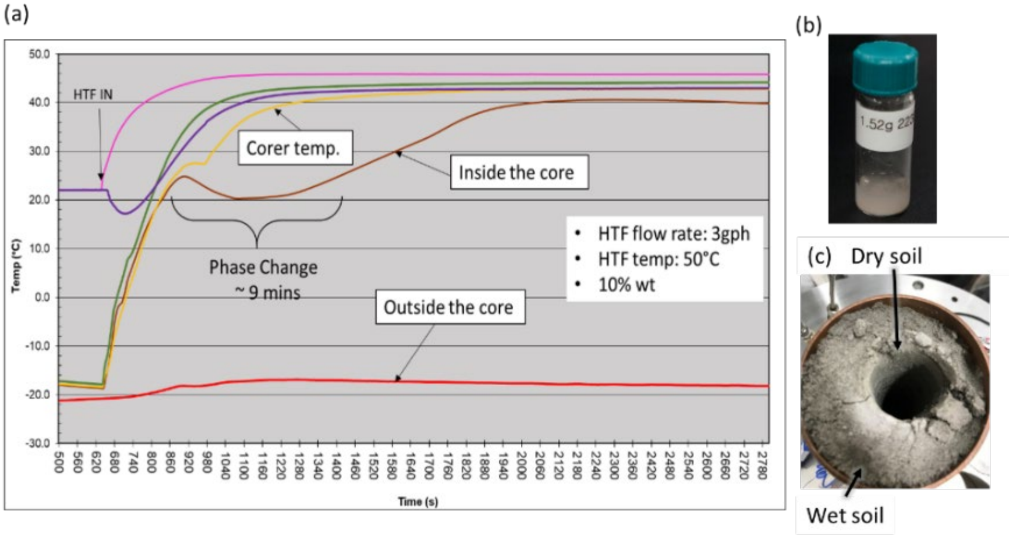

Figure 7. (a) Ice extraction test temperature data (b) the proof-of-concept corer prototype collected 1.52 grams of water from 10% wt icy-soil (c) soil conditions after testing: soil inside and near the corer is completely dry while the soil near the chiller cup wall is still wet

IV. Thermal Extraction Numerical Study

A 2D and transient numerical model capable of simulating ice sublimation from the icy-regolith in a more realistic condition was developed. The goals of this numerical study include:

1. Study heat and mass transfer during the thermal extraction process
2. Study how the geometry of thermal corer would affect the ice extraction rate

3. Study the effect of operating conditions (pressure inside/outside the corer, icy-regolith composition, HTF temperature, etc.) on the extraction efficiency
4. Predict how fast and how much ice can be extracted from icy-regolith on the moon, using a full-length thermal corer with constant temperature boundary condition

A. Model Description

The thermal properties of the icy-regolith below the triple point are based on literature (Ref. 6,7, and 8). The thermal conductivity of icy-regolith is a function of porosity, pressure, and temperature, which can vary widely from 10^{-3} to 1 W/m-K. The correlations developed in Ref. 8 is used in this model, assuming a constant regolith porosity value of 0.3. Before phase transition happens, the specific heat of icy-regolith is a function of specific heat and mass fraction of dry regolith and ice. During sublimation, the specific heat of icy-regolith becomes a function of latent heat. The equation for the specific heat of icy-regolith is:

$$C_P(T) = w_{Regolith} C_{P_{Regolith}}(T) + w_{ice} C_{P_{ice}}(T) \tag{1}$$

Both $C_{P_{Regolith}}$ and $C_{P_{ice}}$ are functions of bulk temperature (T), which are calculated based on the correlation given in Ref. 8. $w_{Regolith}$ and w_{ice} are the mass fraction of regolith and ice. During sublimation, the specific heat of icy-regolith is dominating by the latent heat of sublimation. To simulate this process, an artificial specific heat $\widehat{C_P}$ is introduced, which can be described in the equation below:

$$\widehat{C_P}(T) = w_{ice} \frac{L_s}{\Delta T} \tag{2}$$

Where $\boldsymbol{L_s}$ is the latent heat of sublimation of ice, which is assumed to be constant at 2,800 kJ/kg. ΔT is the temperature window of phase transition, typically less than 5 K. For example, with 5% initial mass fraction of ice and $\Delta T = 2$ K, equation (2) gives a value of specific heat of 70 kJ/kg-K. To calculate thermal conductivity and specific heat above, the saturation pressure of sublimated ice and mass fraction of the ice in the icy-regolith need to be calculated. The equations for saturation pressure (Ref. 6) and water vapor generation are:

$$P_{sat}(T) = 14050.7 T^{3.53} exp\left(-\frac{5723.265}{T} - 0.00728332T\right) \tag{3}$$

$$m_v(t + dt) = m_v(t) + [P_{sat}(T(t)) - P(t)] \times \sqrt{\left(\frac{M_w}{2\pi \hat{R} T(t)}\right)} \times dt \times A_{core} \tag{4}$$

The above equations were implemented into ANSYS-FLUENT as a user-defined function (UDF) to define material properties of the icy-regolith, including specific heat, thermal conductivity, saturation pressure, and mass fraction of ice. During the 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. The schematic of the FLUENT solver with UDFs is shown in Figure 8.

B. Comparison with experimental data

The model was first validated and correlated by HBR's test and then against ACT's test result described in the previous section. Figure 9 shows the temperature comparison between HBR's experiment and ACT's simulation. The temperature was set at 57 °C at the tube wall. Similar to the previous case, the temperature first increased linearly until it reached vaporization temperature. Due to high back-pressure from the test setup at ~ 700 Pa, the water started to vaporize at 20 °C. Again, ACT's simulation results agreed well with the experiment. Using the same high back-pressure, the model was able to capture the increase in sublimation temperature. Both experiment and simulation demonstrate a complete sublimation within ~9 minutes, using ACT's drill.

C. Full-length Drill Extraction Performance Prediction

The simulation of the full-length drill is based on HBR’s thermal corer design (shown in Figure 4). The simulation domain is shown in Figure 10. The drill wall has a uniform temperature throughout the drill length of 400 K. The icy-regolith domain is 10 cm away from the drill and has an initial mass fraction of 5%. Also, the icy-regolith region inside the drill was set to experience higher back-pressure than the region outside of the drill. Inside the corer, the back-pressure will reach the saturation pressure of the sublimation temperature, while the back-pressure of the outside region remains very low since the region connects to the vacuum environment. Figure 11 and Figure 12 show the temperature distribution, mass fractions of ice, and thermal conductivity of the icy-regolith mixture at the 20-minute and 35-minute mark. Due to higher pressure, the thermal conductivity of the regolith inside the drill became higher than the outside, leading to higher heat transfer into the core than the heat loss to the environment. As a result, the ice inside the drill reached sublimation temperature faster and melted faster than the ice outside the drill. At 35-minute mark, the ice inside the drill was completely extracted. Based on the size of the drill, ice’s initial mass fraction of 5% and bulk density of 1300 kg/m3, the amount of water collected is 63.8 grams. The extraction rate is calculated to be 1.82 g/min, or 109.2 g/hr.

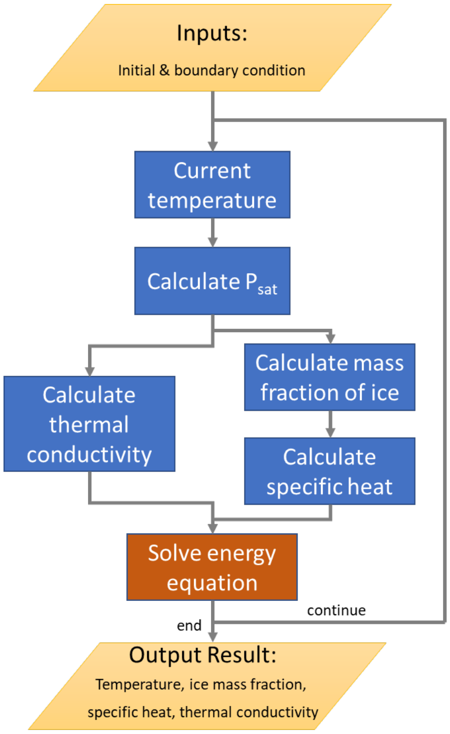

Figure 8. Schematic of FLUENT's solver with UDFs. Based on current temperature, P_{sat} will be calculated and used to obtain conductivity, mass fraction of ice, and specific heat. Then, energy equation will be solve using the new thermal properties to obtain the new temperature in the next time step.

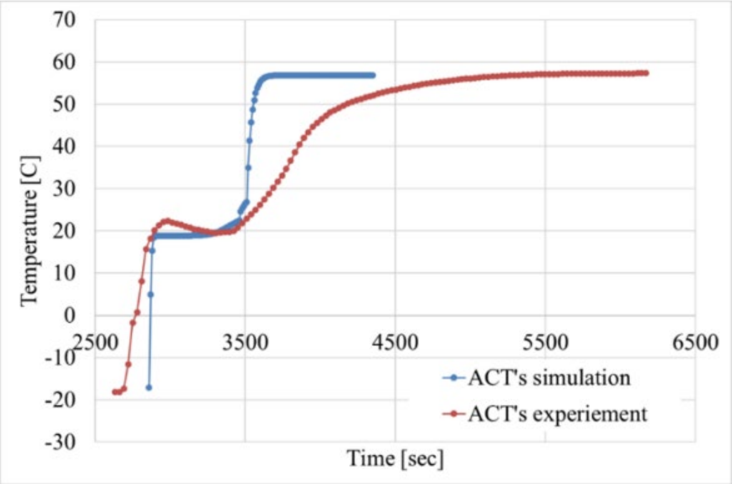

Figure 9. Temperature profile that shows the reasonable agreement between ACT's experiment and ACT's simulation. The initial mass fraction of ice is 10%. The time to fully sublimate the ice is ~8 minutes, after temperature reaches ~20 °C.

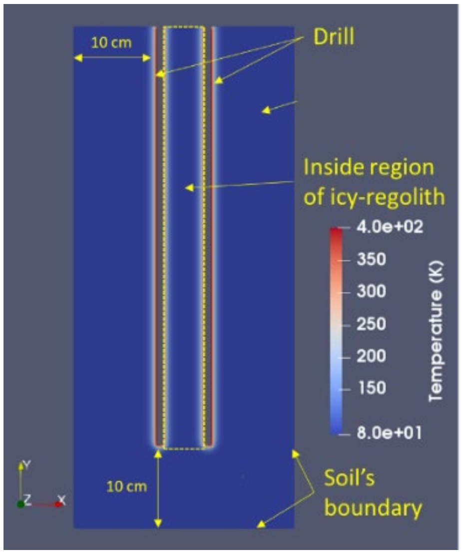

Figure 10. Simulation domain of the full-length drill in icy-regolith environment. The drill length is 50 cm, inside diameter is 5 cm, and thickness is 0.76 cm

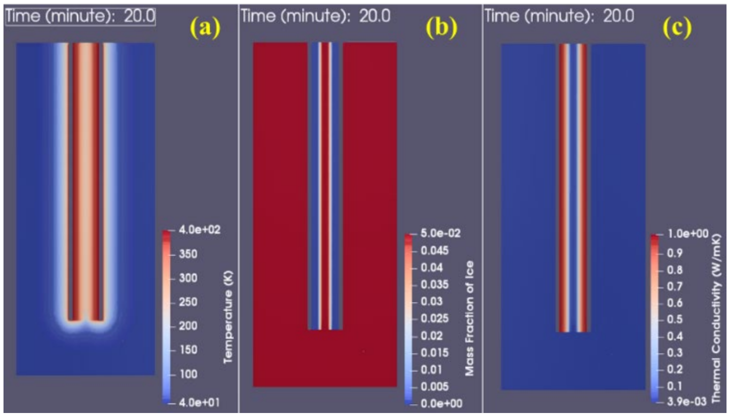

Figure 11. 2D simulation of the full-length drill at 20-minute mark: (a) temperature, (b) mass fraction of ice, (c) thermal conductivity of the icy-regolith. The ice inside the drill is being extracted. The conductivity is increasing due to higher pressure.

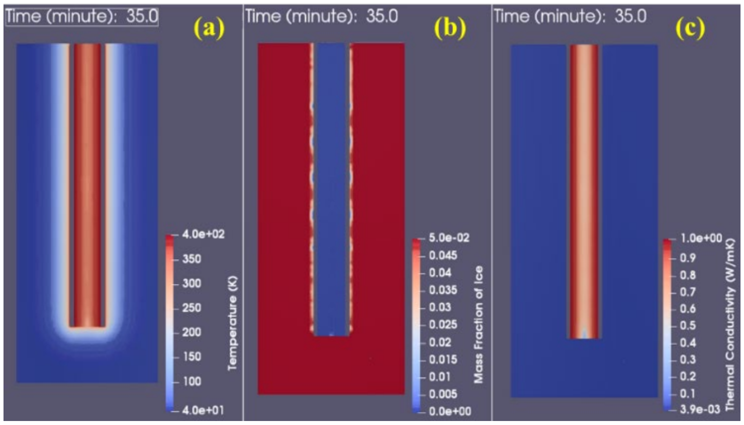

Figure 12. 2D simulation of the full-length drill at 35-minute mark: (a) temperature, (b) mass fraction of ice, (c) thermal conductivity of the icy-regolith. The ice inside the drill is just completely sublimated.

V. VCHP Cold Trap Development

The cooling performance of the cold trap will also affect the overall mining efficiency since the volatile flow is driven by the pressure difference between the extraction site (i.e. the icy-soil core) and the cold trap tank. The latent heat carried by the volatile flow must be effectively removed in the cold trap. Otherwise, the pressure of the system would increase and reduce ice sublimation. Moreover, the volatile may leak out from the boreholes to the lunar environment if the pressure inside the system is too high. ACT developed an innovative cold trap concept that uses multiple variable conductance heat pipes (VCHPs) so that the cold trap can switch between ice collection mode and ice removal mode without using moving parts and electricity. The concept is illustrated in Figure 13. All the heat pipes are joined together by a common vapor space located outside of the cold trap. The common vapor space will be the evaporator all the time. The heat pipe sections inside the tank will operate alternatively as evaporators during ice collection mode and as condensers during ice removal mode. The condenser section located outside of the tank, interfacing with radiator panels will be ON during the ice collection mode and OFF during the ice removal mode. The volatile entering the tank will deposit its latent heat of vaporization into the heat pipe surfaces. Heat pipes will effectively transfer heat from the evaporator to the condenser and further into the radiator for ultimate heat rejection. The volatiles will turn into ice (represented as the light blue color in the figure). During this mode of operation, NCG will be located inside the reservoirs on the top of the condensers. Switching to the ice removal mode can be achieved by heating the reservoir using waste heat (from the MMRTG). NCG being heated will expand and block the condenser. This is called "thermally switch OFF" of the condenser, as Figure 13(b) shows. The heat transfer path between the heat pipe and the ultimate sink is cut-off. Heat applied to the common evaporator at the bottom of the tank will be transferred into the ice, not to the radiator. Ice layers originally attached to the vertical pipe surfaces will melt and fall onto the horizontal surfaces. Ice removal capability will be useful in the following scenario:

a. De-icing: as the ice layers grow thicker on the heat pipe surface, they become thermal insulators between the volatile and ice collection surfaces. The collection rate will drop significantly due to increasing thermal resistance.
b. Improved packing: Melted ice will fall on the horizontal surface of the tank and re-freeze, during this ice-collection mode. This would enable ice accumulation from the bottom to the top.
c. Efficient ice discharging: The vehicle is fully-loaded with ice and needs to discharge all the ice to the processing site on the moon.

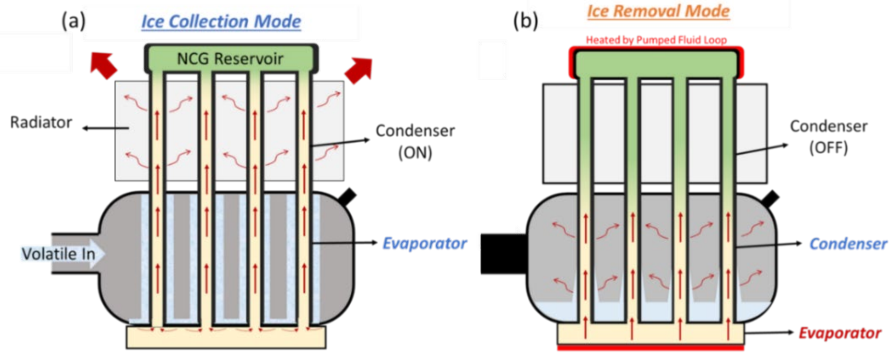

Figure 13. (a) VCHP ice collection mode (b) VCHP ice removal mode

A. Proof-of-concept Prototype Development

A proof-of-concept prototype was developed to demonstrate switching between two modes of operation. As Figure 14 shows, the system consists of a cylindrical vessel, three variable conductance heat pipes (VCHPs) with 1 inch OD and 10 inches length, and a chiller block installed around the external condenser to simulate the radiator. Both ends of the vessel are closed by CF flanges with sight glasses to visualize the process of ice formation and de-icing. Three VCHPs penetrate the cylinder from the top and they are all connected into one common vapor space (i.e. evaporator-2). A film heater is attached to evaporator-2 and will be turned ON only for ice removal operation. The condensers of VCHPs are cooled by a chiller block via LN lines. Three NCG reservoirs on the top of the condenser will be heated with a rope heater, only during the ice removal operation. In nominal ice collection mode, the reservoir temperature (that normally is maintained by the frigid cold environment) is maintained through LN cooling. Acetone is used as the working fluid due to easiness to handle. The envelope material is stainless steel. Non-condensable gas is helium. There are 25 TCs attached to the surface of heat pipes to capture temperature distribution along the pipe.

B. VCHP Cold Trap Tank Demonstration Testing

The experiment was performed in the following sequence:

a. Ice collection: heat pipe condensers are first cooled by a chiller block until the temperature of evaporators reaches below triple point (-5°C). At a steady-state, the valve connecting the volatile source tank and the cold trap tank is opened to introduce volatile (Figure 15A). Volatile deposits its thermal energy into heat pipe evaporators that are located inside the tank and start condensing/freezing (see Figure 15B). The ice layer becomes thicker and thicker (Figure 15C & D).

b. De-icing: When the ice layer forming on the heat pipe surface reaches a certain thickness (i.e. 0.5cm), the VCHP is switched OFF by applying heat to the reservoir (Figure 15E). At the same time, heat is also applied to the bottom evaporator for deicing. The section inside the tank becomes a condenser as Figure 15F shows.

c. Ice re-collection: Once all the ice is removed from the heat pipe surface, the VCHP is switched ON by cooling the reservoir (Figure 15G). The section inside the tank change back to the evaporator and starts collecting volatile efficiently Figure 15H).

A video showing the process described above can be found in https://go.1-act.com/lunar-ice-miner-sbir.

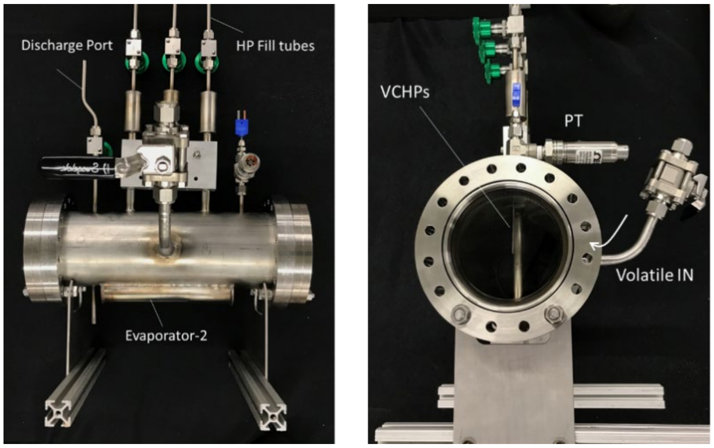

Figure 14. Proof-of-concept VCHP Cold Trap Prototype (front and side view)

VI. Preliminary TMS Design and Analysis

A preliminary TMS design mounted on a mining rover using MMRTG as a major power source is developed and shown in the rendering CAD model (Figure 16**)**. The system has one MMRTG, rechargeable battery, six waste heat-based thermal corers, a VCHP cold trap tank (with 3 radiator panels), and an MPFL for waste heat delivery. In each cycle, this miner will have three modes of operation: drilling, extracting/collection, and relocation. Thermal and electric energy management for three operation modes is illustrated in Figure 17. During the drilling operation, all electricity generated from MMRTG and stored in the battery will be used for operating the drill. The duration of drilling is around 8 mins (depth of penetration 1 mm/s) and the electric power consumption is $100W_e$ for one drill (provided by HBR). After drilling, the waste heat of MMRTG will be used for ice extraction. During this period, all electricity generated from MMRTG will be stored in a rechargeable battery, which will be used in the next drilling cycle. During ice collection, the system will operate simultaneously without using any electric energy (except for the pump). The extraction will take 40 mins. This is based on ACT's numerical model described in the early section. The extracted ice mass is also determined based on the modeling results, assuming 60% efficiency. After drying out the icy-regolith, the miner needs to move to another location. All electricity from MMRTG will be used to support vehicle transport. The average relocation duration is assumed to be 10 mins. The total duration of one operation cycle is around one hour.

During 40 mins thermal extraction period, all electricity generated from MMRTG (0.073 kWhr) will be stored in a battery, which will be used in the next cycle to power 6 drills in parallel. Six drills will have an extraction rate of 0.36 kg/hour (based on the numerical model). The required thermal energy for extraction would be 0.58 kWhr, which includes the sensible heat to increase the temperature of both regolith (95% wt) and ice (5% wt) from 40K to 250K and the latent heat of sublimation. The total waste heat generated from MMRTG is around 1.58 kWh. Hence, there will be around 60% of excessive thermal energy available in each cycle. This preliminary design will consume 91% of electricity and 53% of waste heat from MMRTG in each cycle. Extracting 1 kg of water would consume 2.6 kWh of thermal energy and 0.25 kWh of electricity. The total mass of the preliminary design is 59.6 kg and the heaviest item in the system is MMRTG, with takes more than 70% of the total mass.

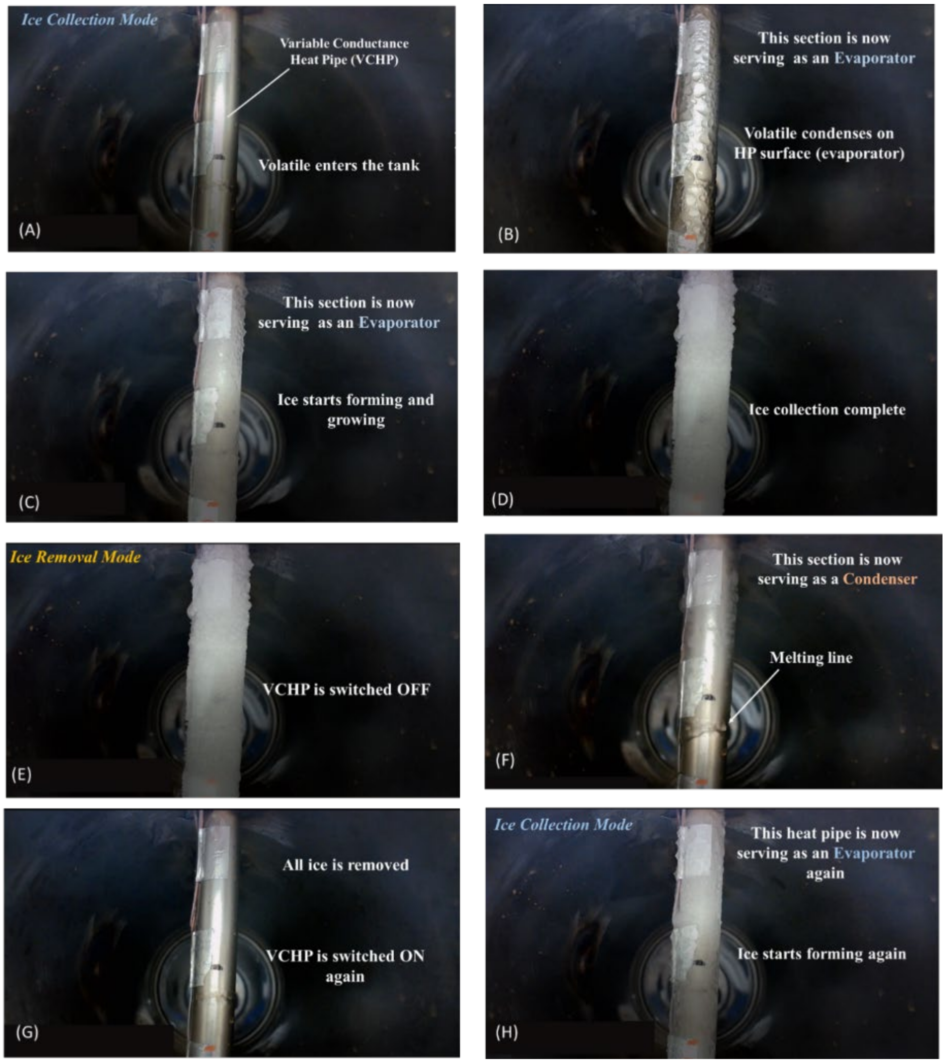

Figure 15. Demonstration of VCHP cold trap concept (A) volatile enters the tank (B) volatile start condensing and freezing on the heat pipe surfaces, that are serving as evaporators (C) ice layer becomes thicker and thicker (D) the system needs to switch to ice removal mode (E) VCHP is switched OFF by heating the NCG reservoir (F) ice started being removed from the heat pipe sections, operating as a condenser (G) all ice has been removed and VCHP is switched back ON for next round of collection (H) ice starts forming again

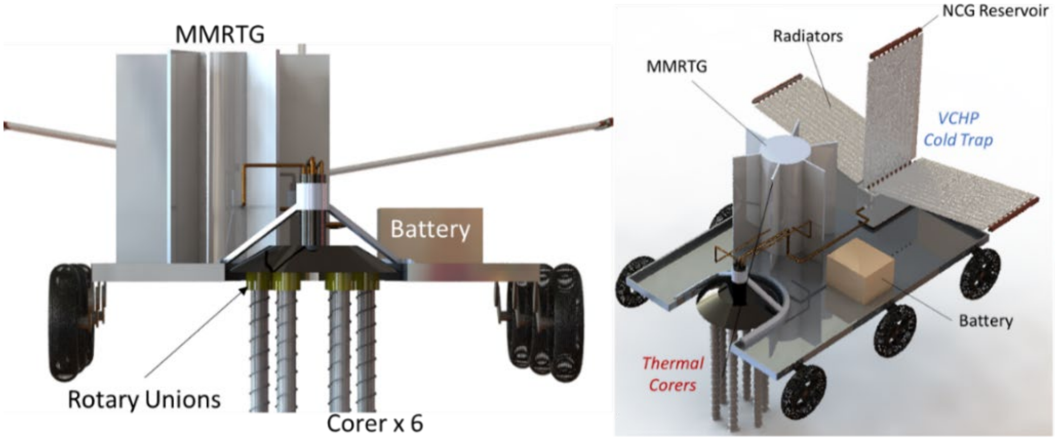

Figure 16. Rendering model of a preliminary ice mining rover using proposed TMS.

VII. Conclusion

ACT in collaboration with HBR developed a TMS concept for a Lunar ice miner that can strategically use the waste heat and electricity of a nuclear power source (MMRTG) onboard to achieve a higher mining rate. The feasibility of two key enabling concepts was successfully developed and demonstrated:

- A waste heat-based thermal corer with embedded mini-channels can directly utilize the waste heat of MMRTG to extract ice from regolith. This technology will open a new path for ice miner design and improve the balance between thermal and electric power consumption.
- A cold trap tank that can switch from ice collection mode to ice removal mode without using any moving parts and electricity. This technology will allow a smaller, lighter, and highly reliable cold trap design.

A preliminary full-scale TMS for a Lunar Ice Miner was designed and analyzed. Because of the new thermal corer design that can directly use the waste heat of MMRTG for ice extraction, the electricity generated during this period can be stored in a battery, which will be used in the next drilling cycle. This would allow 6 drills to operate simultaneously and maximize the mining rate. To harvest 1 kg of ice on the moon, this preliminary mining system will consume 2.6 kWhr of waste heat and 0.25 kWh of electricity. Conclusively, by using waste heat rather than electrical power for soil heating, the proposed concept opens the possibility of reducing the number of MMRTG usage per kilogram of harvested water and therefore less General-Purpose Heat Sources (that are based on Pu238 and so hard to produce). This analysis also shows that the system still has 47% of waste heat not being used. A detailed trade study will be needed to fully utilize both thermal and electricity of the MMRTG.

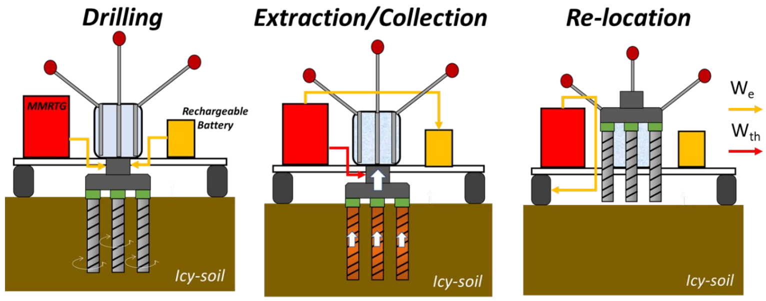

Figure 17. Three operation modes and the power distribution

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