Vibratory Plate Compaction of BP-1 & LHS-1 Utilizing the Planetary Automated Compaction Tool (PACT)

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Space Resources Roundtable XXV

Colorado School of Mines, Golden, Colorado USA

MEERCAT / PACT Summary

- Designed to interface with a robotic arm
- Functionality tested at high vacuum conditions (approaching TRL 5/6)
- Con-ops for ISRU processing of regolith
- Con-ops for Site preparation and construction
- Capable of geotechnical research

Specifications All specs can scale to the mission.	
Mass	1 - 4 kg
Power	24 - 100W
Volume	4000 - 5500 cc
Sieve rate	10 - 40 g/s
Sieved Particle Size	≤ 1 mm pass
Regolith Capacity	0.5 - 3.5 kg per scoop

Multifunctional End Effector for Regolith Construction, Acquisition, and Transfer (MEERCAT) Construction Demonstration using PACT

MEERCAT

[1] E. Bell, et al. "Multifunctional End Effector for Regolith Construction, Acquisition, and Transfer (MEERCAT)," in ASCE Earth and Space, Miami, 2024.

PACT Testing In-Vac & Ambient

- In 2023 testing was performed at medium vacuum levels (1E-3 torr) within the ASSIST vacuum chamber. (ASSIST chamber info in [2])
  - Testing showed the system capable of achieving 82% relative density (RD) in Exolith's Lunar Highlands Simulant 1 (LHS-1)
- 2024 testing included testing under ambient conditions in Black Point 1 (BP-1) to improve the understanding of various compaction parameters and additional testing was done in LHS-1 in ambient to correlate in-vac testing to ambient testing results.
- Planned 2025 testing includes testing in high vacuum conditions with optimized parameters and an improved TRL 5 design.

Previous vacuum testing in ASSIST (proprietary accessory hardware redacted)

[2] G. J. Nathan, et al. "Development of the Advanced Regolith Ground Operations (ARGO) Test Bed - A Robotic Excavation and Construction Test Facility with Simulated Lunar Environments," in ASCEND, Las Vegas, NV, 2023.

PACT Ambient Testing

This presentation is a summary!

For the full story please check out NASA TM-20250005172 on the NASA Technical Reporting Server (NTRS)

https://ntrs.nasa.gov/citations/20250005172

NASA/TM-20250005172

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Utilizing the Planetary Automated Compaction Tool (PACT)

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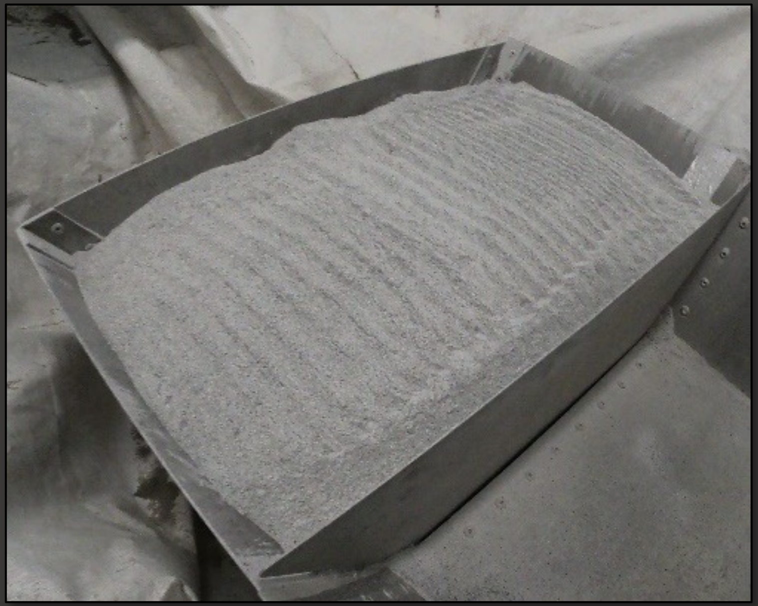
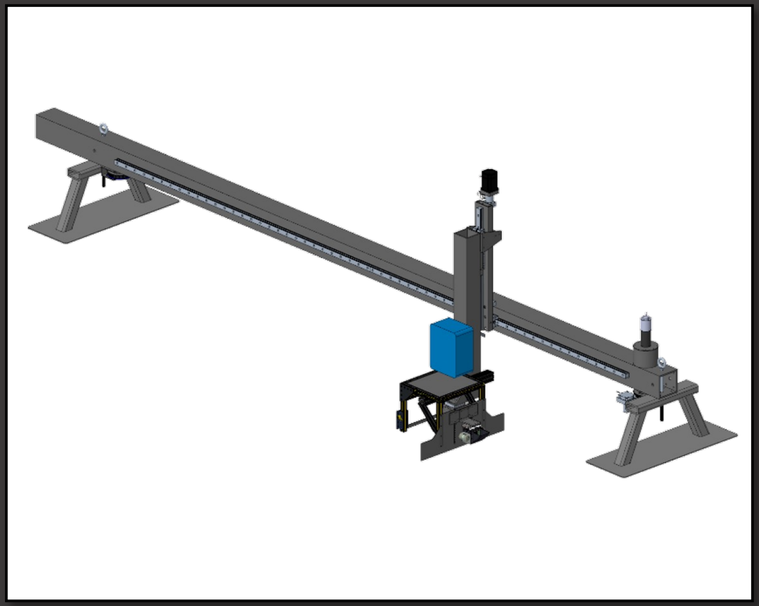
PACT Ambient Testing

- Testing occurred at KSC Swamp Works in the BP-1 Big Bin and in a smaller LHS-1 using a 2-axis gantry system

BP-1 Bin (aka Big Bin) at the KSC Swamp Works Granular Mechanics and Regolith Operations (GMRO) Lab.

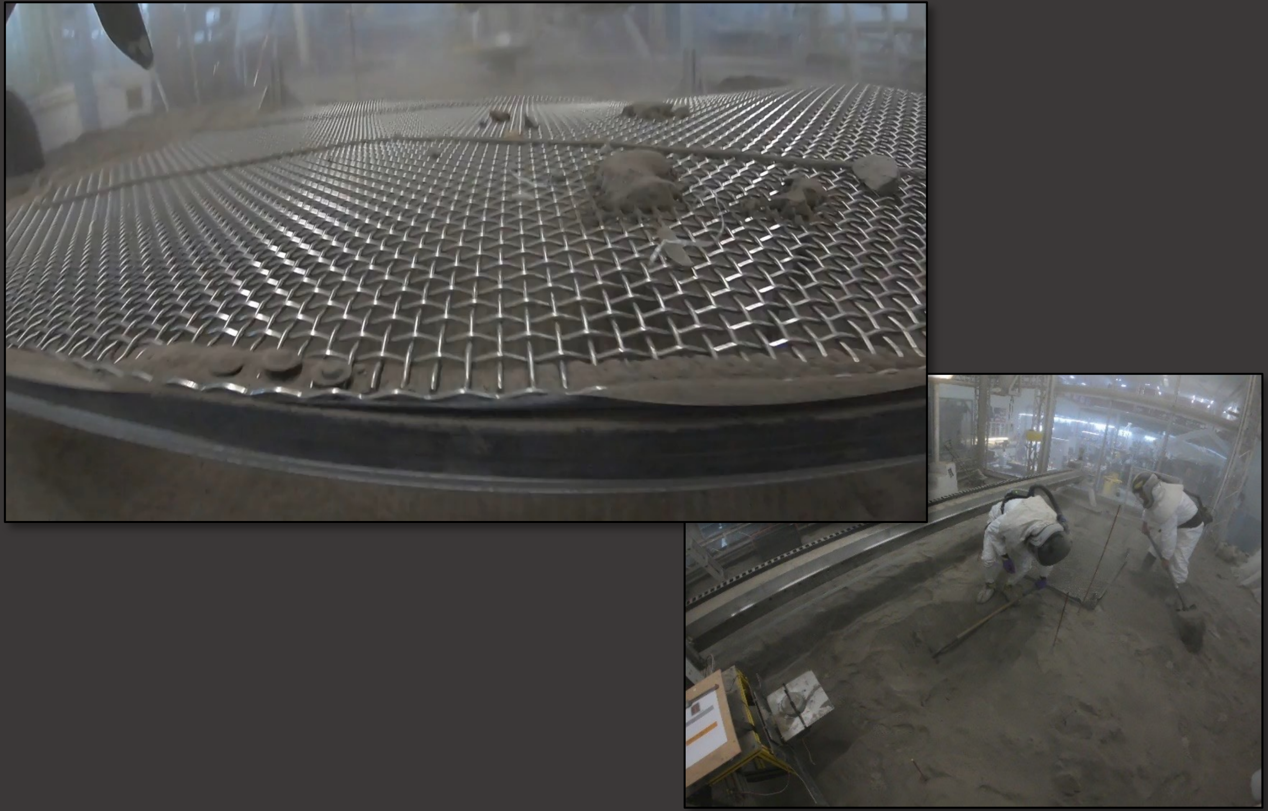


LHS-1 bin.
The bin was placed below the gantry



2-axis gantry with plate compaction assembly

Ambient Test Setup

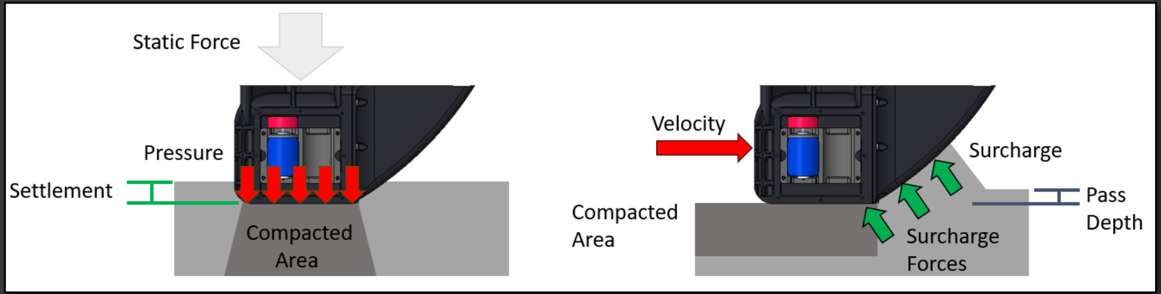


0.3 m deep pits were excavated (right) and filled via pouring simulant through a 1 cm hole size mesh screen (left). Surface was lightly raked smooth then graded flat to the compactor using a grader blade on the test stand achieving a bulk surface density of 1.55 g/cm^3 (57% RD)

Compaction test configuration on the 2-axis gantry.

Compaction Parameters

- Performed 21 unique test variations over 36 test runs
  - 30 spot motions
  - 6 raster motions (each test produces 4 data collection regions)
- Testing collected core samples, pocket penetrometer readings, and cone penetrometer measurements

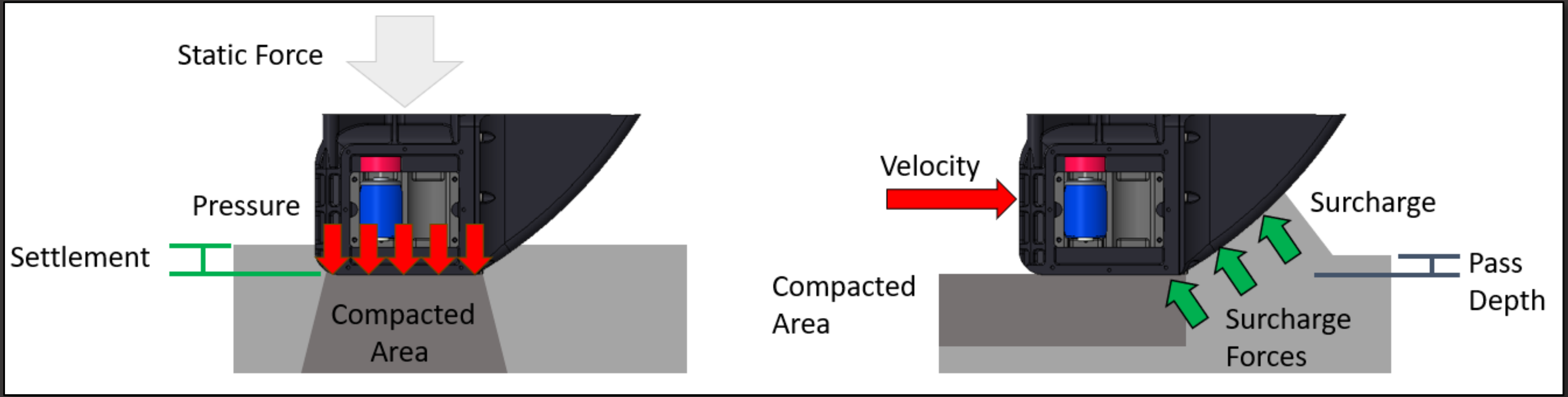


Spot compaction (left) and raster compaction (right) motion methodologies

Test Parameter	Tested Values
Compaction Motion	Spot, Raster
Static Compaction Pressure (Spot Compaction Only)	7, 70 kPa
Pass Depth (Raster Compaction Only)	1 mm, 5 mm
Vibratory Frequency	0, 45, 71 Hz (Dual-Mass Motor) 158 Hz (Single-Mass Motor)
Surface Contact Time	5, 8, 10, 30, 180 seconds (spot) 3.6, 6, 10 seconds (raster)
Simulant	BP-1, LHS-1
Initial Bulk Regolith Density (In percentage relative density)	59%RD (+/-3%RD)

Compaction Motions

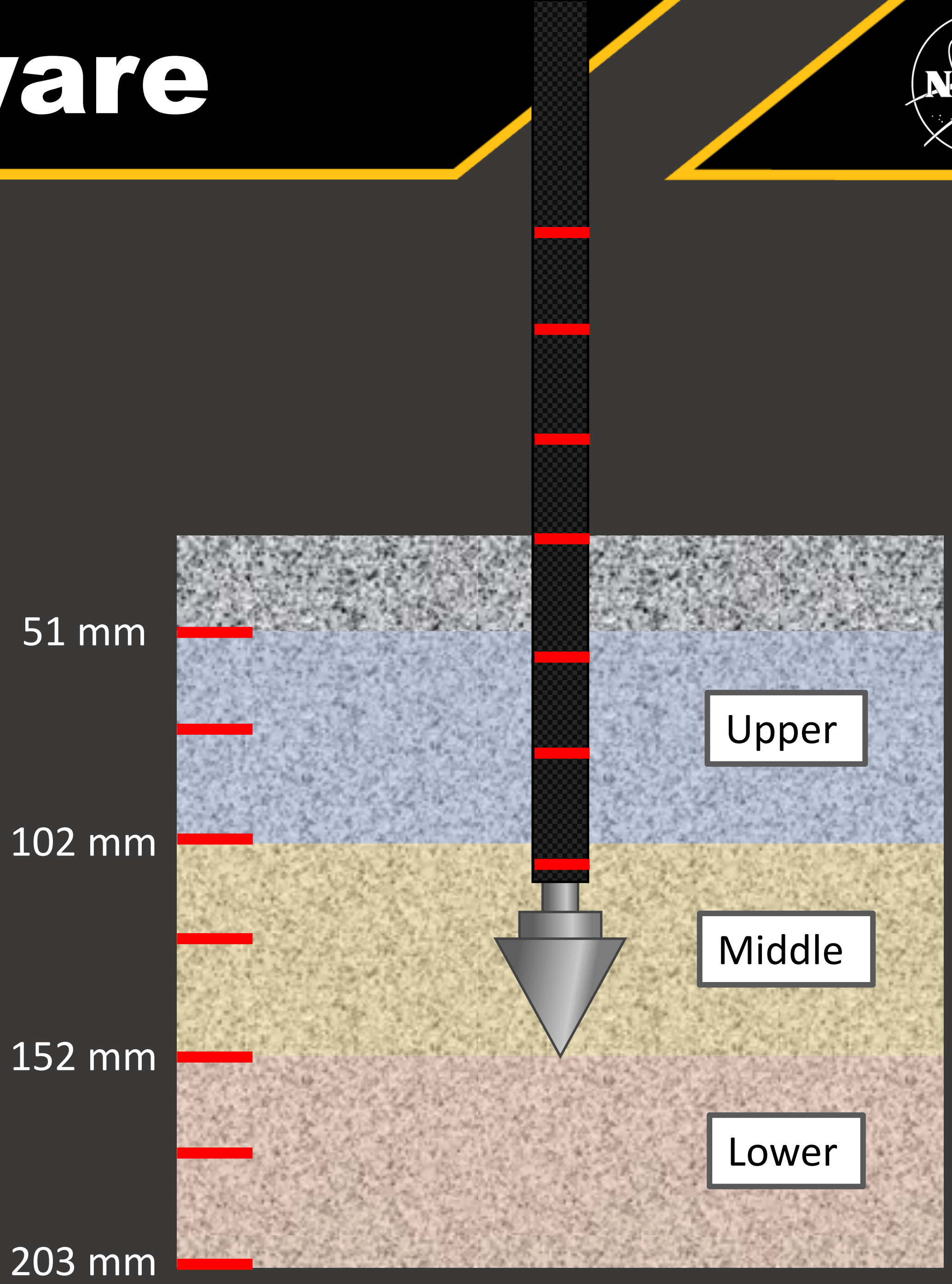
- Spot compaction motion
  - Apply a specified pressure to a location on the surface along with vibratory actuation applied
  - System sinks freely to maintain pressure
- Raster compaction motion
  - Plate compactor is placed a specified depth below surface grade and travels along the surface at a specified rate with vibratory actuation applied
  - Surcharge is created and pushed along by the compactor



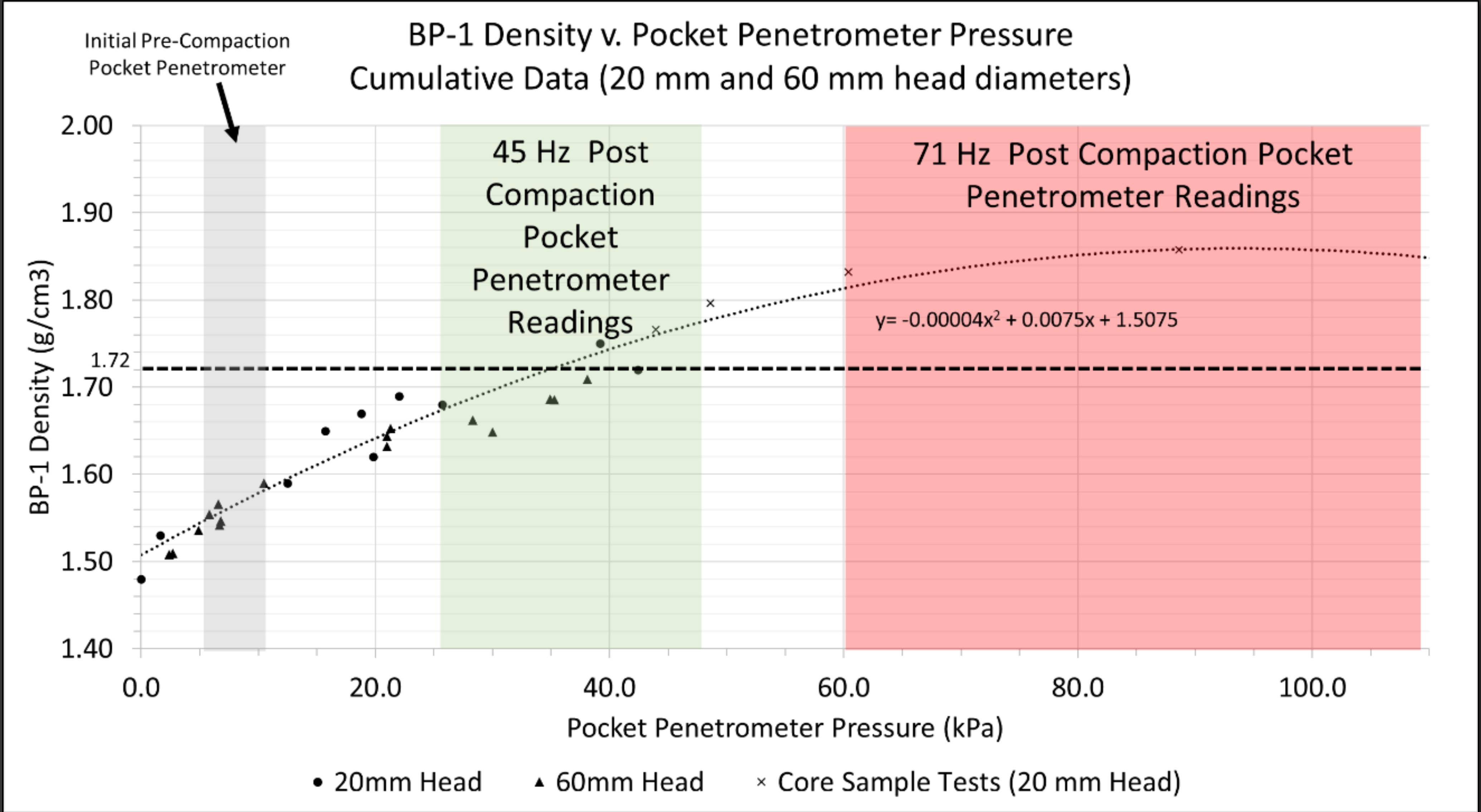
Spot compaction (left) and raster compaction (right) motion methodologies

Measurement Hardware

- A correlation curve was developed to estimate surface bulk density by pocket penetrometer pressure reading
- Cone penetrometer readings of 7 regions were combined into 3 zones. Pre and post compaction cone readings were taken for relative comparisons.



Pocket Penetrometer Correlation Curve (BP-1)



Relative Density Methodology

- Relative Density calculated using method in ASTM D4254, 2016 [3]
- BP-1
  - ρ_{min} = 1.27 g/cm^3 using ASTM D4254 method A[4]
  - ρ_{max} = 1.86 g/cm^3 using the Kolbuszewski dry method[5]
  - 80% relative density correlates to 1.70 g/cm^3
- LHS-1
  - ρ_{min} = 1.27 g/cm^3 using ASTM D4254 method C[6]
  - ρ_{max} = 1.86 g/cm^3 using a mechanical tapping method[6]
  - 80% RD correlates to 1.70 g/cm^3

$$\rho_R = \left(\frac{\rho_{max}}{\rho} x \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}}\right) x100\%$$

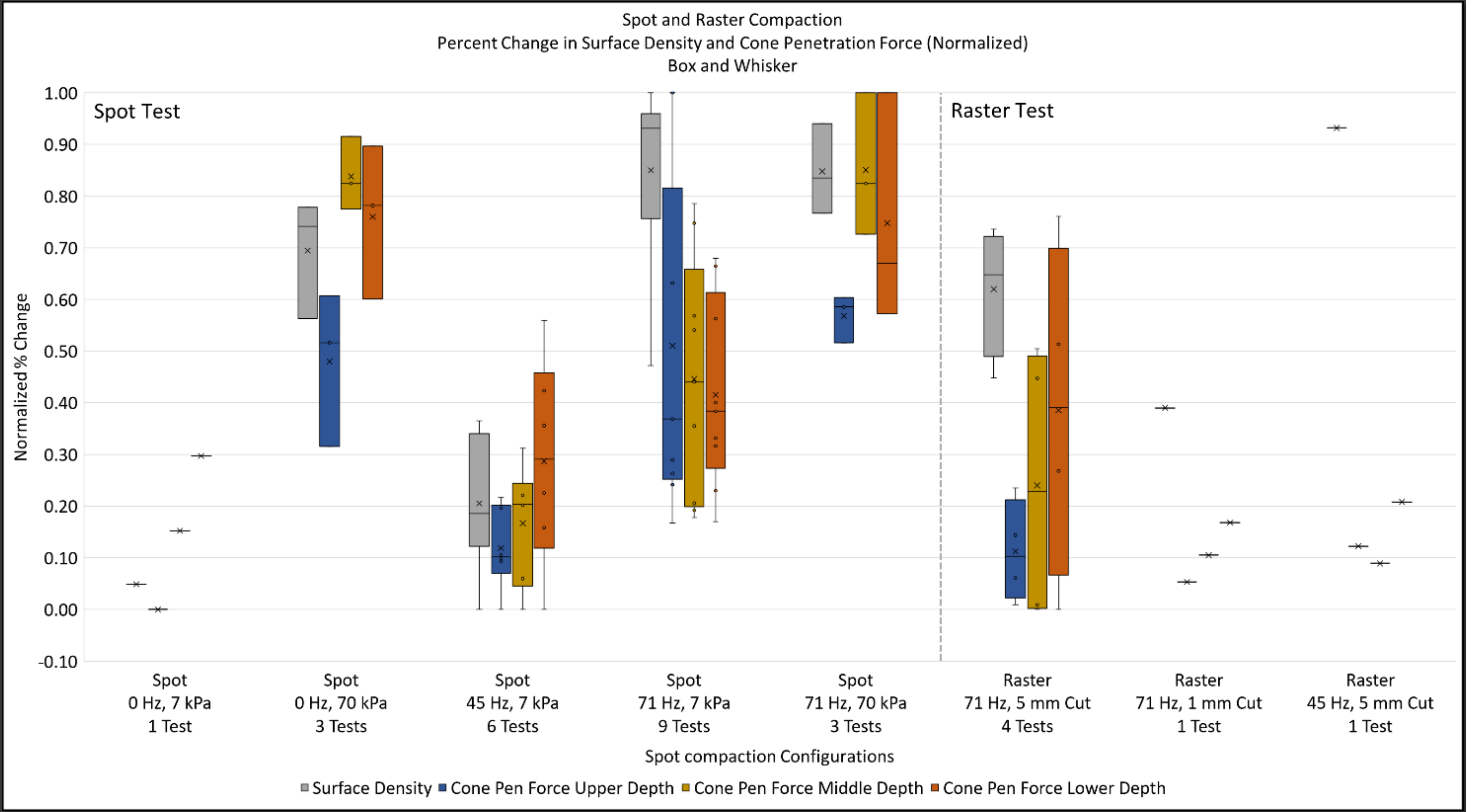
[3] ASTM Standard D4254, Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density, West Conshohocken, PA: ASTM International, 2016.

[4] E. Suescun-Florez, S. Roslyakov, M. Iskander and M. Baamer, "Geotechnical Properties of BP-1 Lunar Regolith Simulant," Journal of Aerospace Engineering, vol. 28, no. 5, p. 04014124, 2015.

[5] J. J. Kolbuszewski, "An Experimental Study of the Maximum and Minimum Porosities of Sands," in International Conference on Soil Mechanics and Foundation Engineering Vol. 1., Gebr, Keesmaat, Haarlem, The Netherlands, 1948.

[6] J. M. Long-Fox, Z. A. Landsman, P. B. Easter, C. A. Millwater and D. T. Britt, "Geomechanical Properties of Lunar Regolith Simulants LHS-1 and LMS-1," Advances in Space Research, vol. 71, no. 12, pp. 5400-5412, 2023.

Results: Normalized Comparison



Results: Compaction Times

- Times over 10-30s did not improve compaction for optimal compaction methodologies.
  - Compaction times could possibly even be reduced below 10s
- There may be some improvement for sub-optimal configurations

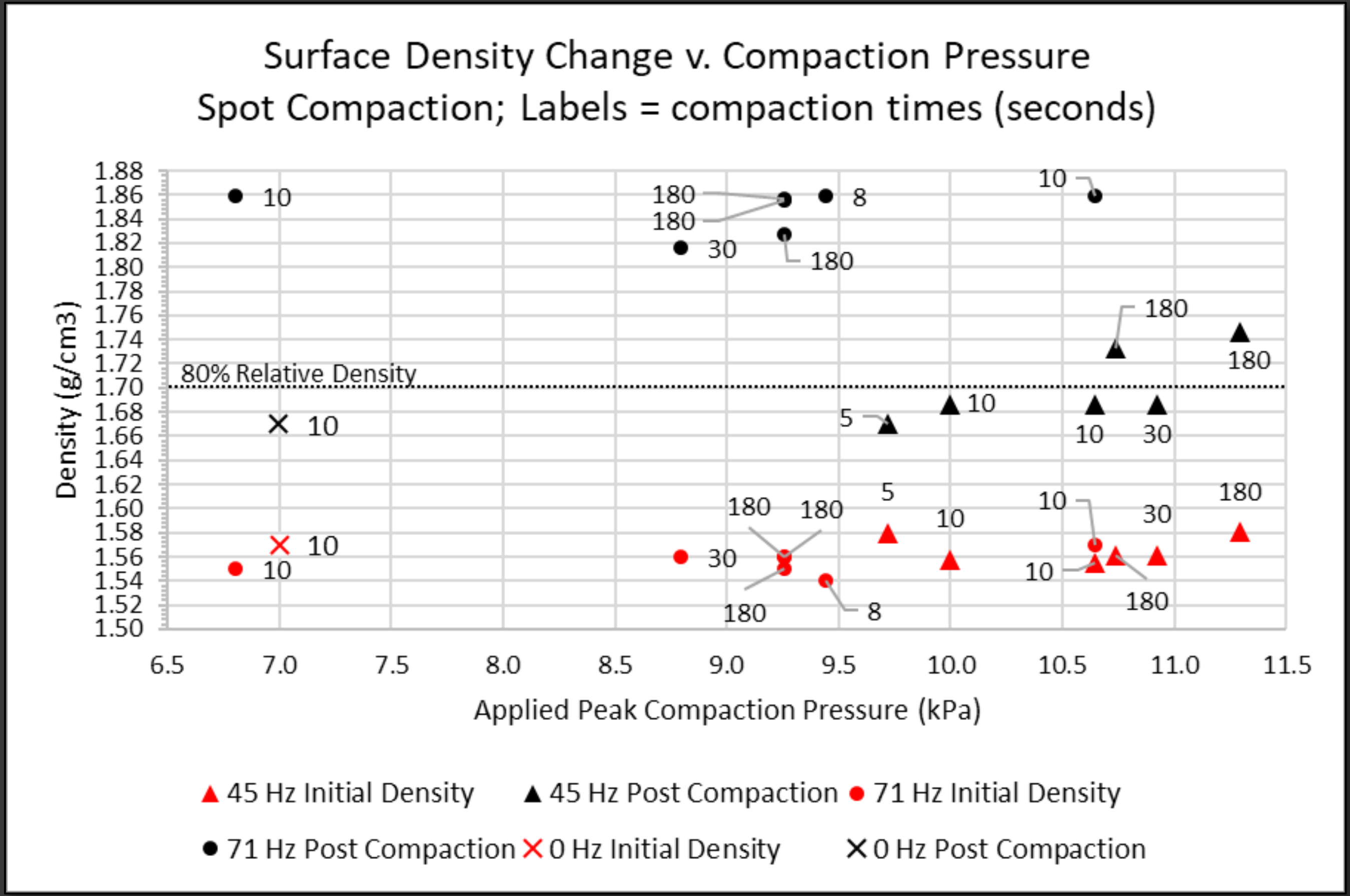


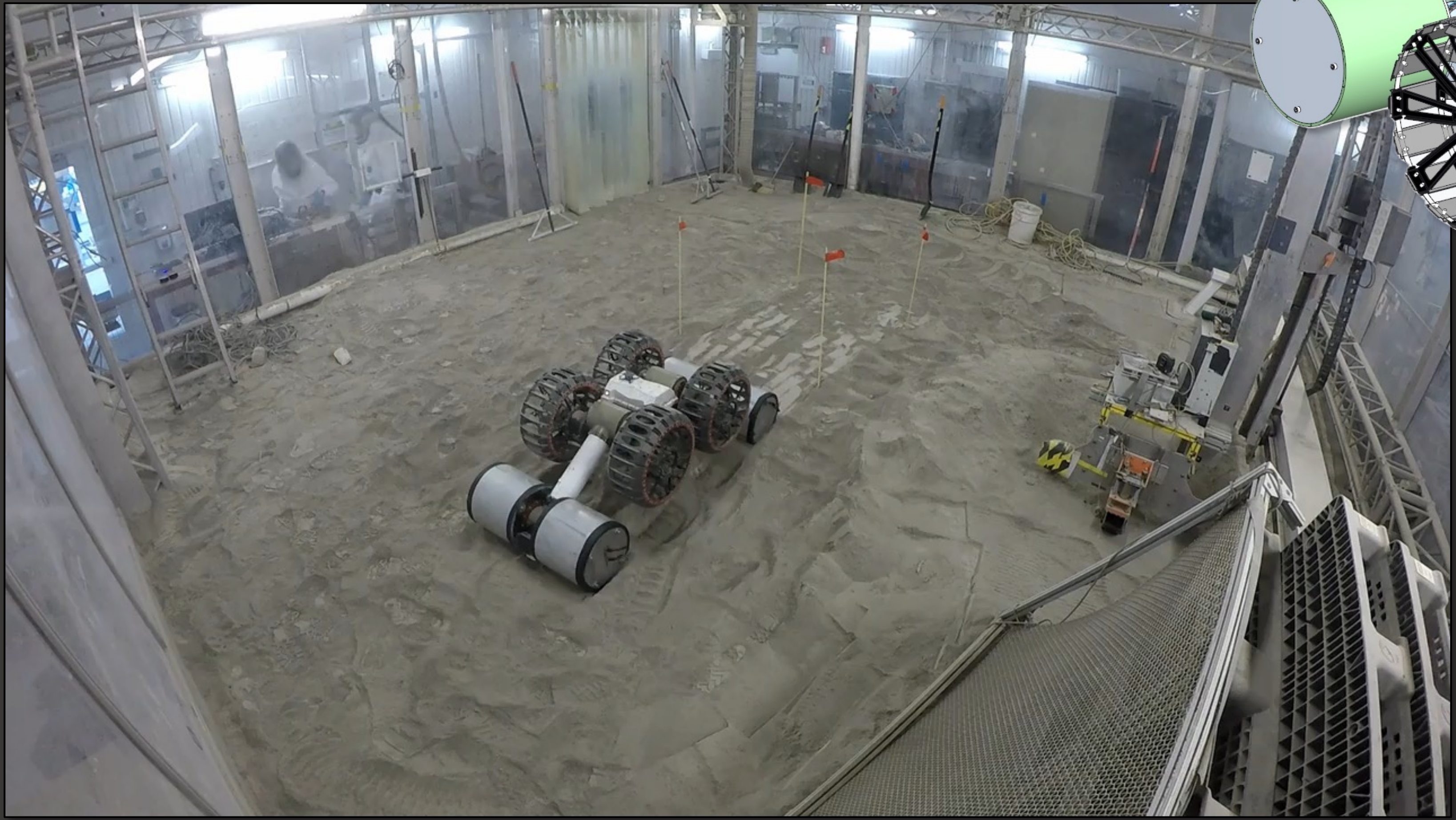
Plate Compaction Future Work

- Lunar gravity and in-situ lunar regolith may modify the performance of a plate compaction system.
- A system that allows for tuning of frequency, amplitude, and compaction pressure would reduce risk and allow for tailoring of a compactor system for a given application.
- KSC is developing an updated design with improved control authority over these critical functions
- TRL 5 testing of the system is planned for late-summer 2025.

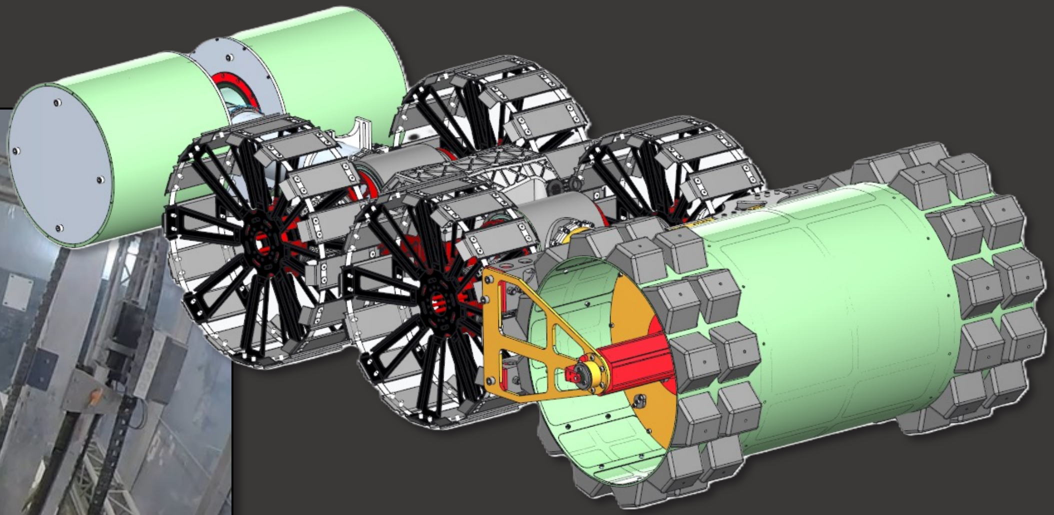
Lunar footprint

STOMP Roller Compactor

See the STOMP poster for more details



STOMP TRL 3 testing



STOMP TRL 4 design
Currently being assembled for testing late-summer 2025.