Poly-Hydrated Sulfate Mining and Water Extraction on Mars: Experimental Results and System Requirements

J. Allen, T. Eisele, E. Medici, M.S. Foetisch - MTU
K. Zacny, and Z. Fitzgerald - Honeybee Robotics

Paul van Susante, Ph.D.
Senior Lecturer / Assistant Professor
Michigan Technological University
Dept of Mechanical Engineering

pjvansus@mtu.edu

Wednesday 6/12/2019 – 8:40 AM

Michigan Technological University 1885

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

ESI17 Award: 80NSSC18K0252

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

Acknowledgements

This work was supported by an Early Stage Innovations grant from NASA's Space Technology Research Grants Program

- Many students:
  - Shahab Bayani Ahanger (Grad Student, year 1)
  - Wonyoung Choi (Highschool Student, year 1)
  - Michael Foetish (Grad Student, year 1 & 2)
  - Preston Hogue (Undergrad Student, year 1)
  - Udit Sharma (Grad Student, year 1)
  - Andrew Watson (Undergrad Student, year 1)
  - Ben Wood (year 2)
  - Mining INnovation Enterprise students (12 + 6)

Michigan Technological University 1885

HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation

ESI17 Award: 80NSSC18K0252

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

ISRU Resource Trade Tree

Use ISRU to generate consumables / propellant (source: HLS^2)

Equator — **Mid Latitude (45 – 55 Deg)** — **Polar**

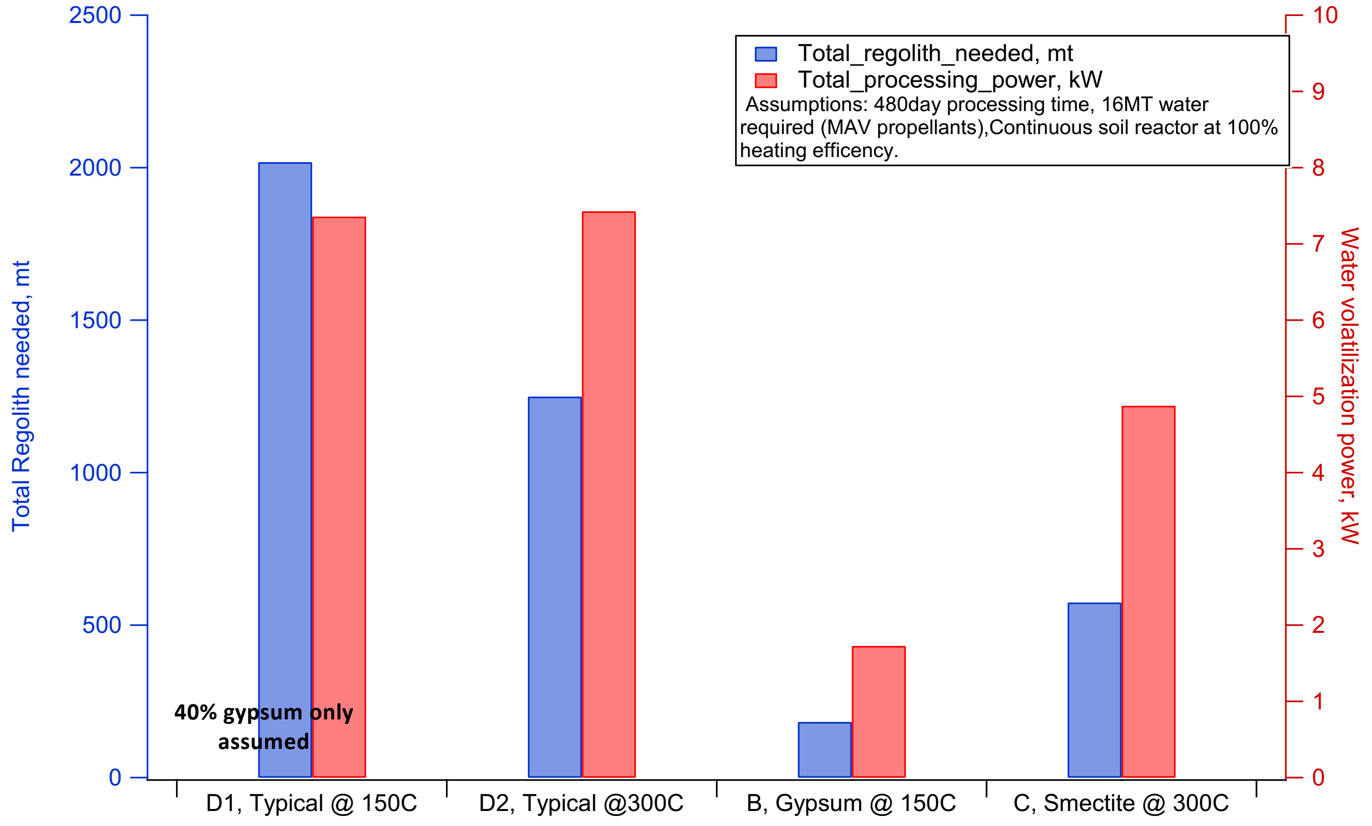
- Use Atmosphere
- Use Mineral Deposits
  - D: 'Common' Regolith
  - C: Phyllosilicates
  - B: Poly-hydrated Sulfates
- Use Water Ice Deposits
  - A: Buried Glacial Ice
  - ~~Recurring Slope Lineae~~
    Accessibility and minimal volume
  - ~~Deep Groundwater~~
    Accessibility & Location
  - ~~Permafrost~~
  - ~~High Latitude Ice~~
    Outside of Acceptable Human Landing Sites

Abbud-Madrid, A., D.W. Beaty, D. Boucher, B. Bussey, R. Davis, L. Gertsch, L.E. Hays, J. Kleinhenz, M.A. Meyer, M. Moats, R.P. Mueller, A. Paz, N. Suzuki, P. van Susante, C. Whetsel, E.A. Zbinden, 2016, Report of the Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study; 90 p, posted April, 2016 at http://mepag.nasa.gov/reports/Mars_Water_ISRU_Study.pptx

Michigan Technological University 1885 | HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation | Space Resources Roundtable Planetary & Terrestrial Mining Sciences Symposium

Key Characteristics by Feedstock (Assume Granular Deposit)

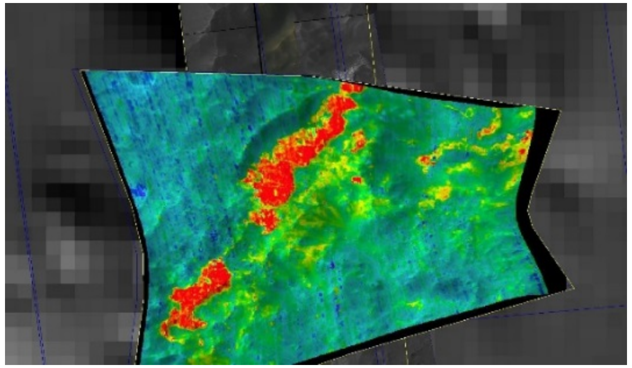
- Gypsum deposits would have the lowest mass AND power requirements of the granular deposits. Ice mining power not established due to less experience and available data.
- Typical martian regolith processed at low temperatures doesn't result in lower power (due to production rates) AND requires more mass -> NO ADVANTAGE

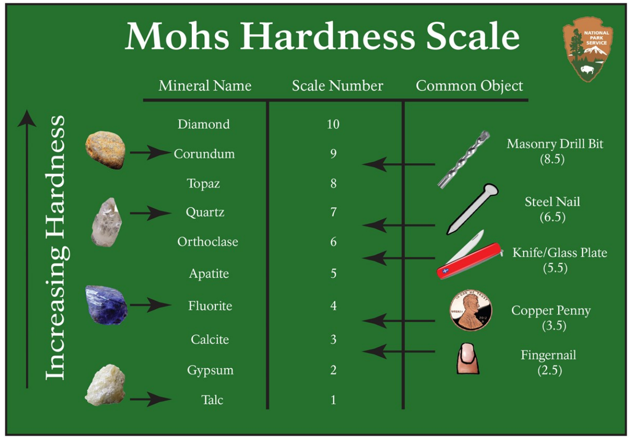


Gypsum ($CaSO_4 \cdot 2H_2O$) is promising, but in what form does it exist?

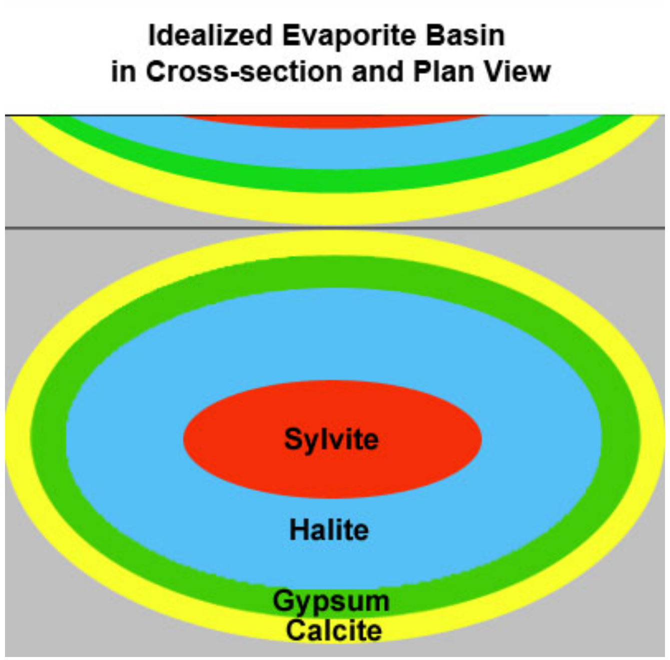
- Exists on Mars in all hydration forms (Gypsum, Basanite, Anhydrite)
  - Gypsum ($CaSO_4.2H_2O$)
  - Alpha and beta hemihydrate ($CaSO_4.0.5H_2O$) (Basanite)
  - Anhydrite ($CaSO_4$)
- Exists in many places
  - Noctis Labyrinthus, Melas Chasma, Columbus Crater, Gale Crater, Mars poles etc.
- Promising source of water
  - 20.9% water by mass
  - Water bound in crystal, disassociates around 150 °C
  - Soft (Moh's Hardness of 2, 3-60MPa)

Rim of Columbus Crater

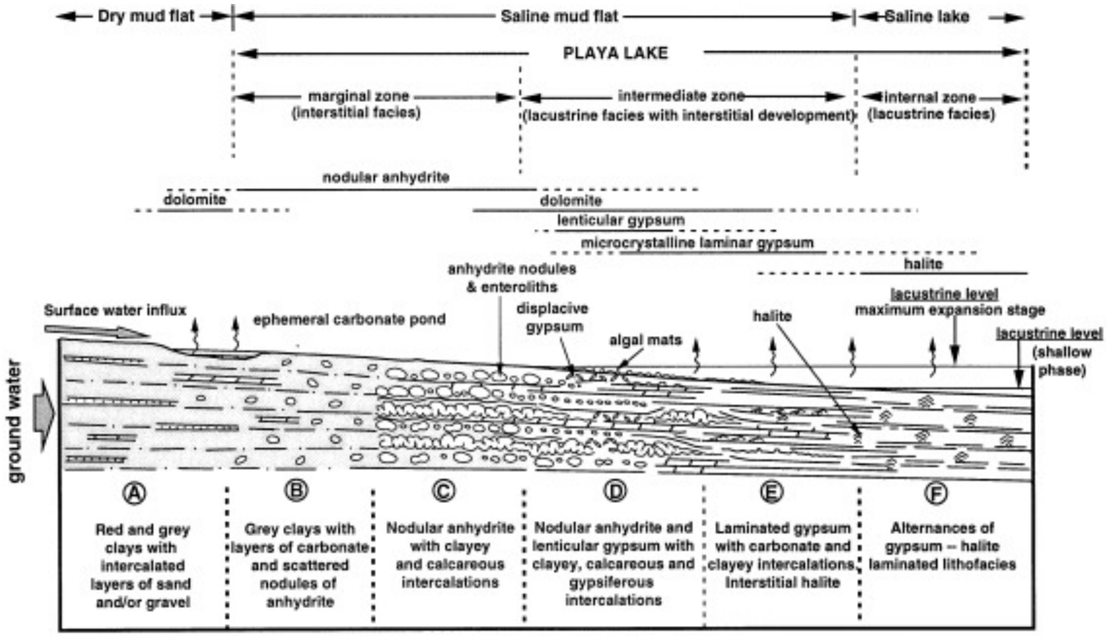




Deep Basin Deposit vs. Sabkha Deposit



https://www.geologyforinvestors.com/potash-and-other-evaporite-deposits/



Deposition and early alteration of evaporites, Sedimentology 47(s1):215 - 238 · February 2000

DOI: 10.1046/j.1365-3091.2000.00002.x

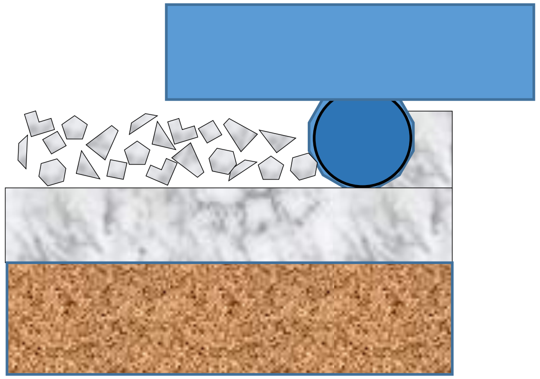
Michigan Technological University 1885

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

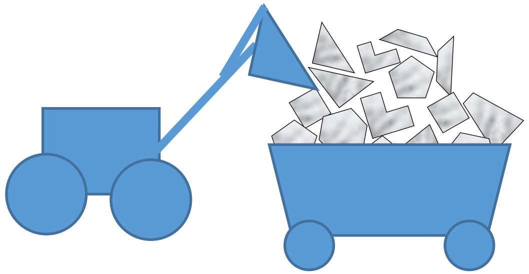
Surface Miner Process

Natural state

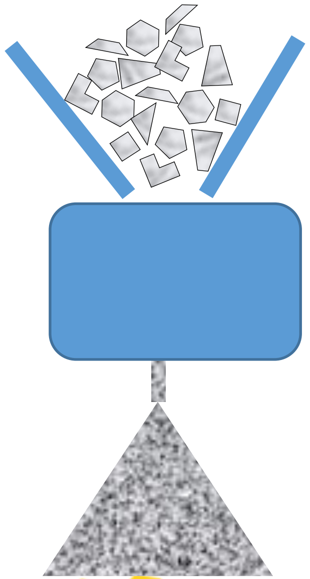


Fracture top layer

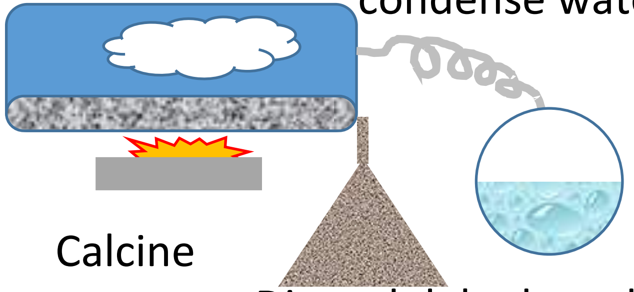
- Drum rotates
- Teeth easily replaced (by 1 person)
- Does not really slow production down
- In Gypsum need slowest setting to get desired rock size



Load & Transport



Crush / Mill rocks

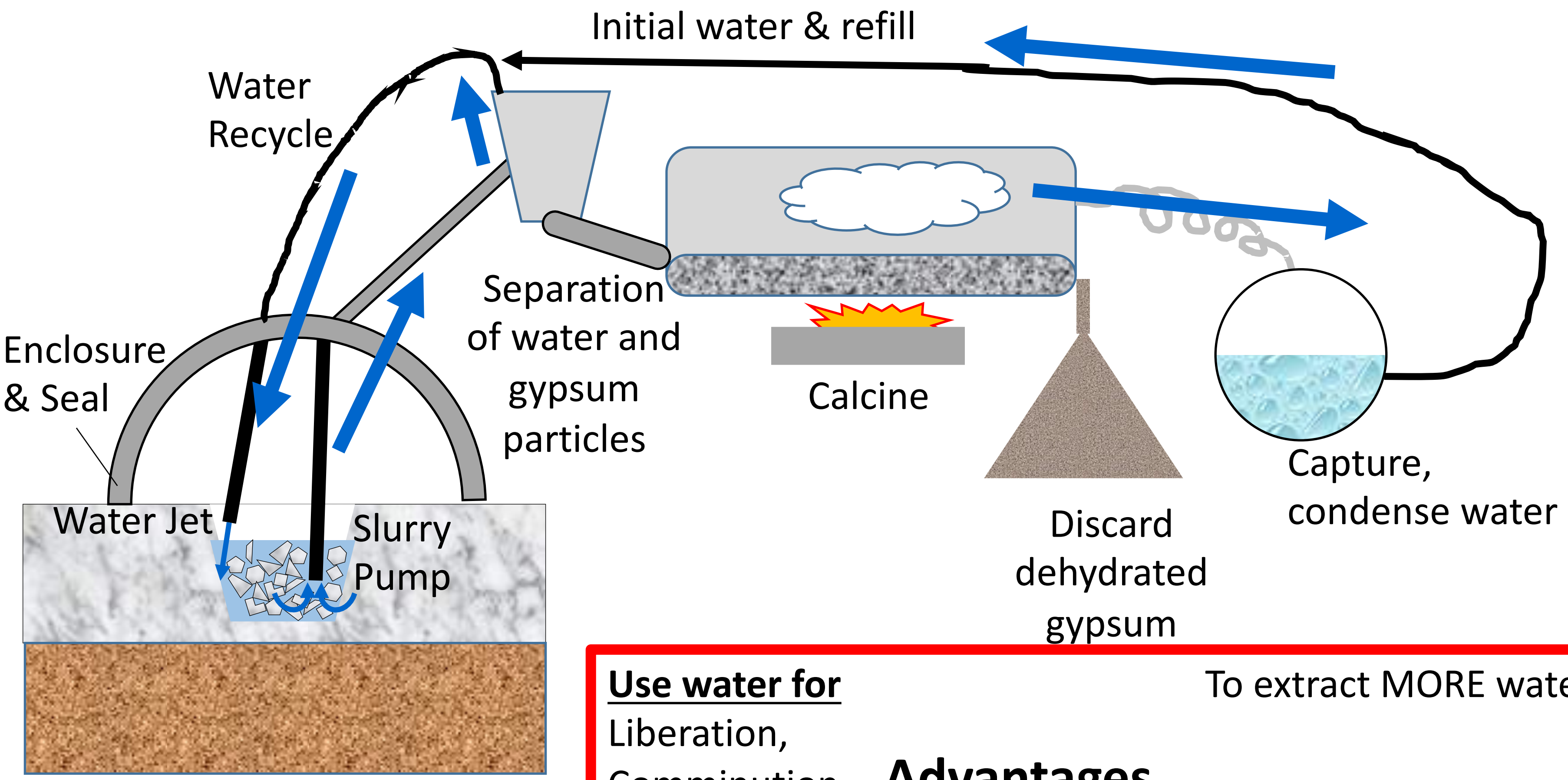


Capture, condense water

Calcine

Discard dehydrated gypsum

Alternate Excavation & Calcination Process



Use water for To extract MORE water

Liberation,
Comminution
Transportation
Separation

Advantages

No mechanical excavation and comminution = no wear

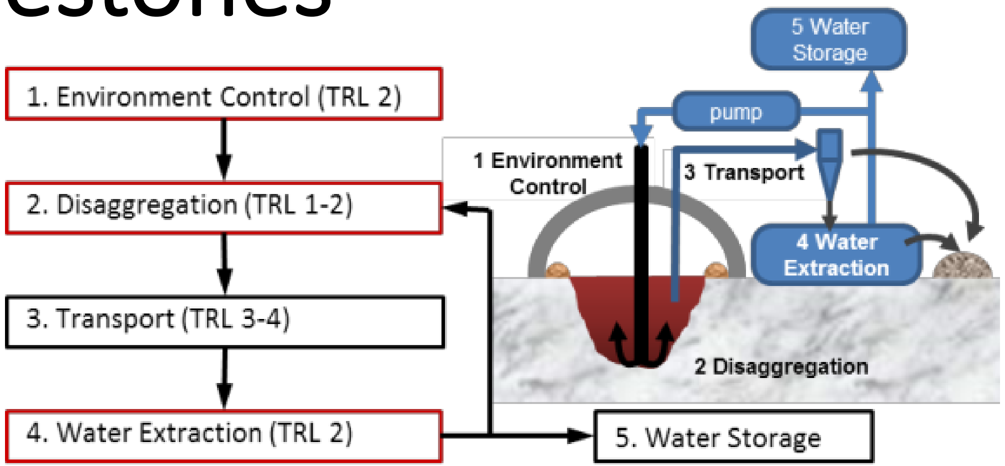
Michigan Technological University 1885

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

Schedule and Milestones

- January 2018 – January 2021
- Just finished 5th Quarter
- Work with HBR continuing
- US Gypsum
- Requirements
- System Model
- Design



		Year 1				Year 2				Year 3	
	Tasks	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Phase I	A Characterization & Disaggregation										
	B Separation & Precipitation										
	C Environment Constraints										
	D Sealing Constraints										
	E Energy and Size Constraints										
Milestone I: Component-Level Process Requirements					◆						
Phase II	A Bootstrapping Process										
	B Disaggregation										
	C Brassboard-Level Design										
Milestone II: CDR								◆			
Phase III	A Hardware Fabrication										
	B Brassboard Testing										
	Brassboard testing complete										◆

Michigan Technological University 1885

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

Hole Saw Testing – 25lbf Preload

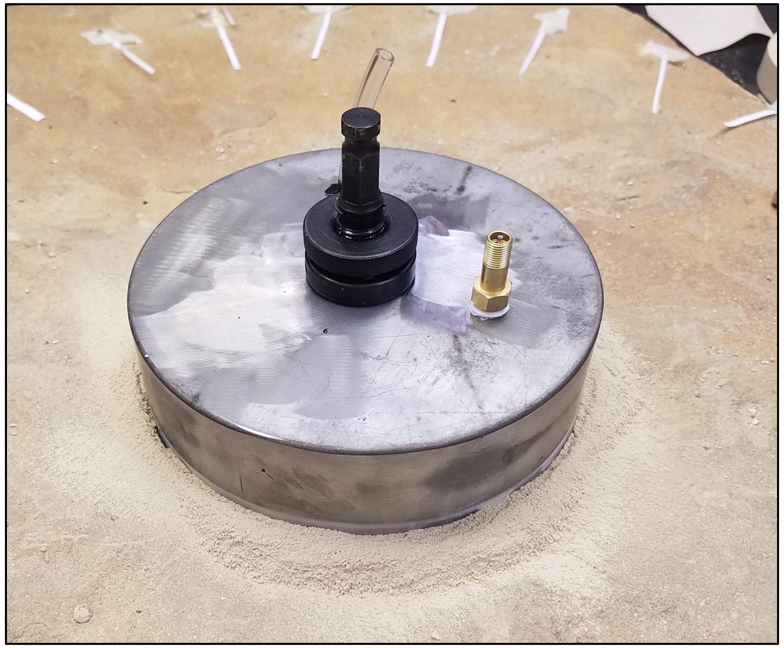
Test 019

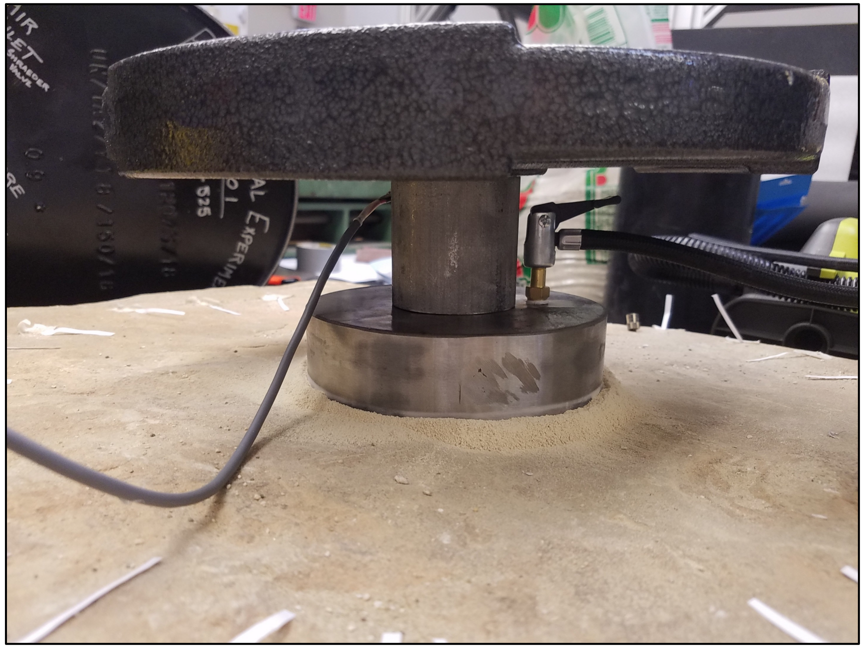
Test 019 was tested at a depth of approx. 0.375”. This is approximately 0.125” past the top of the abrasive cutting edge of the bit.

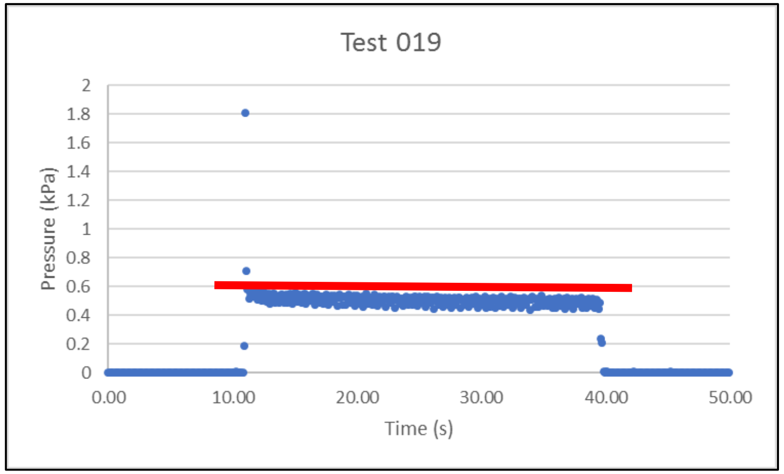
The bit was not removed to control for the possibility that the cuttings themselves create the seal.

The bit was preloaded with 25lb and pressurized using an electric pump.

Could not pressurize past about 0.5kPa.

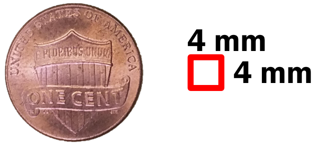




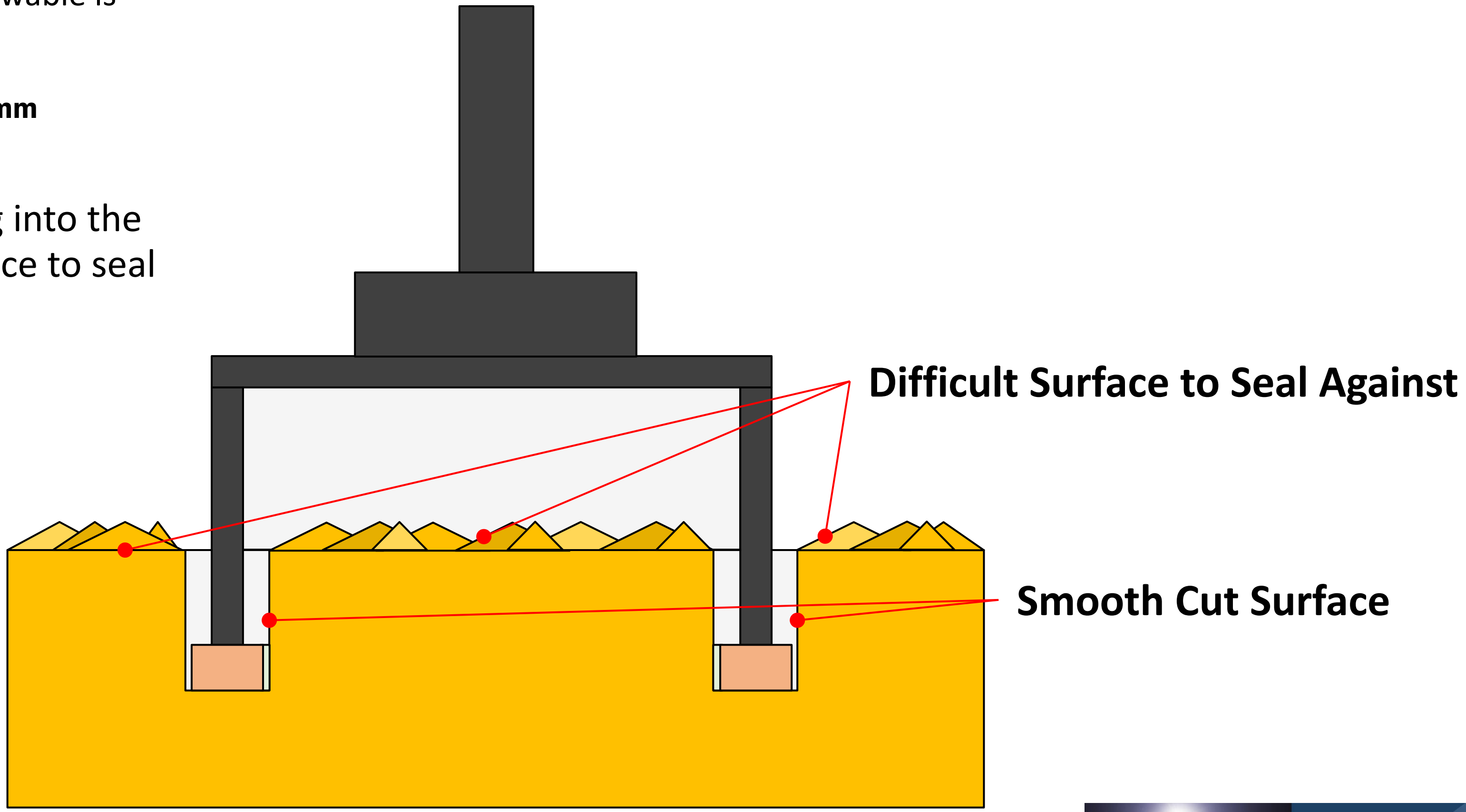


Sealing Against the Martian Surface

- Sealing against the Martian surface will be nearly impossible with normal irregularities in the surface.
  - Rough estimates suggest that to maintain a water vapor leak rate <0.8kg/hr, the maximum gap allowable is ~15mm^2.

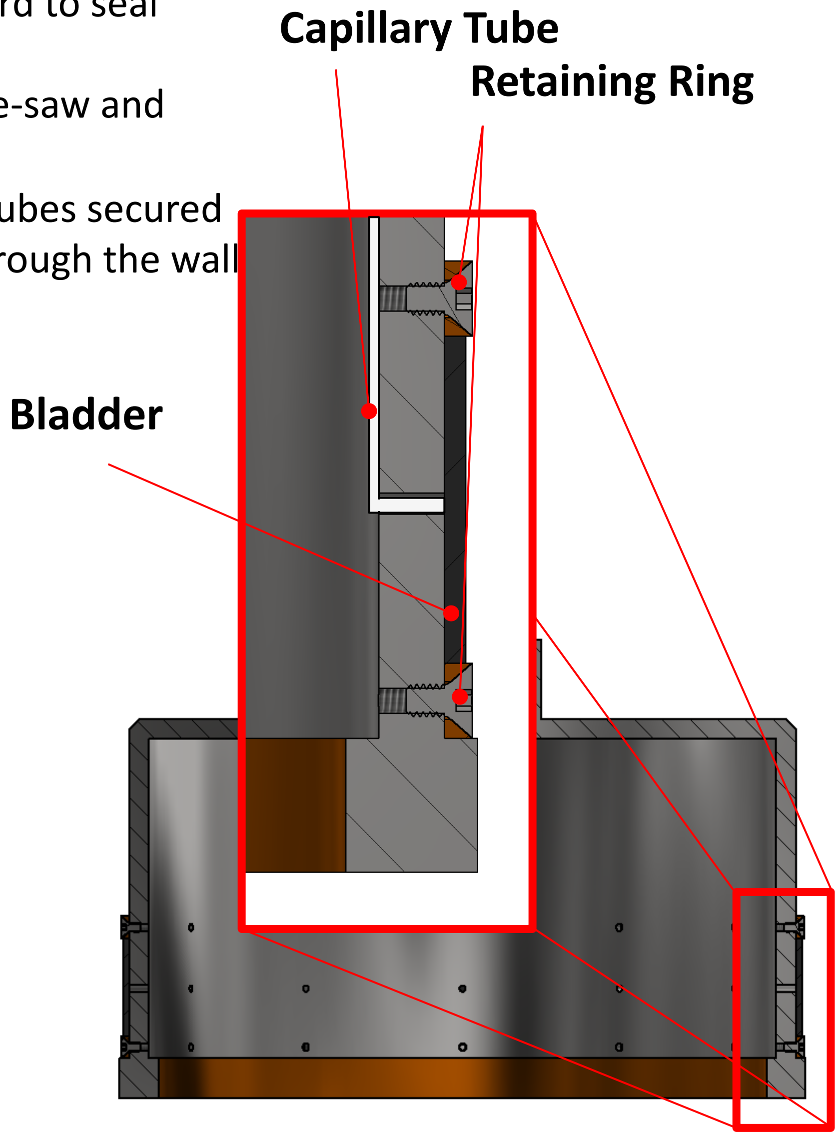


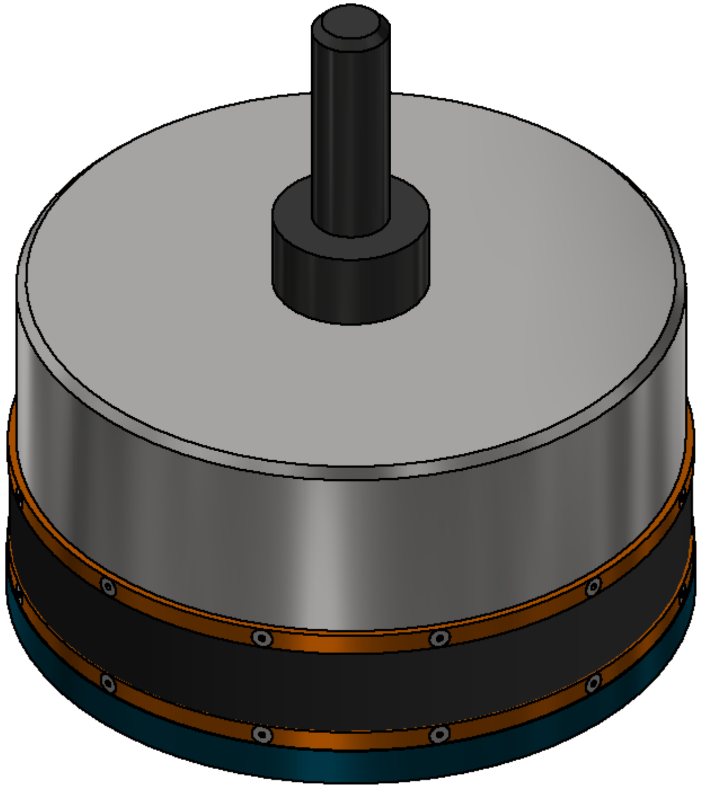
- The interior wall surface created by cutting into the ground provides a smooth consistent surface to seal against.
  - Any sealing mechanism here must exist in the annular space between the diameter of the hole-saw body and outer diameter of the cutting bit.



Hole Saw with Bladder

- An inflatable bladder is a possible path forward to seal against this smooth cut surface.
  - The bladder is wrapped around the hole-saw and captured by two aluminum rings.
  - The bladder is filled by a series of thin tubes secured in the interior annular space and fed through the wall of the hole saw.





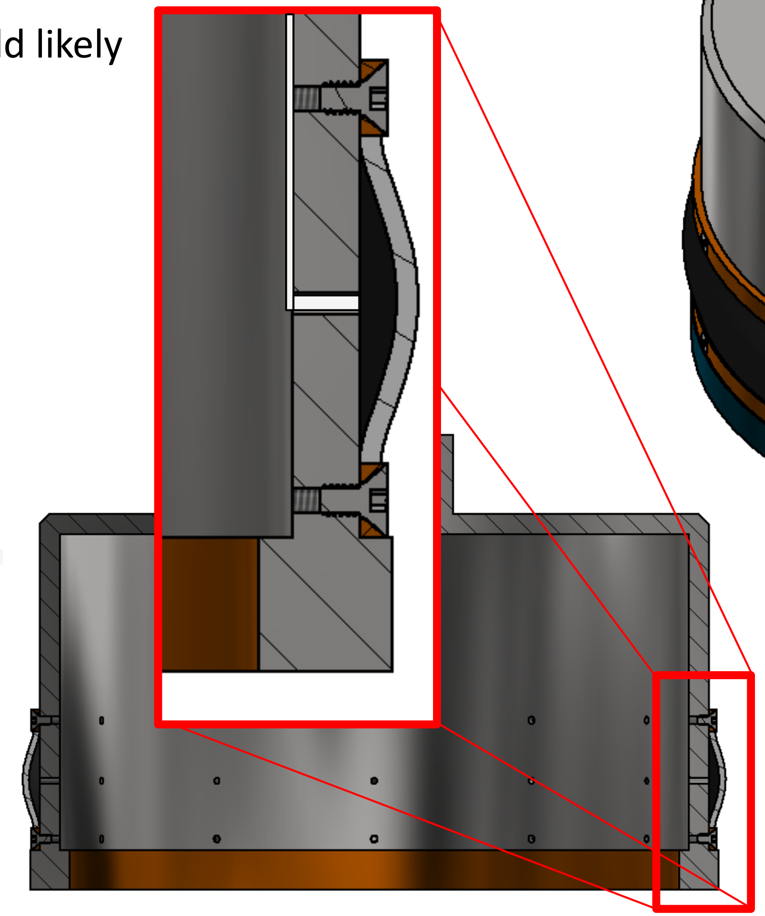
Michigan Technological University 1885

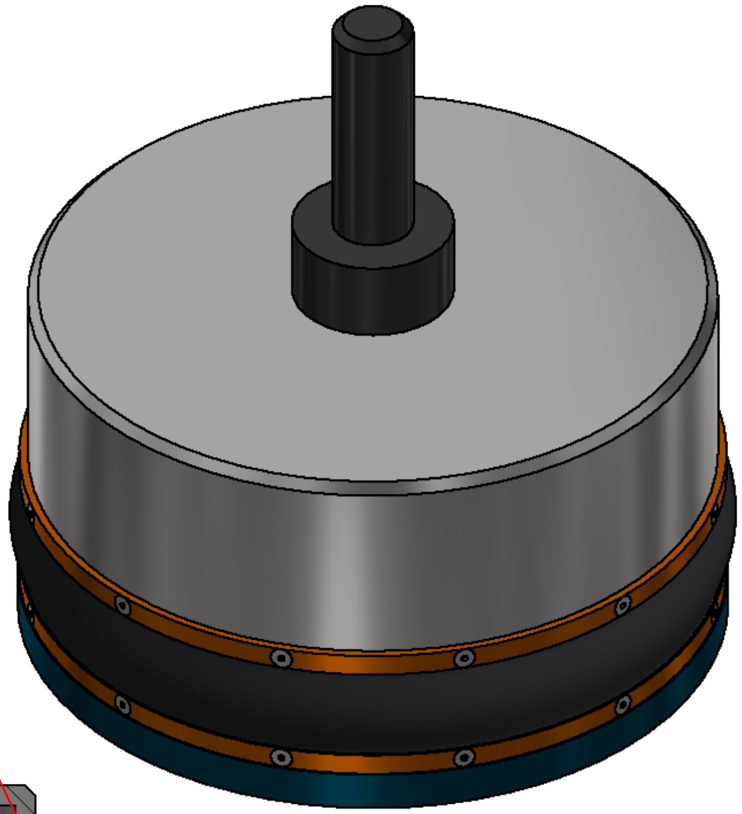
HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

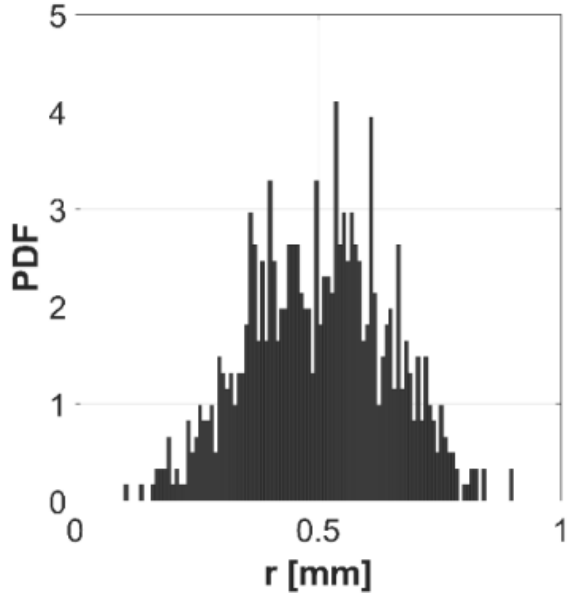
Hole Saw with Bladder cont.

- Air is supplied through a pneumatic slip ring on the shaft of the sealing surface.
- The design and fabrication of a custom hole saw would likely be needed to provide sufficient annular space to accommodate this sealing feature.

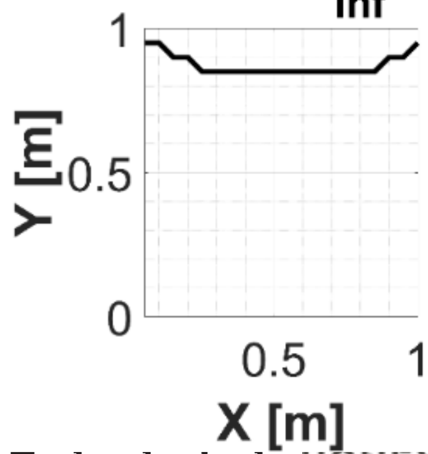




Modeling: Analytical & Pore Network Model

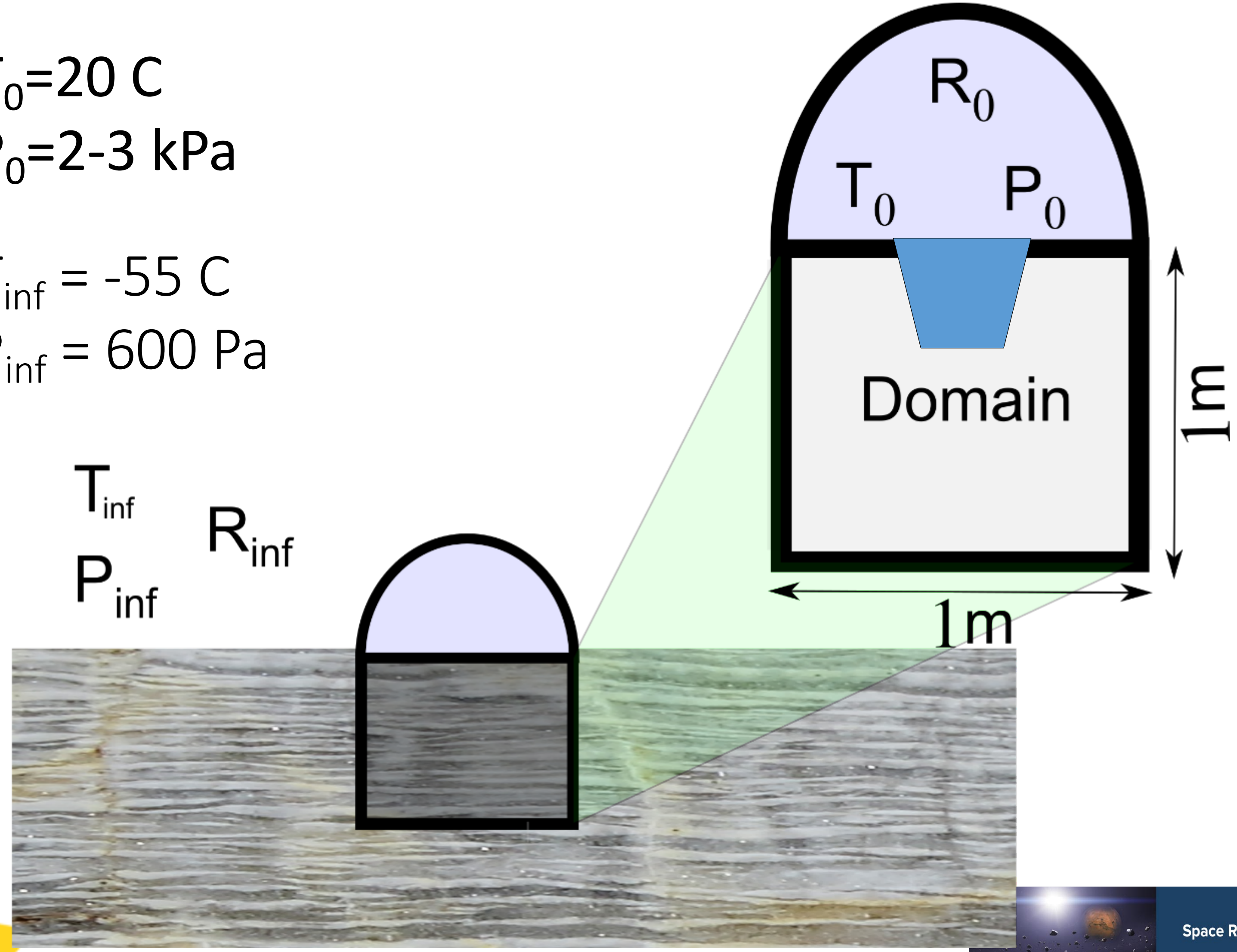


Frost line at T_{inf}= -55°C

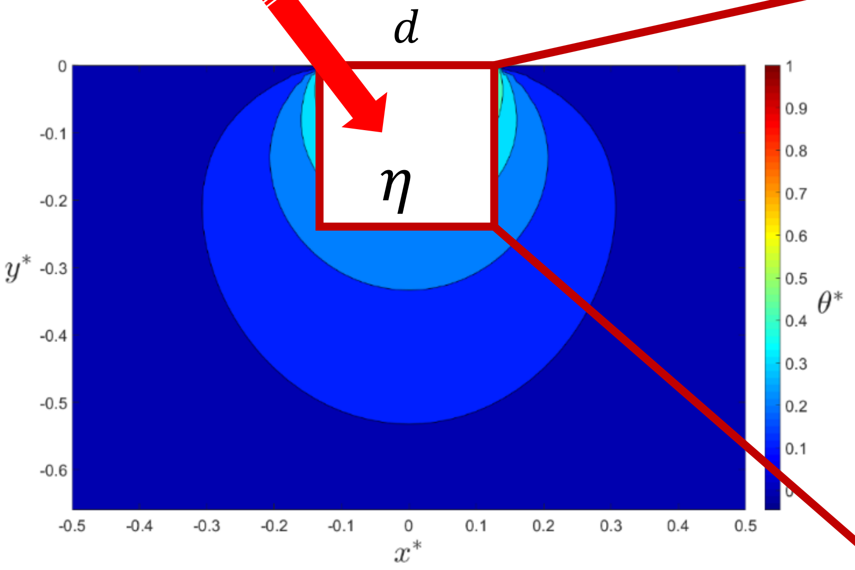


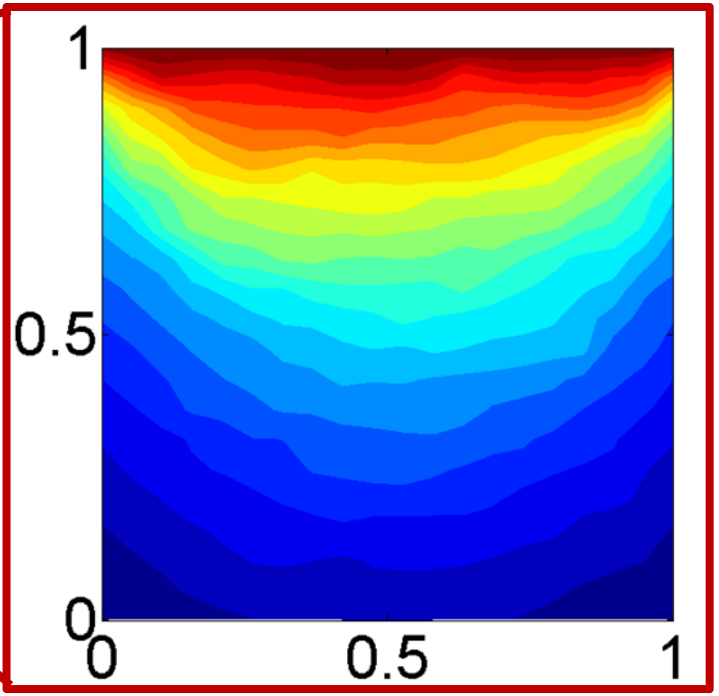
T_0=20 C
P_0=2-3 kPa

T_{inf} = -55 C
P_{inf} = 600 Pa

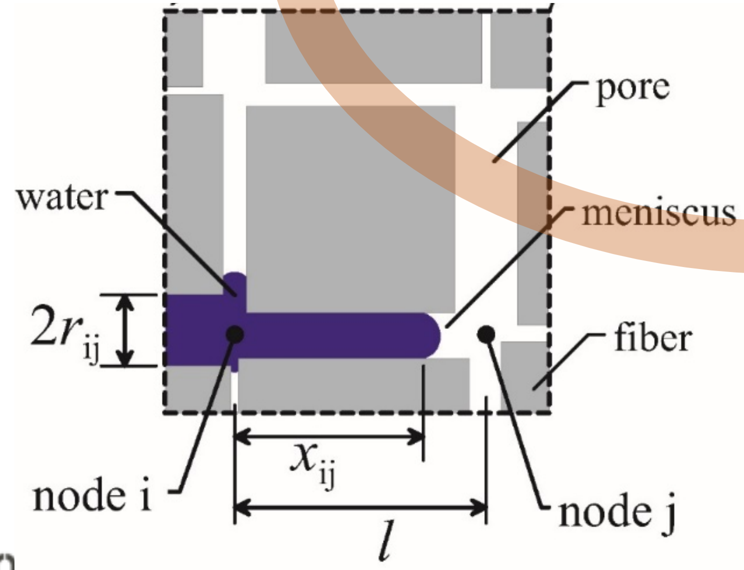


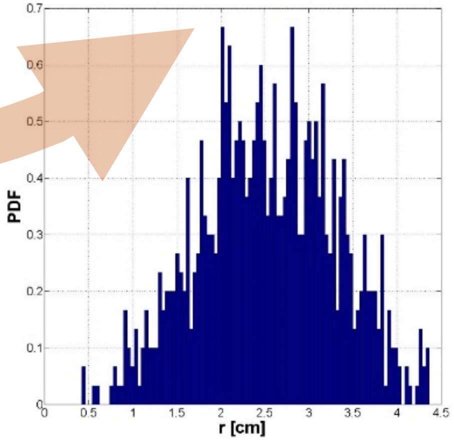
PNM Simulations





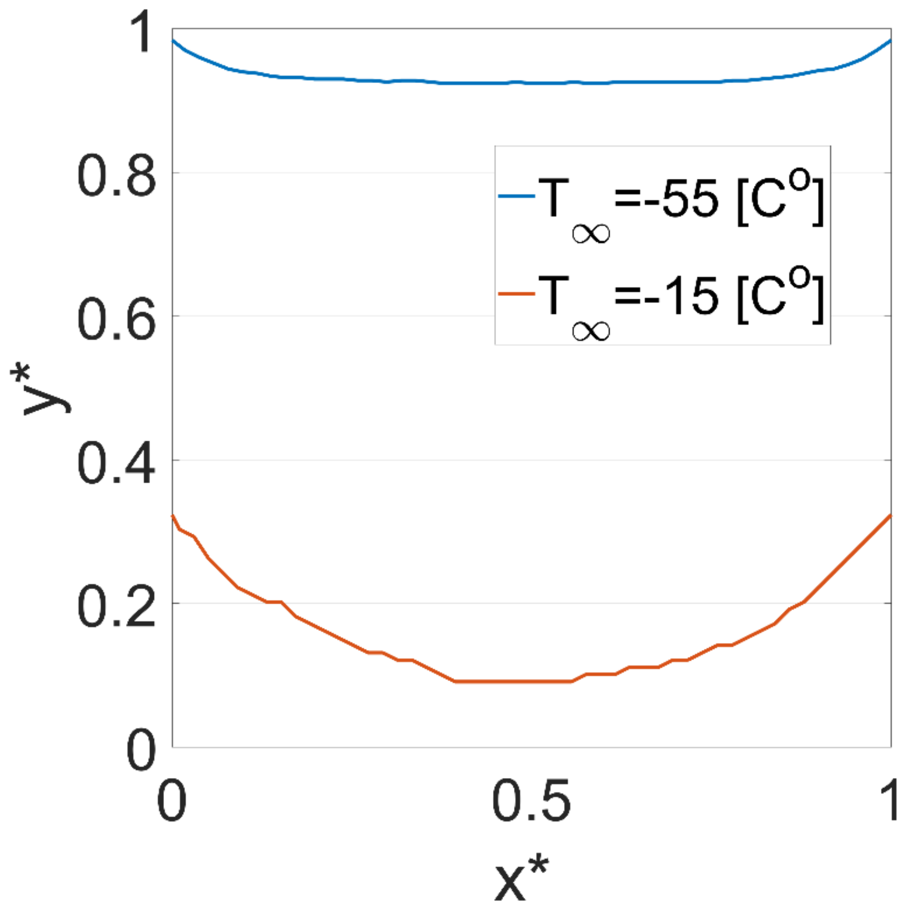
Pore Network Model



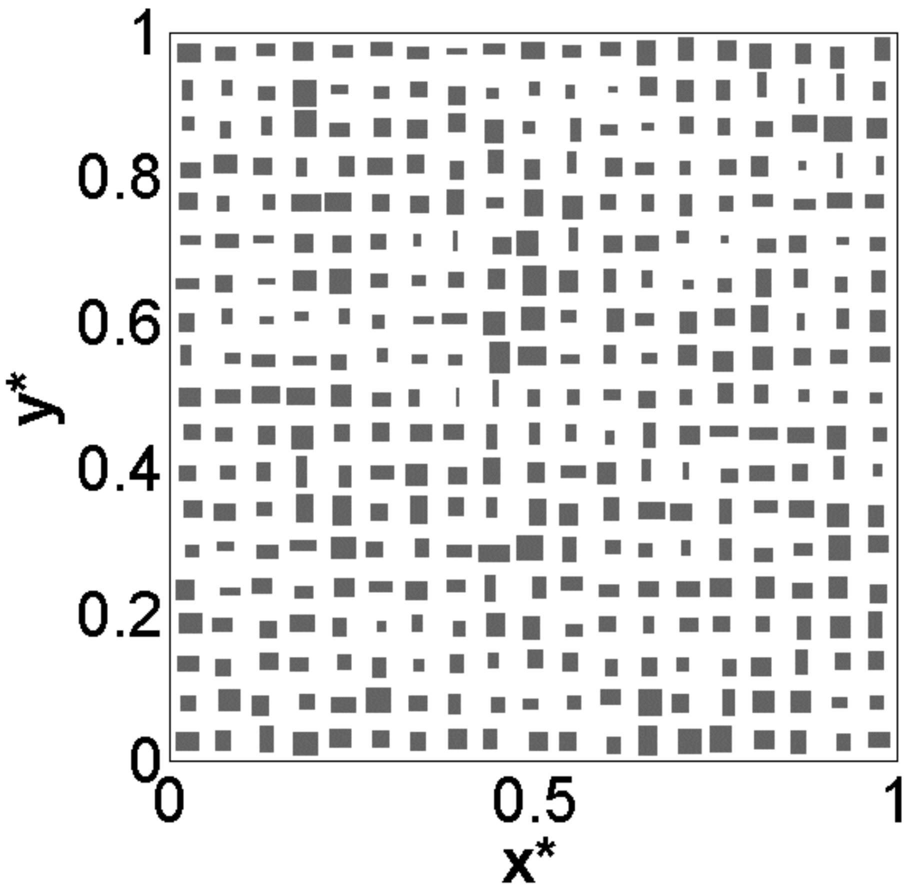


PNM Simulations

Frost line Simulation



Excavation simulation



Michigan Technological University 1885

Spacecraft Mechanisms Corporation

Space Resources Roundtable

Planetary & Terrestrial Mining Sciences Symposium

Energy Lost

Excavation rate:

0.8 Kg/h of water

6 Kg/h of Gypsum

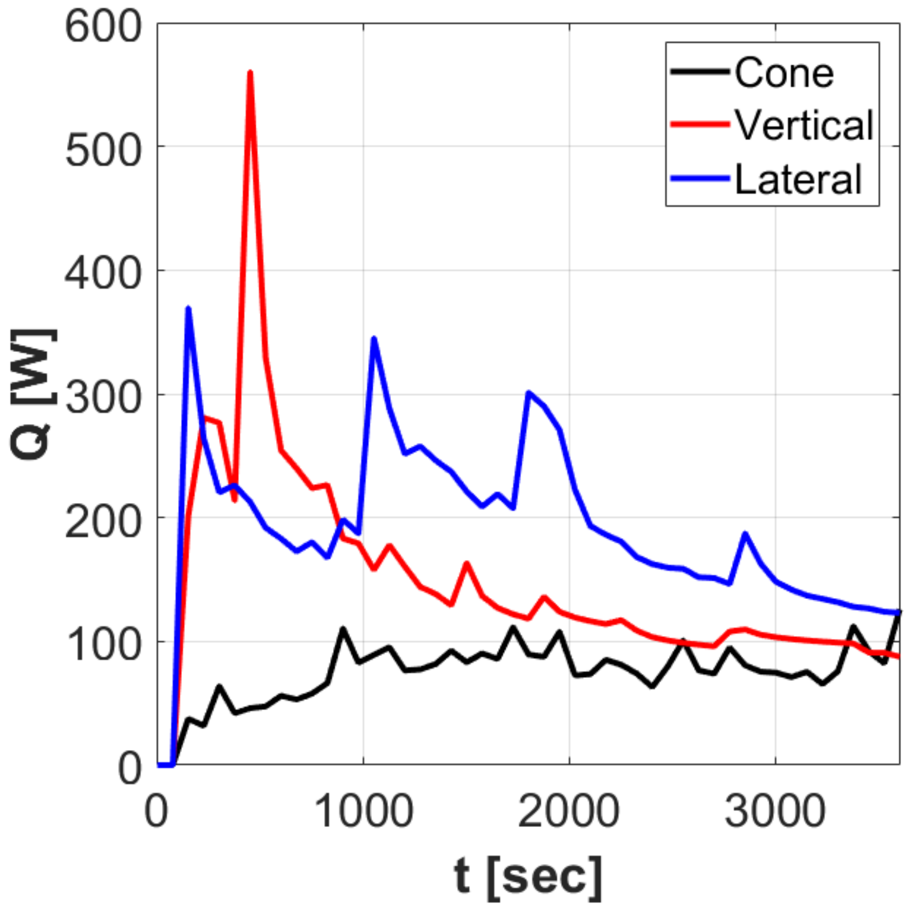
6 L/h of Gypsum

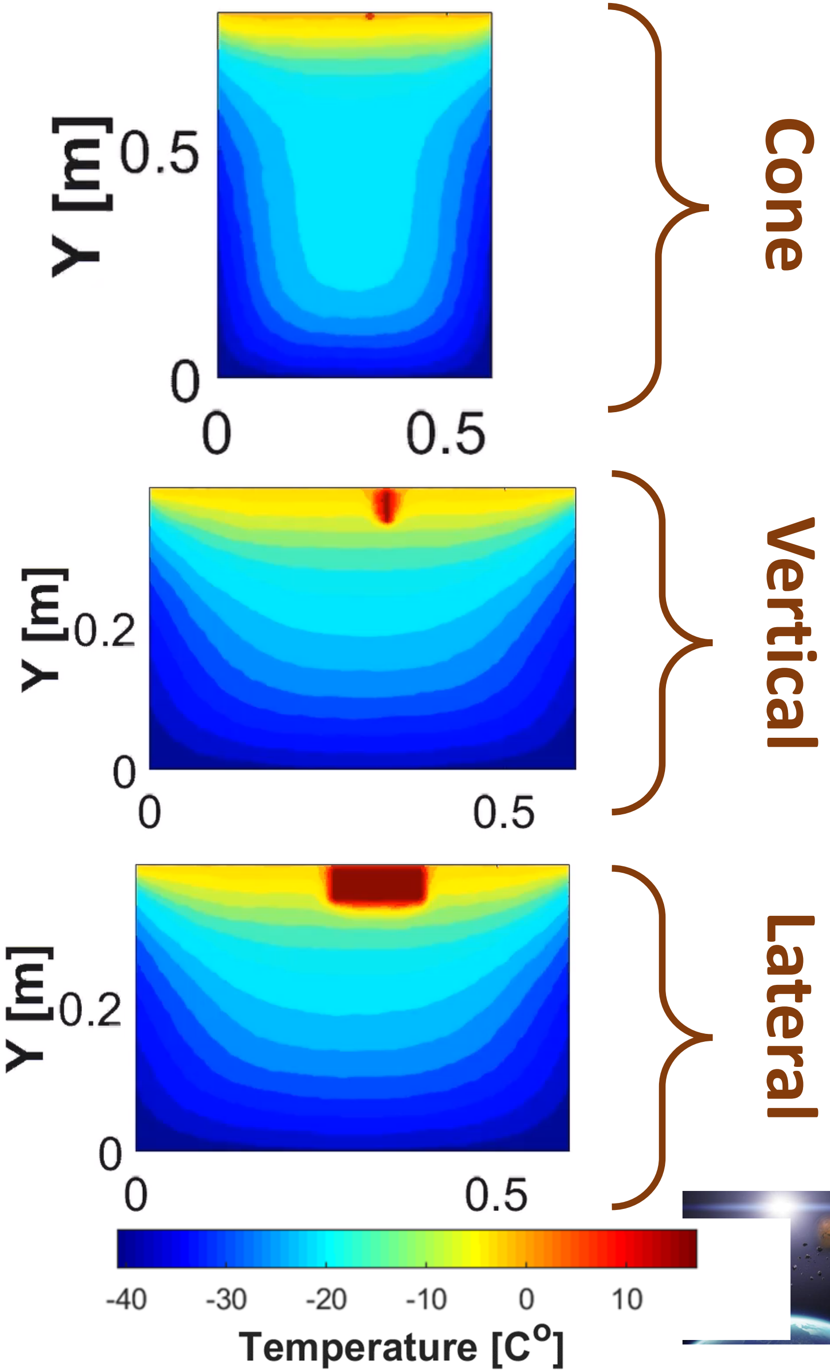
Total Energy

Cone: 2.75e5 [J]

Vertical: 5.45e5 [J]

Lateral: 7e5 [J]





Michigan Technological University 1885

Space Resources Roundtable

Planetary & Terrestrial Mining Sciences Symposium

- We are modifying the model to understand the bootstrapping thermal behavior and depth penetration.

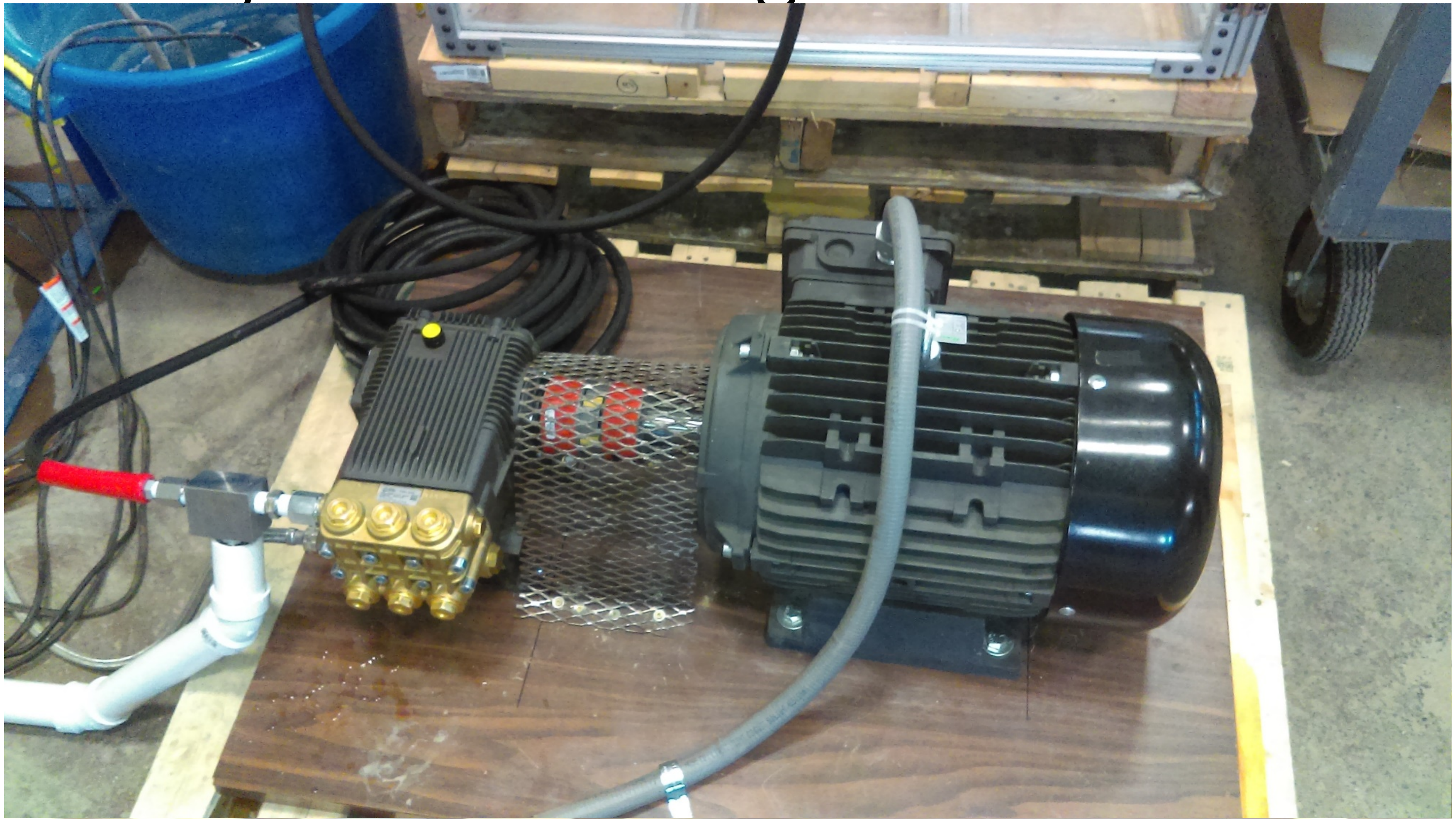
Bootstrap (how to get initial water)

- Microwave
- Solar

Disaggregation and transport Test setup

5000 PSI System Building

5000 PSI System Building



Michigan Technological University 1885

HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

5000 PSI System Building

5000 PSI System FD-2 Before

5000 PSI System FD-2 After

Michigan Technological University 1885

HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation

Space Resources Roundtable

Planetary & Terrestrial Mining Sciences Symposium

Preliminary Results – 1 day old

- Preliminary results show 4 times higher excavation rate when going from 2700 psi to 5000 psi

Gypsum calcining video

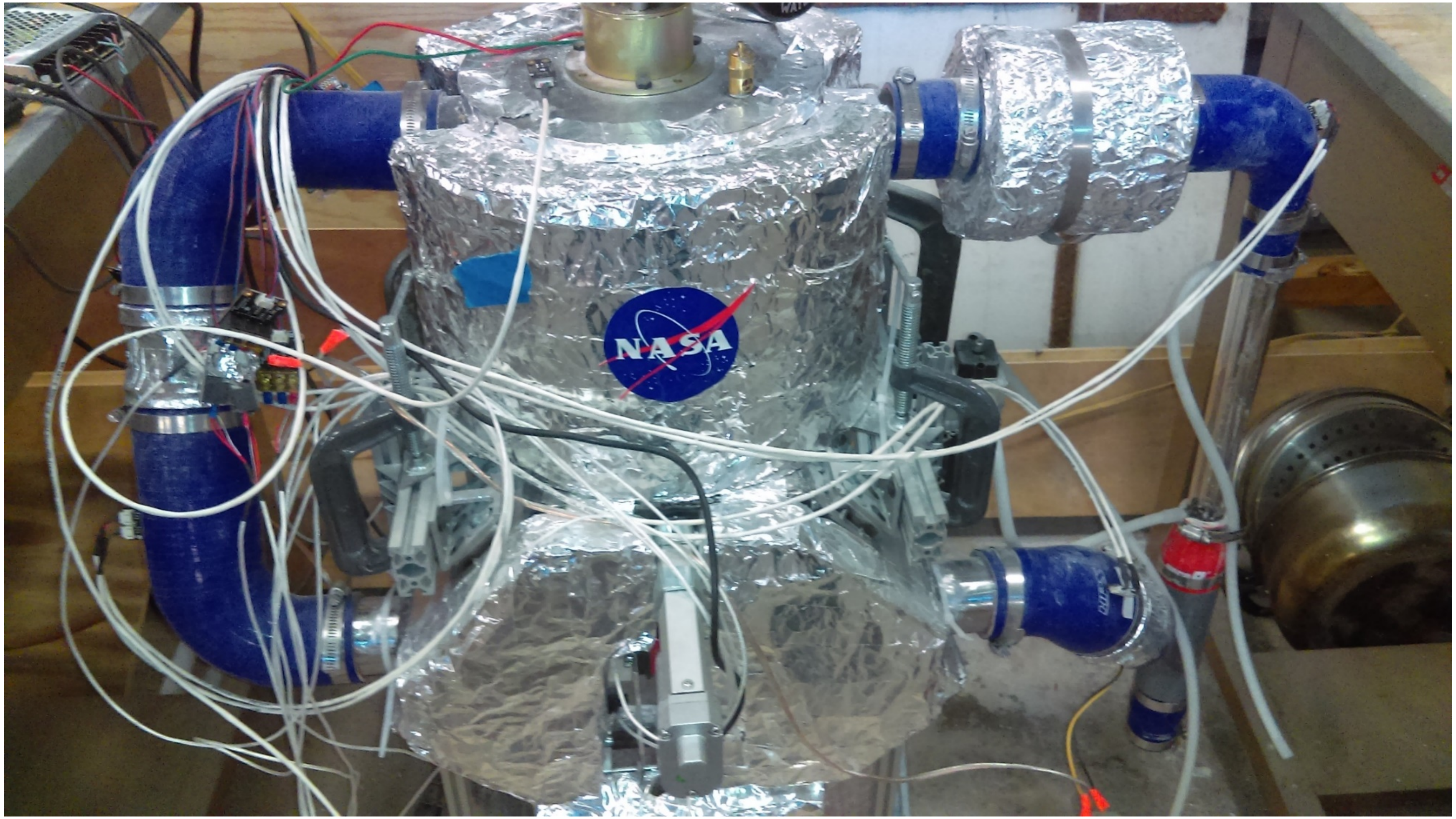
Calcining Reactor

Ta3, Ha3

Lid, stirrer, honey well

Ta1, Ha1

Fan



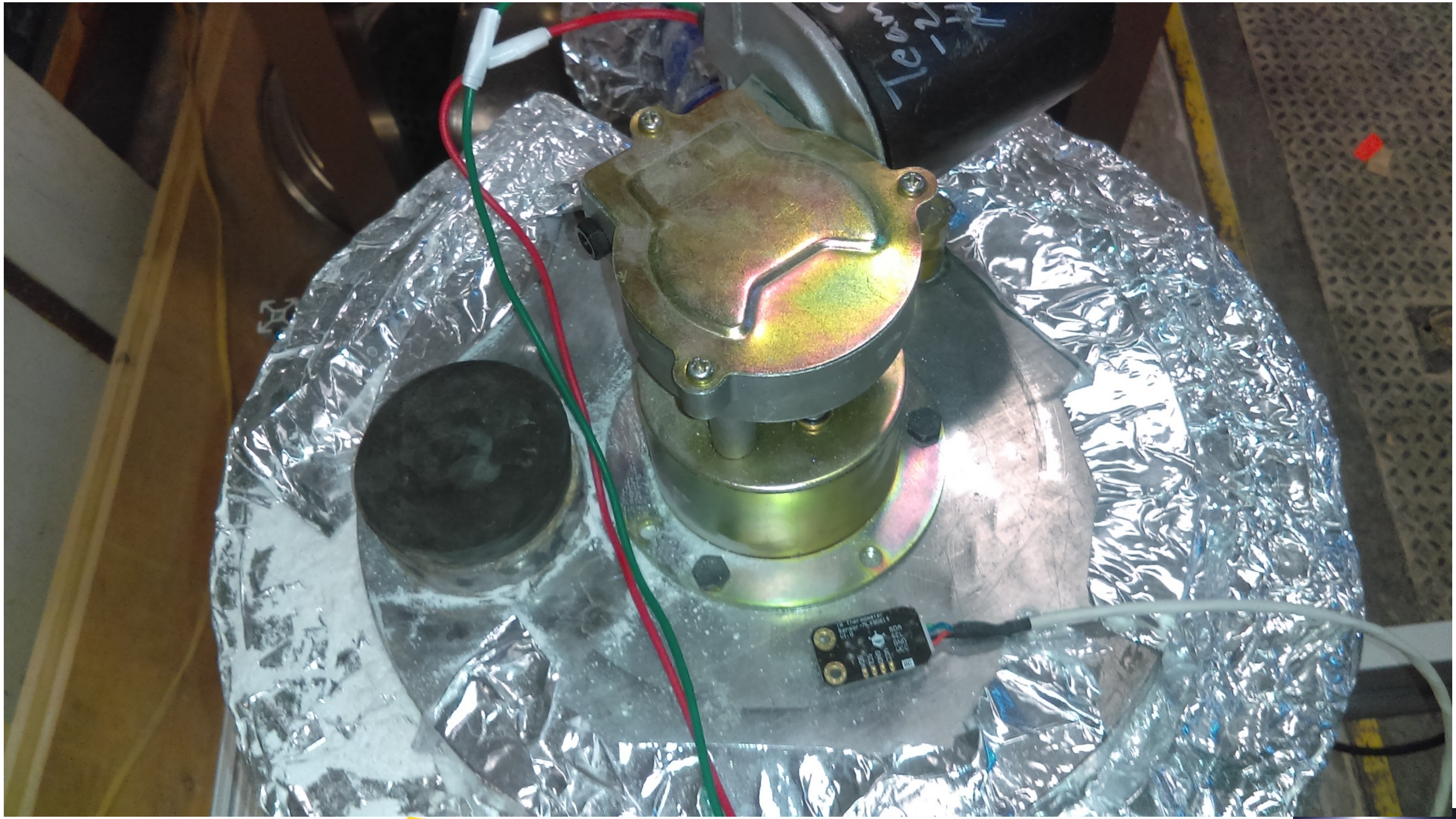
Condenser

Ta2, Ha2

Heat Recovery,
T11, T12, T21, T22

Water
collection

Calcining Reactor



Michigan Technological University 1885

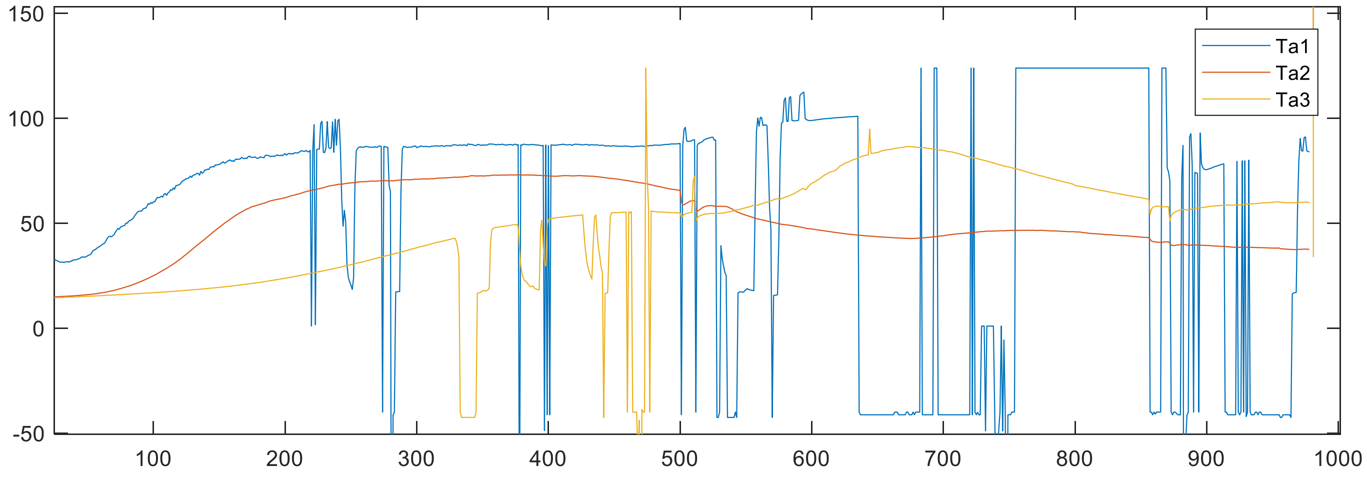
HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation

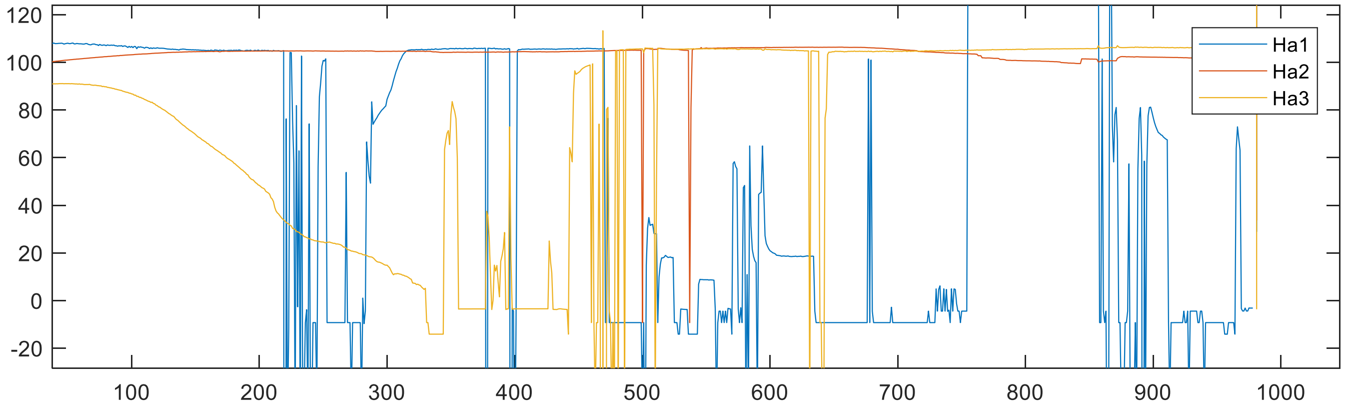
Space Resources Roundtable

Planetary & Terrestrial Mining Sciences Symposium

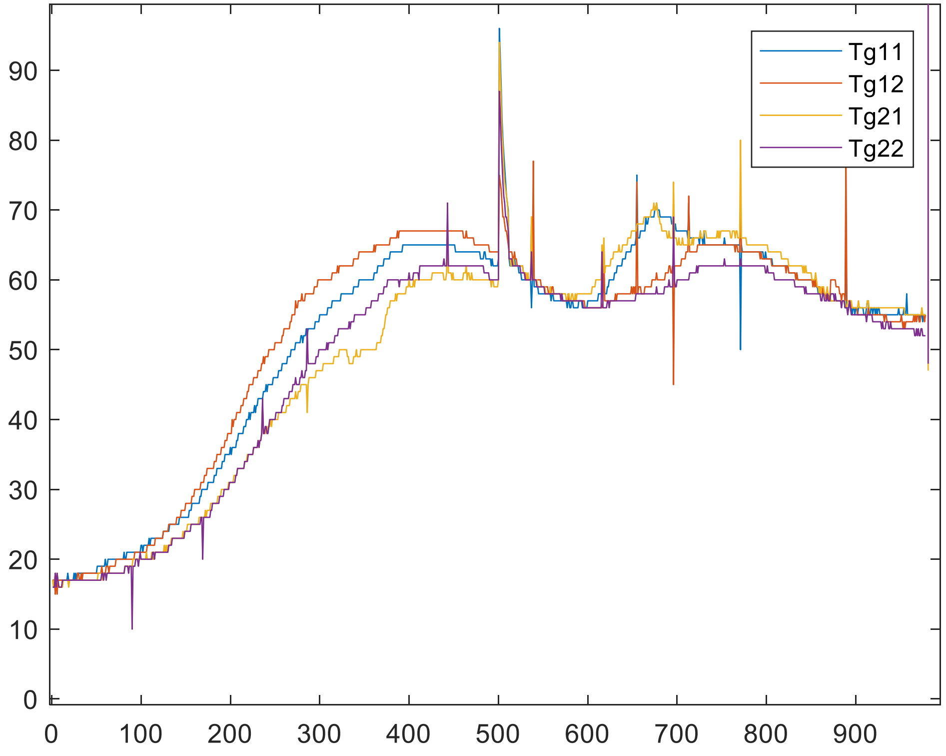
Calcining Reactor

Water Extraction Results





Water Extraction
Liquid water & Crystalline bound water
Successfully got 90+ % of water expected



Michigan Technological University 1885

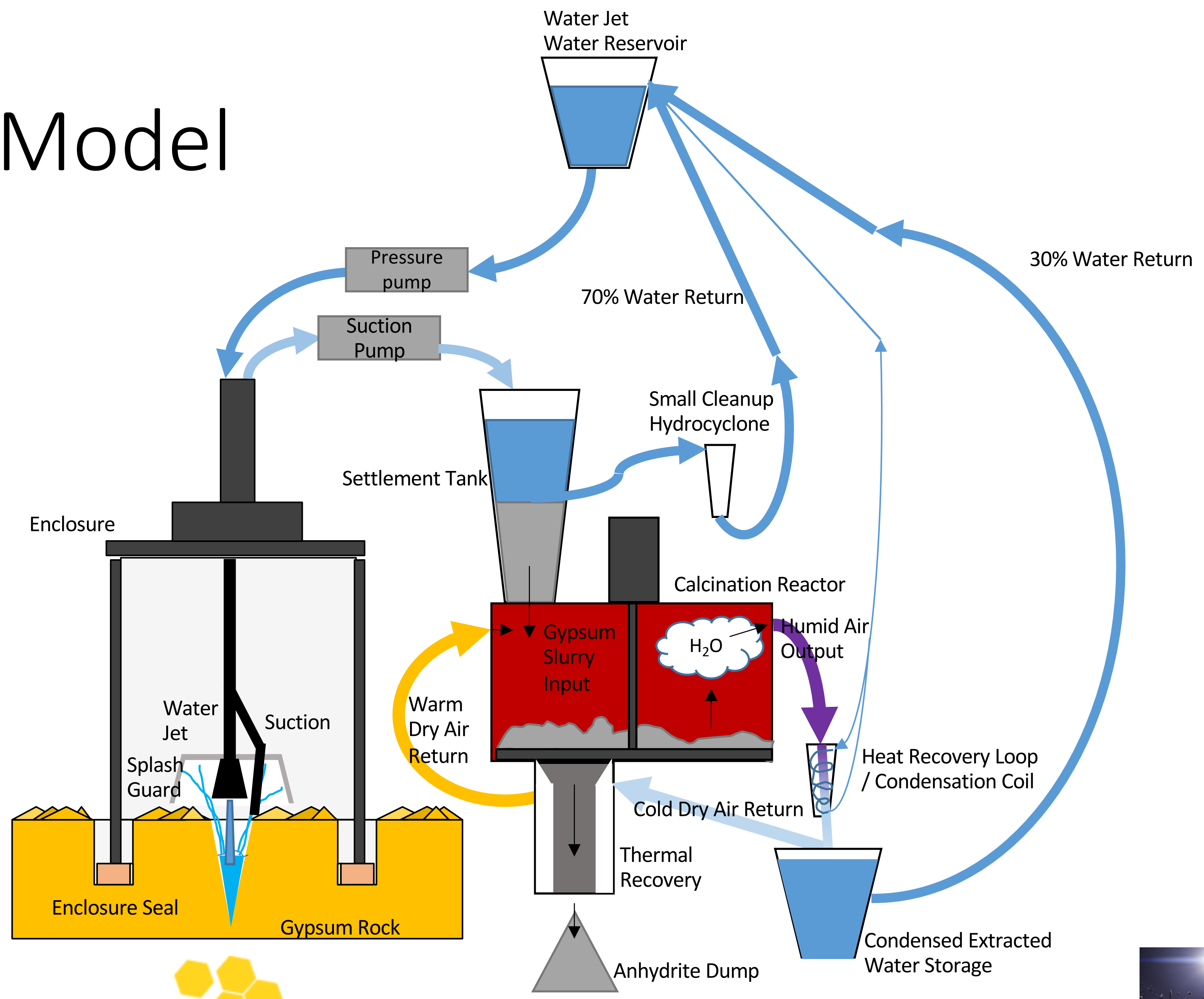
HONEYBEE ROBOTICS Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

Requirements & TRL 4 testing

subsystem name	subsystem ID	ID	Requirement	Description	Value	Unit(s)
Overall Production Rate	1	1	Water Production	Sufficient Avg. Prod. Rate to extract 16 metric tons of water in 480 sols	1.4	kg/hr
Gypsum properties	2	1	Porosity	Virtually no porosity	--	--
		2	Permeability	--	TBD	TBD
		3	Thermal Conductivity	--	1.318	W/mK
		4	Thermal Diffusivity	--	?	?
		5	Density	--	2305	kg/m^3
		6	Young's Modulus	--	~6	Gpa
		7	gypsum water content by mass		20.9	%
		8	hemi-hydrate (bassanite)		5	%
		9	anhydrite		0	%
		10	temperature at which water disassociates from gypsum at atmospheric pressure		150	°C
		11	temperature at which water disassociates from hemihydrate at atmospheric pressure		210	°C
Location	3	1	Local Gypsum	enough exposed gypsum on the surface to excavate	TBD	TBD
		2	Variation	Minimal spatial and depth Variation of Gypsum in a given deposit	TBD	TBD
		3	Purity	Minimal other minerals mixed in deposit		
Mars Environment	4	1	Temperature	Ambient Maximum Temperature (Mars Equator)	20	°C
		2		Average temperature	-55	°C
		3	Solar irradiation		590	W/m2
Enclosure	5	1	Enclosure	Enclosure maintains pressure	3	kPa
		2		Enclosure maintains liquid water temp	1	°C
		3		Enclosure size minimized for repositioning	--	--
				limit leak rate to <10% of production rate		
		4		Enclosure is large enough to fit excavation area and excavation subsystem and slurry suction system	--	--
Bootstrapping	6	1	Initial Water Extraction	Extract sufficient water without a water jet to begin using the water jet	--	--
		2		capture water vapor	--	--
		3		--	--	--
		4		--	--	--
Water Jet Buffer Tank	7	1	Water Jet Buffer Reservoir	Large enough to use water jet for a full cycle	--	--
		2		heated to maintain liquid water at exit temperature	20	°C
Water Jet	8	1	Pressure Generation	Required Pressure at level of UCS of gypsum	4500	PSI
		1	Nozzle	Nozzle applies water jet as close to surface as possible	2	cm
		2		Ability to rotate/translate within enclosure	--	--
		3		Maintain perpendicularity with local slope of rock	--	--
		4		ability to reach max depth of excavation		
		5	spray cover	spray cover to minimize water spraying against dome		
Suction	9	1	slurry transport particle size	Retrieve particles of sufficient diameter	2	mm
		2		Transport and deposit slurry in Settlement Basin	--	--
		3	height of suction column	suction height shall be minimized by geometry		
		4		suction pump shall be self priming		
Separation	10	1	gypsum particle concentration	Slurry needs to settle until particles larger than 20 microns are settled	~1	hr
		2		Siphon off excess water prior to transfer into calcining reactor (70 % particles / 30% water by weight)	--	--
		3		Siphoned water to be recycled into Water Jet Buffer Reservoir	--	--
		4		concentrated slurry shall be input into calcination reactor		
		5		batch size shall be determined based on overall system model and production rate		
Calcining	11	1		Temperature of gypsum shall be raised to anhydrite level to remove all water	210	°C
		2		Water Vapor shall be collected in condensator	--	--
		3		Part of liquid siphoned off to long term storage, adherent water portion shall be cycled back to water jet reservoir	--	--
		4		Tank size sufficient to continuously calcine gypsum as concentrated slurry batch is loaded	--	--
		5		Recycle excess heat from end anhydrite by flowing fluid past the container to help maintain heat in calcine and dome	--	--
		6		hot anhydrite will be loaded in heat recovery chamber to extract as much thermal energy as possible		
		7		calcining reactor shall be insulated to minimize energy losses		
		8		reactor shall be able to accommodate one batch of concentrated slurry at a time		
Additional Lunar Requirements	12	1	Vacuum	Ability to operate under vacuum	--	--
		2	Light	Ability to operate without direct sunlight	--	--
		3		ability to disaggregate fully ice saturated lunar regolith at -196 C		

System Model

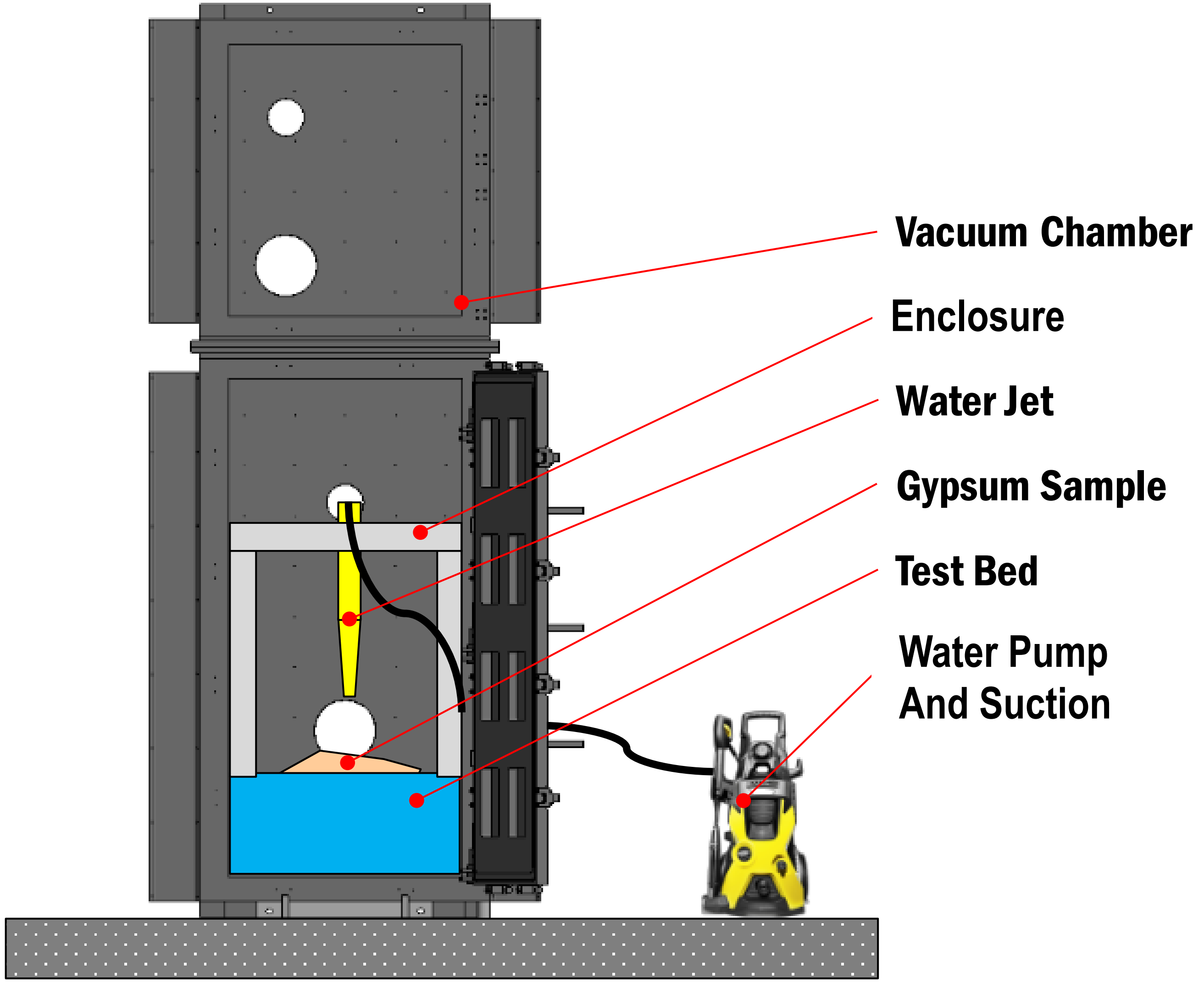


Michigan Technological University 1885

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation

Space Resources Roundtable
Planetary & Terrestrial Mining Sciences Symposium

Mars Vacuum Chamber Testing Requirements



Vacuum Chamber

- rectangular dusty thermal vacuum chamber with an
- interior dimension of 60x60x80 inches (inside shroud)
- with an internal thermal shroud and thermal base plate.
- The effective internal space 50x50x60.
- 10^{-4} to 10^{-6} torr
- and cooled by LN2 (plan is to have a 3000 gal LN2 tank so we can test for many days in a row, with refills even weeks if needed).
- The temperature range: -196 C to +150C.
- Several feedthroughs (data & power up to 3 phase 440V)
- Built in LED lighting and several windows (upgrade to vertical height)

Abstract due July 12

https://www.earthspaceconference.org/

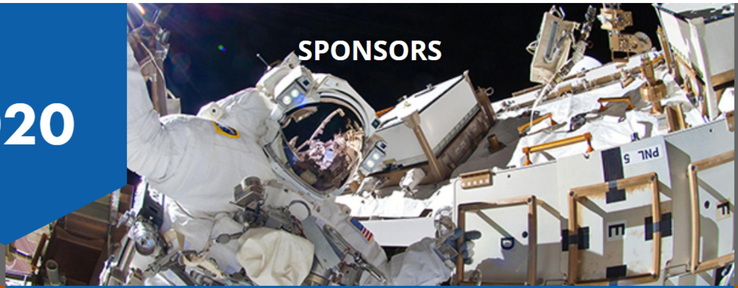
ASCE

Earth & Space Conference

Seattle, Washington | April 20–23, 2020

Engineering for Extreme Environments

2020



SPONSORS

PROGRAM

CONTACT

CALL FOR PAPERS

Renaissance Seattle Hotel
515 Madison Street
Seattle, WA 98104

Michigan Technological University 1885

HONEYBEE ROBOTICS
Spacecraft Mechanisms Corporation