



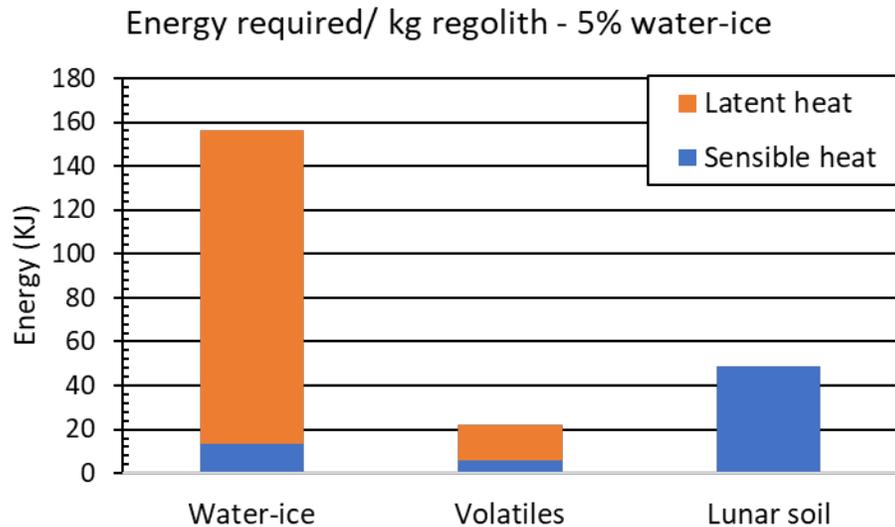
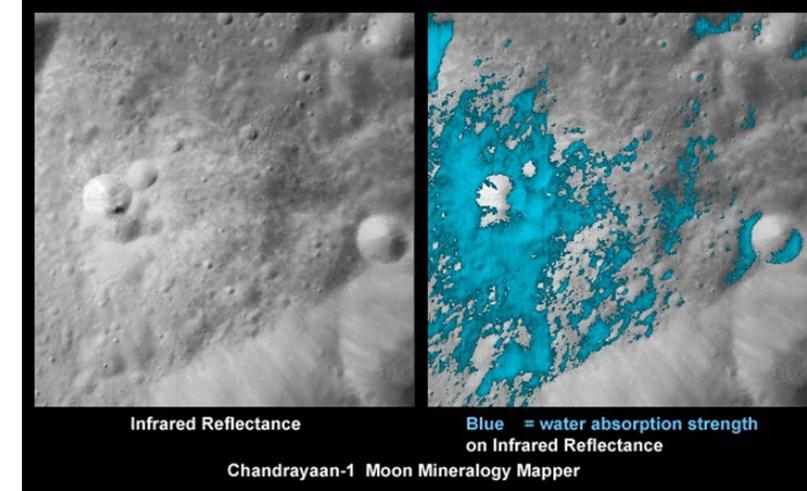
Demonstration and Analysis of Thermal Management System (TMS) for Ice Extraction and Ice Collection for Lunar Ice Miners

Sai Kiran Hota, Kuan-Lin Lee, Quang Truong, Calin Tarau
Advanced Cooling Technologies, Inc.
Kris Zacny
Honeybee Robotics



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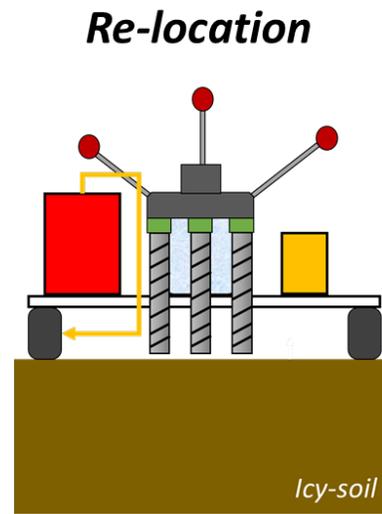
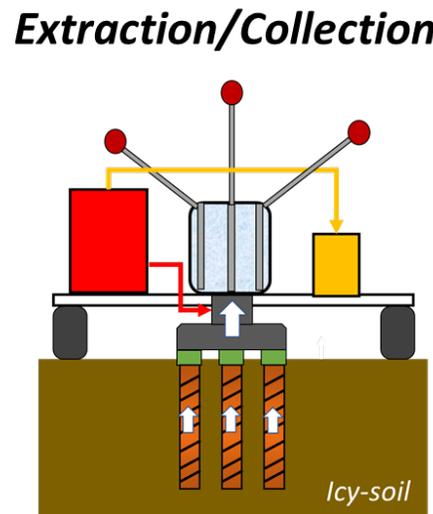
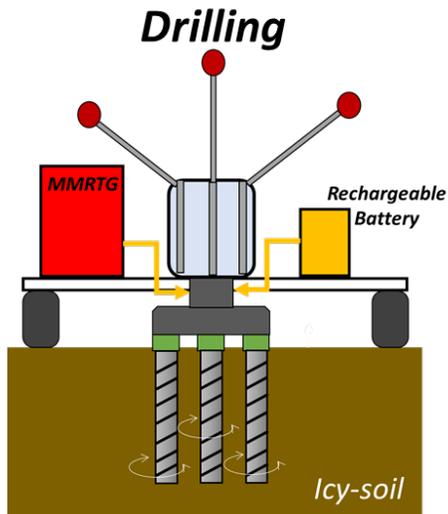
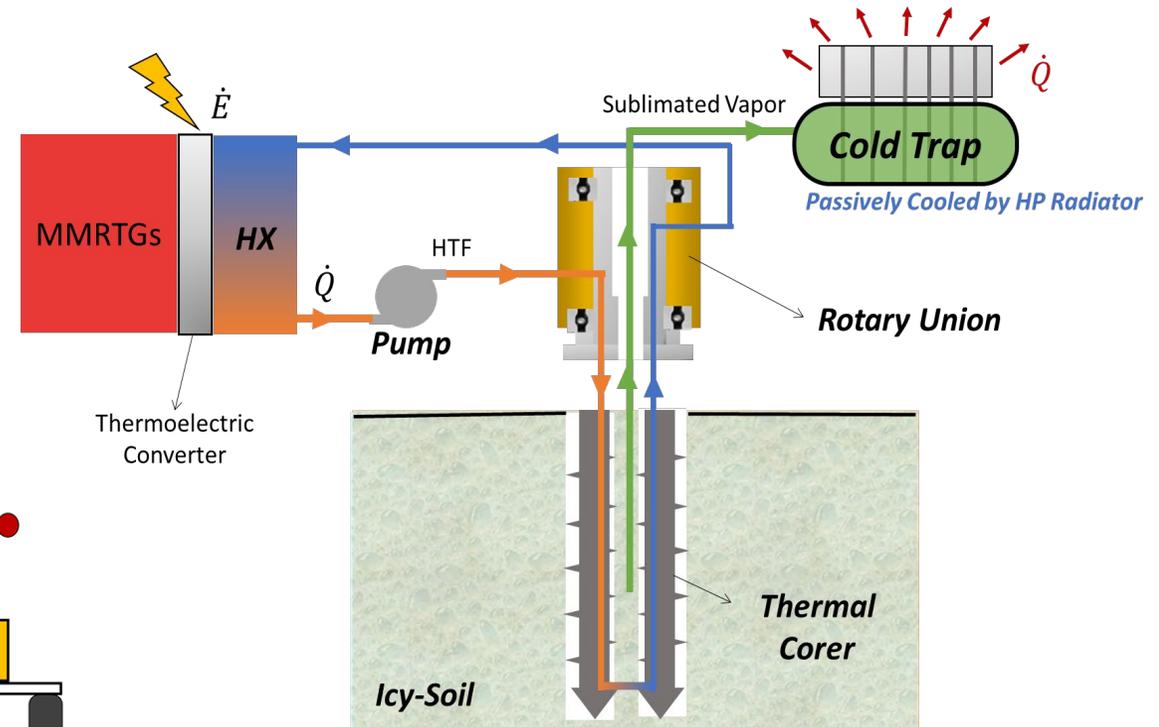
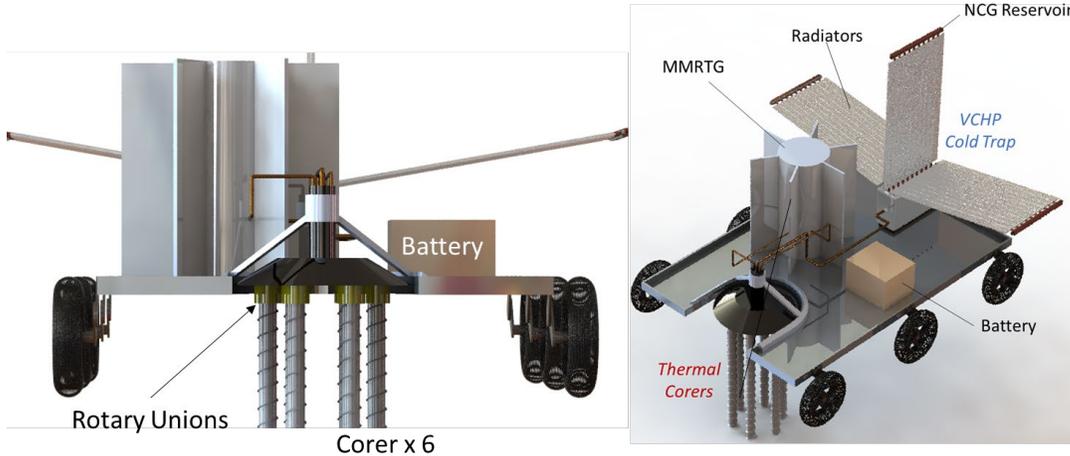
- Sustaining future space explorations including those on the moon depend vastly on ISRU activities
- Water-ice is a valuable resource available on lunar south pole (in PSR)
 - About 600 million tons of water is estimated to be trapped within the lunar soil
 - Mean concentration of water-ice: 5% by mass
- Lunar conditions are vastly different from Earth
 - Pressure: $< 1E-10$ Torr
 - Temperature: 40 K to 80 K



- Thermal mining of ice consumes a total of 227 kJ of energy per kg of soil
- An example case: 10 mT O₂ □ 15 mT H₂O/225 days □ 2.78 kg/h
- Total thermal energy required for ice extraction is 3.5 kWh (70% used for sublimation)
- To collect ice, 2.5 kWh energy must be rejected by radiation

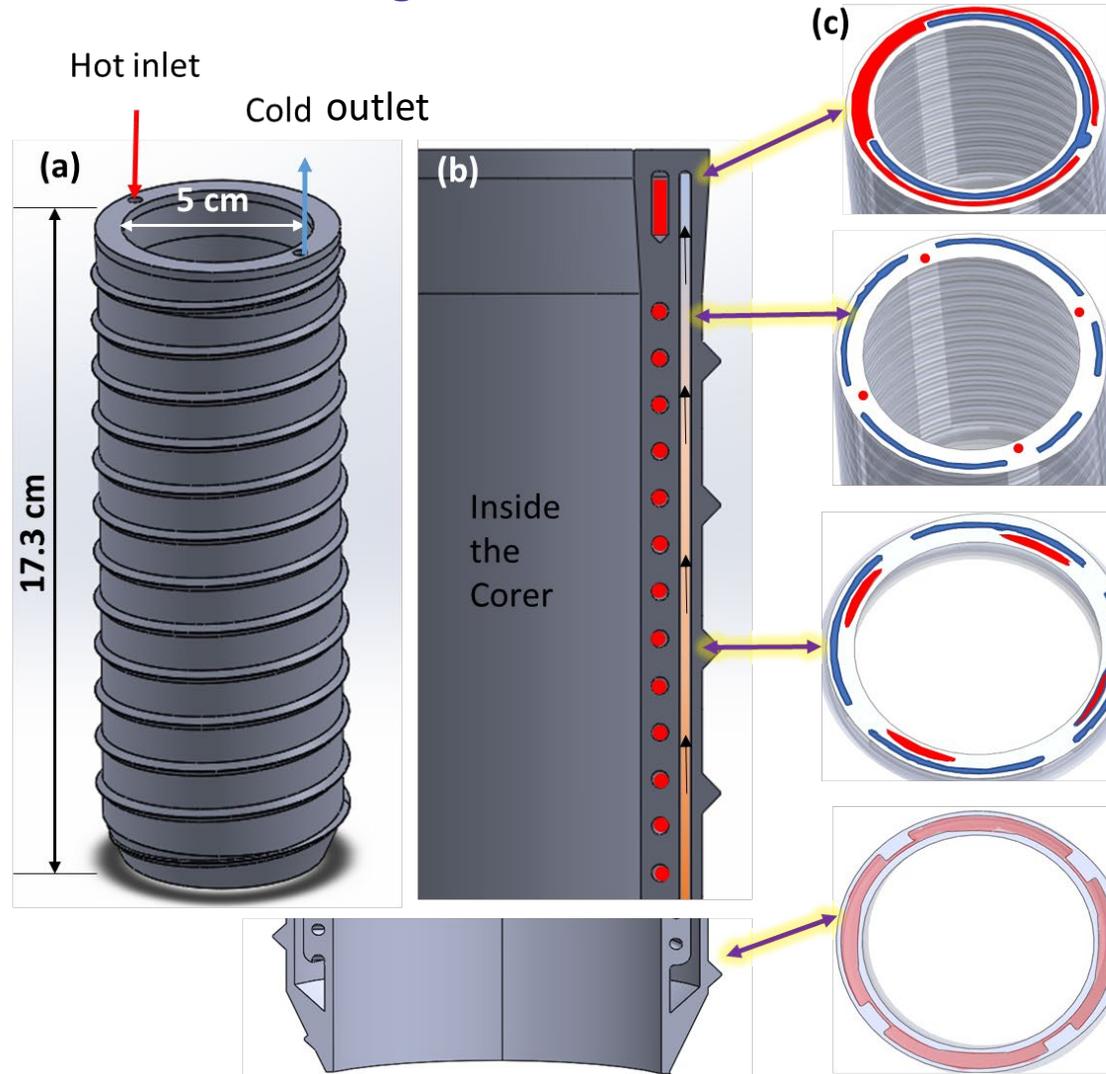
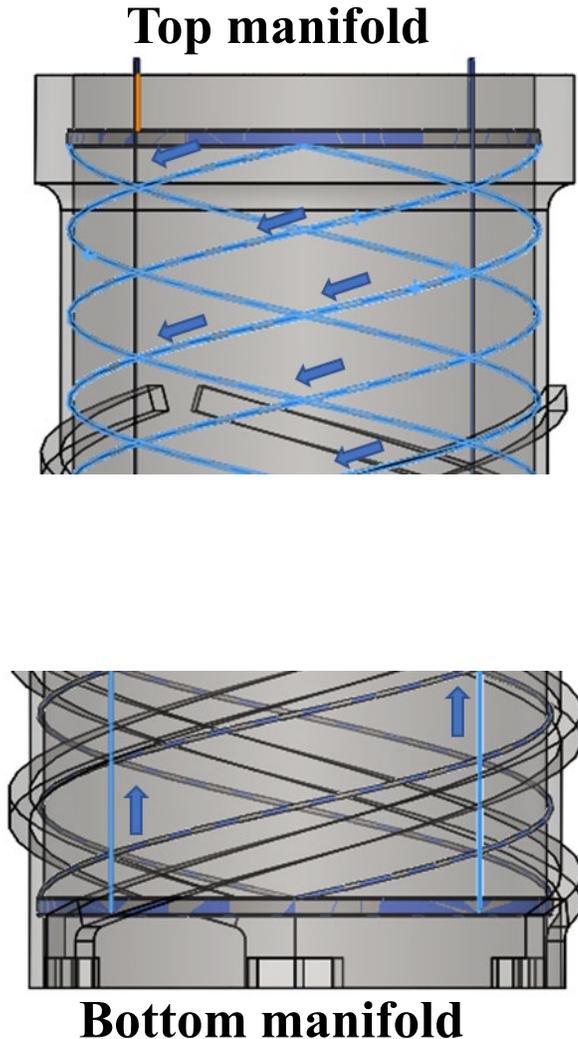
Thermal Management System for Lunar Ice Miner

- ACT with HBR is developed a thermal management system for ice mining: extraction & collection
- The thermal energy for extraction is based on utilizing waste heat from onboard power source



Concept of operations of system components

Thermal corer is a drill corer with integrated minichannels to facilitate heat transfer.



Splitting of incoming and outgoing channels along the annular space at the top of the thermal corer

4 minichannel spiral passages for hot fluid to flow downwards

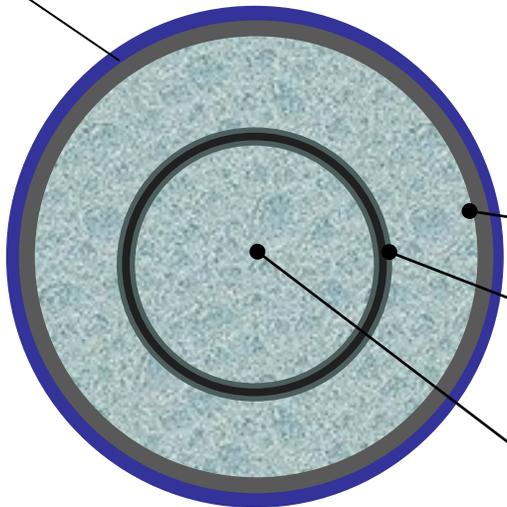
Hot fluid spiral passages growing in size axially downwards

Minichannel and annular flow passages converging at the bottom for flow reversal

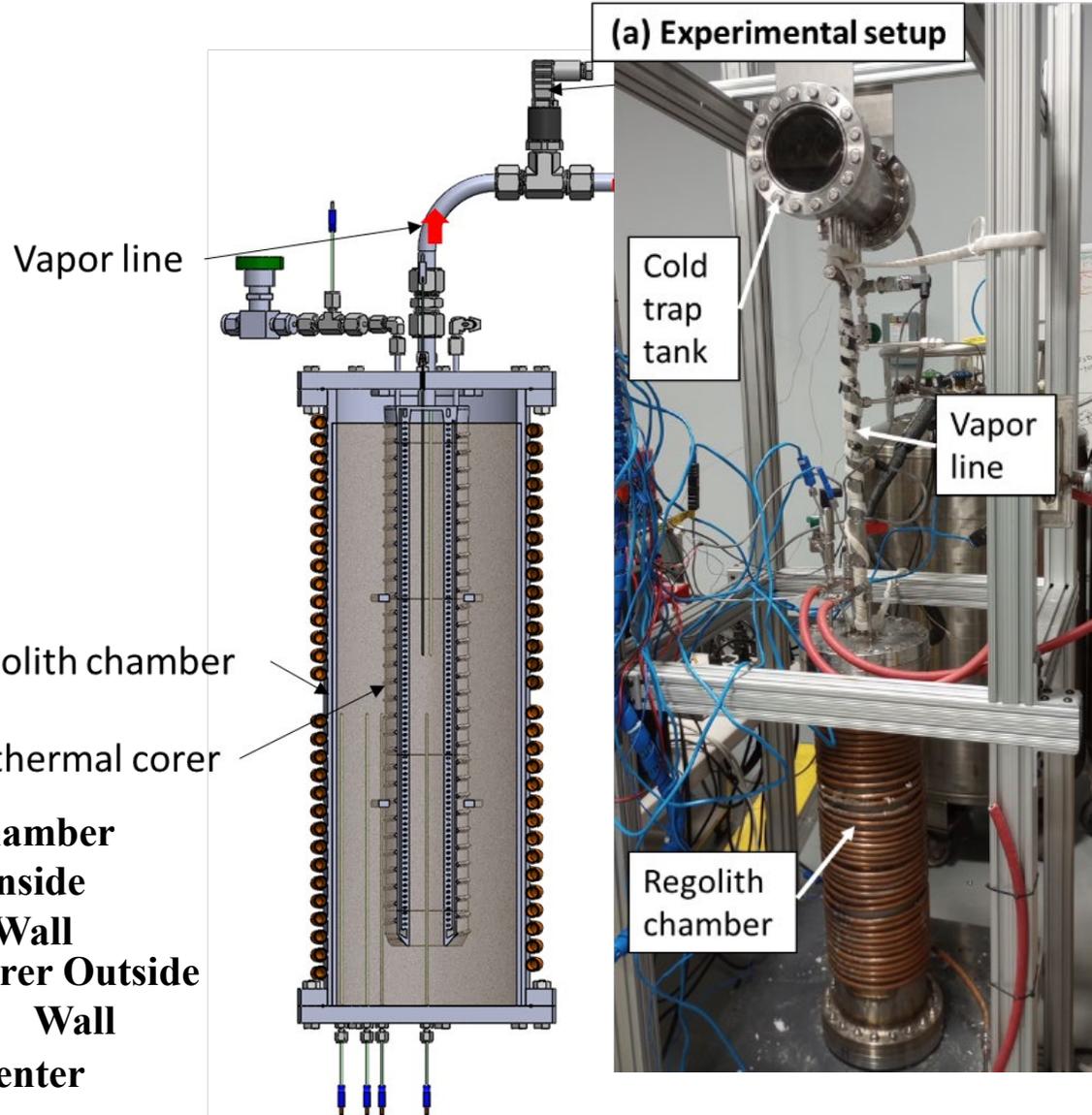
Description of Ice Extraction Experimental System

- Regolith chamber: Mixture of LHS-1 @ 5% water ice
- Sub-Scale Prototype Thermal Corer: 5 cm ID x 17.3 cm long (SS316)
- Cold trap tank: for vapor deposition as ice
- Vapor line: to connect regolith chamber to cold trap tank

LN Tubing



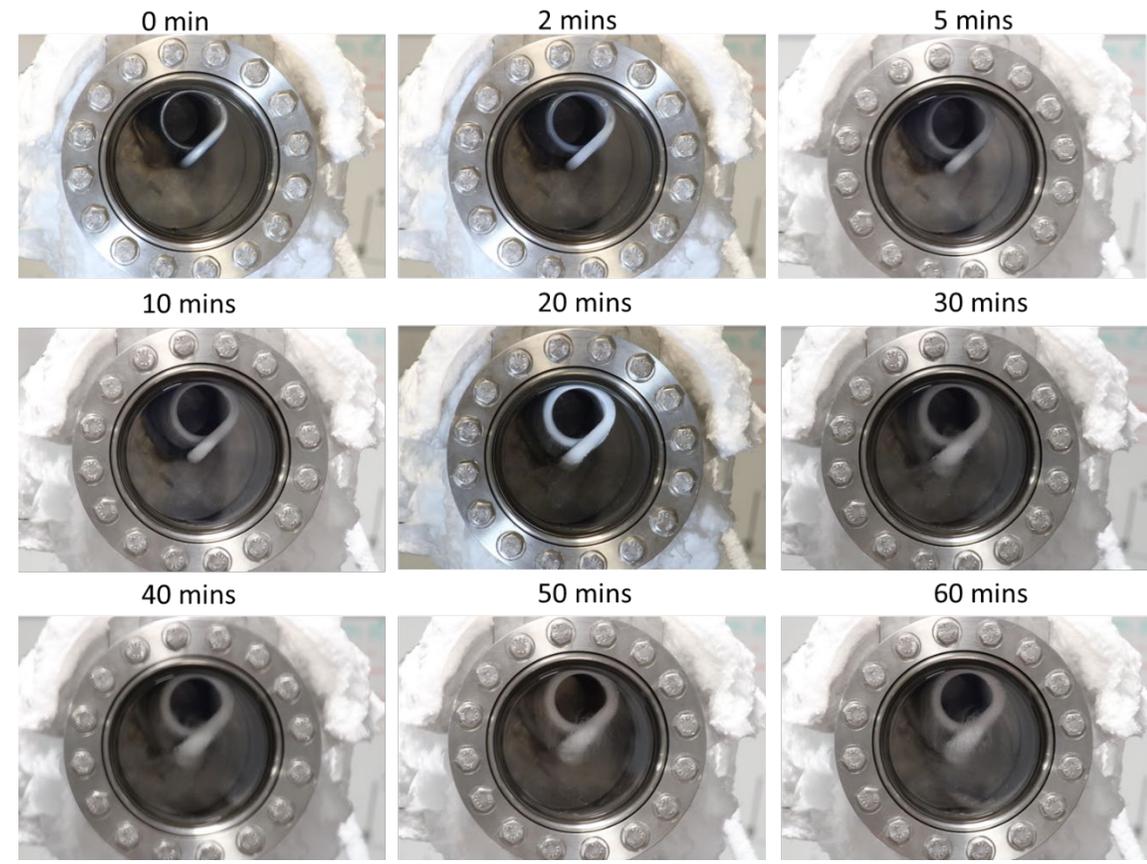
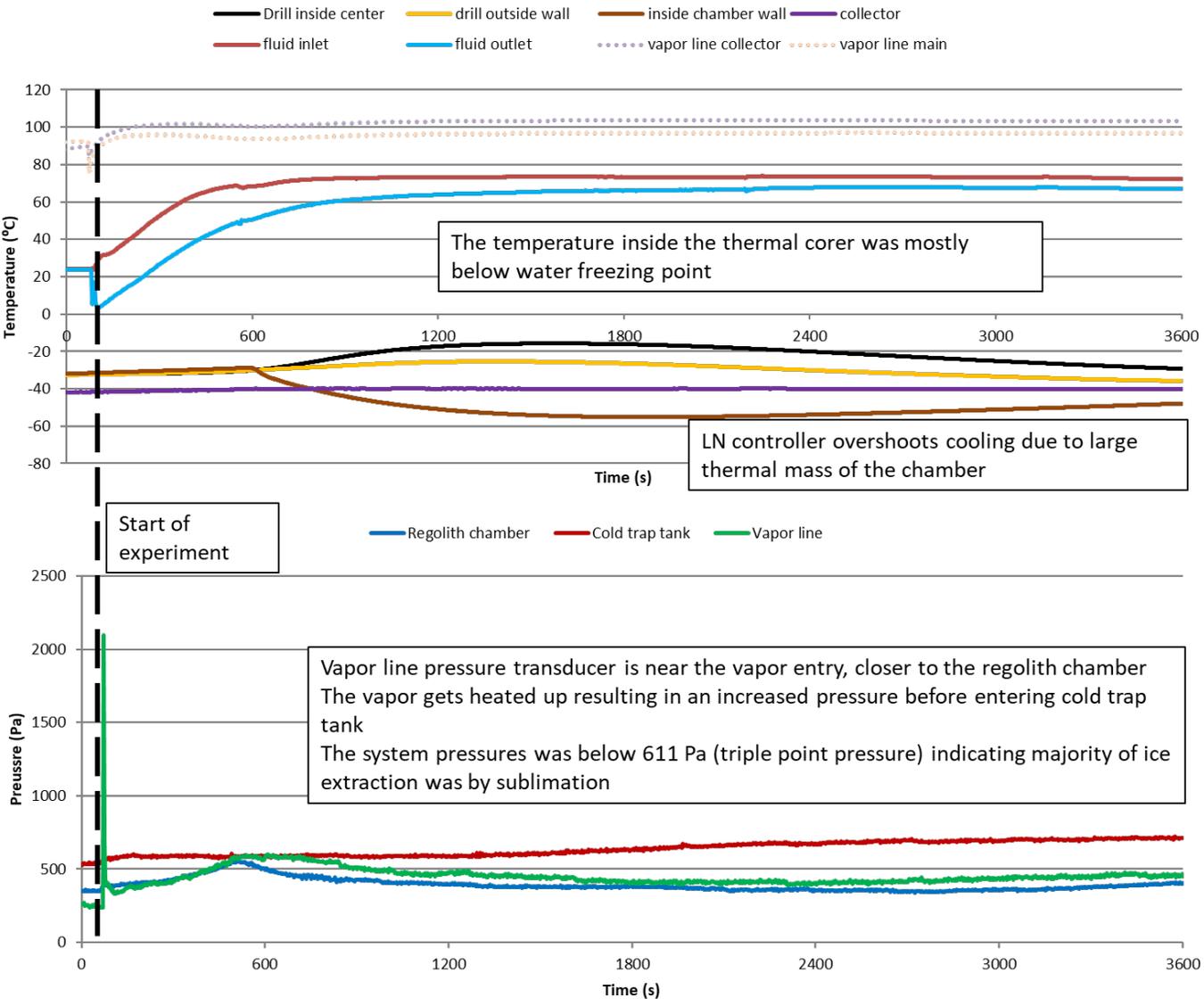
Regolith chamber
 Scale-up thermal corer
 Chamber Inside Wall
 Chamber Outside Wall
 Corer Outside Wall
 Corer Center



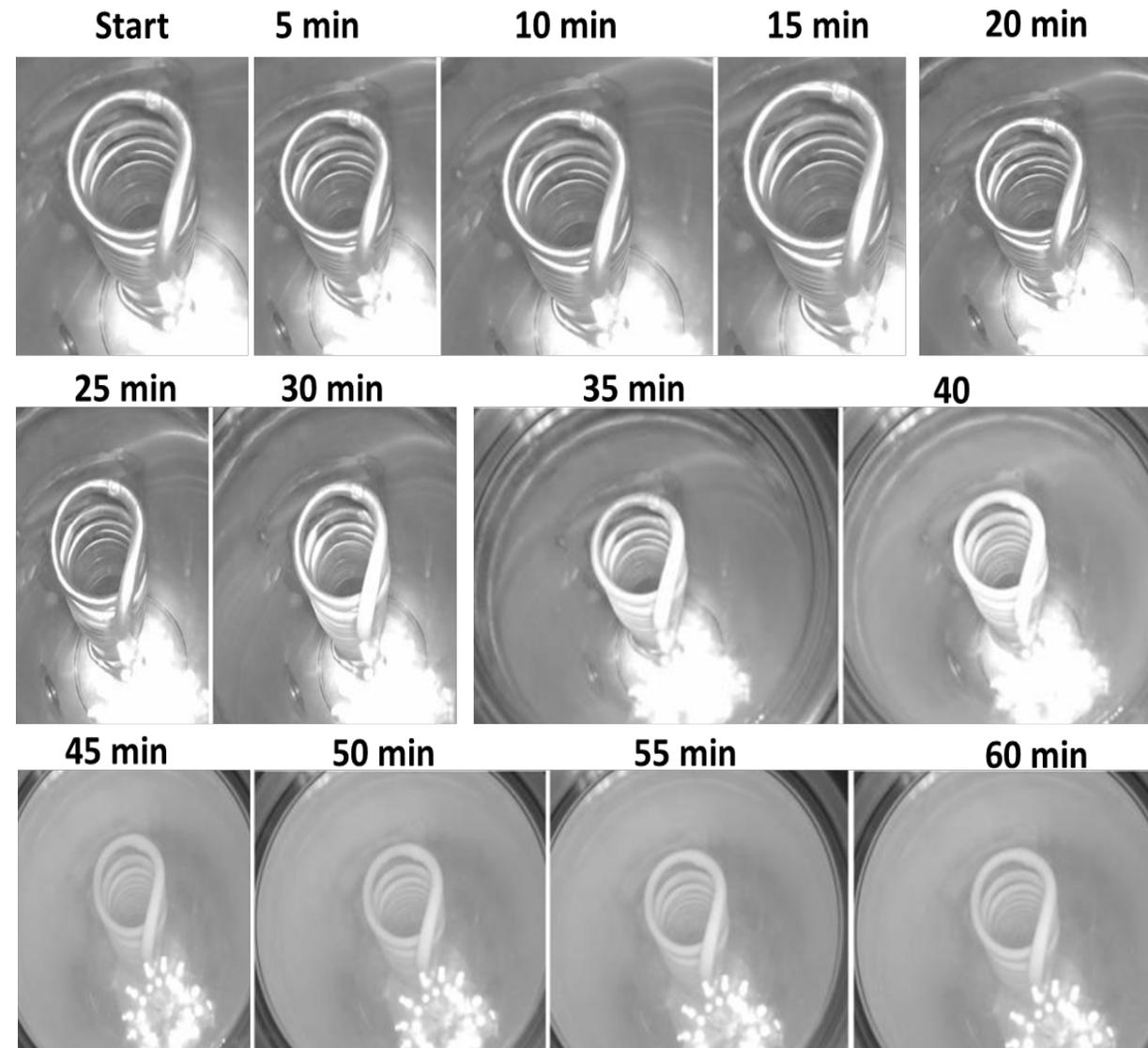
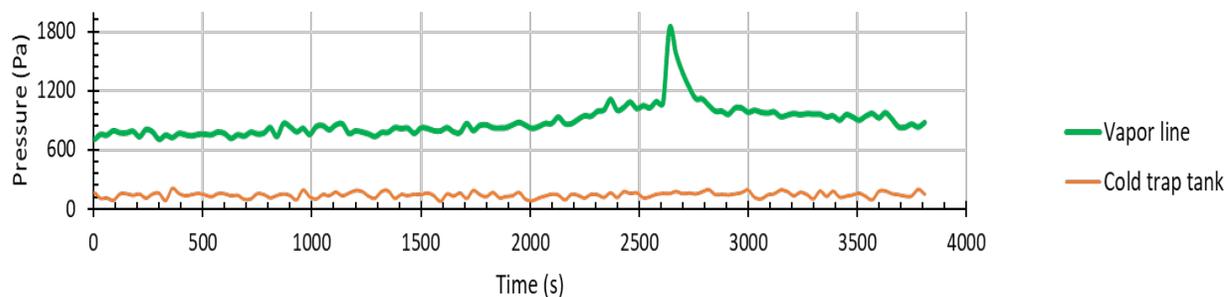
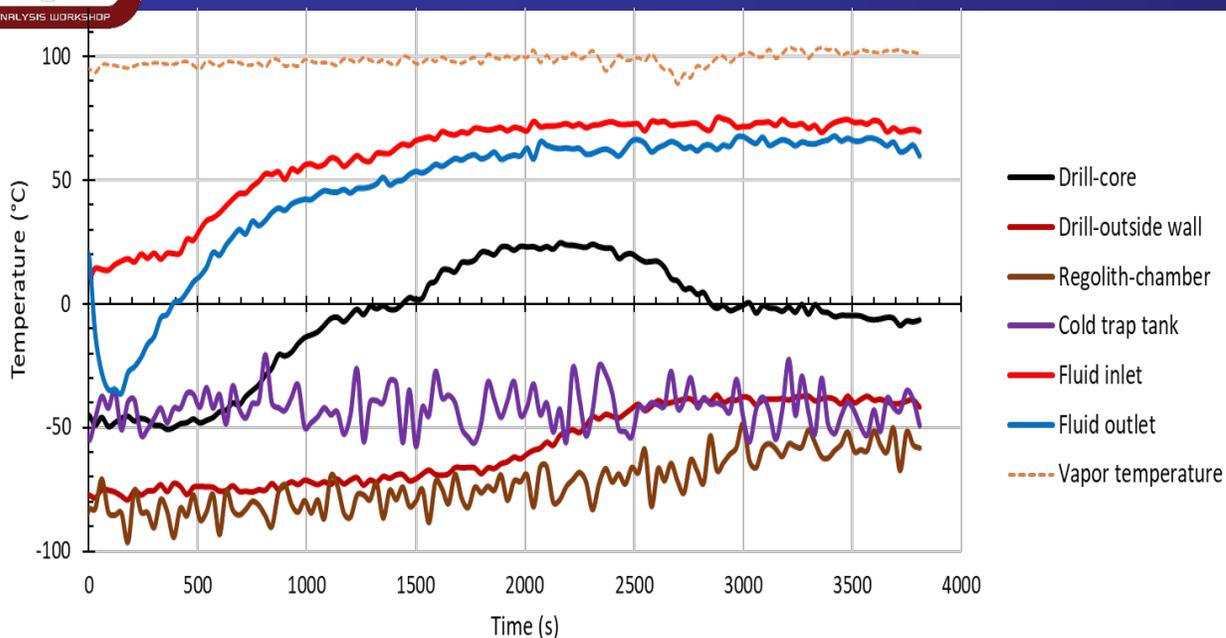
(b) Thermal corer



System Operating Conditions & Ice Extraction Characterization



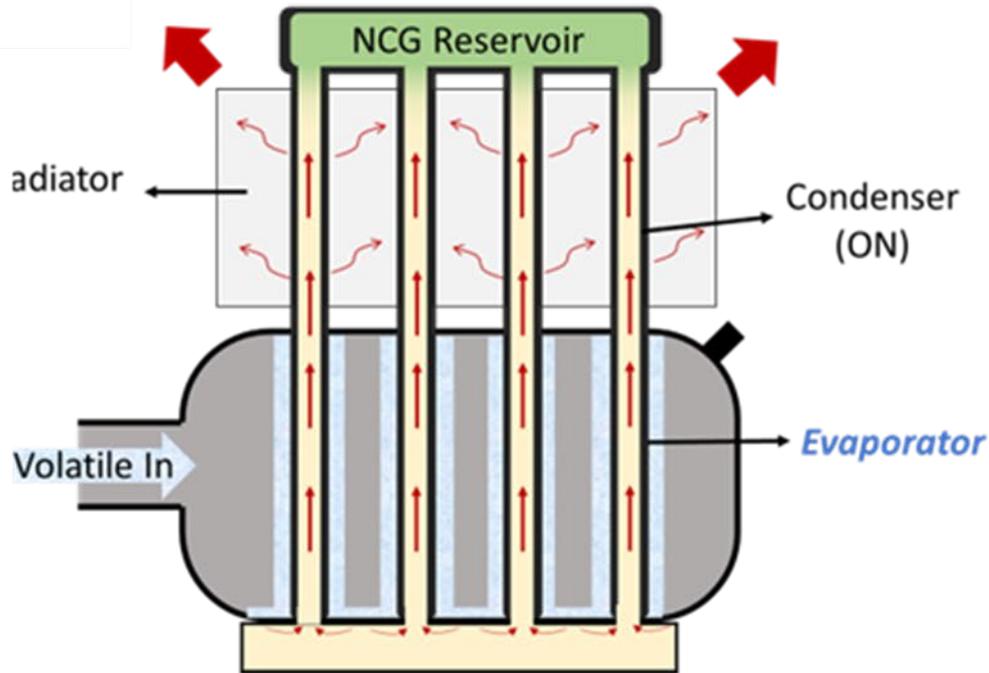
- Total ice extracted by the thermal corer: 13 grams
- Ice recovery rate: ~60%



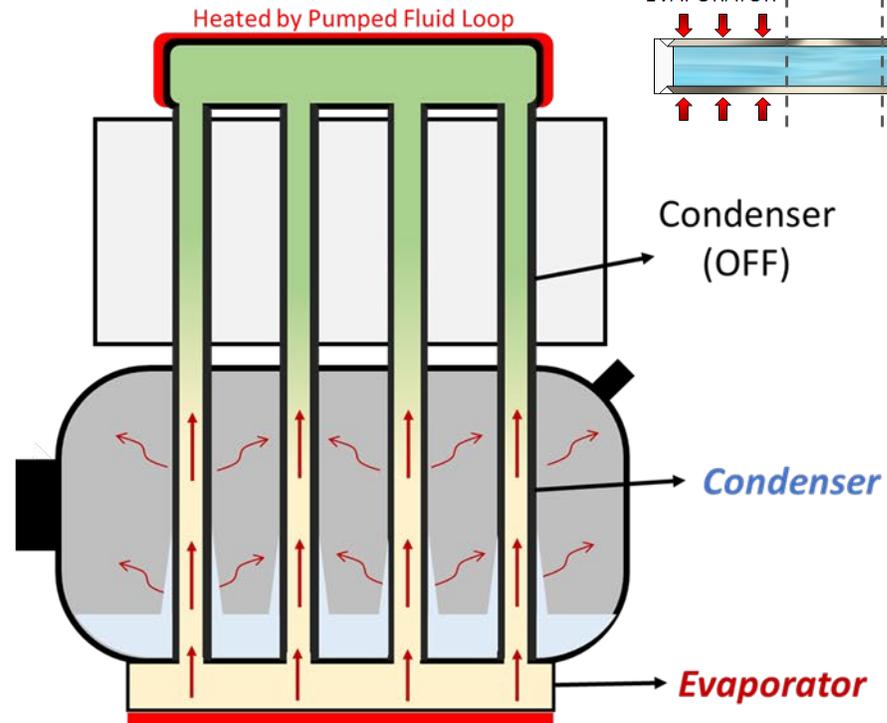
- Ice-recovery rate up to 18.2%* was achieved with the test
- Observation (*): LSP-2 simulant was trapped along with ice, thus presenting muddy-soil to ice recovery measurement. The simulant transport during sublimation of ice must be mitigated for improved efficiency

Variable Conductance Heat Pipe (VCHP) Cold Trap Tank

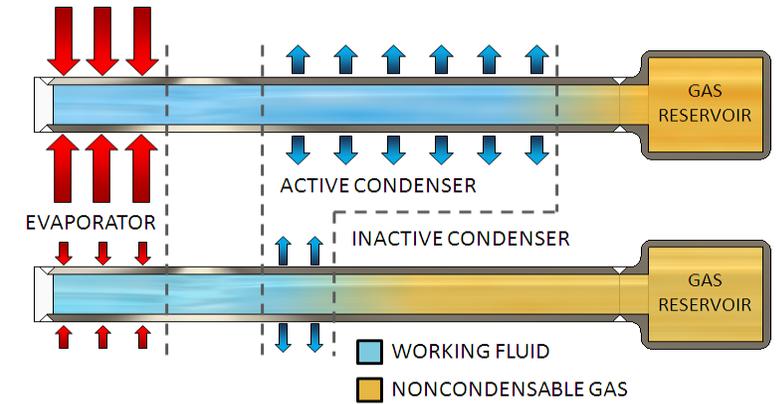
- VCHP: Has a Non-Condensable Gas (NCG) column that can be modulated to regulate heat transfer to the condenser
- Heat pipe mode: NCG is in reservoir and condenser is fully active
- VCHP mode: NCG partially or fully blocks the condenser



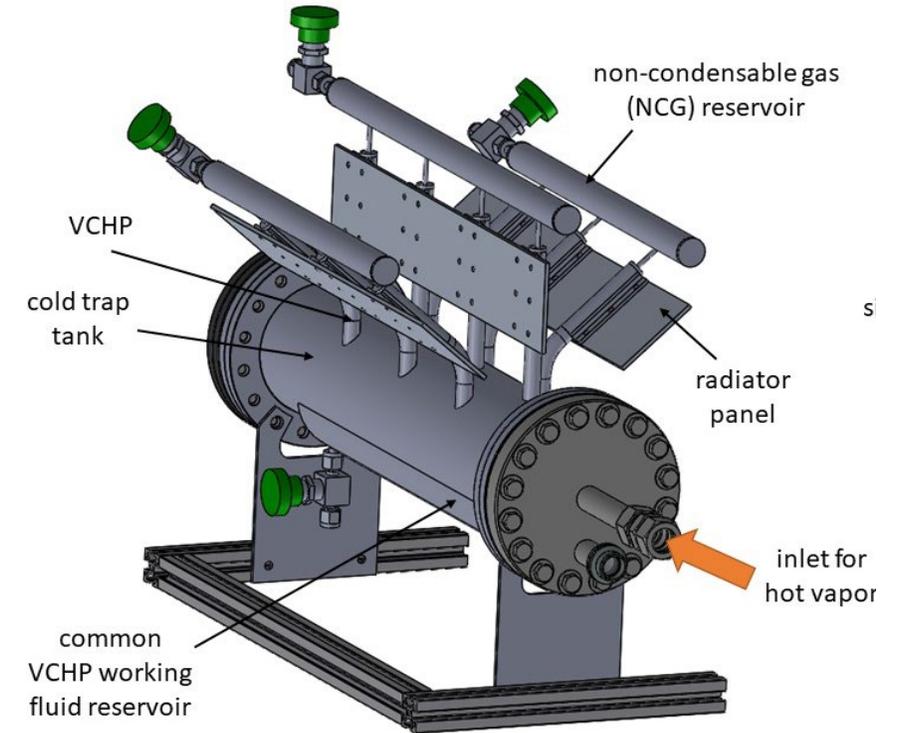
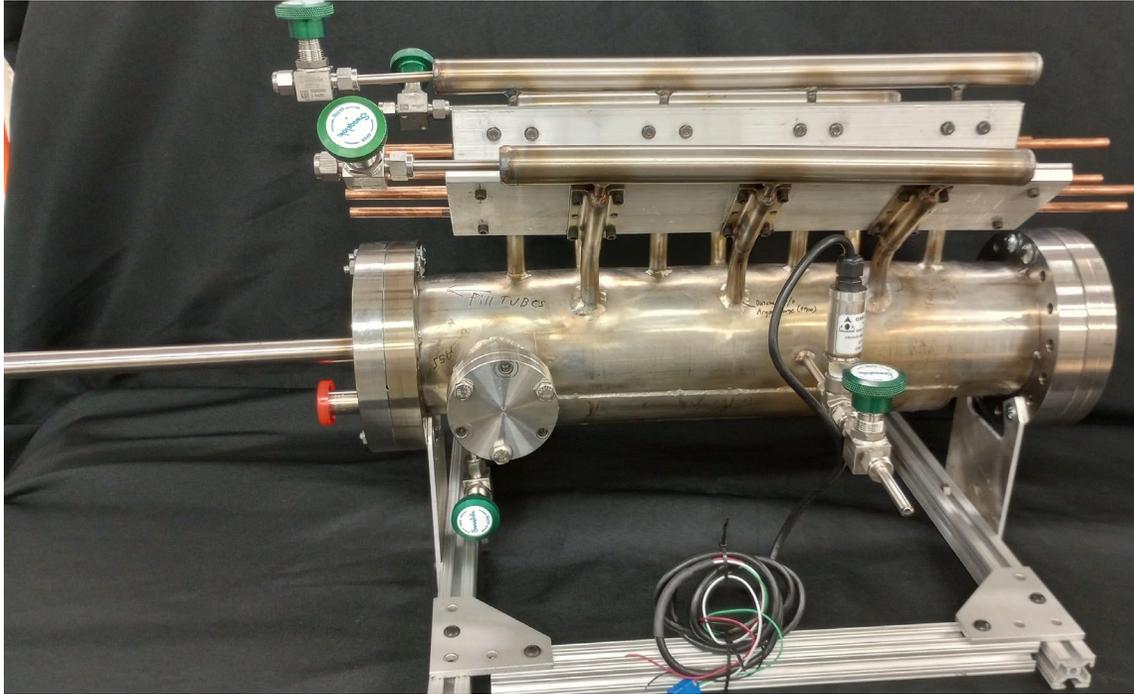
Ice-collection Mode



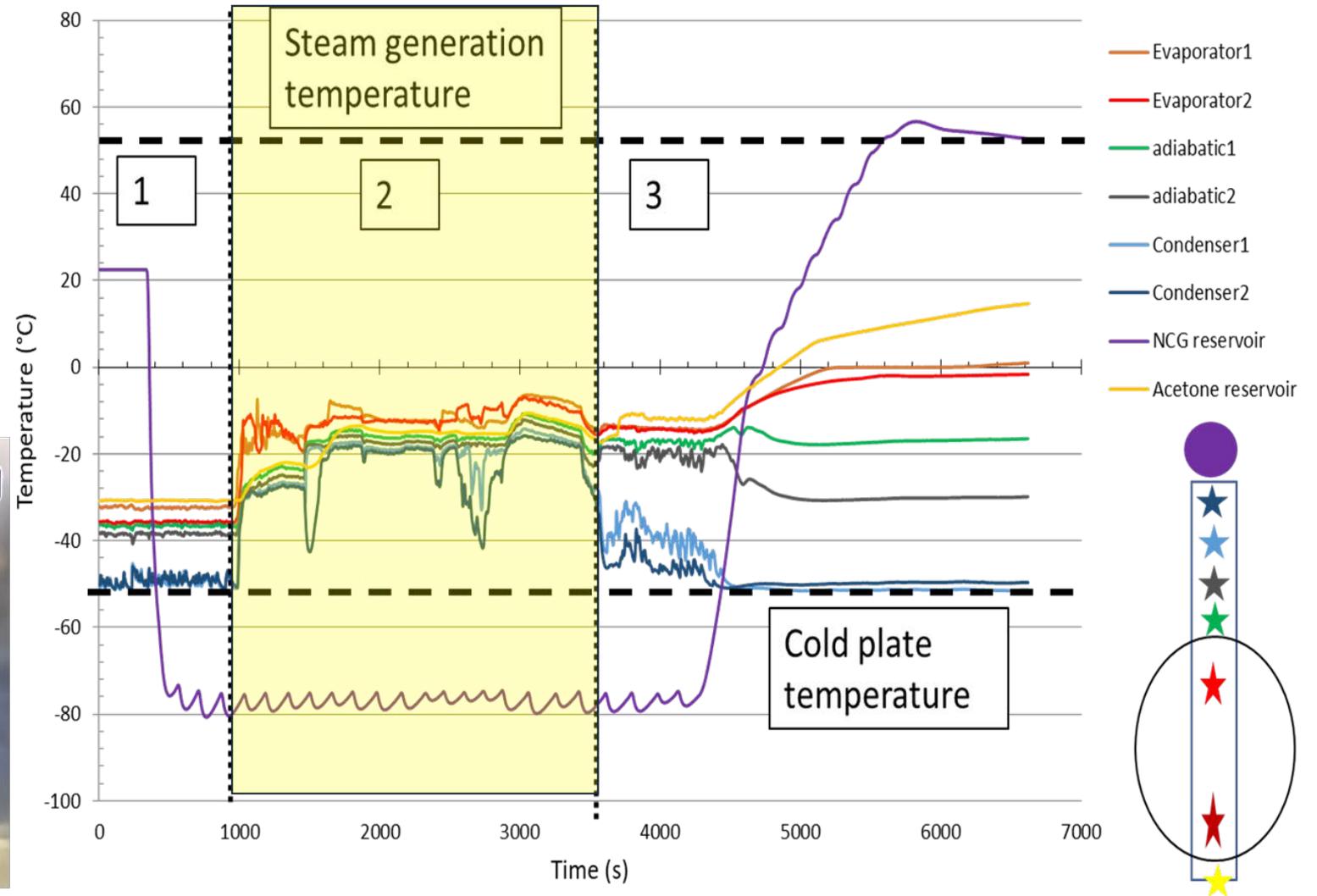
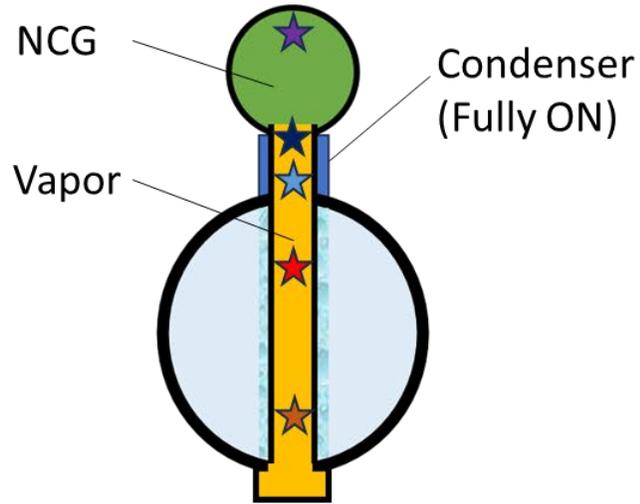
Ice-removal Mode



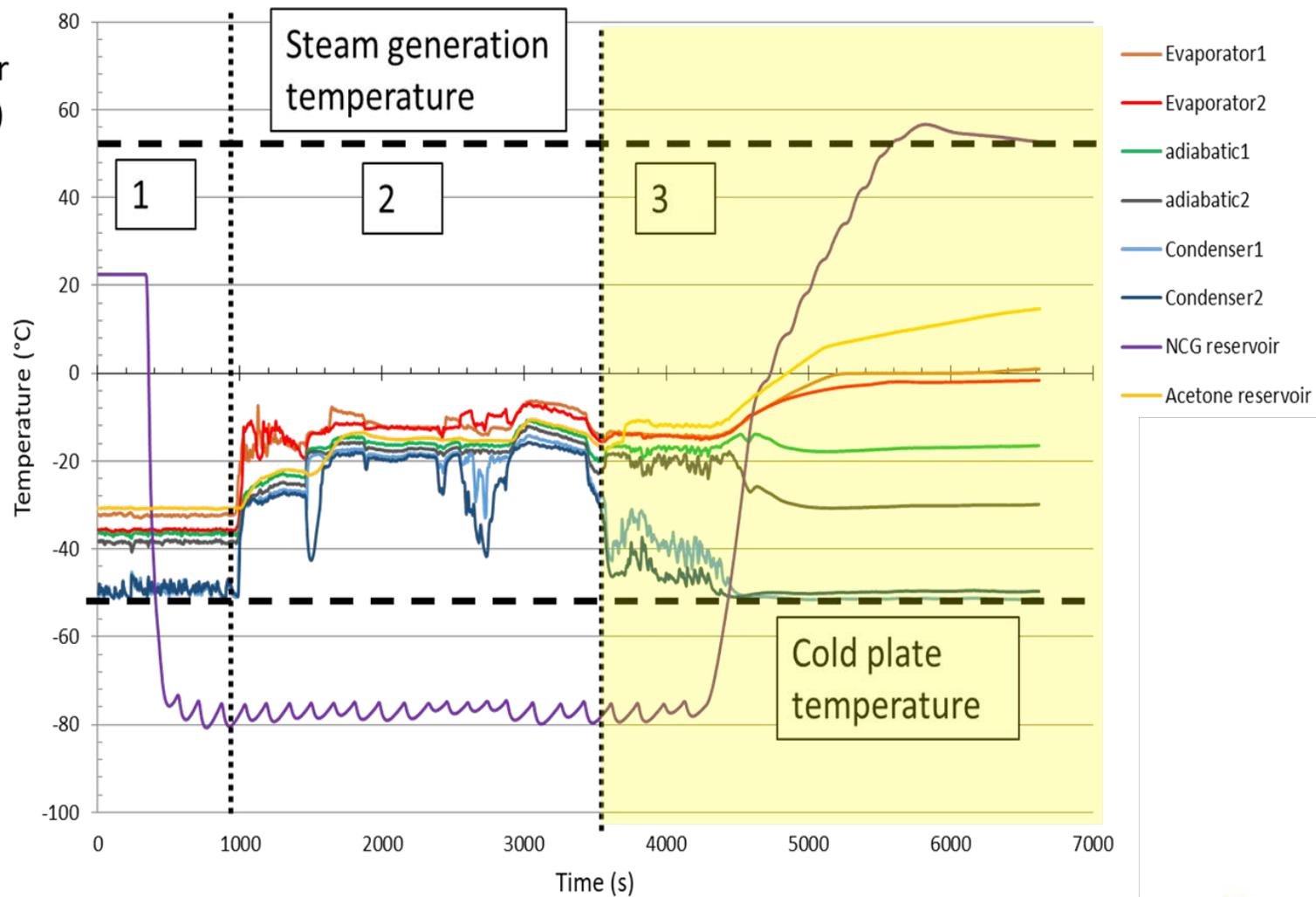
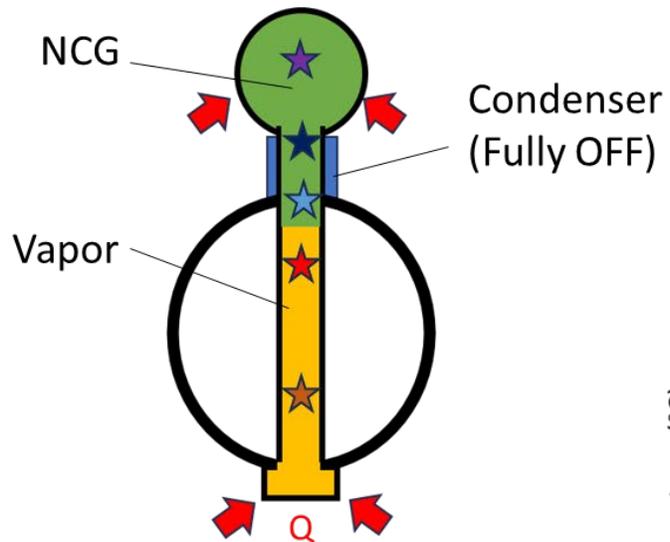
Assembled VCHP Cold Trap Tank



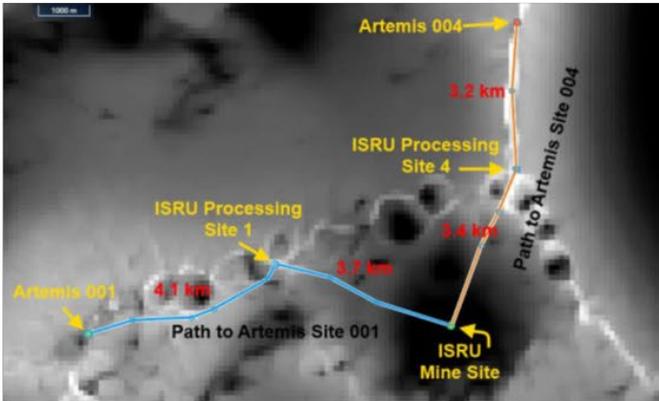
- A VCHP cold trap tank assembled with 10 heat pipes arranged in three rows uniformly
- Condenser of VCHPs were cooled by LN Cold Plates
- Each row of heat pipes were manifolded to respective NCG reservoirs.
- A larger NCG reservoir was connected to facilitate larger easier control on VCHP mode



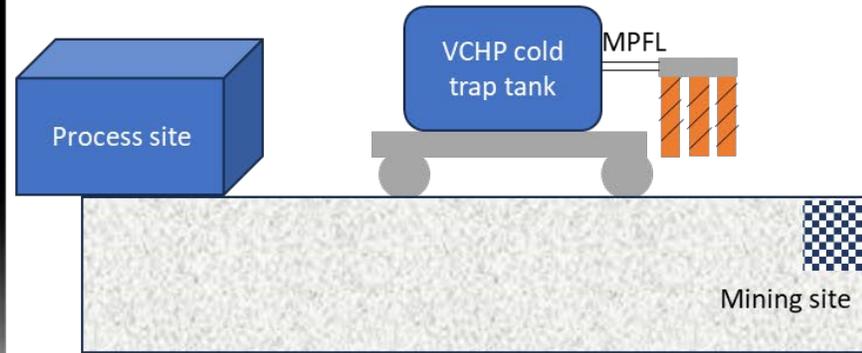
Demonstration of VCHP Cold Trap – Ice Removal Mode



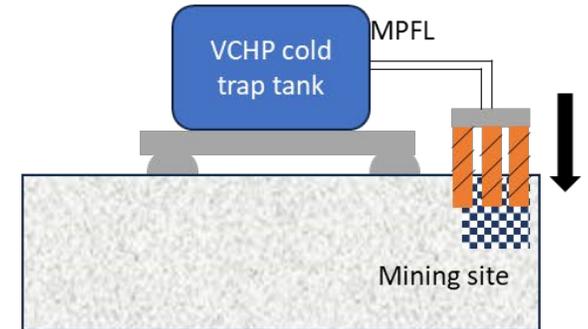
Process to mining site: 3.5 km
Contingency distance: 5.2 km



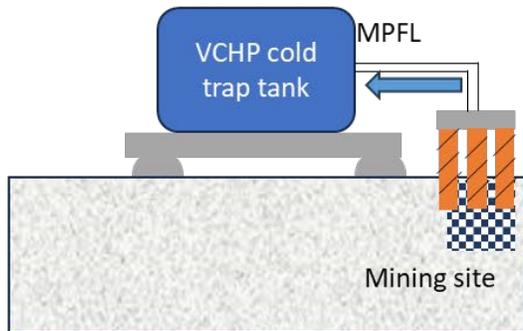
Stage 1, Traverse: Electrical



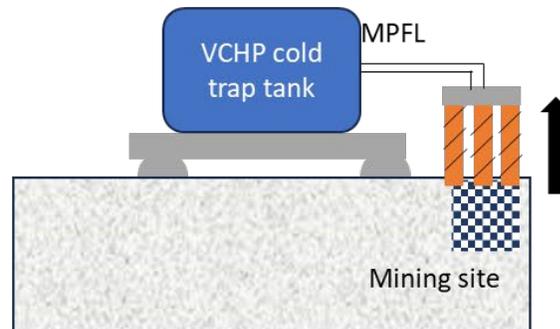
Stage 2, Drilling: Electrical



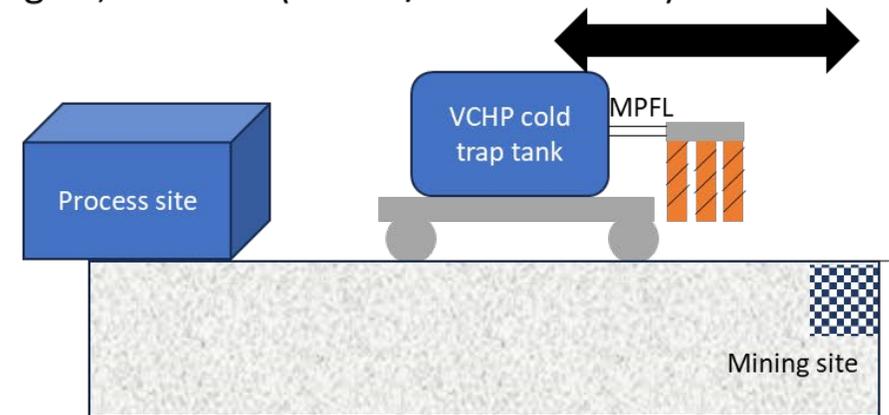
Stage 3, Ice Mining: Thermal



Stage 4, Corer retraction: Electrical
Ice removal from VCHP: Thermal

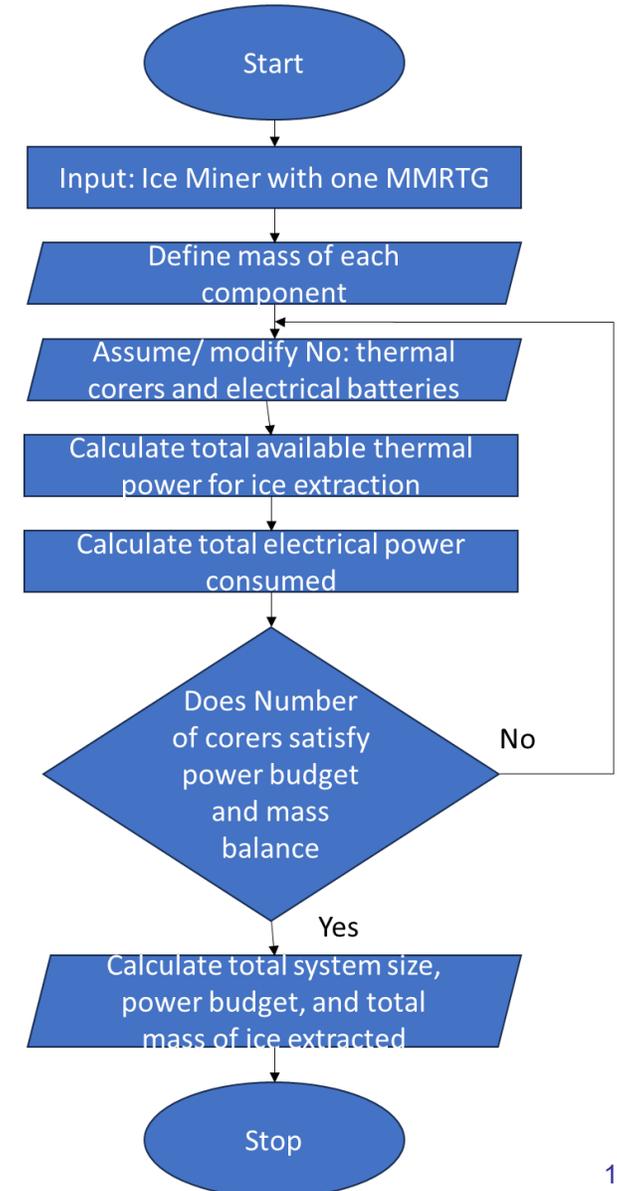


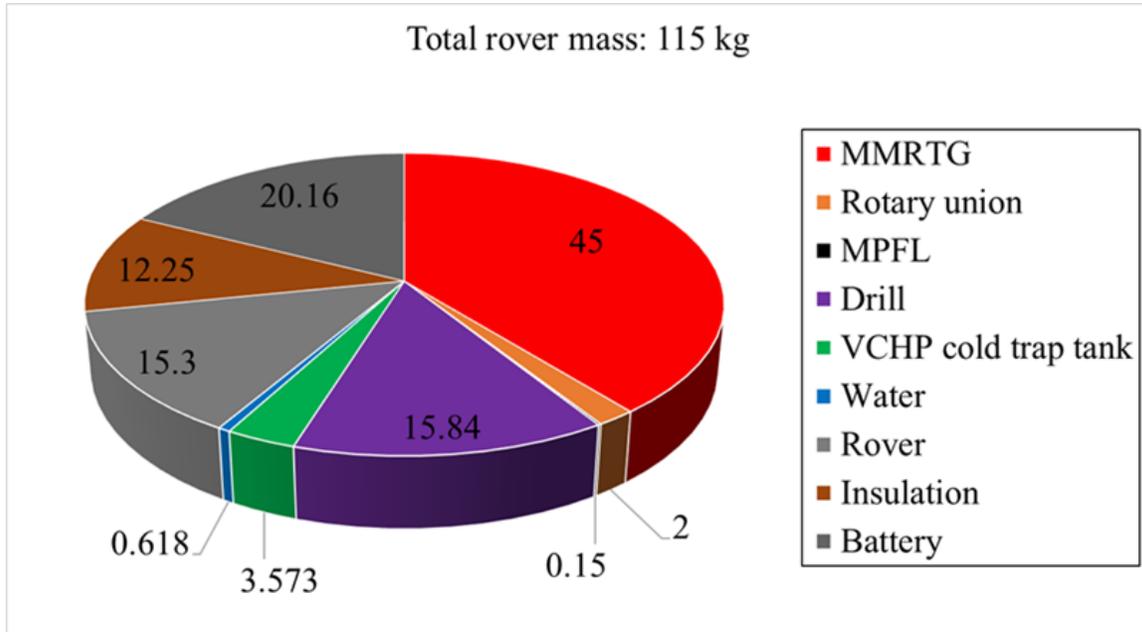
Stage 5, Traverse (return/ new location): Electrical



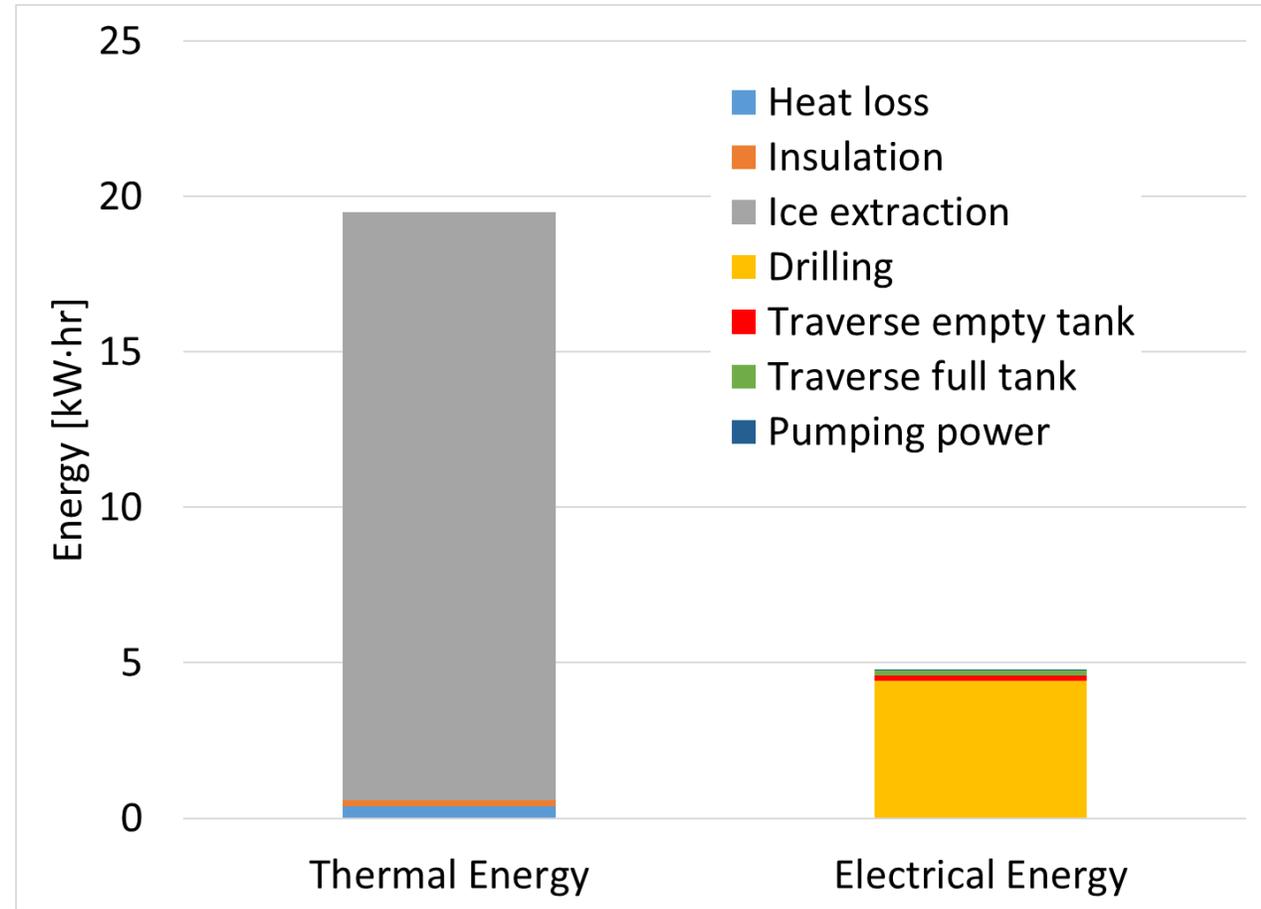
Scheme for Sizing & Power Budget Estimation

- Each rover is equipped with 1 MMRTG source producing 110W electrical power and 2000W thermal power
- Several batteries of capacity 150 Wh/kg were used for electrical operation (suggested by TDA Research)
- Ice recovery was estimated to be 60% of available ice mass for each mining operation
- Electrical power consumption and time for traverse considered
 - Lunar surface coefficient of friction: 0.6
- System components assumed to be made of Titanium
- Electrical power consumed by a single corer at 1 mm/s: 100W (suggested by Honeybee Robotics)





- Mass of each rover estimated to be 115 kg
- Each rover can recover 8.1 kg ice in 24-hour operation cycle
- Total energy consumed in 24 hours ~ 24.3 kWh

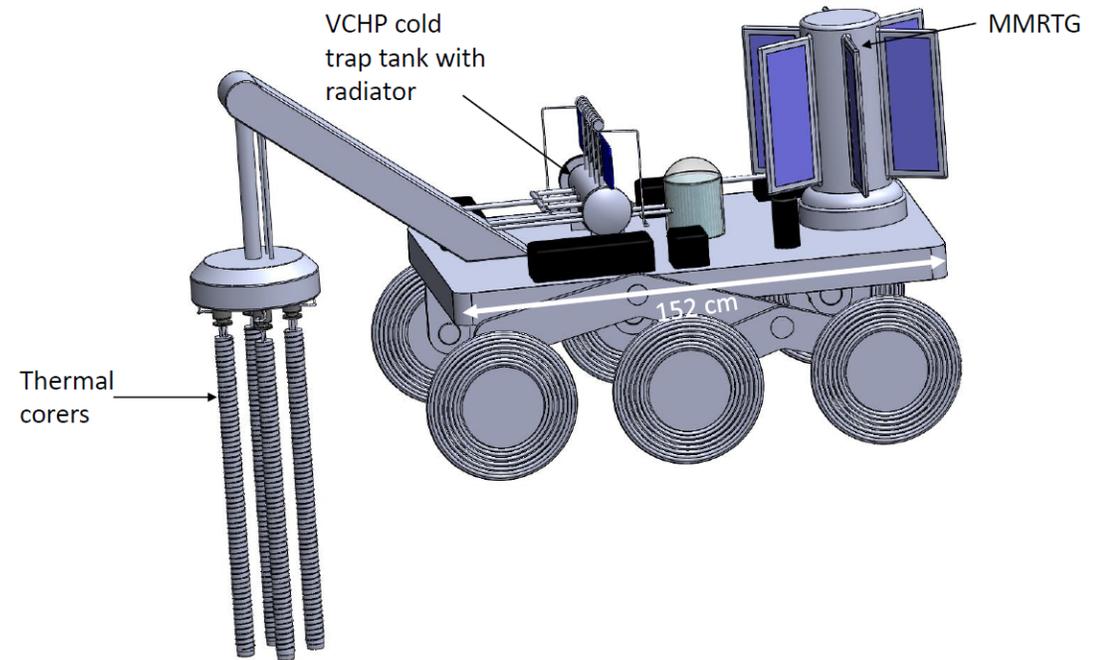


- To achieve ice mining target of 2.78 kg/h, total number of rovers required: 8

- ACT in collaboration with Honeybee Robotics, developed a thermal management system for lunar ice miners based on waste heat from on-board power source.
- Functionality of VCHP cold trap tank demonstrated for ice collection and ice removal modes
- Thermal corer ice extraction tests performed at lab scale (> 60% ice recovery rate) and in relevant TVAC (>18.2% ice recovery rate)
- **Waste Heat-based Ice Extraction Drill is now TRL 6**

System sizing

- Each rover weighing 115 kg can potentially extract ice with a rate of 0.33 kg/hr
- Require at least 8 rovers with the proposed to meet ISRU goal of 2.7 kg/h
- **Room for improvement:**
- Longer thermal corer
- Larger Drill ID with higher HTF temp – reduce extraction time





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