# Swamp Works Compaction Technologies

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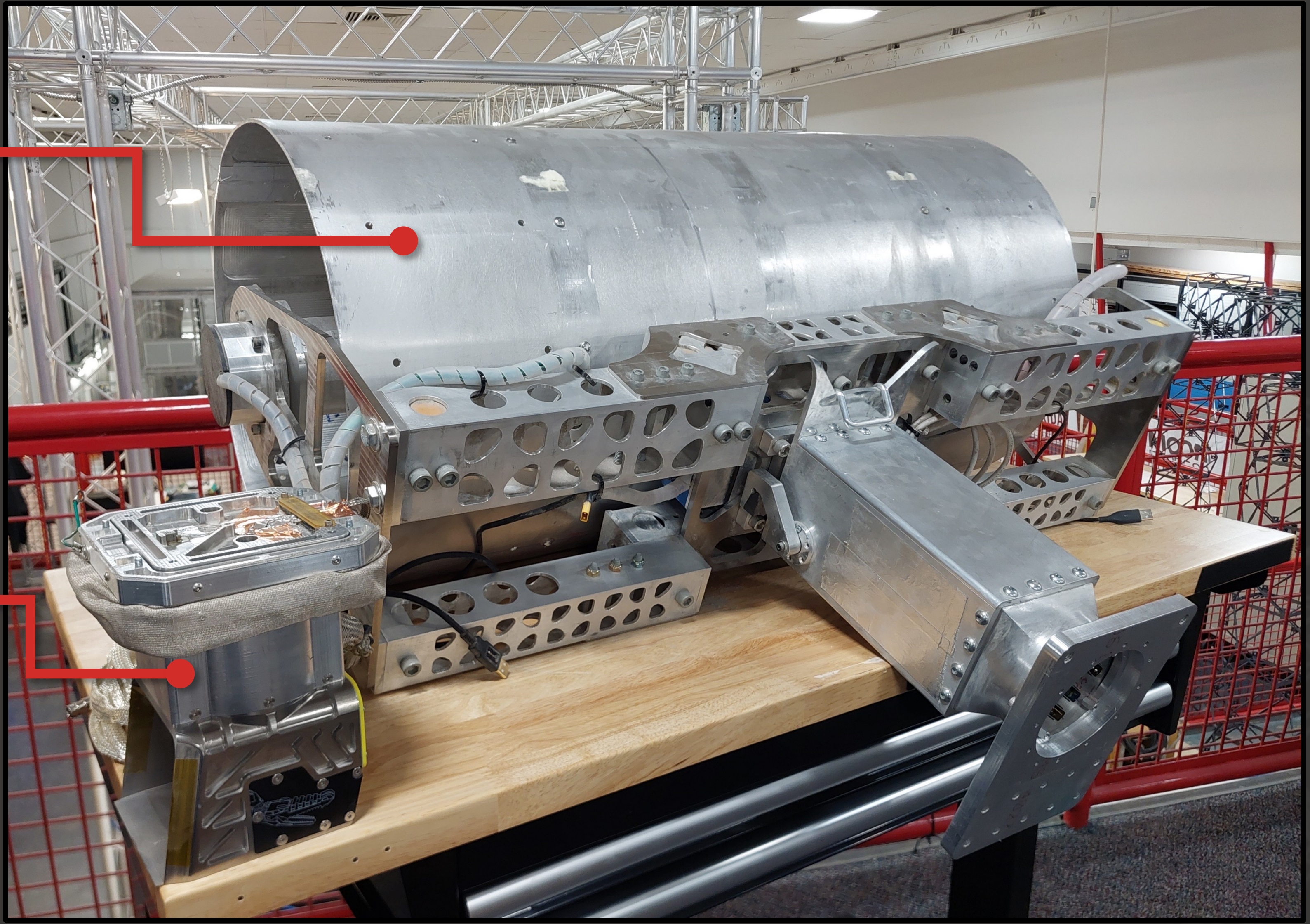
Space Resources Roundtable XXVI

Colorado School of Mines, Golden, Colorado USA

# Compaction Systems

STOMP
Vibratory Roller Compaction

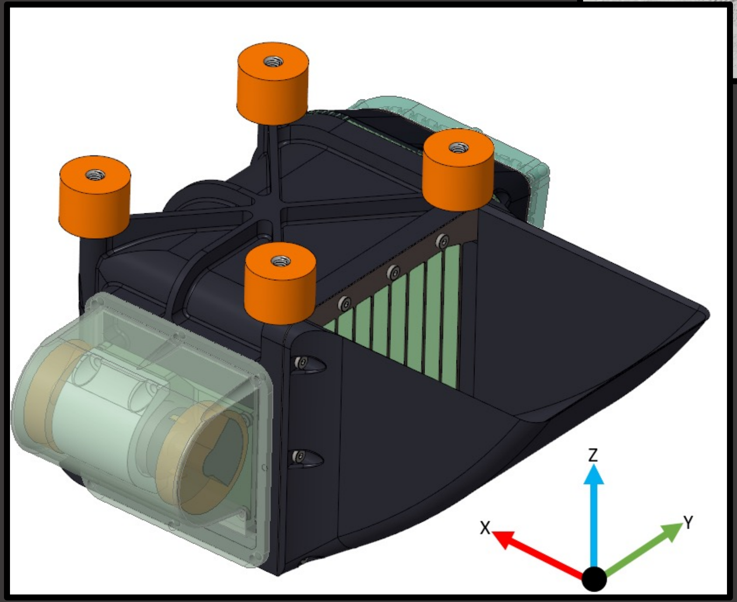
MEERCAT / PACT
*Vibratory and Tamping Plate Compaction*



# MEERCAT

## *Multifunctional End-Effector for Regolith Construction, Acquisition, and Transfer*

- Designed to interface with a robotic arm or gantry
- Functionality tested in TVAC
- Con-ops for ISRU processing of regolith
- Con-ops for Site preparation and construction
- Capable of geotechnical characterization
    - Bulk density
    - Angle of repose
    - Pressure-sinkage

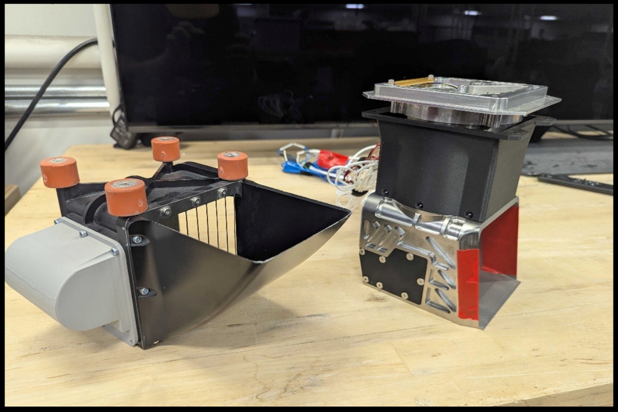



*[1] E. Bell, et al. "Multifunctional End Effector for Regolith Construction, Acquisition, and Transfer (MEERCAT)," in ASCE Earth and Space, Miami, 2024.*

*[2] E. Bell, et al. "Vibratory Plate Compaction of BP-1 and LHS-1 Utilizing the Planetary Automated Compaction Tool (PACT)," NTRS – NASA Technical Reports Server, 2025.*

# MEERCAT with PACT

- Previous design updated to support advanced compaction capabilities under the moniker “PACT” (Planetary Automated Compaction Tool) to meet needs of Redwire’s Mason Tipping point
- Independent control of
  - Frequency
  - Power
  - Amplitude
  - Static force output
- 1.25-micron linear optical encoder



*MEERCAT v1 (left) MEERCAT/PACT (right)*

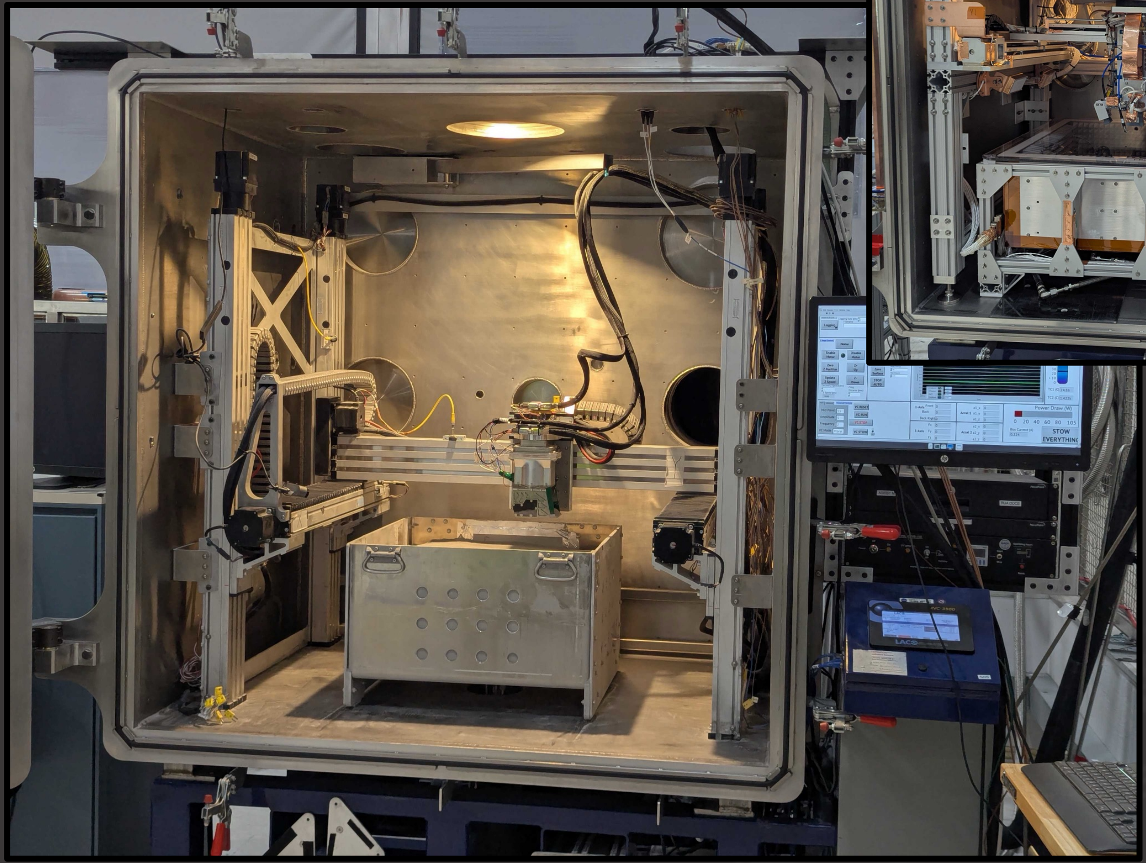

*MEERCAT/PACT on robotic arm*

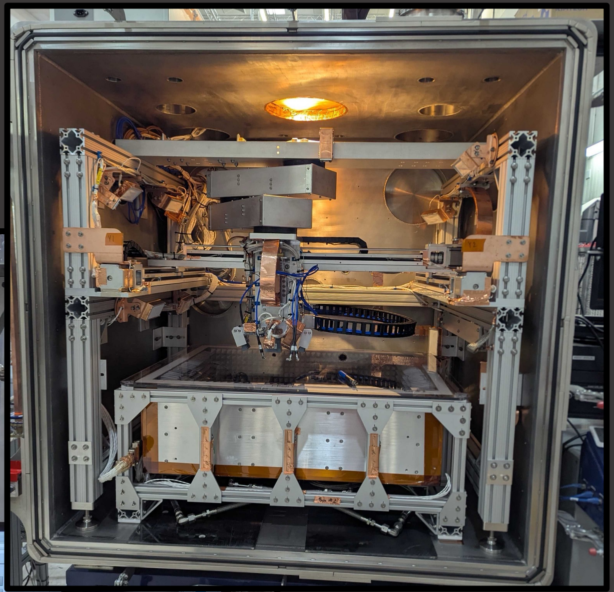
REDWIRE

| **Specifications (as of May 2026)**<br>*All specs can scale to the mission* | |
|---|---|
| Mass | 3.7 kg |
| Peak Power | 100 W |
| Sieve Rate | 2-3 kg/min |
| Regolith cap. | 1 kg per scoop |
| Compaction Capability | 80-120 % Relative density |
| Force Output | ≤100 N |
| Frequency | 0-1kHz |

# Environment and Bin Prep

- PACT Testing occurred in ASSIST TVAC Chamber
- Ambient Temperature
- 2 Setups
  - Compaction optimization
    - Simulant ICN-LHT-1G
  - Integrated with Redwire's M3LT (Microwave Melter of Martian and Lunar Terrain)
    - Simulant RDW-LHT-1G-h





[3] N. Gelino, 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.

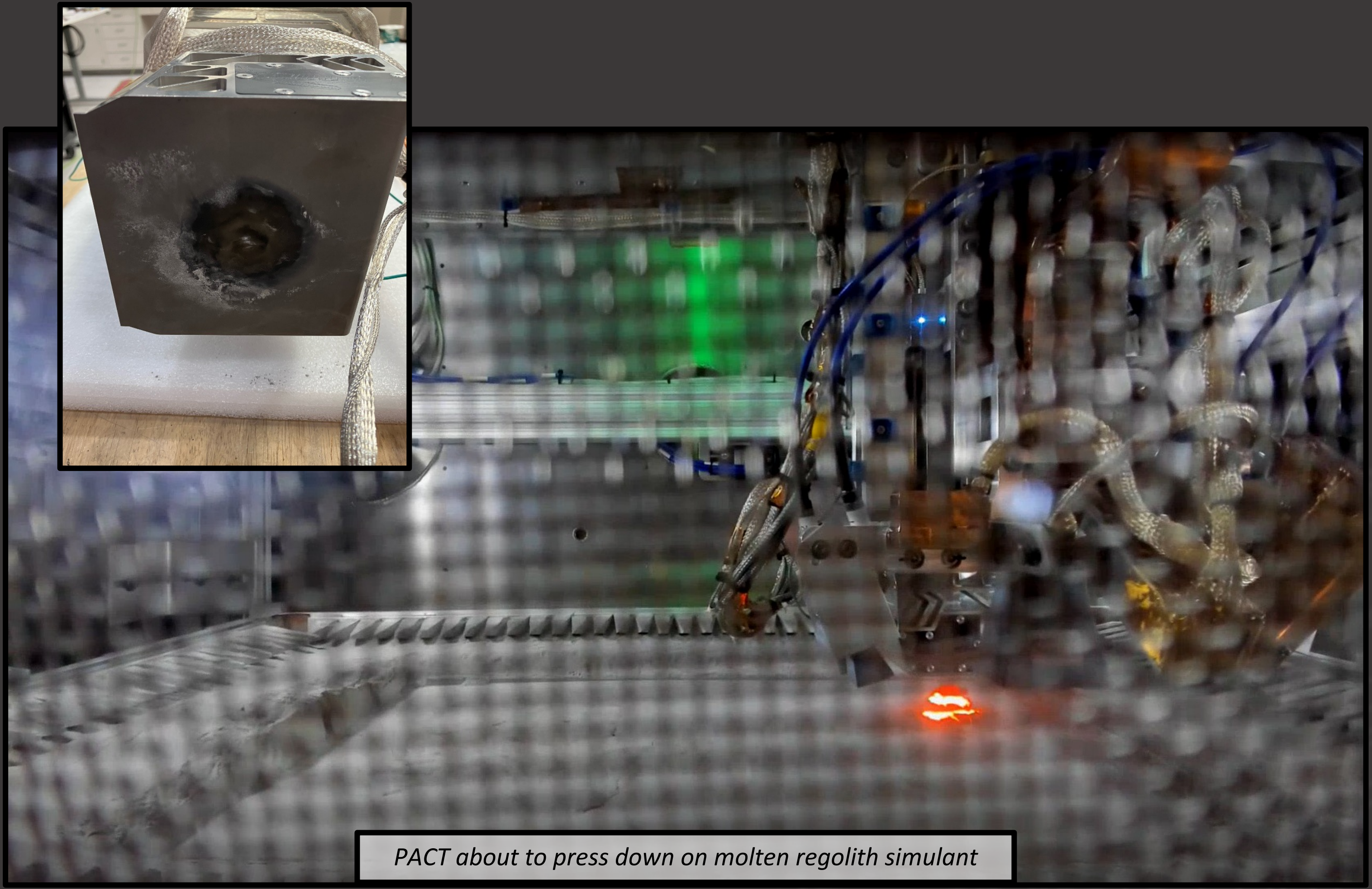
# PACT Compaction Process

- Simulants
  - ICN-LHT-1G
  - RDW-LHT-1G-h
  - Prepared uncompacted
- Vacuum conditions
  - “Medium” (~5.4 E-4)
  - High (3.5 to 9.8 E-5)

- 10 Hz Tamping
- 45 mm settlement target
- 0-10s dwell
- 0.2 $m^2$/hr. coverage
  *(includes gantry motion)*
- 100-155 $m^2$ /kWh eff.
  *(affected by dwell time)*

# Integration with Mason M3LT

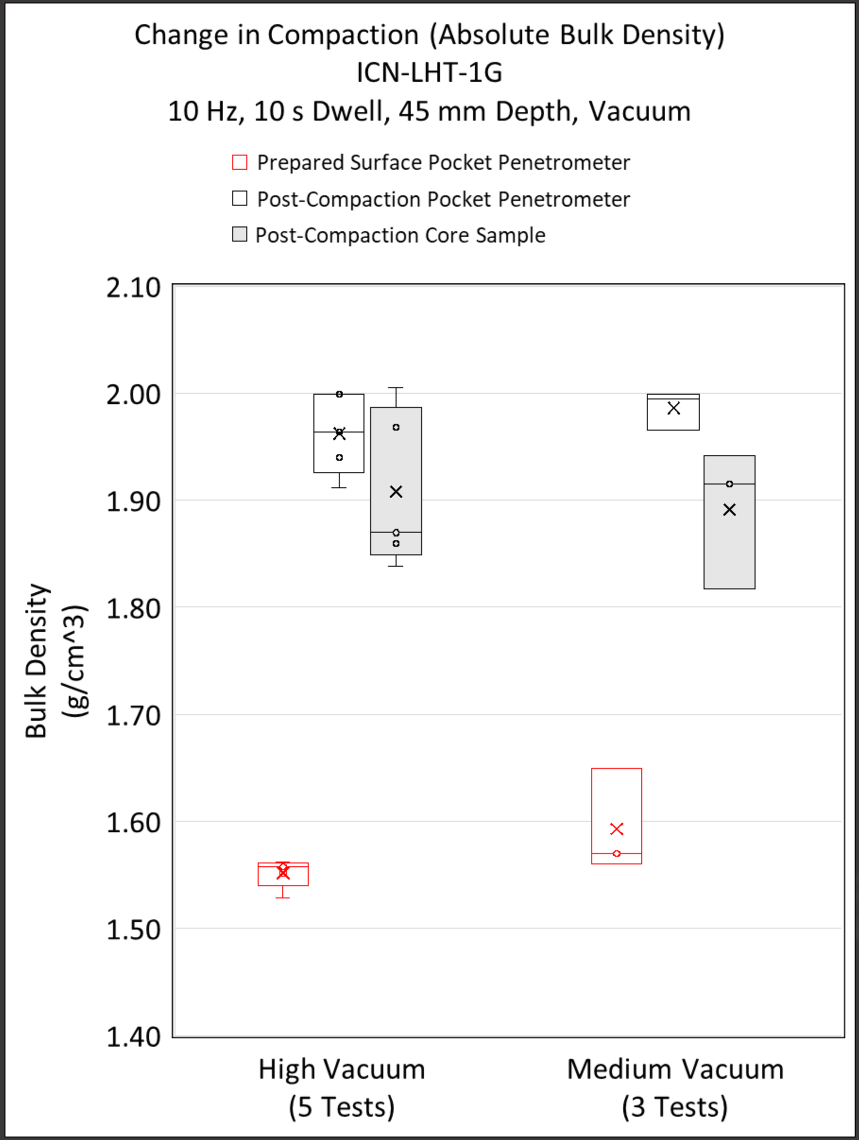
- Additional considerations were made for integrated testing with Mason's microwave sintering technology M3LT
- RF shielding of PACT and ASSIST chamber
- High temperature titanium scoop body

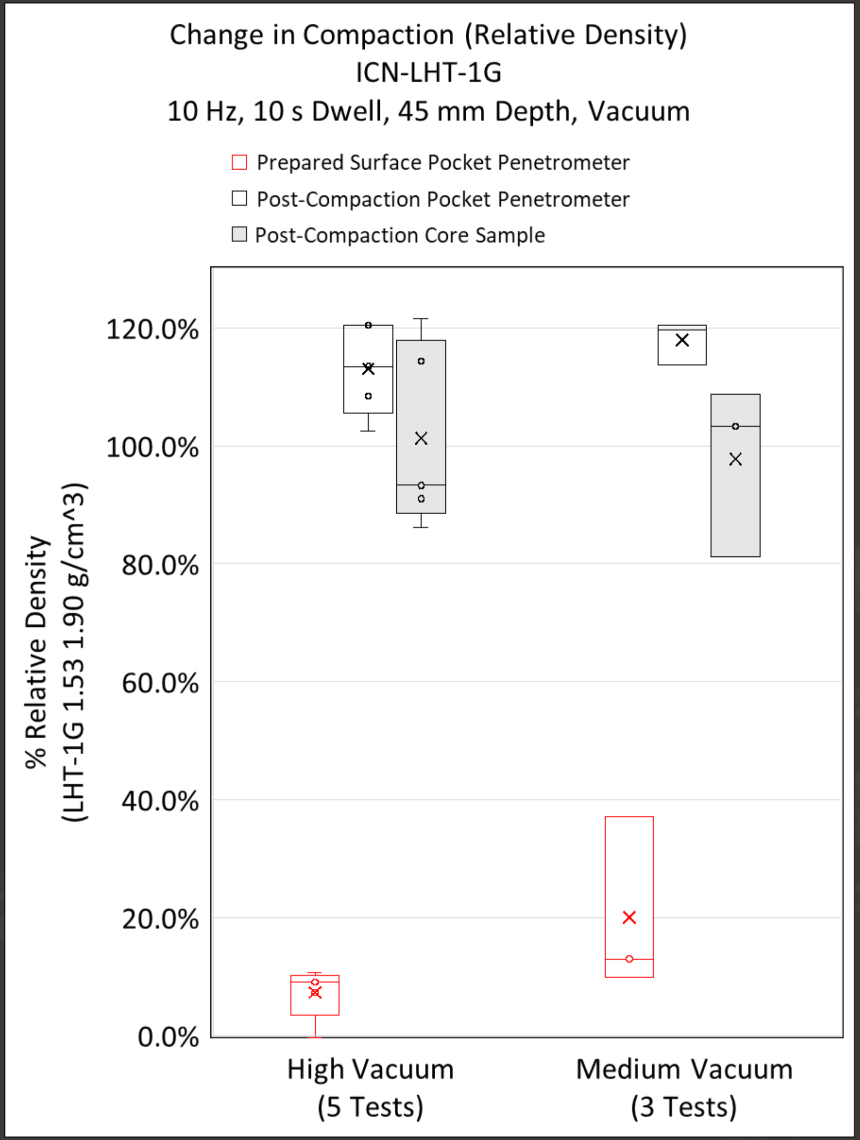


PACT about to press down on molten regolith simulant

# PACT Compaction Results

- Measurements taken at ambient before and after vacuum testing.
- High final density after compacting using PACT.
- Core samples showed lower average densities but are in range with pocket penetrometer values.

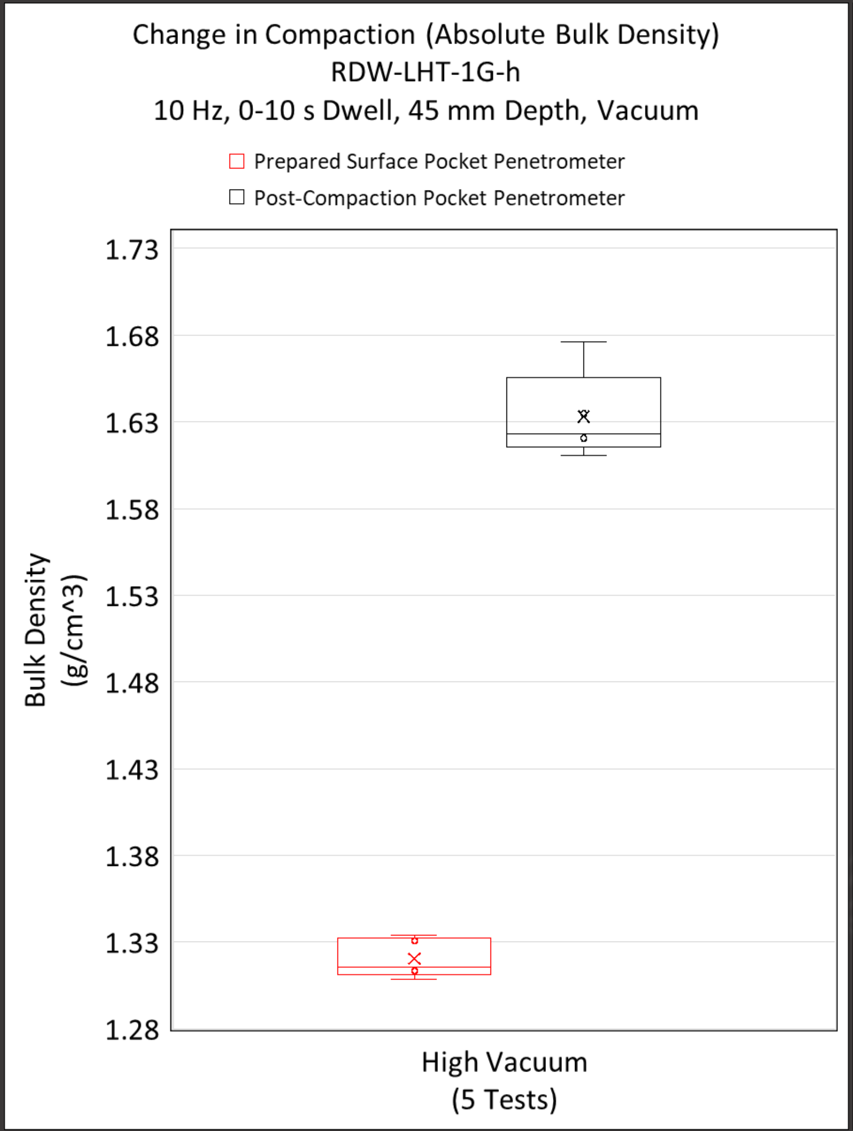


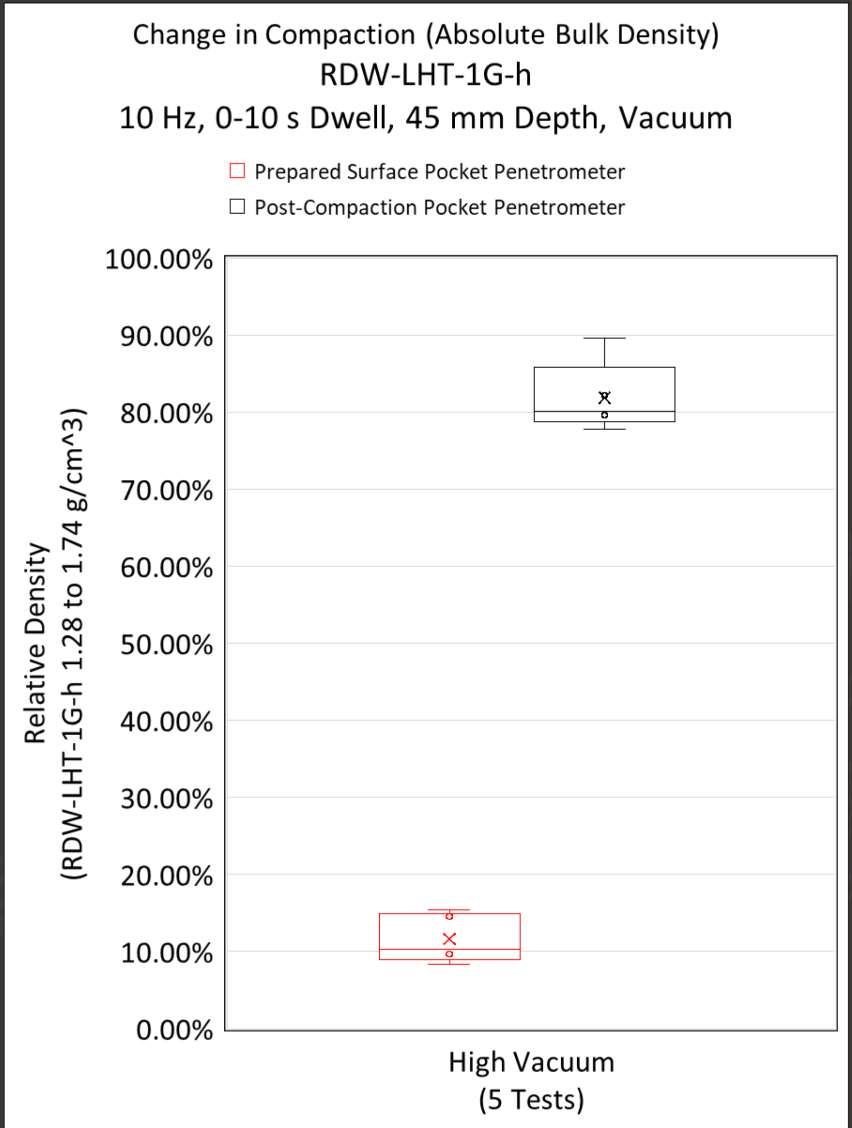




Max Density Testing: 1.90 g/cm$^3$ (ASTM D4253, Method 1A)
Min Density Testing: 1.53 g/cm$^3$ (ASTM D4254, Method B)

# PACT Compaction Results

- Performance reduced in RDW-LHT-1G-h
  - Possible reasons include simulant differences, boundary conditions, and microwave testing post-compaction
- Simulant characteristics unusual compared to other lunar simulants.
  - Min/max bulk density
  - Pocket penetrometer correlation pressures
  - Particle size
  - To be published (B. Kemmerer *"Geotechnical Characterization and Correlations of BP-1, LHS-1E, CSM-LHT-1G, and RDW-LHT-1G-h Lunar Regolith Simulants"*)



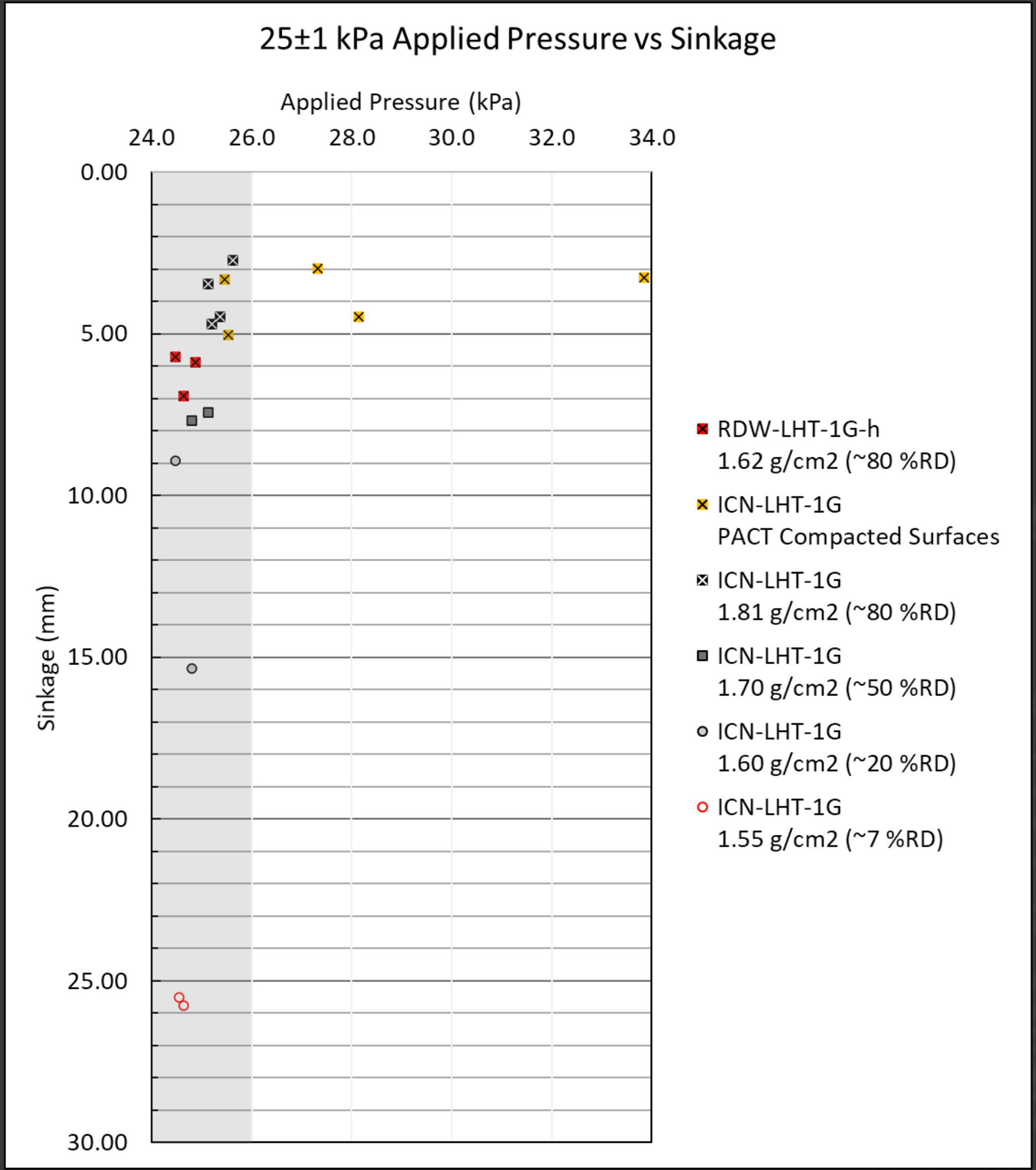




Max Density Testing: 1.74 g/cm3 (ASTM D4253, Method 1A)
Min Density Testing: 1.28 g/cm3 (ASTM D4254, Method B)

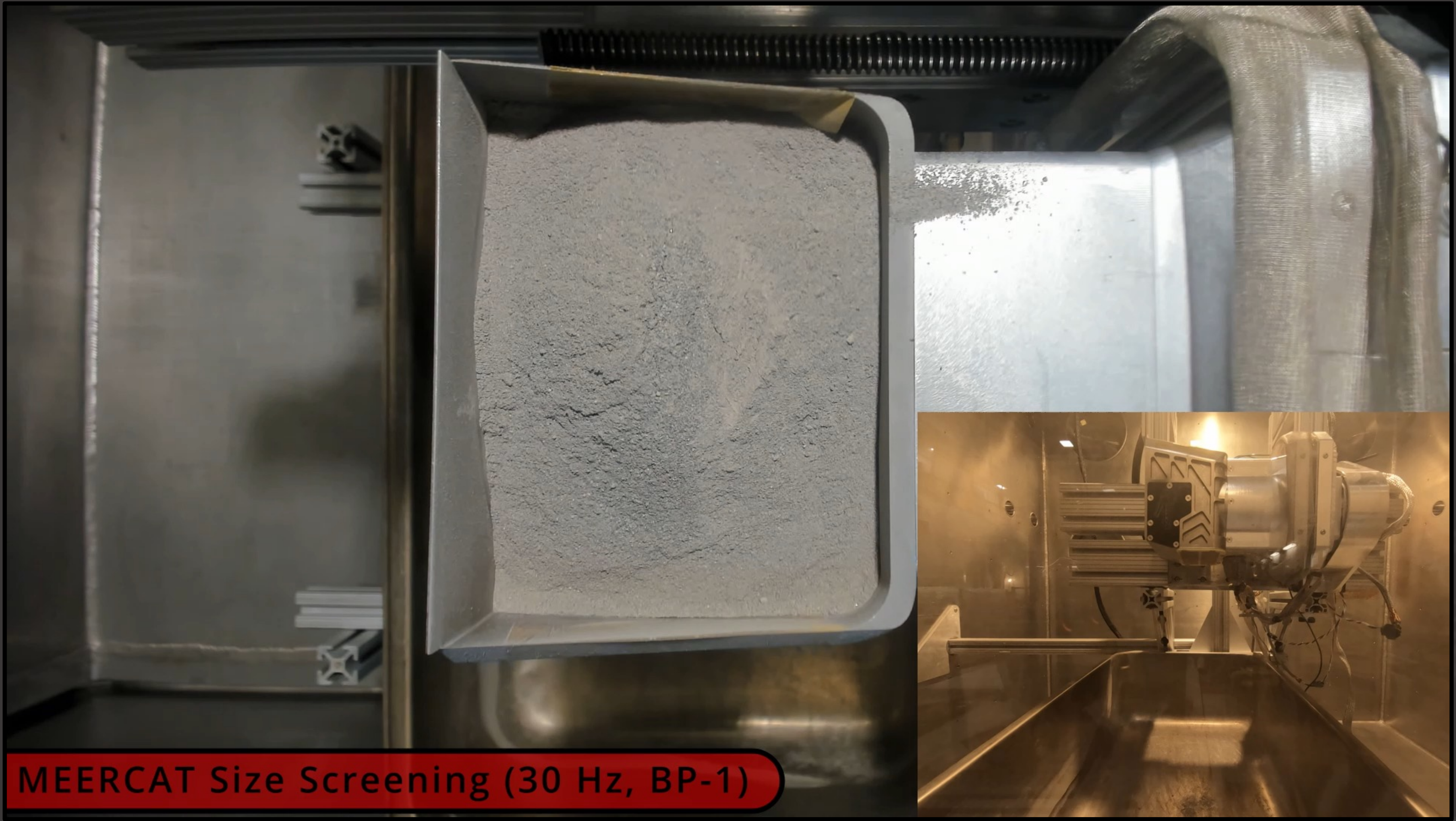
# Density Estimation

| Simulant | %RD | Sinkage Range @ 25 kPa | Avg Sinkage @ 25 kPa |
|---|---|---|---|
| ICN-LHT-1G | 80 | 2.7-4.7 mm (4 tests) | 4.1 mm |
| RDW-LHT-1G-h | 80 | 5.7-6.9 mm (3 tests) | 6.2 mm |

- To verify 80%RD or higher was achieved in-vacuum, system was lowered onto simulant surface and performed a pressure sinkage measurement.
- To correlate this value, bins were pre-prepared at various %RD's and pressure sinkage was performed in-vacuum using the PACT compaction surface.
- Pressure sinkage results in RDW-LHT-1G-h prepared with PACT show greater than 80 %RD before microwave sintering occurs.



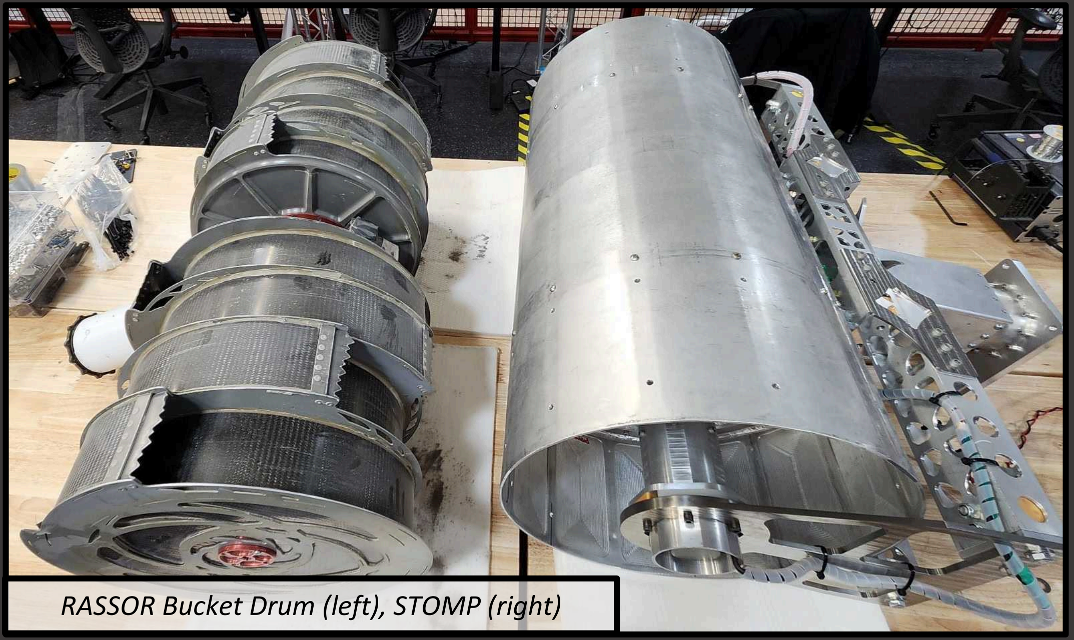
# Self-cleaning Size Screen



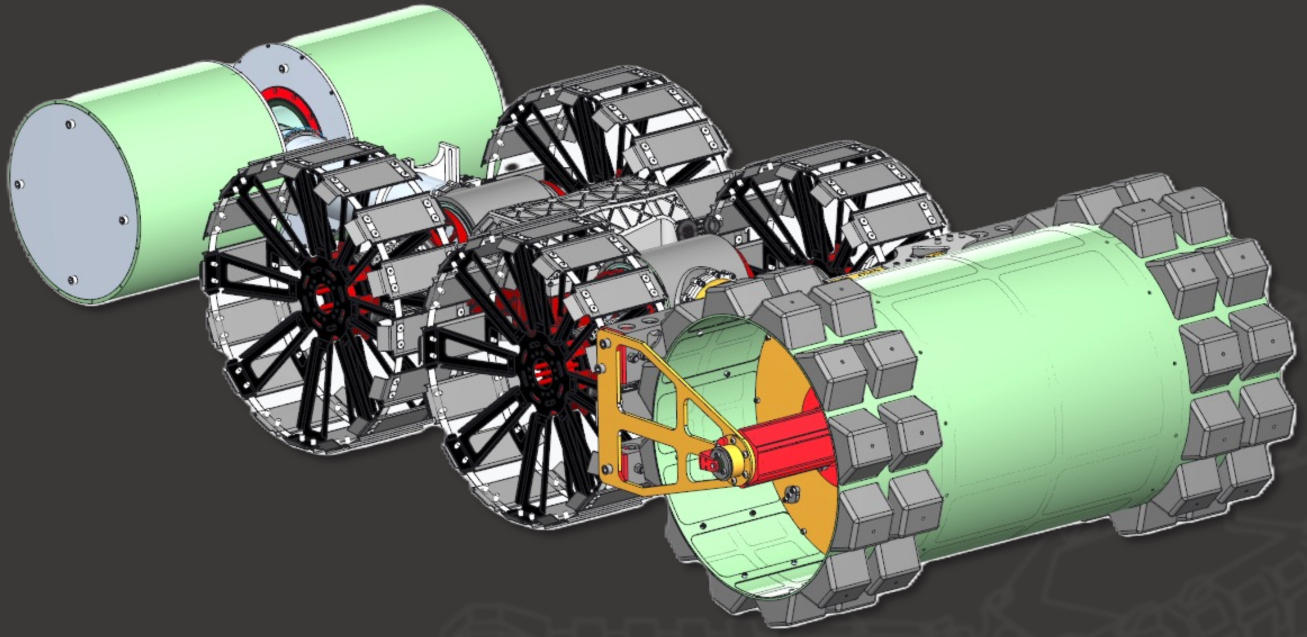
# STOMP

## *Site Preparation Tooling for Operations on Mobility Platforms*

- Vibratory roller compactor with a modular disconnect to the Swamp Works RASSOR robotic platform (predecessor to IPEx).



*RASSOR Bucket Drum (left), STOMP (right)*

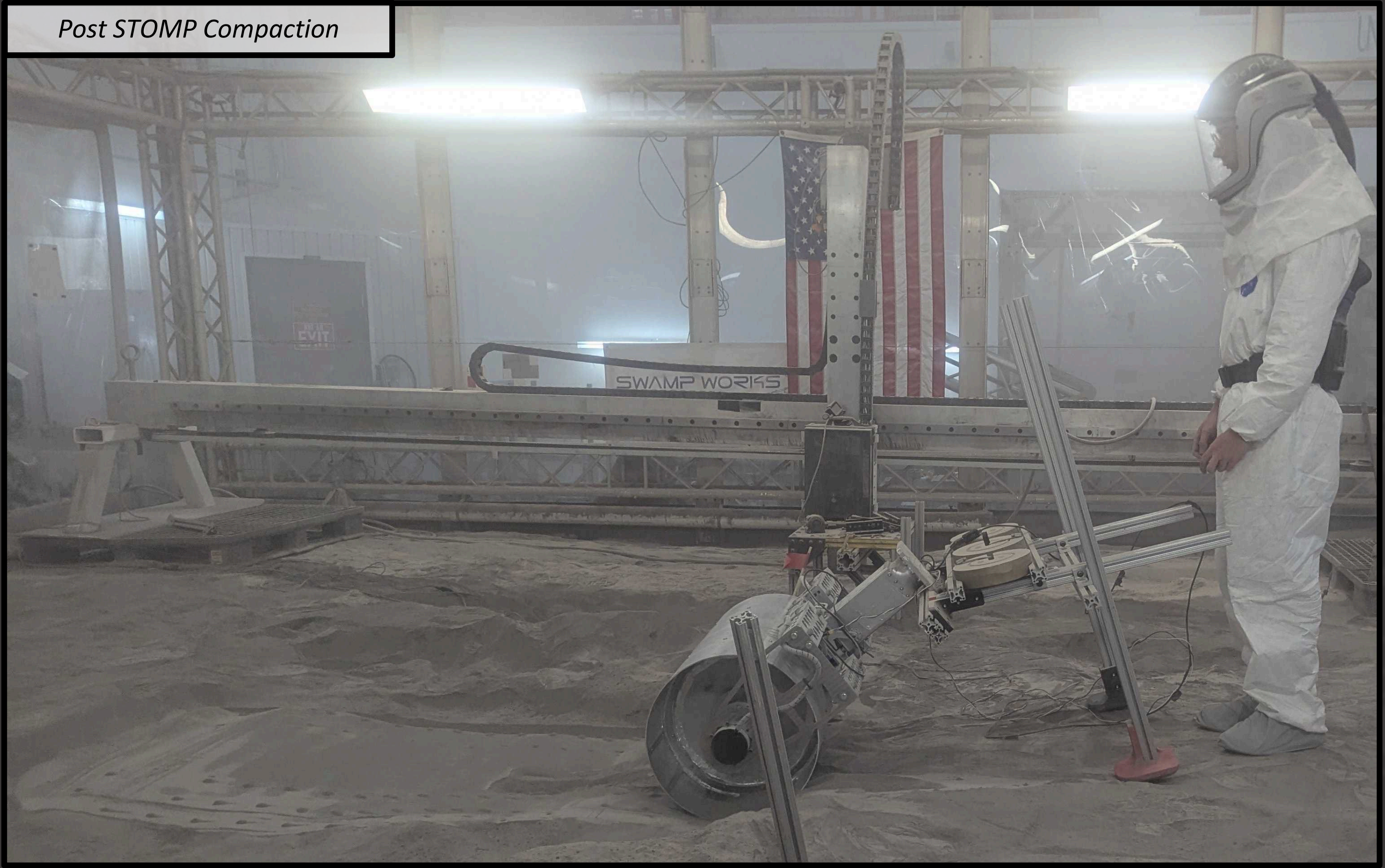


*STOMP on RASSOR*

# STOMP Testing

- Testing occurred in BP-1
- Simulant was prepared to low density (~1.6 g/cm³)
- STOMP was fixtured with a RASSOR simulated mass

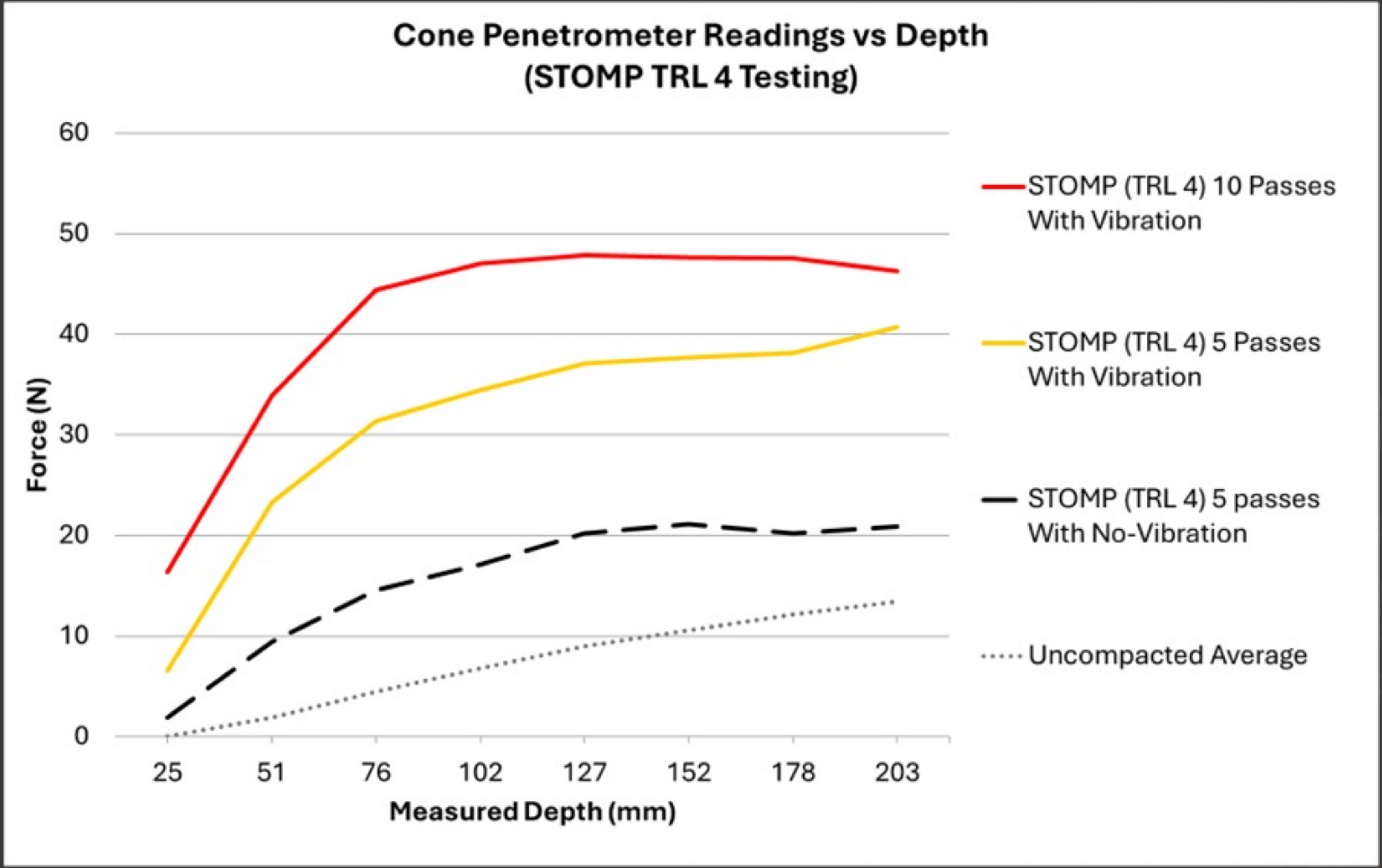
Post STOMP Compaction




BP-1 Preparation

# STOMP Cone Penetrometer

- Cone penetrometer shows compaction effects to 20cm (limited by cone pen. read depth).
- 10 passes shows significant increase in cone penetrometer reaction forces over 0 or 5 passes.



# STOMP Results

- Maximum compaction between 5-10 passes
- Coverage Rate: ~ 150 $m^2$/hr. (based on 10 passes required)
- Power: 480 W
- Mass: 18 kg (STOMP only, not including RASSOR)

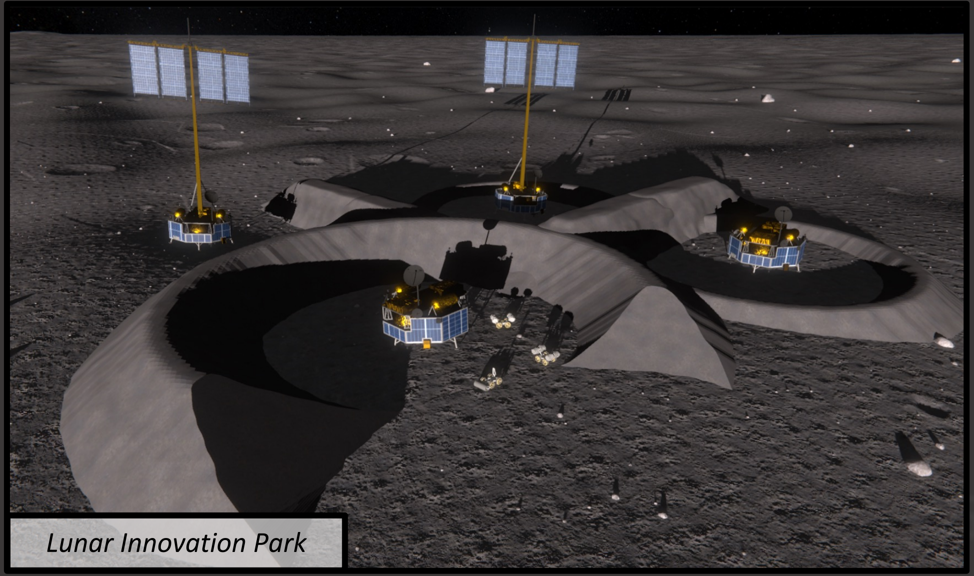
| | Uncompacted | Compacted via STOMP No-Vibe (5 passes) | Compaction via STOMP With Vibe (5 passes) | Compaction via STOMP With Vibe (10 passes) |
|---|---|---|---|---|
| **Surface Bulk Density ($g/cm^3$)** | **1.61** | 1.69 | 1.78 | Exceeded 1.86 |
| **Relative Density (1.43-1.86 g/cm3 [4])** | **44%** | 66% | 85% | Exceeded 100% RD |



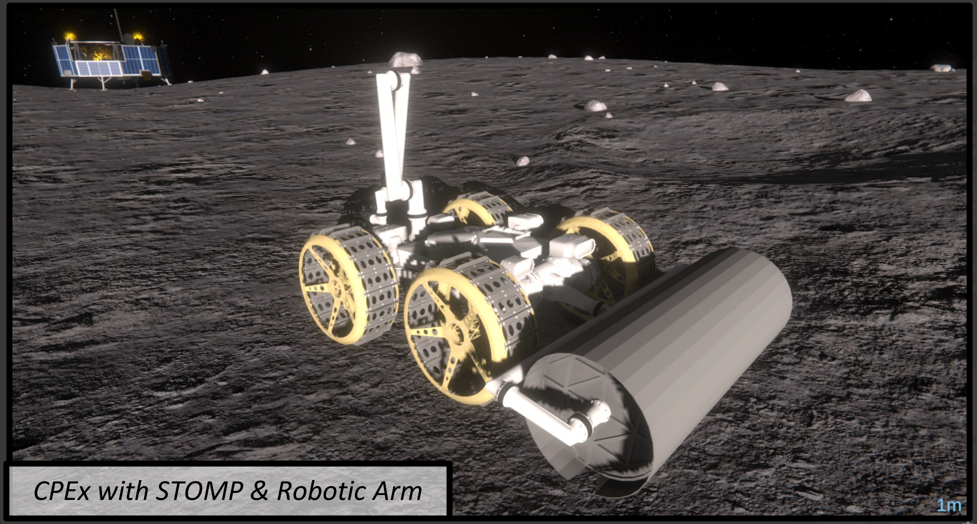
*[4] A. Slabic, et al. "Lunar Regolith Simulant User's Guide Revision A", table 16, NTRS – NASA Technical Reports Server, 20240011783, 2024*

# Forward Work

- MEERCAT / PACT
  - MEERCAT is internally funded to complete environmental testing of all capabilities to achieve a system TRL of 6.
    - TVAC
    - Shock & Vibe
    - EMI
- STOMP
  - Implement Modularity and roller compaction will be integrated into future CPEx (Construction Pilot Excavator) work.
  - CPEx and other construction systems will be a needed for the Lunar Innovation Park and potentially other Moon Base concepts.



*Lunar Innovation Park*



*CPEx with STOMP & Robotic Arm*

*[5] M. Hilburger, N. Gelino. "Lunar Innovation Park," NTRS – NASA Technical Reporting Server, NTRS – NASA Technical Reports Server, 20260002820, 2026.*