ADVANCED COOLING TECHNOLOGIES

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Waste Heat-based Thermal Corer for Lunar Ice Extraction

XXII Space Resources Roundtables
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ACT Company Overview

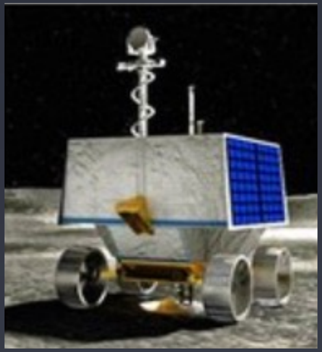
Founded 2003 | 210+ Employees | 204,000 ft^2 on 6/2022

Locations

- Lancaster, PA (ACT)
  - Operations (Manufacturing)
  - Product Development
  - R&D
- York, PA (Tekgard)
  - Operations (Manufacturing)

Awards

- 3 time winner of Top 100 Best Places to Work in PA
- US SBA Tibbetts Award
- Several time winner of Fastest Growing Company in Central PA



R&D Overview

Government Sponsors

Commercial Sponsors

- Defense Primes, Aerospace Contractors, Vehicle Manufacturers, Energy Companies, Start-ups

Innovation

- 26 U.S. Patents
- Routinely publish journal & conference papers

- 25 Engineers, 13 Technicians
  - Engineers have an education in mechanical, chemical, nuclear, material science, & aerospace engineering
    - 17 PhD, 4 MS, 4 BS
    - 215+ years of experience
  - Specialization
    - two-phase heat transfer
    - heat pipes & vapor chambers
    - thermal energy storage
    - computational modeling
    - coatings
    - phase separations
    - combustion & plasma sciences
    - desalination
    - pumped two-phase cooling

Lunar Ice Mining Challenge

- Recent LCROSS and SOFIA missions verified presence of water in the cold regions of the Moon
  - Form: icy-soil @ 5% concentration by mass
  - Total estimated quantity of water: 600 million Tons
- Water can be harvested to sustain future NASA's space exploration activities
- NASA indents to mine water from icy-soil mixture at a target rate of 2.78 kg/h (ISRU goals)
- Climatic conditions on the moon surface: 40 K, < 10^{-6} Torr
- Estimated **Thermal power Requirements:**
  - **Extraction: 3 KW**
  - **Collection: 2.8 KW**

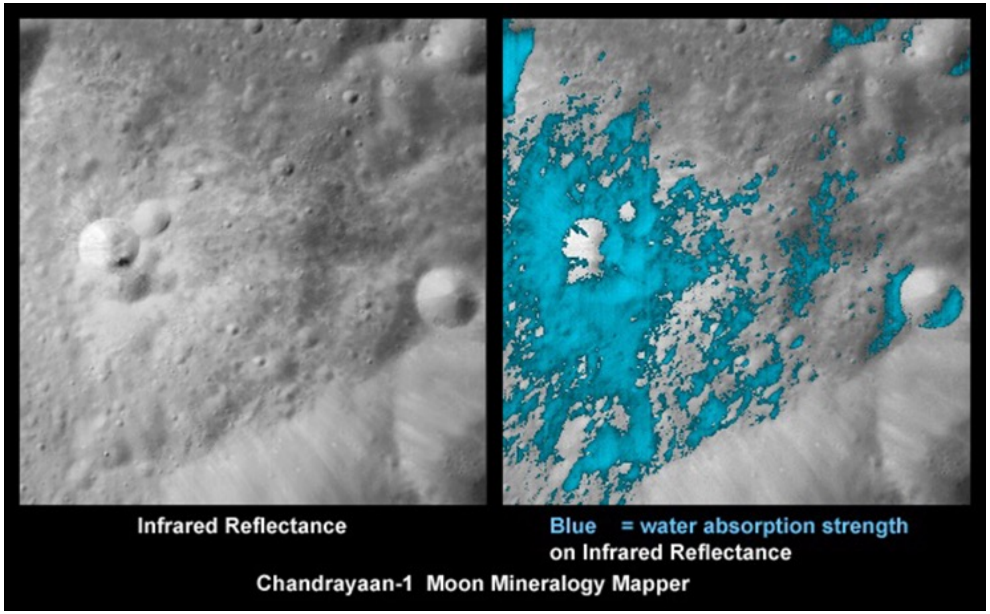
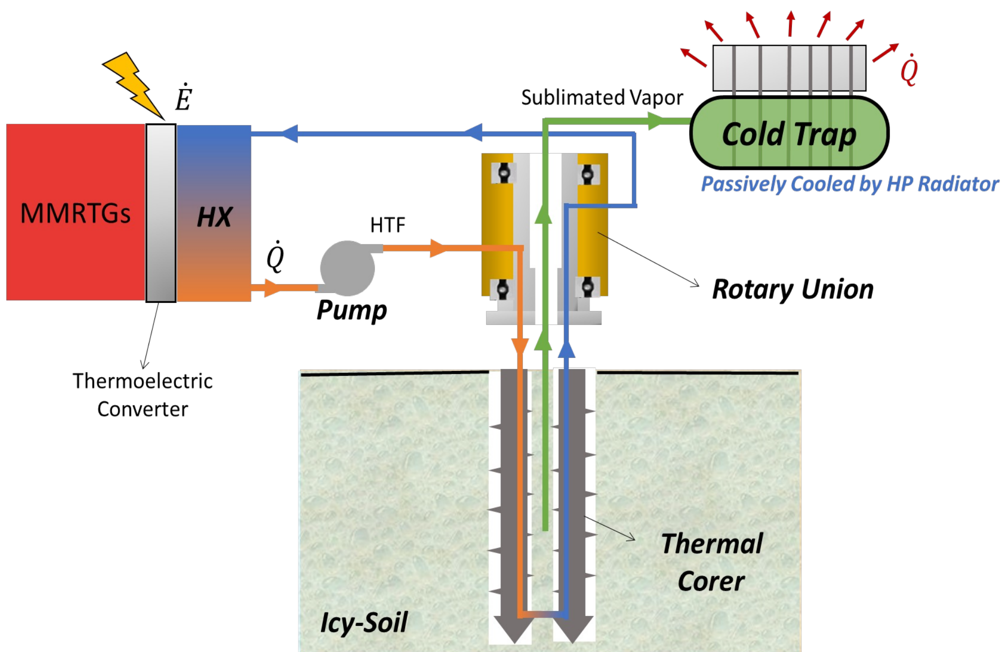


Image taken by NASA Moon Mineralogy Mapper (M^3) (credit: ISRO/NASA/JPL)

Thermal Management System for Lunar Ice Miner

- ACT/HBR is developing a **Thermal Management System** for volatile extraction & collection based on effective utilization of onboard waste heat source (e.g. MMRTG, high power electronics, thermal battery)
- Key components
  - **Mechanically pumped fluid loop**: deliver heat from heat sources to ice extractor (thermal corer)
  - **Waste Heat-based Thermal corer**: embedded mini-channel coring augar for ice-extraction
  - **Volatile Collector**: with integrated heat pipes radiator for volatile collection (passive)
  - **Rotary Union**: couple fluid path between a rotating components (thermal corer) and a stationary component (HX)

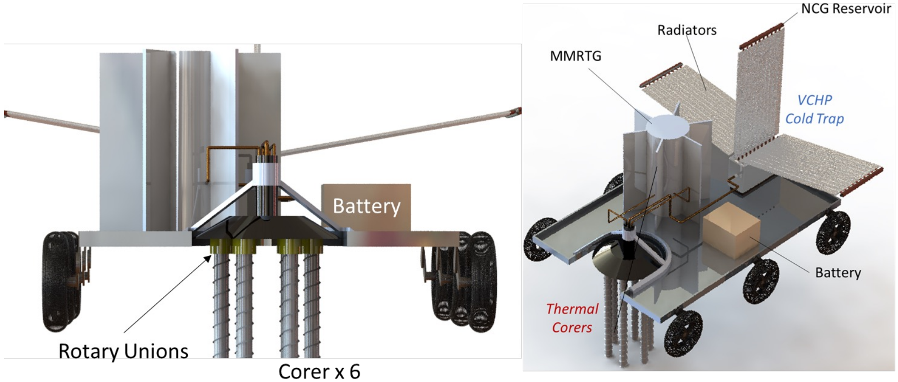


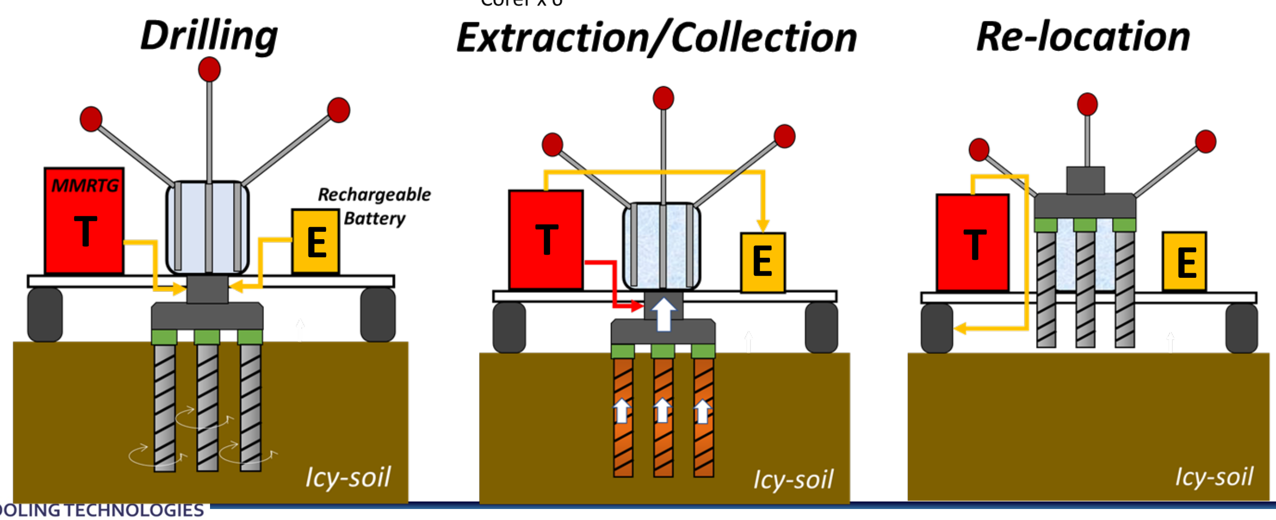
Lunar Ice Miner TMS Concept

Advantage of Waste heat-based Ice Extraction

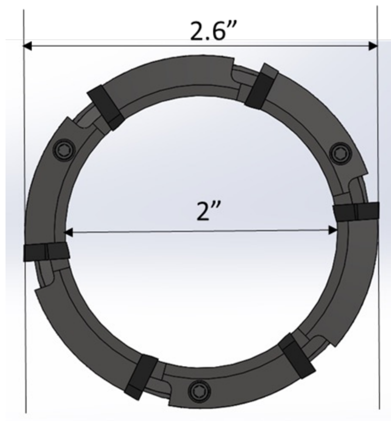
Improve usage of thermal and electric energy to achieve higher mining efficiency

- During thermal extraction, electricity generated from MMRTG can be used to charged batteries, which will be used for powering drills and the rovers
- Enable a miner design with multiple drills

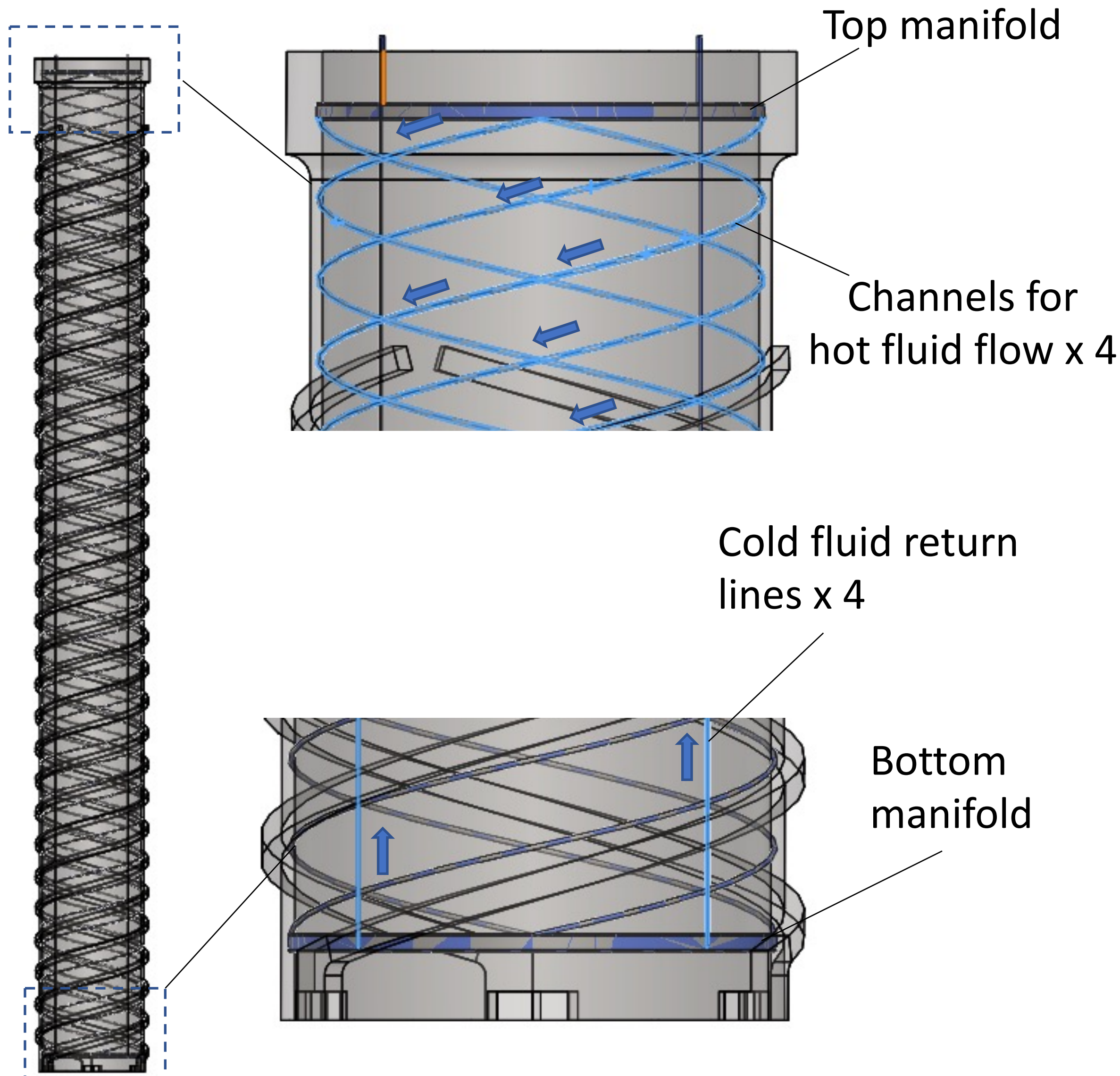




Waste Heat-based Thermal Corer Design



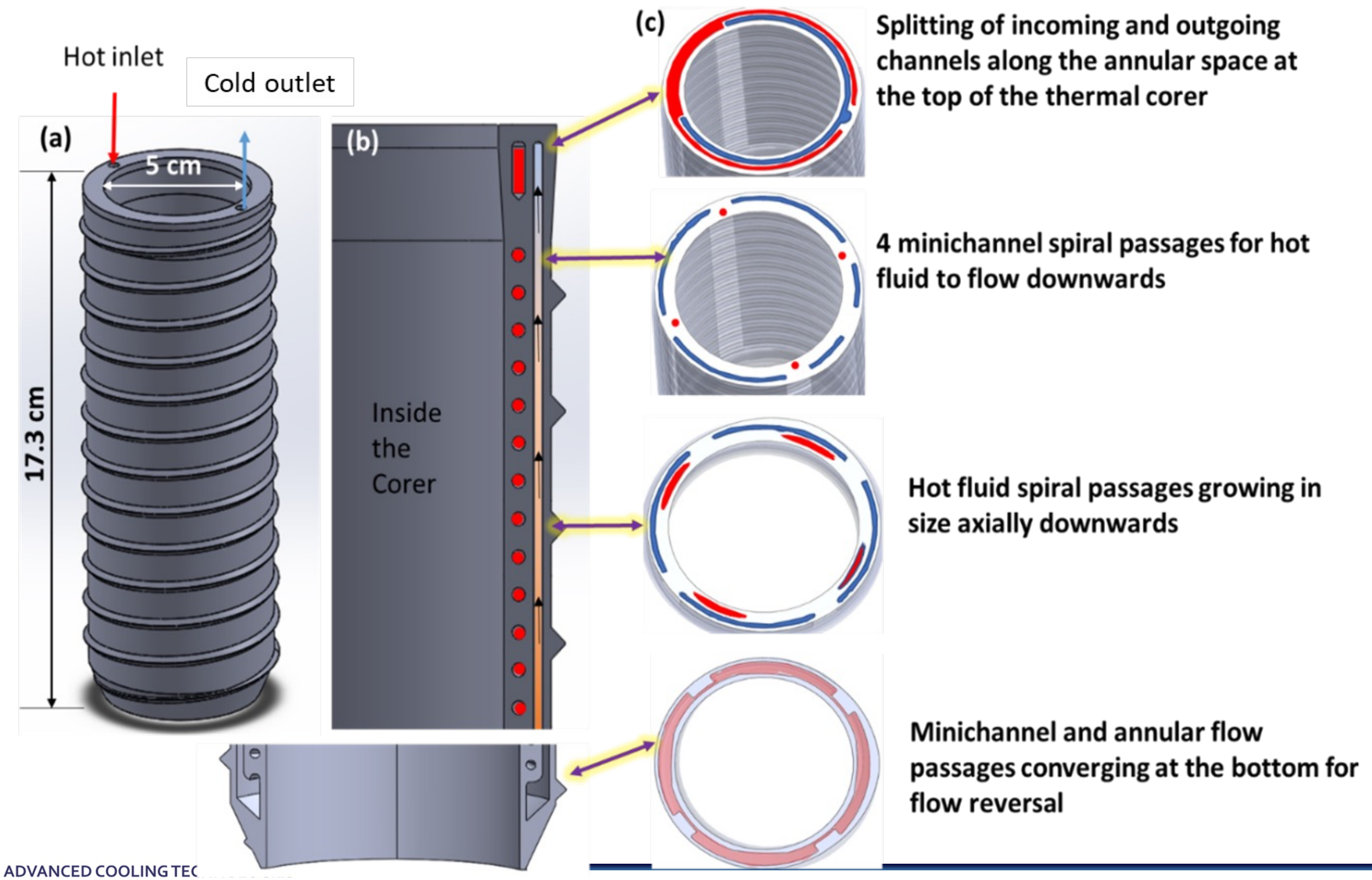
Wall Thickness:
0.3” (0.76cm)



Sub-Scale Prototype Design

Thermal corer is essentially a mechanical auger with integrated minichannels to facilitate heat transfer.

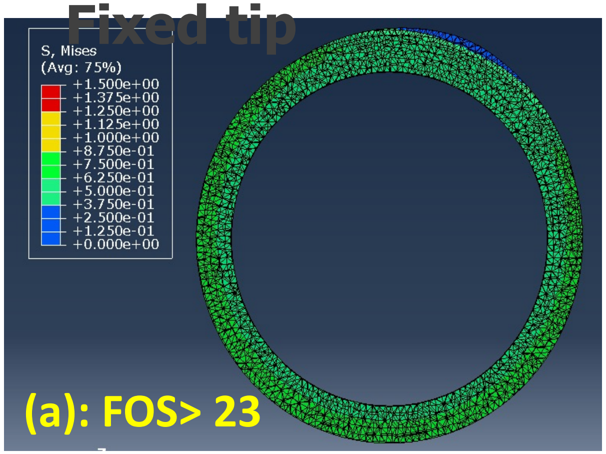
ID- 5 cm | Length- 17.3 cm | Mini-channel size < 1.5 mm | Material: SS316

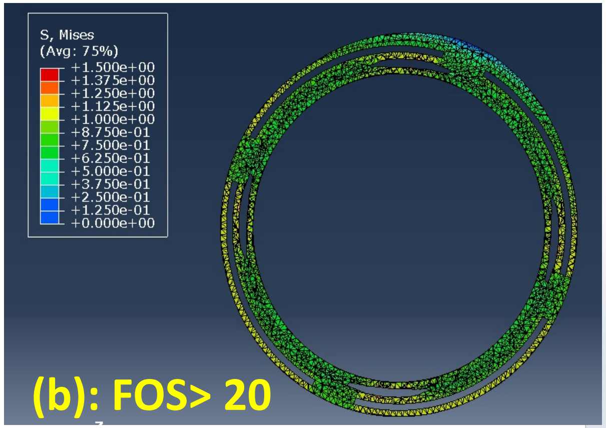


Structural Analysis of Thermal Corer

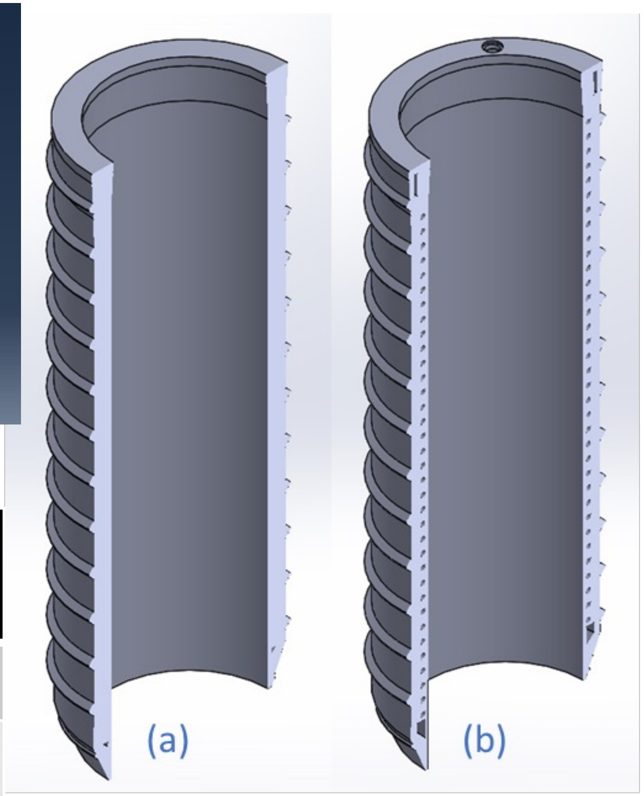
Structural analysis was performed to determine wall thickness

Boundary Conditions: Torque: 10 N.m; Force: 100 N; Fixed tip





Corer Length (cm)	Max Stress (MPa)	Factor of Safety
17.3	8.6	23
50	9.6	21
100	10	20



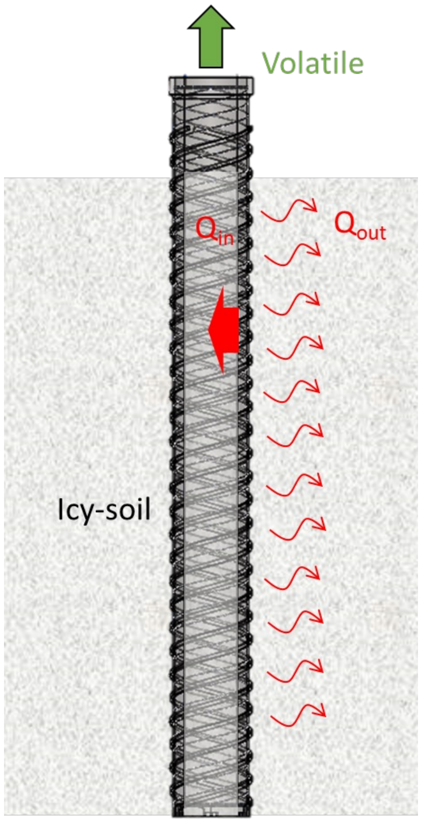
(a) Standard Corer, (b) ACT's corer

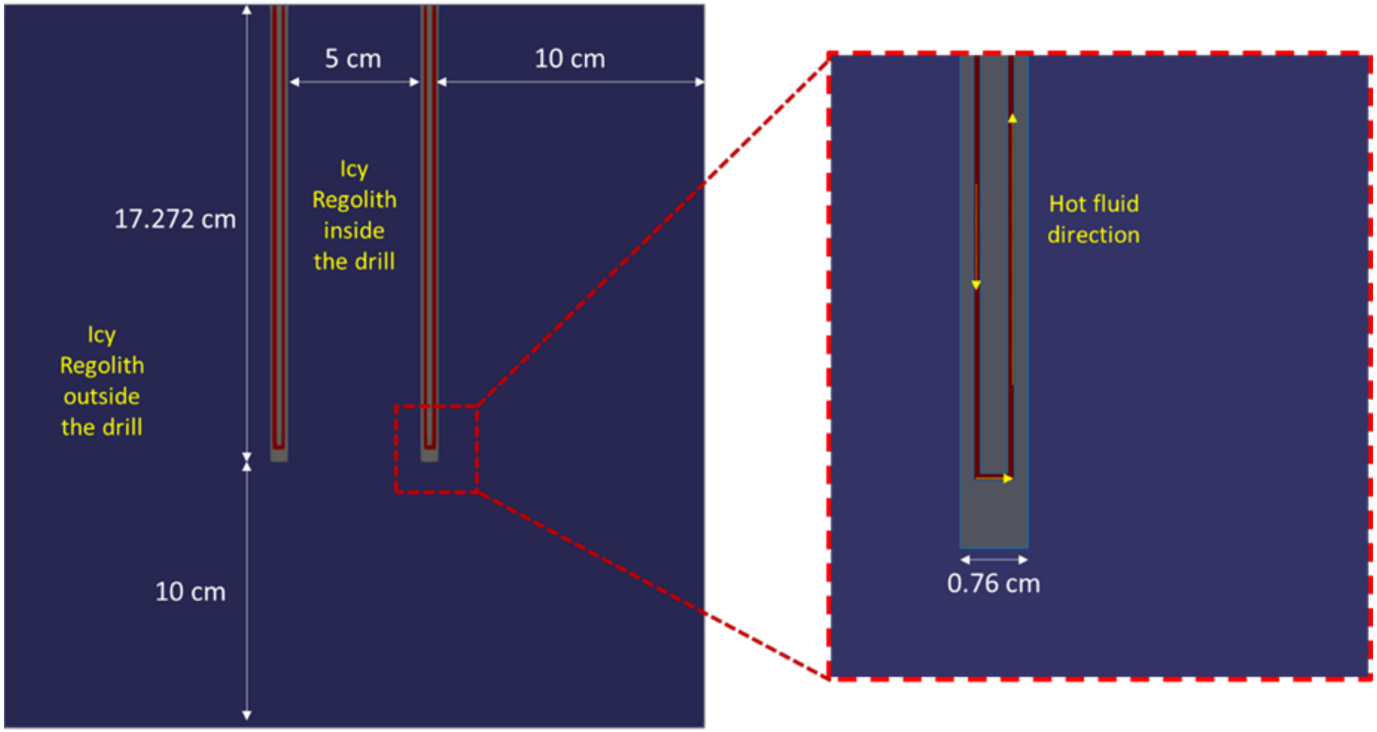
Thermal Analysis of Thermal Corer

Numerical analysis performed to predict the performance of the thermal corer

2D Numerical model developed in ANSYS Fluent with user defined functions (UDF) to input properties and conjugate heat transfer physics

(Ref. Metzger, Kris Zacny et al.2020)



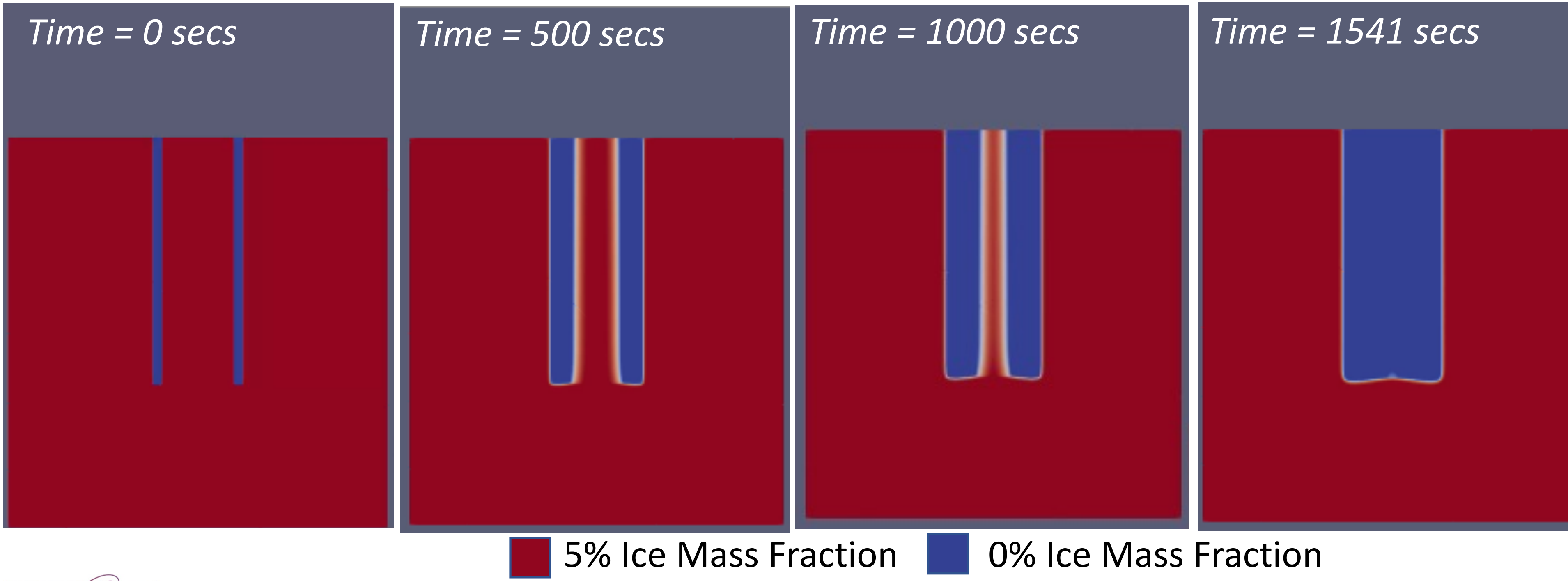


Simulation domain of the printed corer in icy-regolith environment (5% ice mass fraction)

Thermal Analysis of Thermal Corer

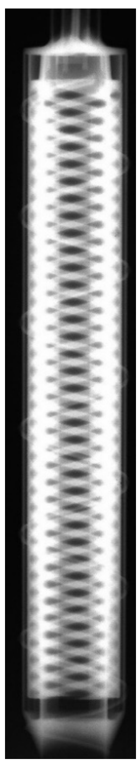
In the baseline case, 100% ice-extraction is expected to be completed in 25 mins

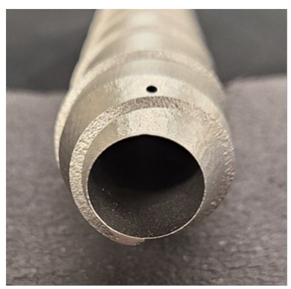
- Thermal corer internal volume: 340 cc
- Mass of ice being extracted (assumed 100% extraction): 22 g
  - HTF inlet temperature: 50 °C
  - HTF flow rate: 3.38 cc/s (pumping power < 1W)
  - Back pressure: 5 Pa (assuming collection tank temperature -50 °C)



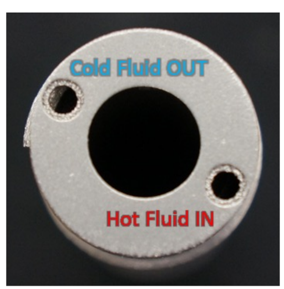
Proof-of-Concept Prototype Testing in Phase I

- 3D printed thermal corer with embedded mini-channels
- A proof-of-concept prototype (6 inch) was fabricated in Phase I
- A bench-top ice extraction system was built to demonstrate thermal extraction capability

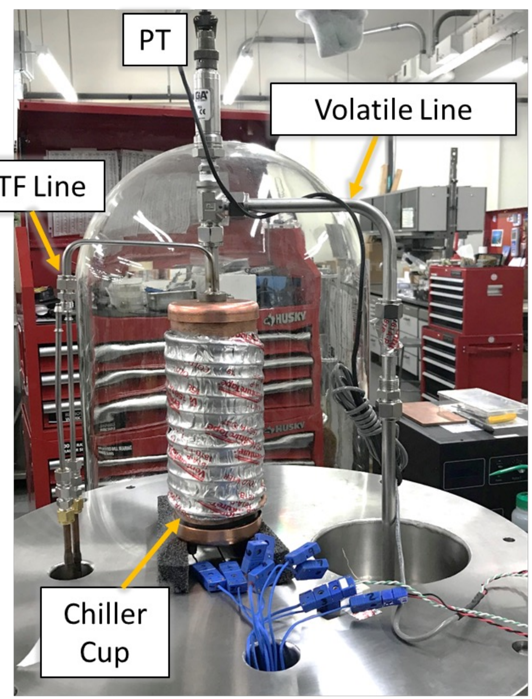


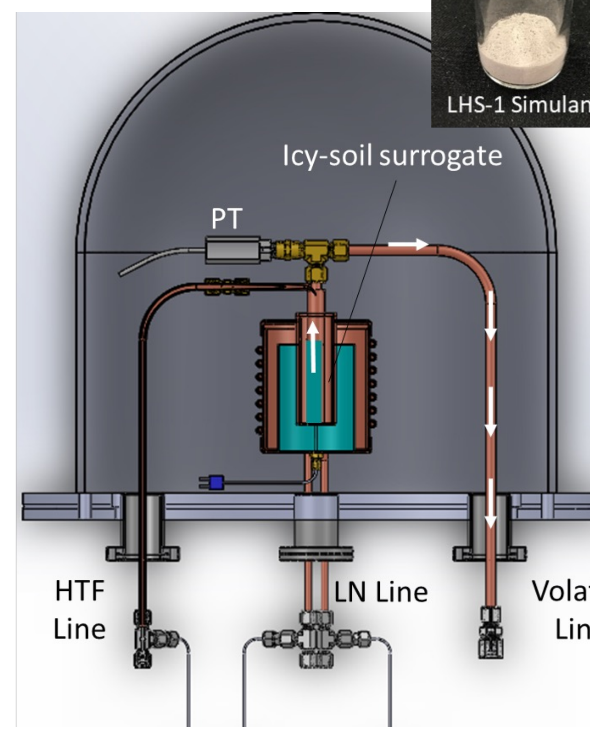


Bottom View



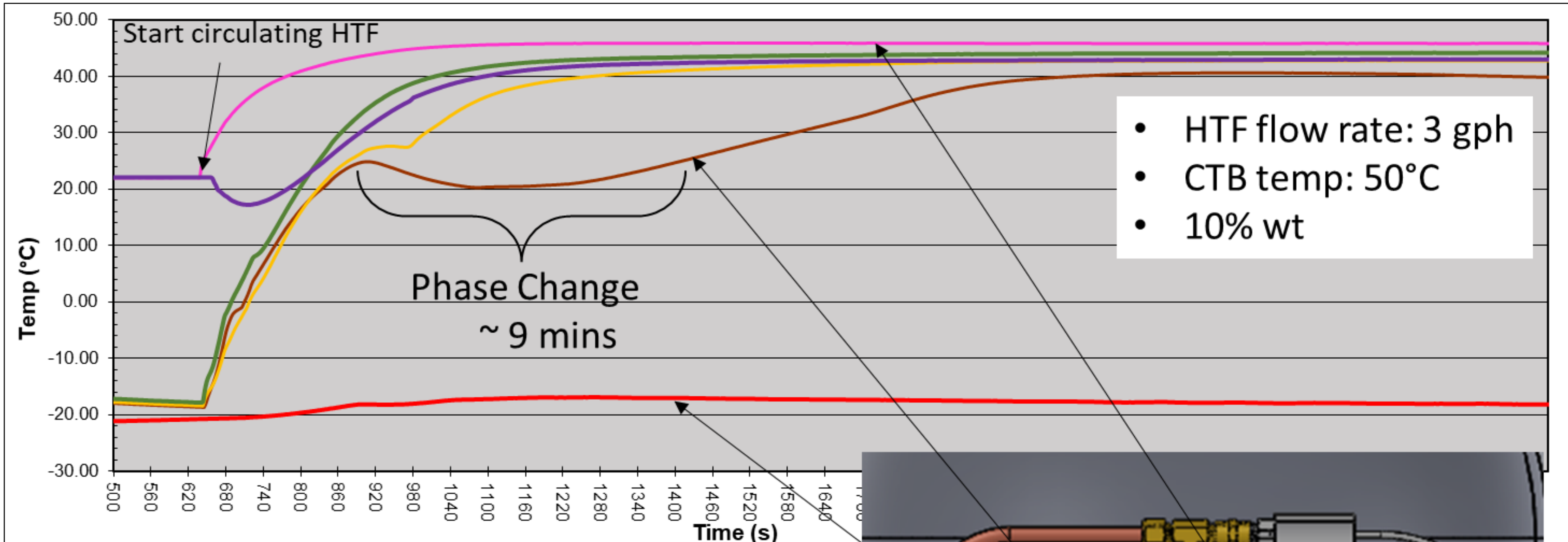
TOP View



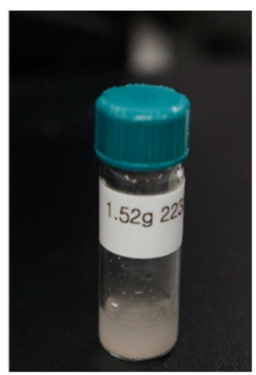


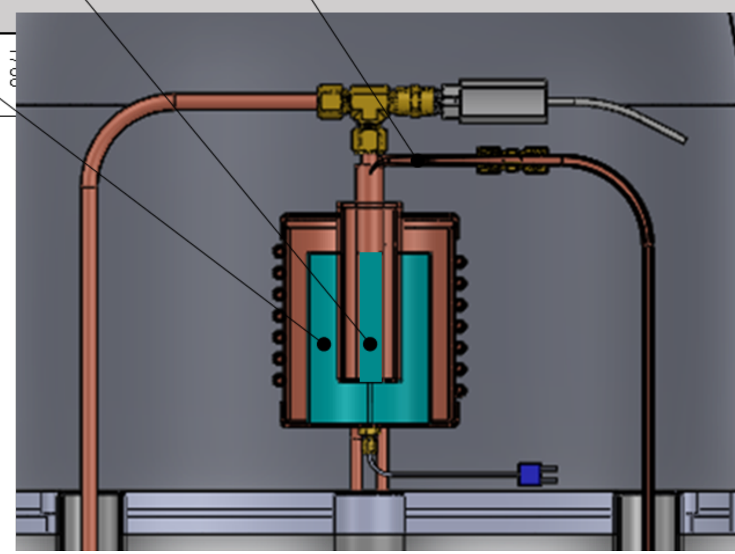
Thermal Extraction Test Results (Phase I)

Performance Analysis of sub-scale thermal corer @ 0.1 Torr and 50 °C HTF



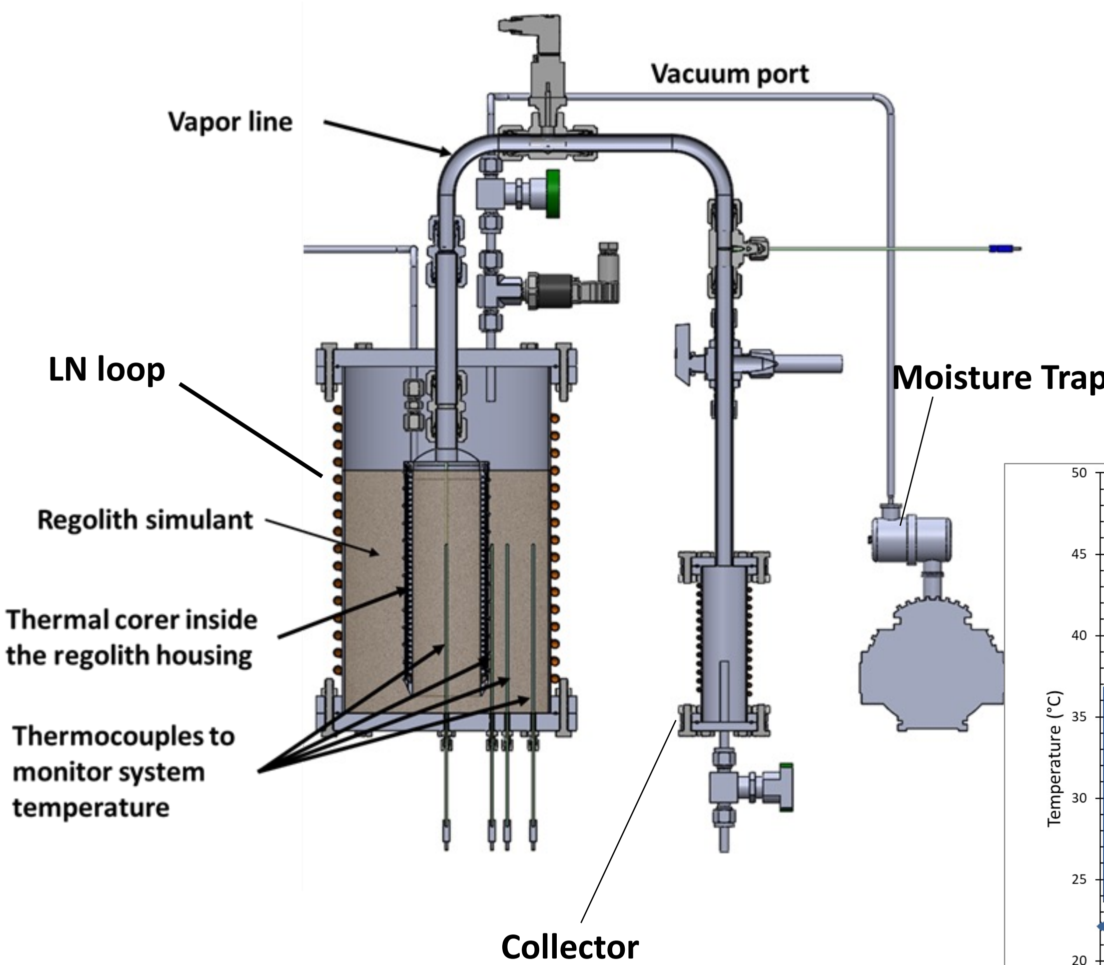
- ❑ Steady state temperature profile after 35 mins
- ❑ About 1.5 grams ice-extracted
- ❑ 44% of extractable water

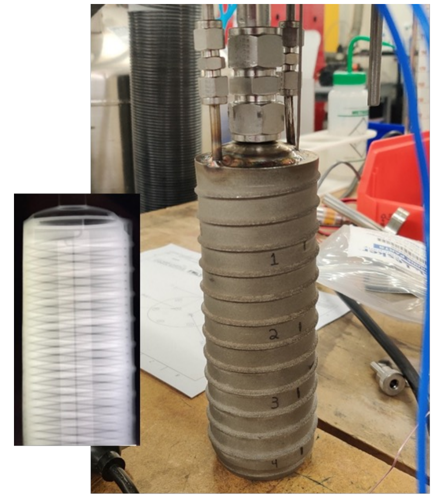




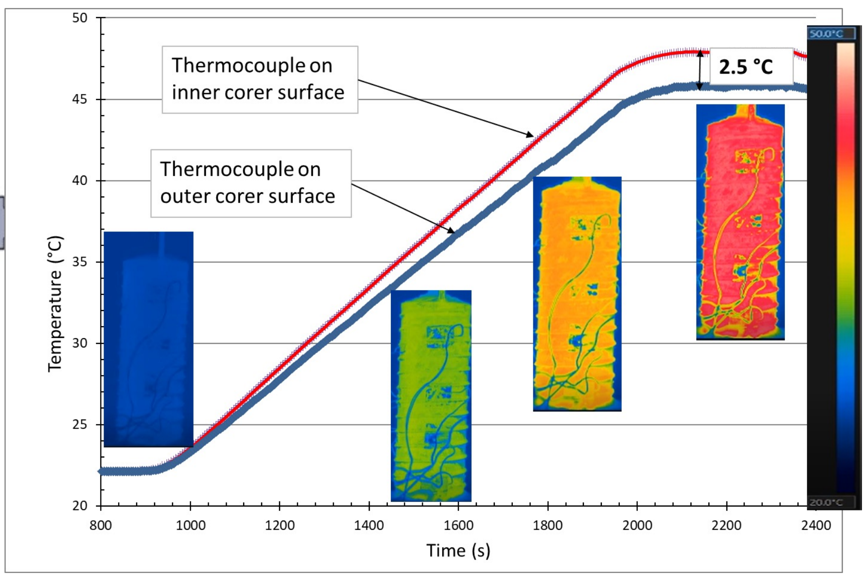
Scale-up Ice Extraction Testing – Ongoing Effort

Schematic of the experimental system assembled to characterize thermal corer



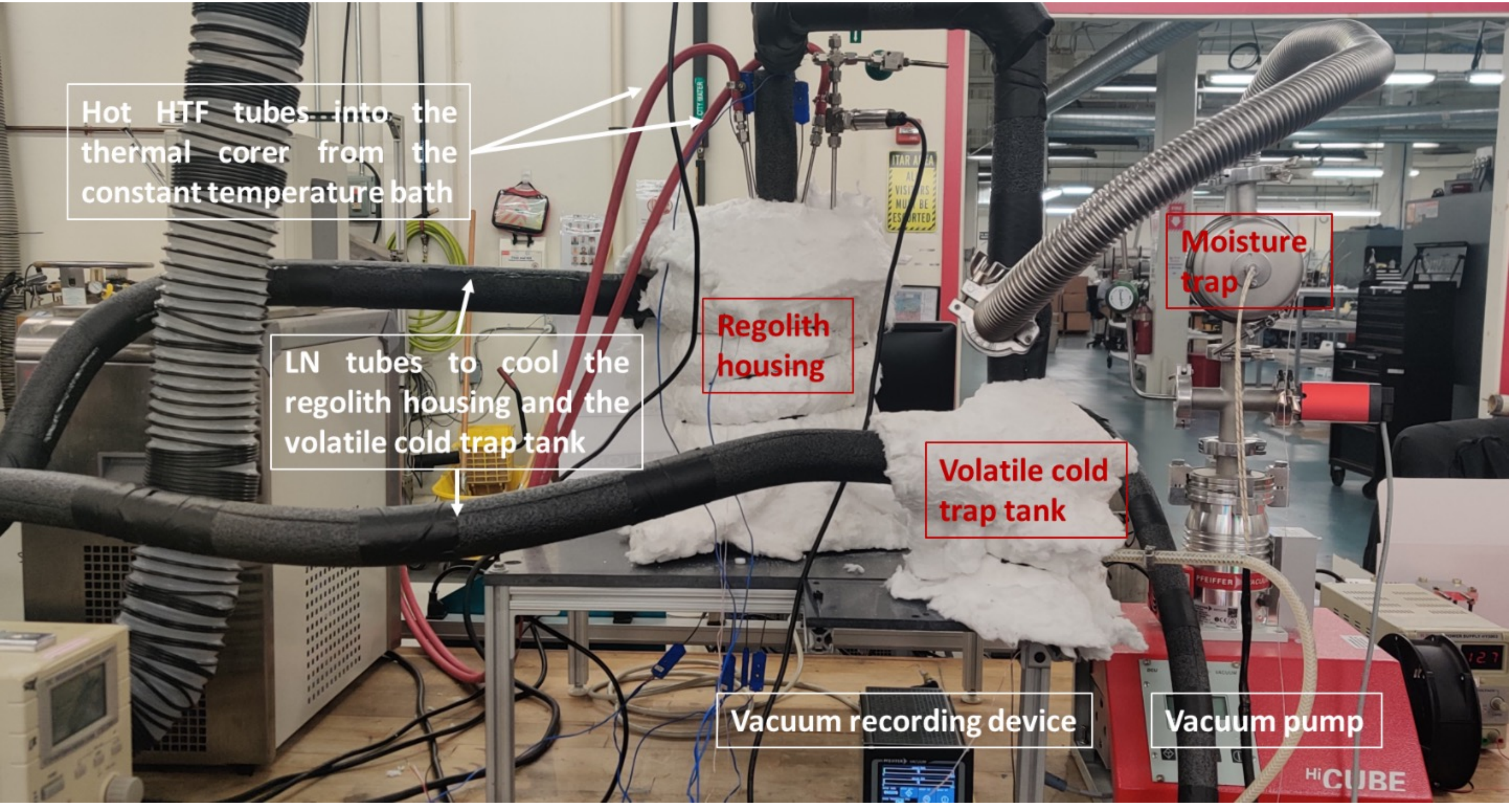


3D printed thermal corer



Scale-up Ice Extraction Testing – ongoing work

Experimental system was assembled to characterize the performance of the thermal corer and validate the numerical model



Summary

- Waste-heat extraction would enable more efficient usage of on-board thermal energy and electricity for future ice mining
  - Strategic allocation of heat and electricity
- Embedding mini-channels into a thermal core via 3D printing is feasible
  - Proof-of-concept prototype (Phase I) : 2 cm ID x 12 cm
  - Sub-scale prototype (current): 5 cm ID x 18 cm
  - Envisioned Large-scale Prototype: 5 cm ID x 40 cm (manufacturer identified)
- Thermal extraction model is under development.
  - Only consider solid-vapor transition (sublimation)
  - Back pressure (collection tank pressure) was as assumed to be constant
- A scale-up ice extraction experiment is being performed at ACT
  - Larger corer (5 cm x 18 cm)
  - Lower vacuum level (< 1E-3 Torr)
  - Instrumentation includes pressure, temperature and flow measurement
  - Test result will be used to validate/correlate numerical model

Acknowledgement

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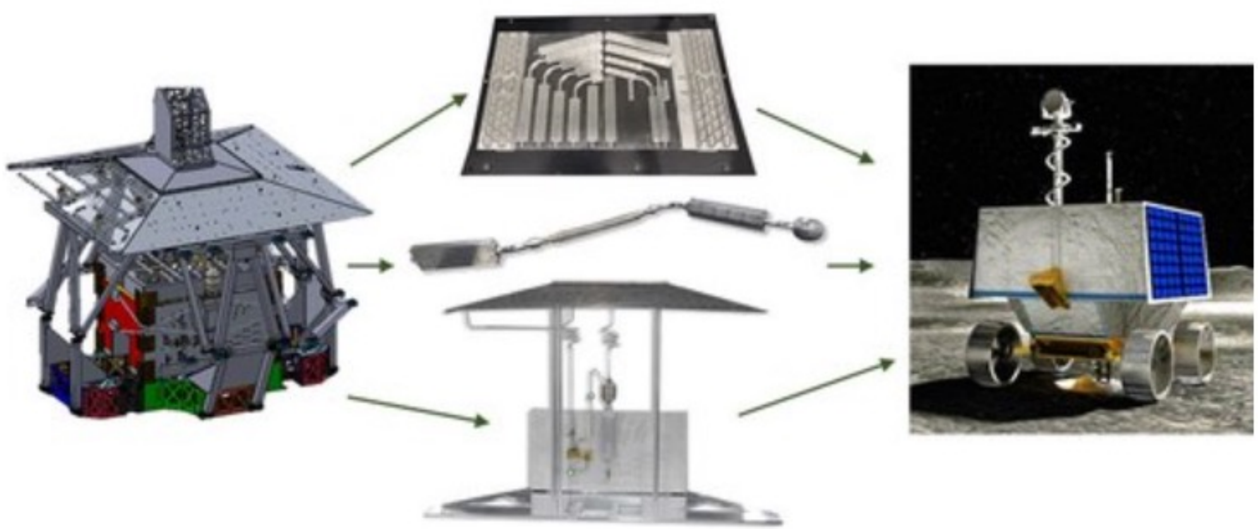
  - Special thanks to Naina Noorani (Technical Monitor) the rest of JSC ISRU team
- ACT Technicians: Phil Texter, Larry Waltman, Justin Boyer
- Honeybee Robotics (HBR): Kris Zacny and Hunter Williams

HONEYBEE ROBOTICS

Thanks for your attention!



ACT developed the flight TMS for NASA's VIPER which includes a combination of custom-engineered Loop Heat Pipes (LHPs), Constant Conductance Heat Pipes (CCHPs) and Aluminum Honeycomb Radiator Panels. Photo Credit: NASA & Advanced Cooling Technologies