Effects on Force, Power, and Wear from Excavating Beds of Icy Highlands Lunar Regolith Simulant Using a Chain Trencher with Point Attack Picks

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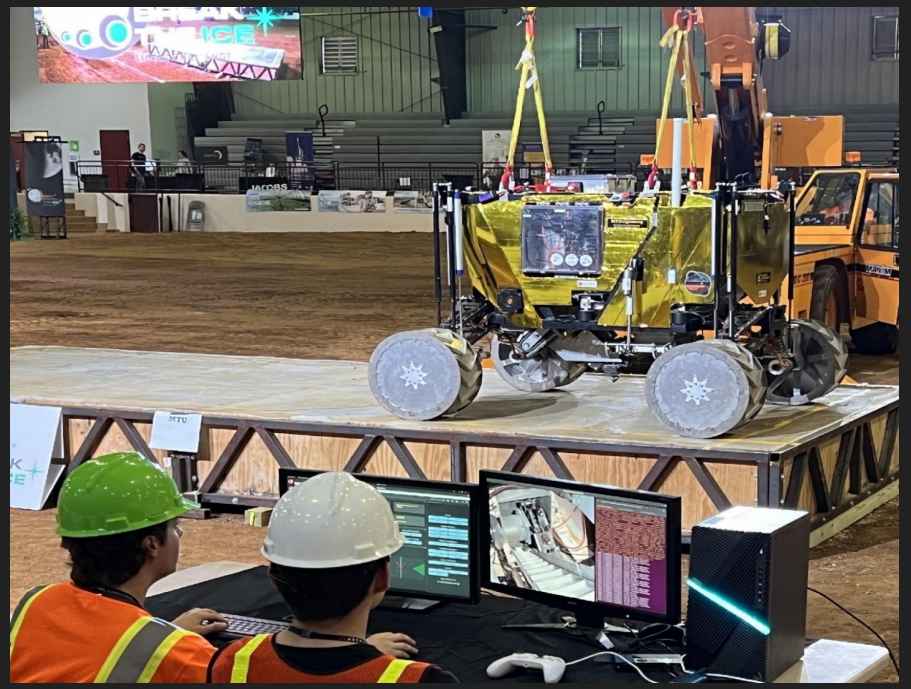
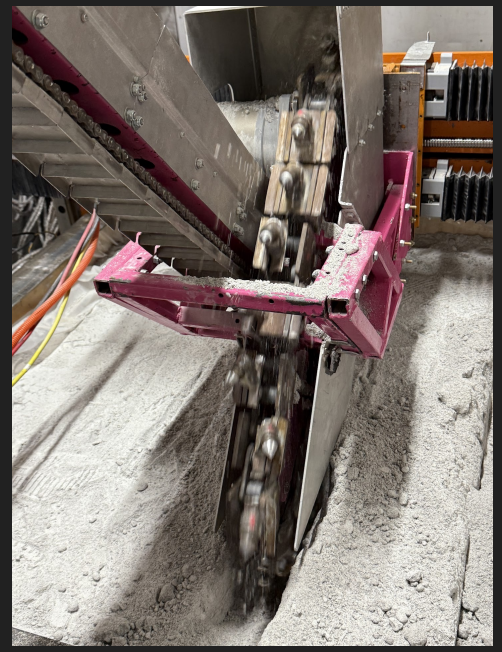
Space Resources Roundtable

Past Research: PRIMROSE & Break the Ice

Past Work

1. Built and tested the PRIMROSE rover for NASA's Break the Ice centennial challenge. 2021 - 2024
2. Unique chain trencher excavator & mobility system
3. Completed driving and gravity offloaded cemented simulant excavation tests
4. One of three finalists invited to test at MSFC DTVAC
5. We did a *wide* range of tests but were limited in focus. In particular, we found that excavation could be further optimized





A New Facility: The Force Test Stand (FTS)

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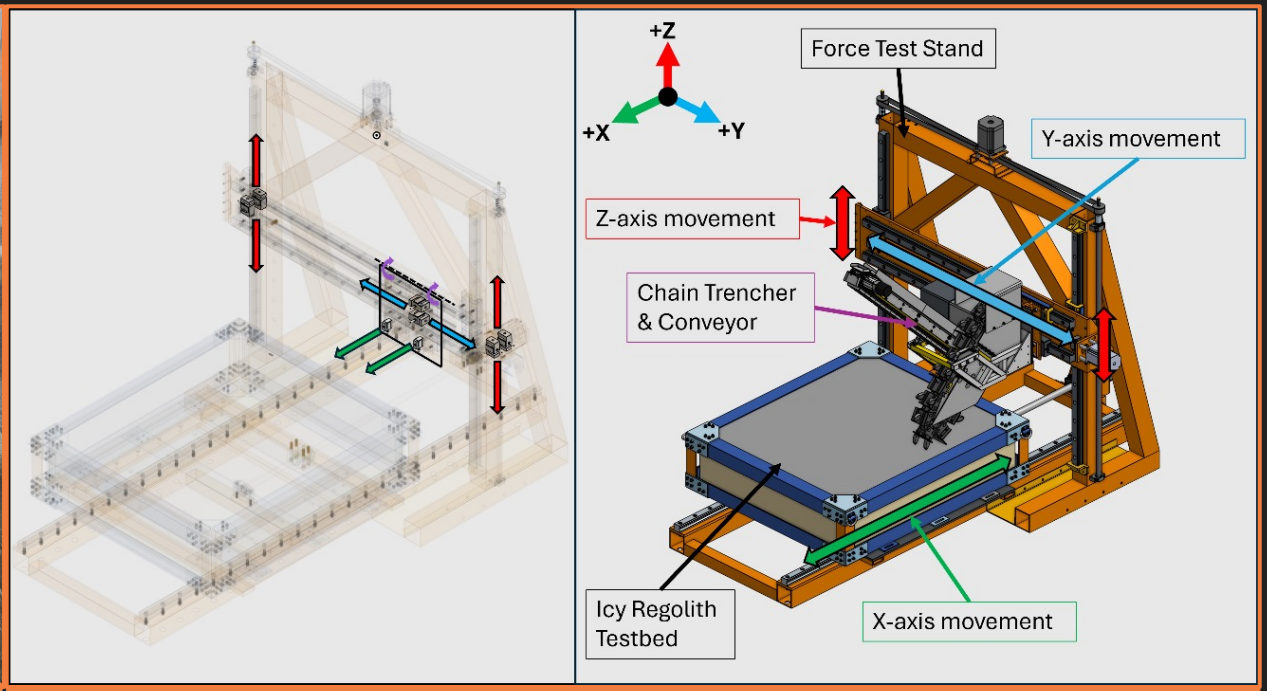
System Information

- Modular test facility that measures reaction forces and power data from excavators.
- Operates in subzero temperatures inside walk-in freezer.

FTS and operators prior to test with chain trencher [1].

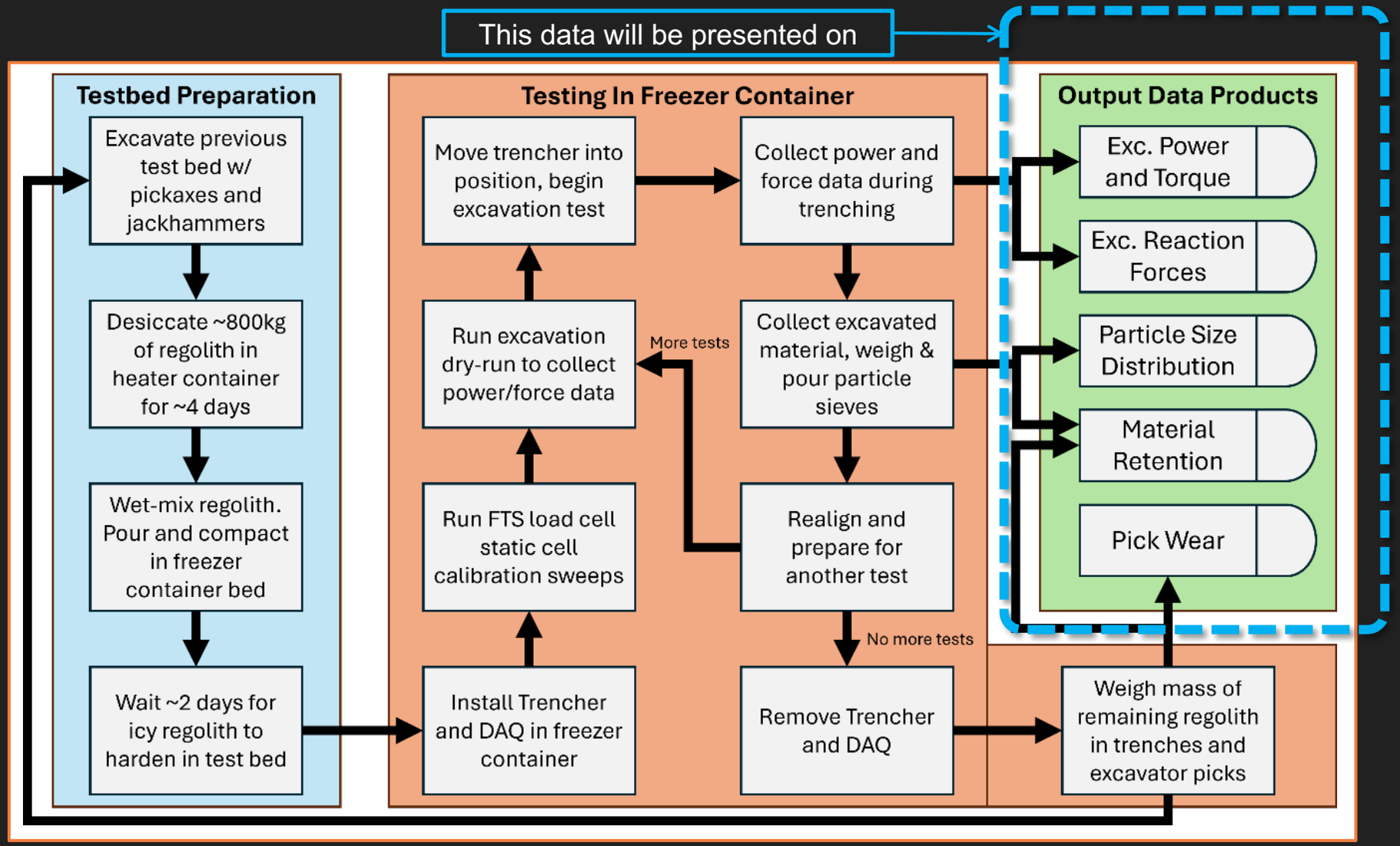


CAD drawings showing load cell placement and coordinate axis.

Running Excavation Tests

Process Summary

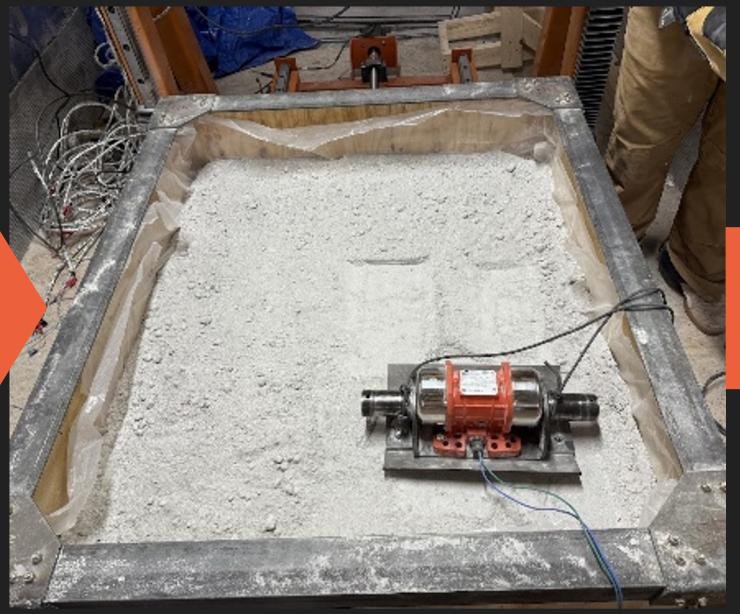
1. Prepare Testbed
2. Test In Freezer
3. Collect Data
4. Improve Procedure
5. Process Data
6. Extrapolate to BTIL mission scenario



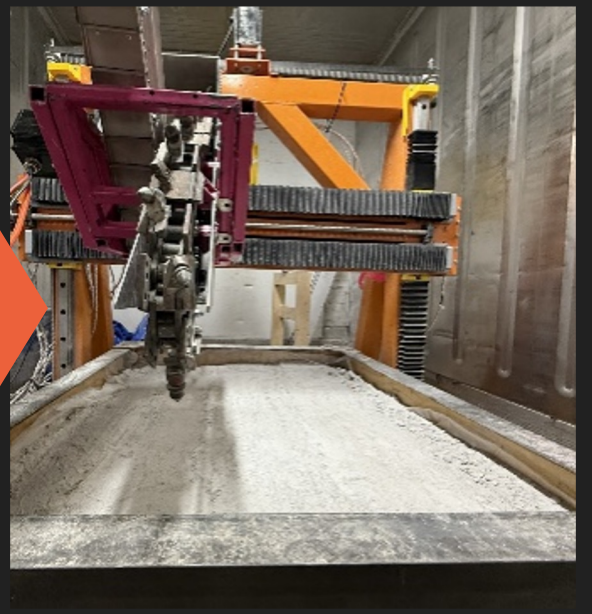
FTS Regolith Bed Preparation

Desiccate regolith in heater container

Mix with liquid water matching target ice % level



Pour wet regolith into layers and compact to target height. Corresponding to desired bulk density with plate compactor.



Allow two days for regolith to harden at -12 to -15C.

UCS of Icy Regolith Simulant

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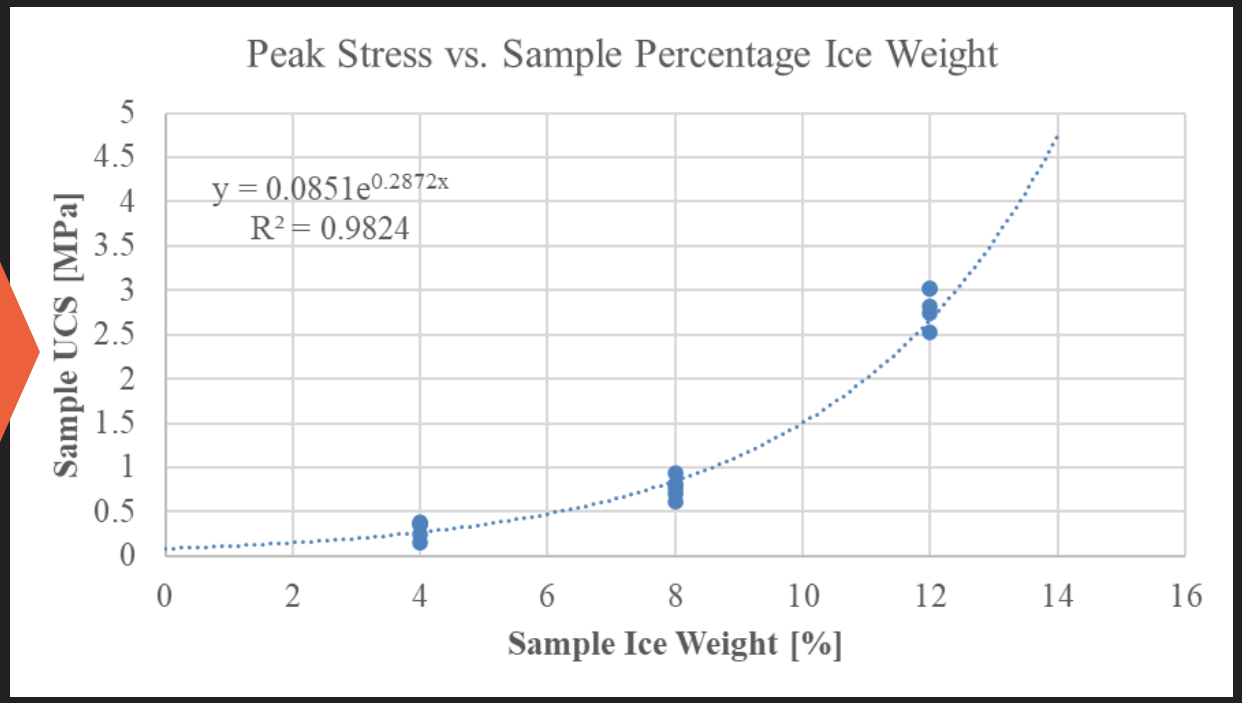
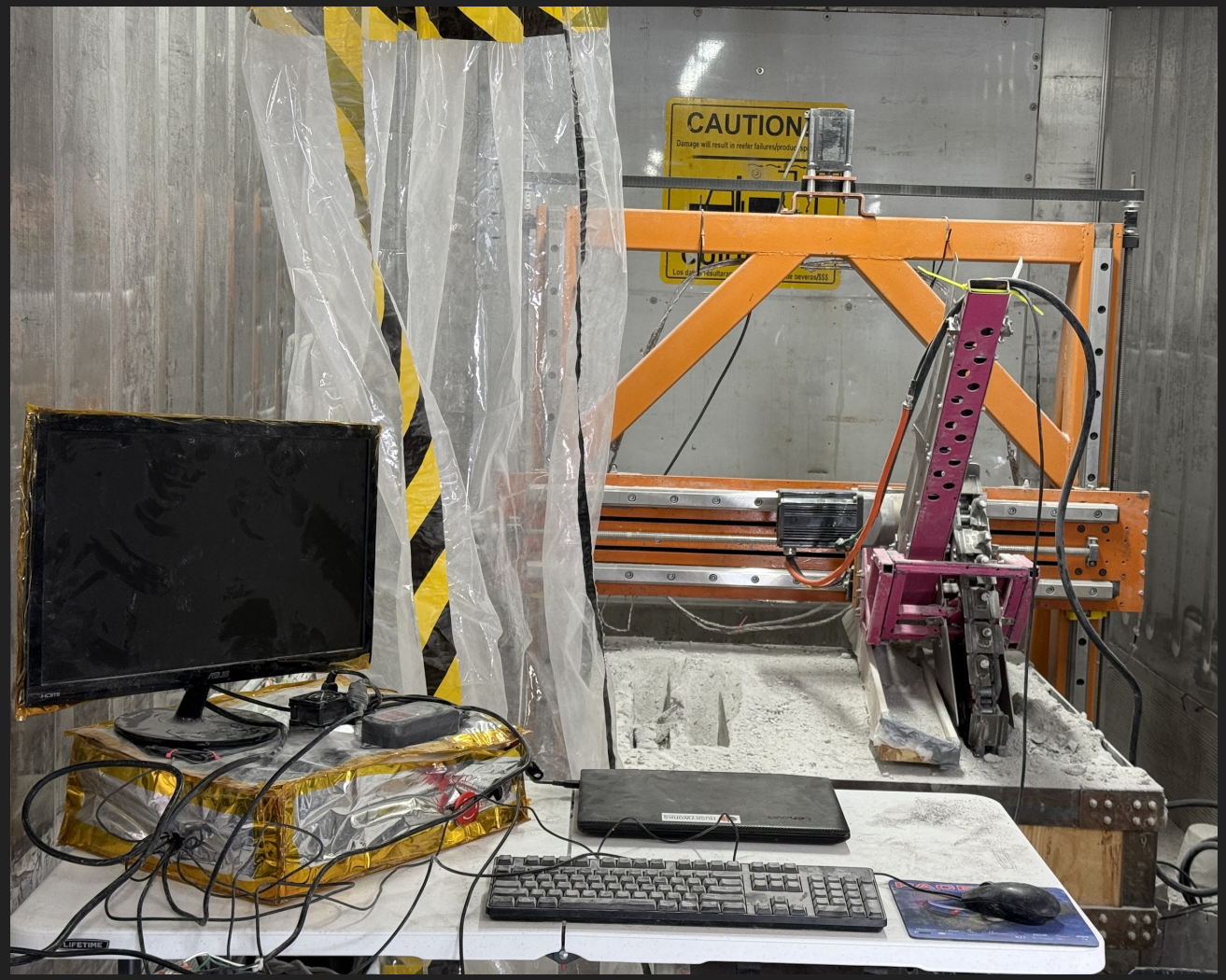
System Information

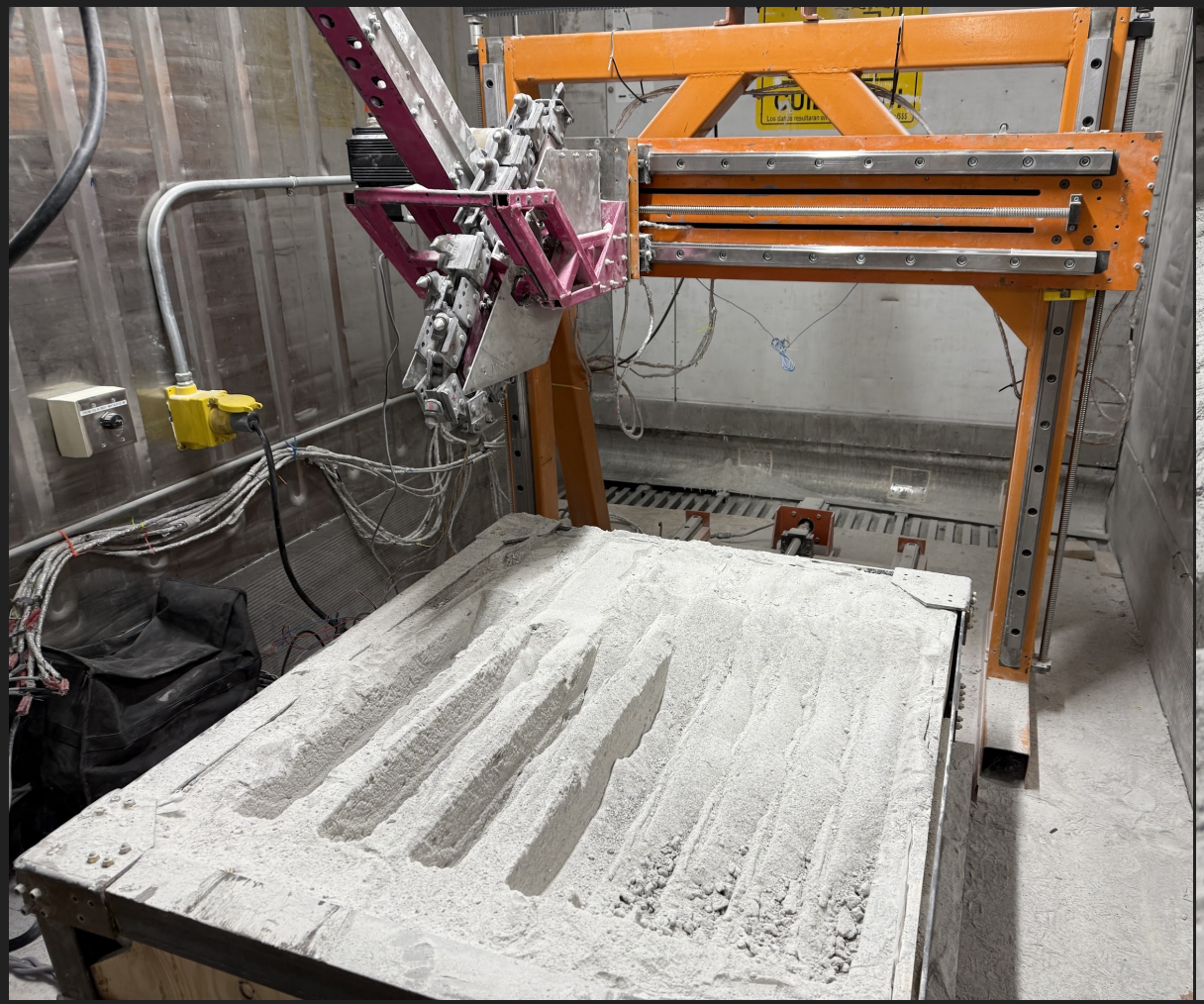
- Made cylinders of cemented MTU-LTH-1A, compacted same way as FTS bed. Varied ice content.
- Compressed cylinders following standard for CLSM UCS testing.
- Found strong exponential correlation between UCS and ice content.



Running Excavation Tests: Before & During



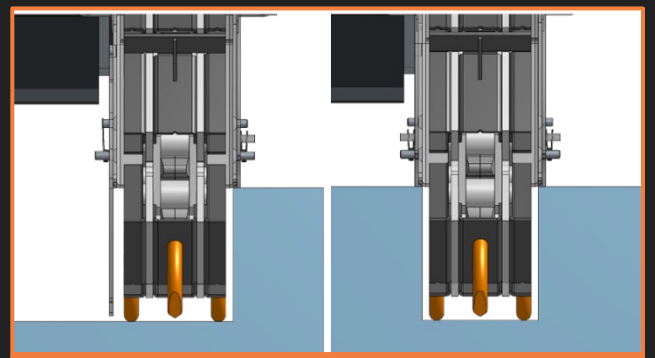
Running Excavation Tests: Post-Dig



Results: Force and Power Data (1)

Key Findings

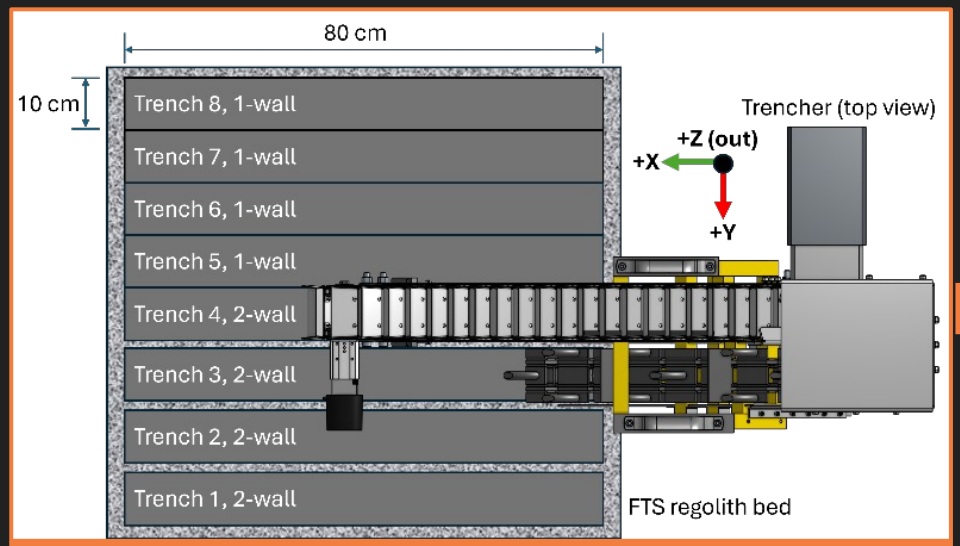
- Explored effect of wall cut type and trencher speed on motor torque/power and forces.
- No statistically different findings for force.
- Ice content is strong predictor for power use.



One-wall (left), two wall (right)

Table: average forces across all trenches in test 5, 4% ice.

F_x	F_y	F_z
70.83	27.4	74.65



Excavation plan. Descend in –Z, advance in +X 80

Trencher in test 5 making 1-wall cuts

Fully excavated regolith bed

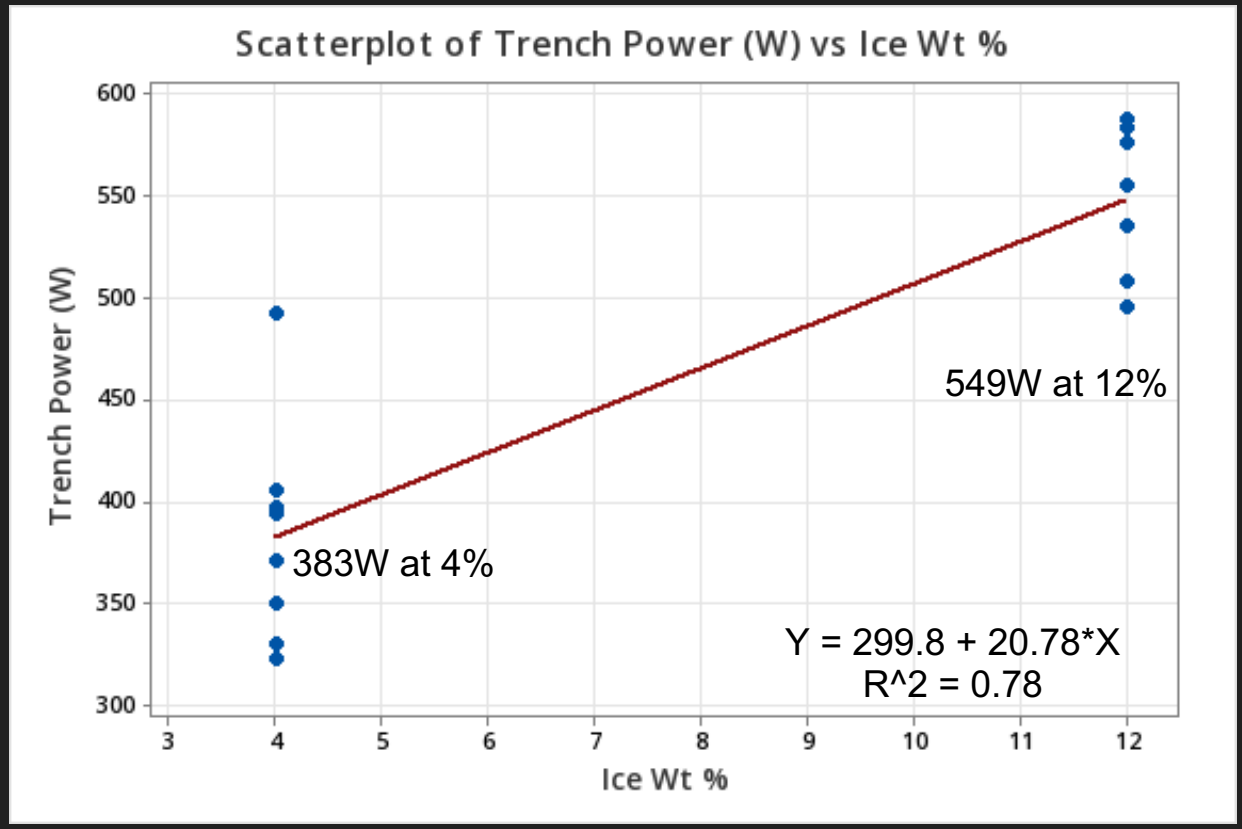
Results: Force and Power Data (2)

Key Findings

- Explored effect of wall cut type and trencher speed on motor torque/power and forces.
- No statistically different findings for force.
- Ice content is strong predictor for power use.

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Ice Wt %	1	80831	80831	32.28	0.000
Trench Speed (mm/m)	2	2080	1040	0.42	0.671
Walls	1	1938	1938	0.77	0.400
⊞ Error	10	25039	2504		
Total	14	131549			

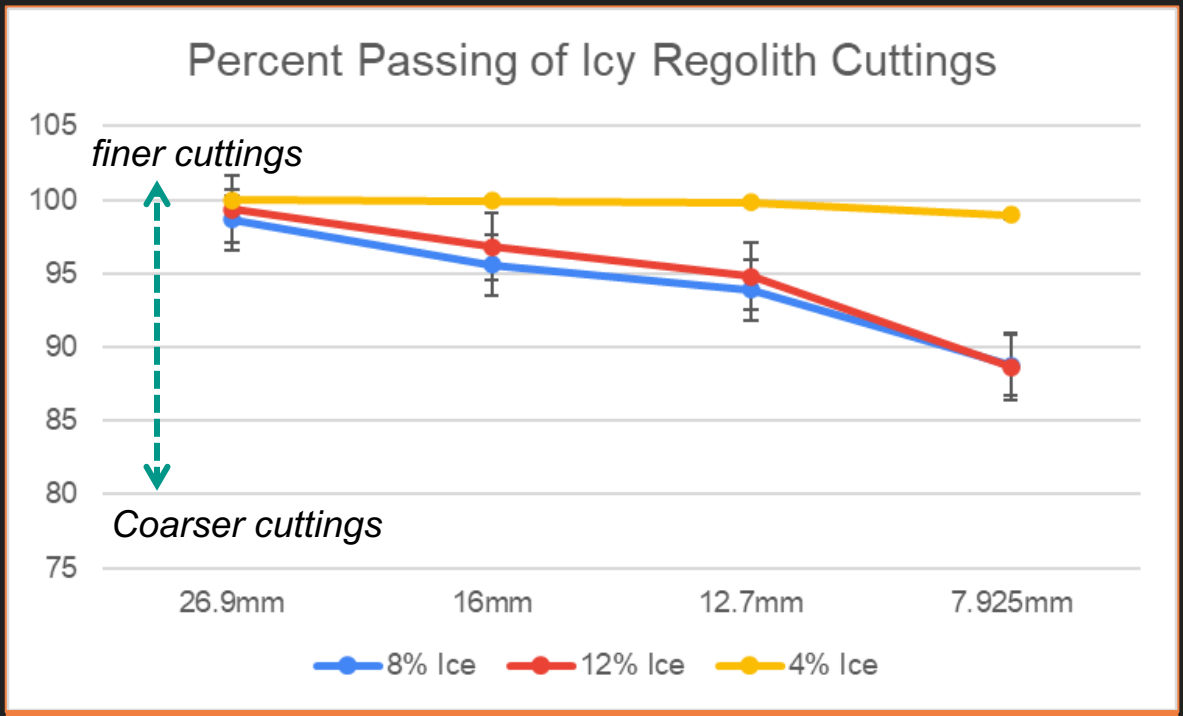


Results: Particle Size Distribution

Key Findings

- Particle sieved cuttings from each trench
- Ice content effects cutting size at low %'s.
- # of walls and trencher forward speed has no statistically significant impact on cutting size.
- Qualitatively: 12% has largest cuttings.

4%	8%	12%

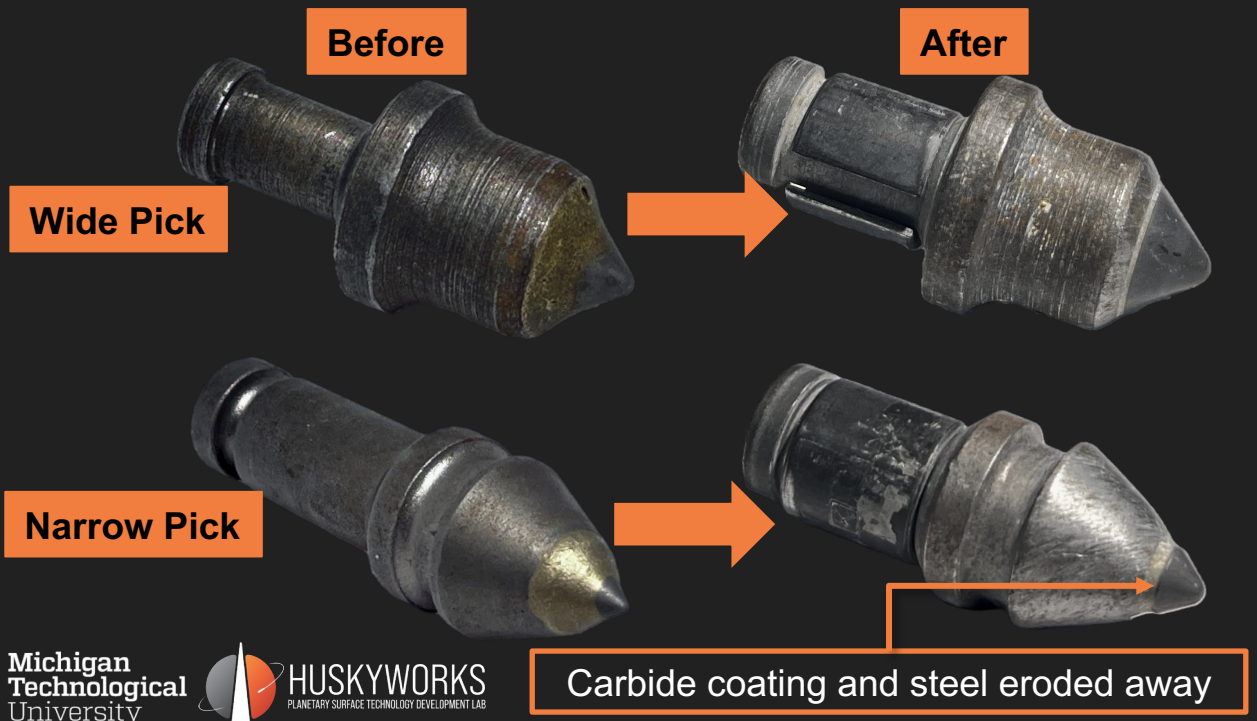


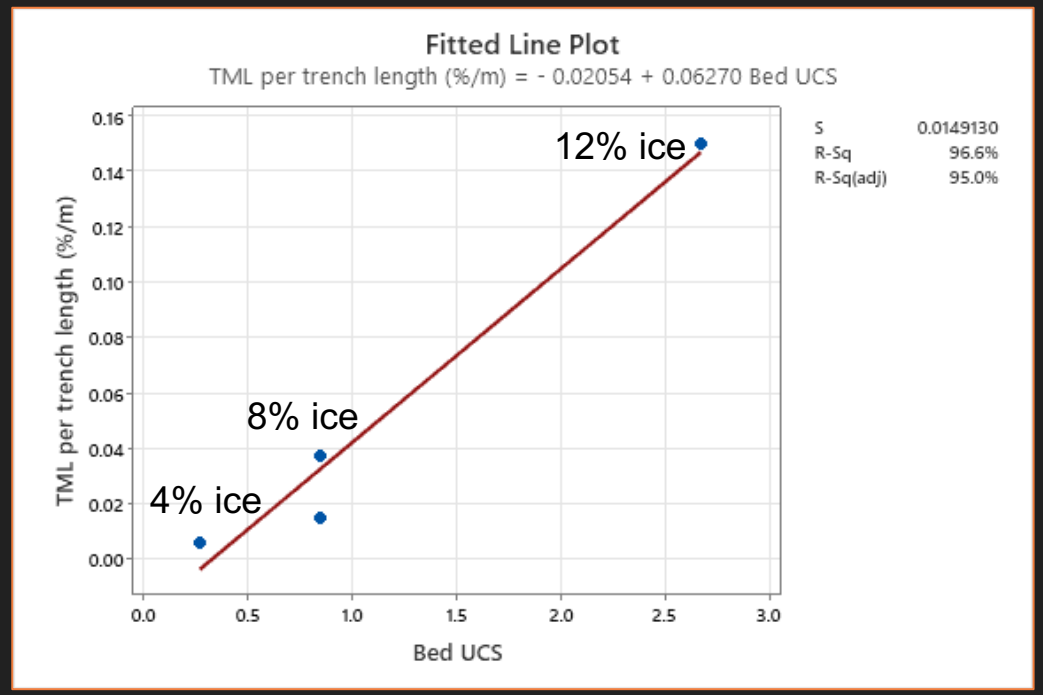
Percent passing graph shows how much regolith is smaller than sieve opening. Lower percent passing = coarser material

Results: Wear Data (1)

Key Findings

- Measured change in mass per pick with scale
- Total mass loss per length of cut trench has strong linear correlation to bed UCS.
- Wear rate dramatically increases beyond 8%





Picks and linkages coatings deposited on regolith

Results: Wear Data (2)

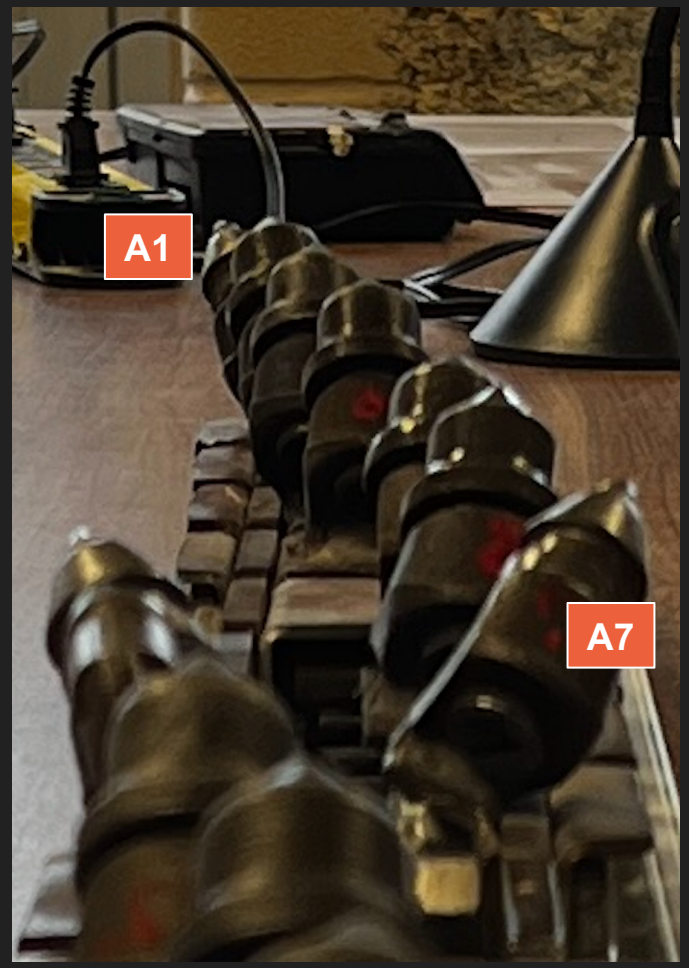


Figure: Close-in image of first 7 trencher picks

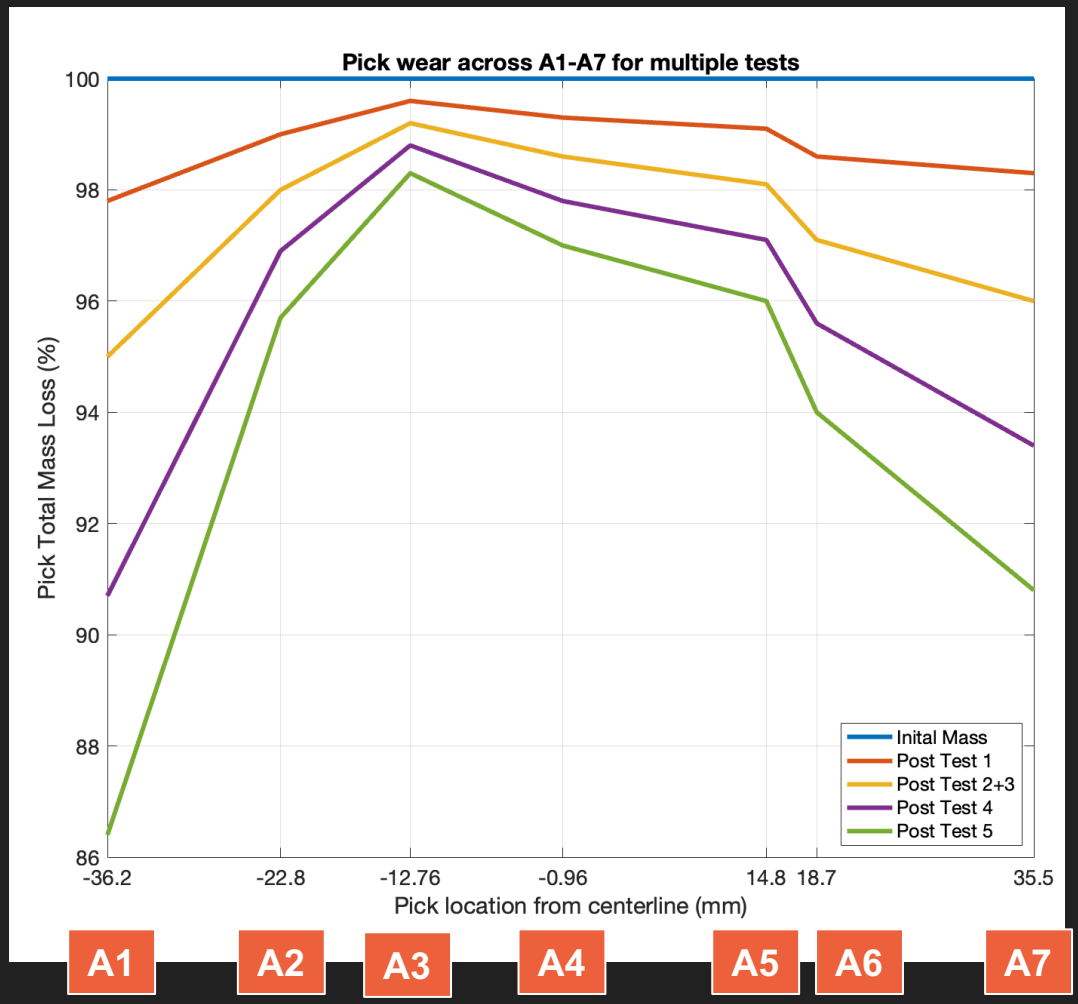


Figure: Wear pattern per test of first 7 picks on trencher chain in head-on view

Key Findings

- Trencher trended to wear more along the outside edges than center
- Generally, the further spaced the picks are, the more they wear.

Implications of Wear Data on BTIL Scenario

	Phase 2 Level 3 Competition Data	
Scenario:	10,000 kg	To 1 year
Time to completion (days):	192	365
Mass of ice delivered (kg):	10,000	18,966
Excavation Energy Use (kW-hr):	1,268	2,405
Total landed mass (kg)*:	1,855	1,855
Ice mass delivered to landed mass (kg/kg):	5.39	10.22
Number of All-Pick Replacement Events:	n/a	
Mass of Replacement Picks (kg):	n/a	
Excavator Energy used to Ice Mass Production Ratio (kW-hr/kg):	0.13	

This table is the extrapolated performance of the PSTDL's PRIMROSE rover from Break the Ice

Implications of Wear Data on BTIL Scenario

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These two new columns are the same data but now account for pick wear rate and replacement events

	Phase 2 Level 3 Competition Data		FTS 4% Icy Regolith at Avg Dig Speed Data		FTS 12% Icy Regolith at Avg. Dig Speed Data	
Scenario:	10,000 kg	To 1 year	10,000 kg	To 1 year	10,000 kg	To 1 year
Time to completion (days):	192	365	300	365	96	365
Mass of ice delivered (kg):	10,000	18,966	10,000	12,161	10,000	38,111
Excavation Energy Use (kW-hr):	1,268	2,405	2119	2576	917	3496
Total landed mass (kg)*:	1,855	1,855	1,867.58	1869.87	1917.92	2092.95
Ice mass delivered to landed mass (kg/kg):	5.39	10.22	5.39	6.56	5.39	20.54
Number of All-Pick Replacement Events:	n/a		11	13	55	208
Mass of Replacement Picks (kg):	n/a		12.58	14.87	62.92	237.95
Excavator Energy used to Ice Mass Production Ratio (kW-hr/kg):	0.13		0.21		0.09	

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Implications of Wear Data on BTIL Scenario

SPACE RESOURCES ROUNDTABLE

- Ice content & more realistic test environment changes the BTIL scenario duration by +/- 50%

- Excavating harder regolith quickly increases pick consumption
- Assumes replacement at 20% TML

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Summary of Findings & Path Forward

Key Findings

Wear

- Uneven spacing leads to uneven wear: edges wear faster than center.
- Pick wear rate increased by an order of magnitude from 4% to 12% ice content in cemented regolith.

Force & Power

- Average power to excavate doubled between 4% and 12% ice content.
- Force data is still being processed; Working to improve SNR.

PRIMROSE Rover Performance

- We find that there is no significant difference to the PRIMROSE rover ConOps when accounting for higher fidelity excavation testing results.

Path Forward

- Conduct single pick testing to get cleaner force data.
- Better account for human factors when doing this type of testing; accidentally made an analog astronaut experiment.