Comparative Experimental Study of Terrestrial Compaction Methods on Lunar Regolith Simulant

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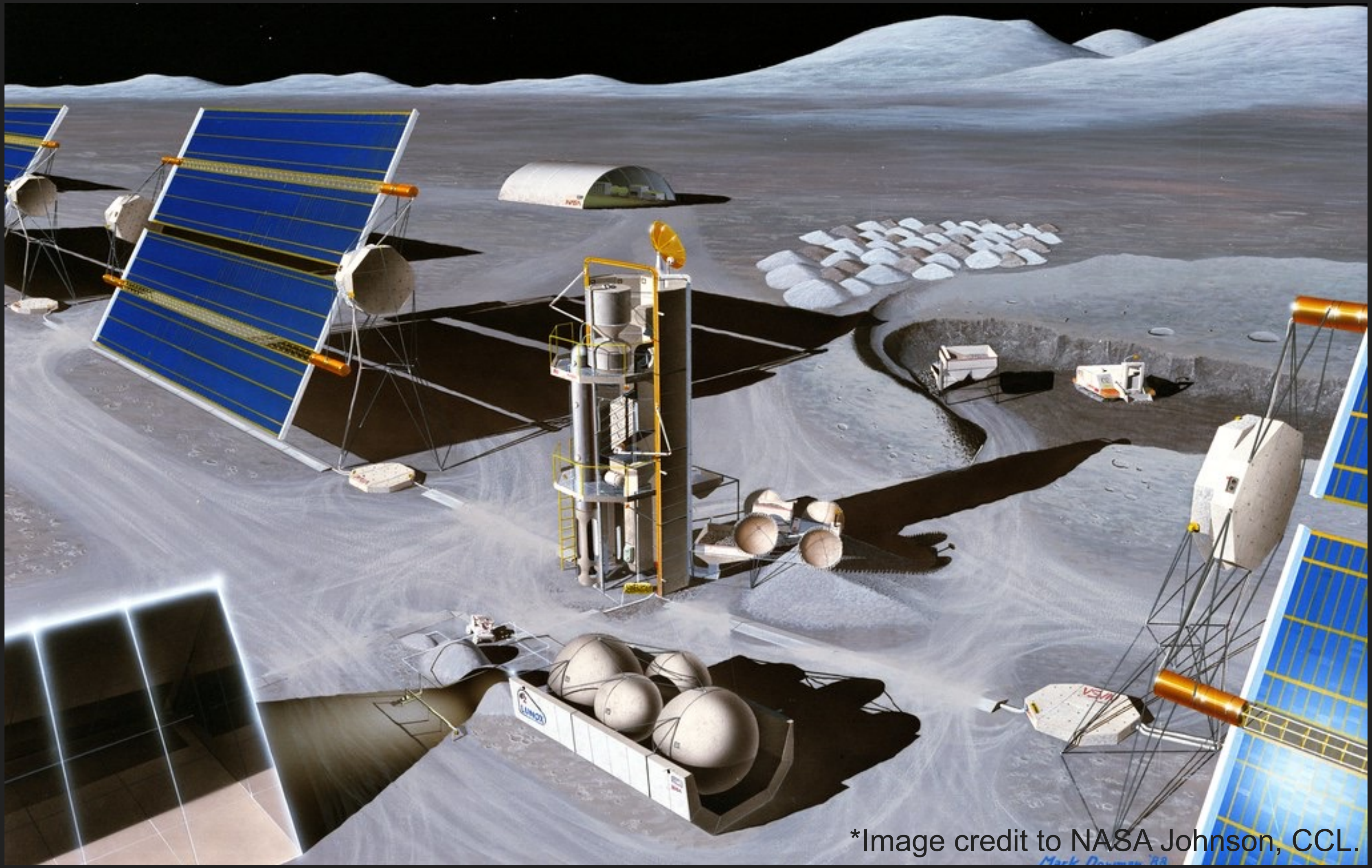


*Image credit to NASA Johnson, CCL.

Study is part of STTR project to develop a software called REGOWORKS to optimize lunar regolith construction

Study provides ground truth performance data so model achieves more accurate results

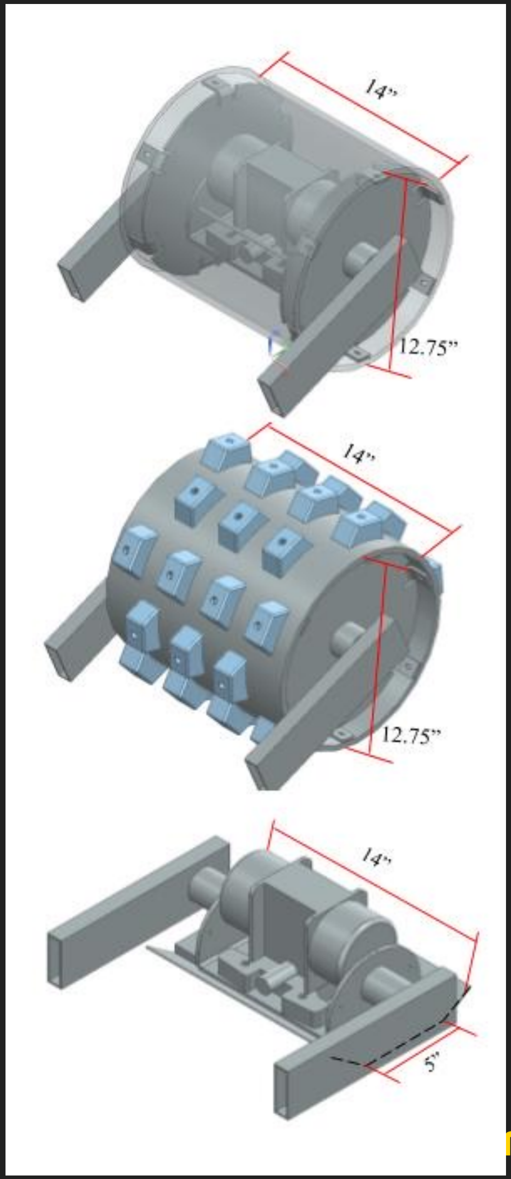
Test Objectives

3 models tested to determine which one to evaluate in an in-depth performance test:

- Rolling Vibratory Compactor (RVC)
- Sheepsfoot Compactor (SC)
- Plate Compactor (PC)

Important considerations

- Not testing "best case" of one against "worst case" of another
- Small simple models, similar payload mass for all
- Consistent time spent in/over one area



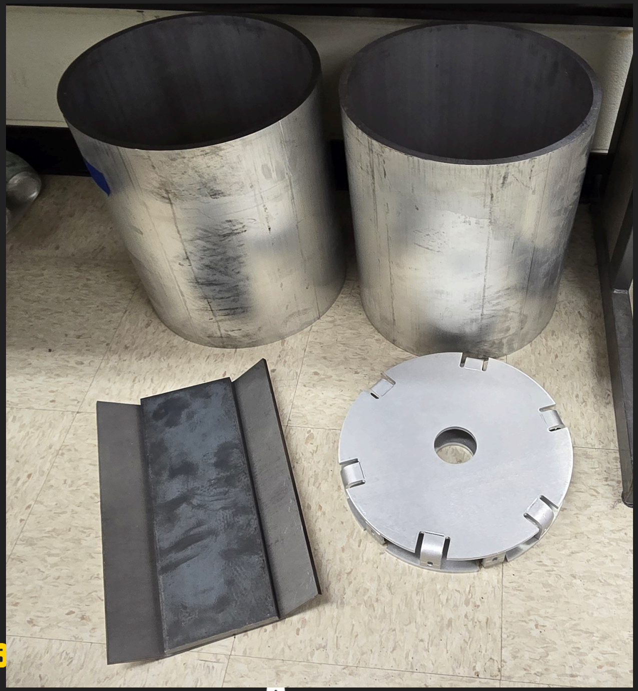


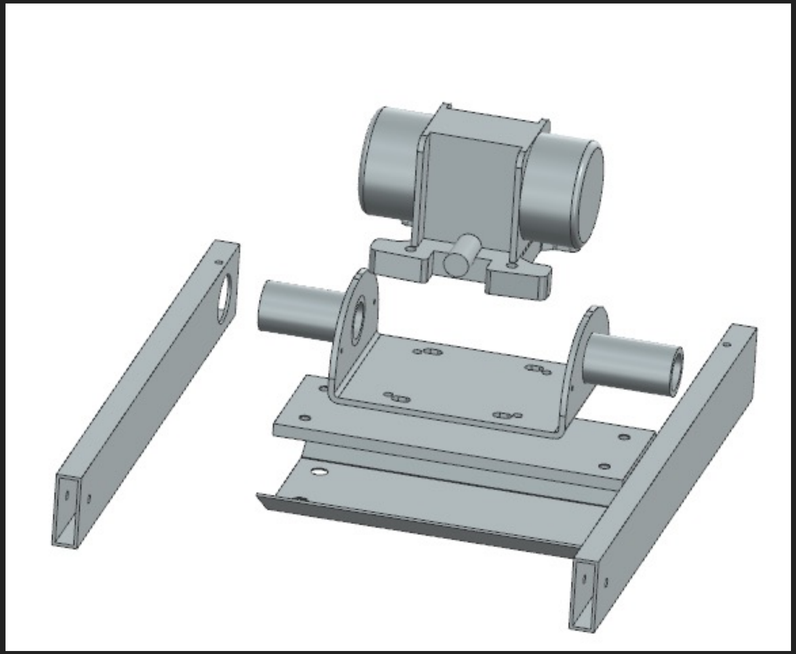
Plate Compactor

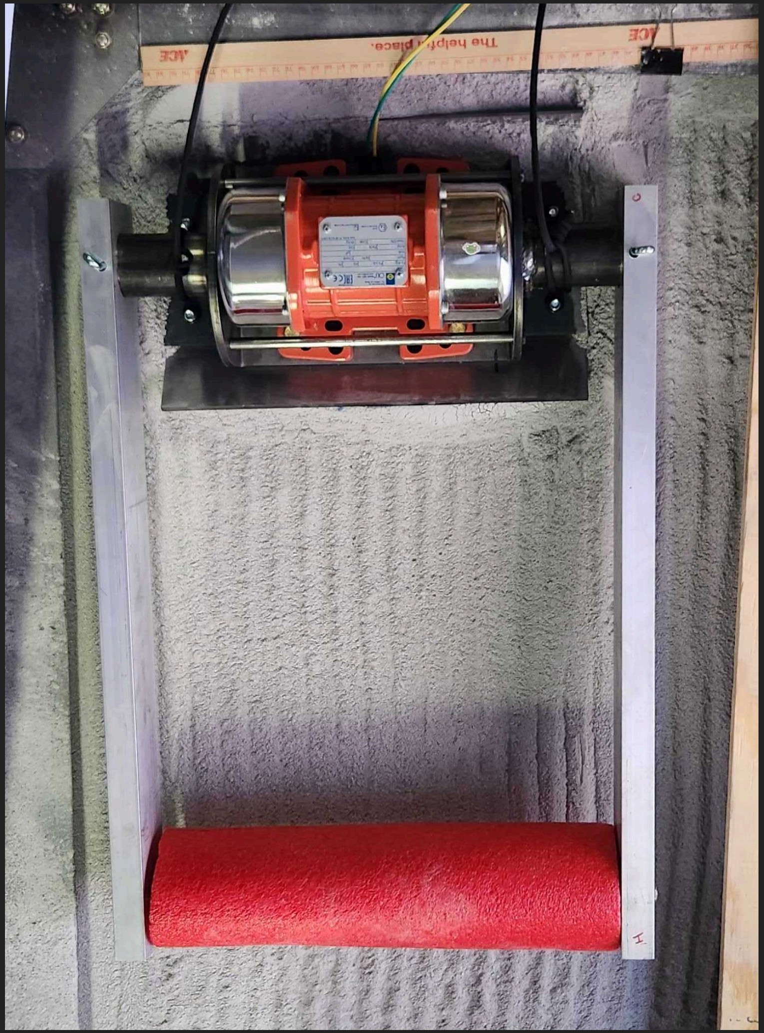
Materials

- 1/8” steel plate with bent sides for base
- ½” steel plate for spacing and mass
- Welded ¼” thick steel motor crib
- 2 1” x 2” aluminum tube arms
- MVE 200/3N-23A0-24V vibrator

Notes

- Lightest system
- First system tested
- Simplest





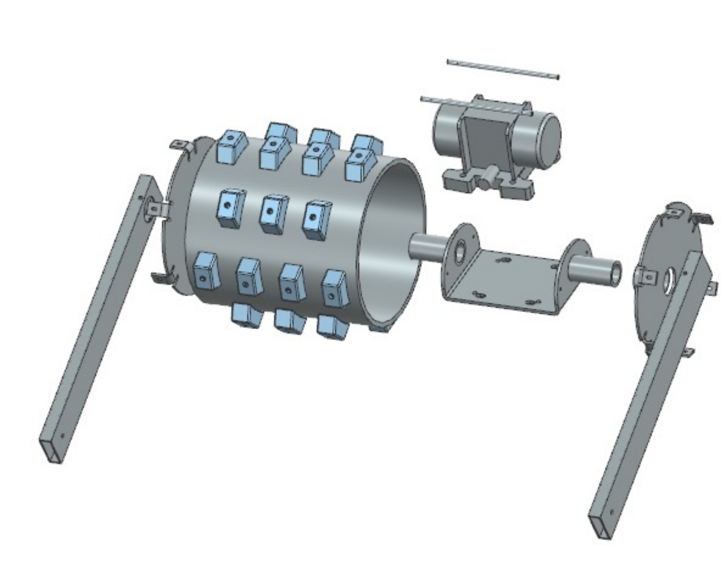
Sheepsfoot Compactor

Materials

- 12.75” OD x 14” wide aluminum tube
- 2 – ¼” cover plates for support and dust mitigation
- MVE 200/3N-23A0-24V vibrator
- Welded ¼” thick steel motor crib
- 2 1” x 2” aluminum tube arms
- 28 PLA 3D printed cleats
- 2 solid lubricant sleeve bearings

Notes

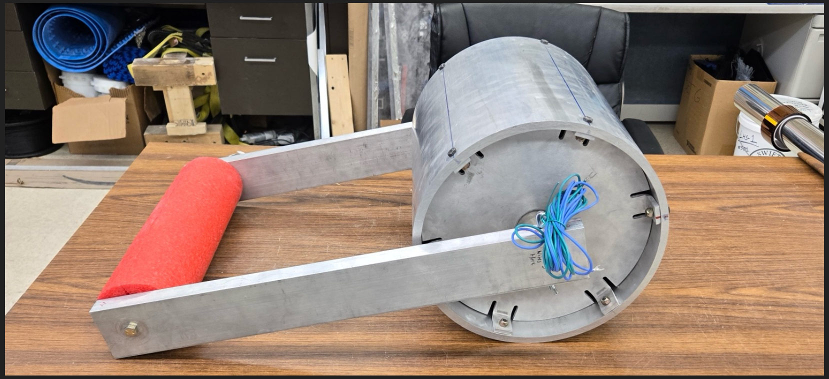
- Despite having motor onboard, was not vibrated
- Rolled very well in regolith
- Heaviest system

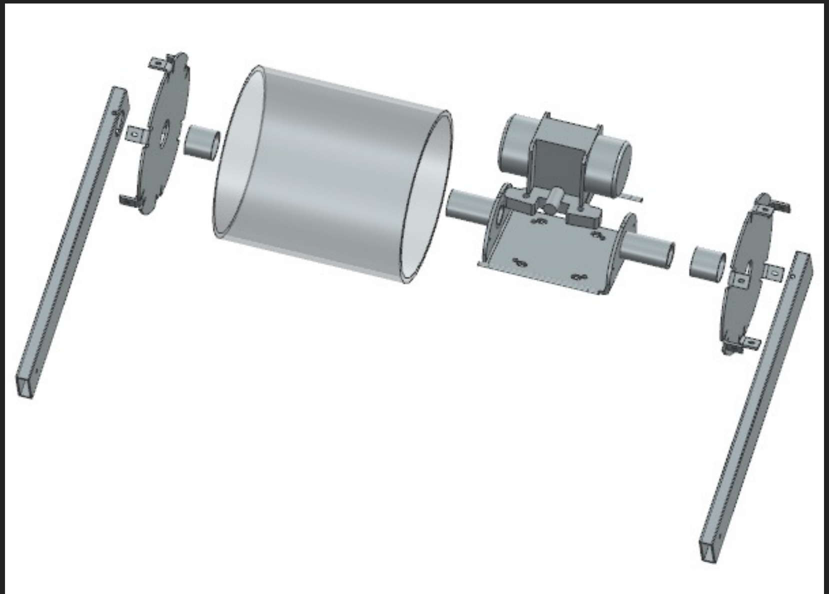


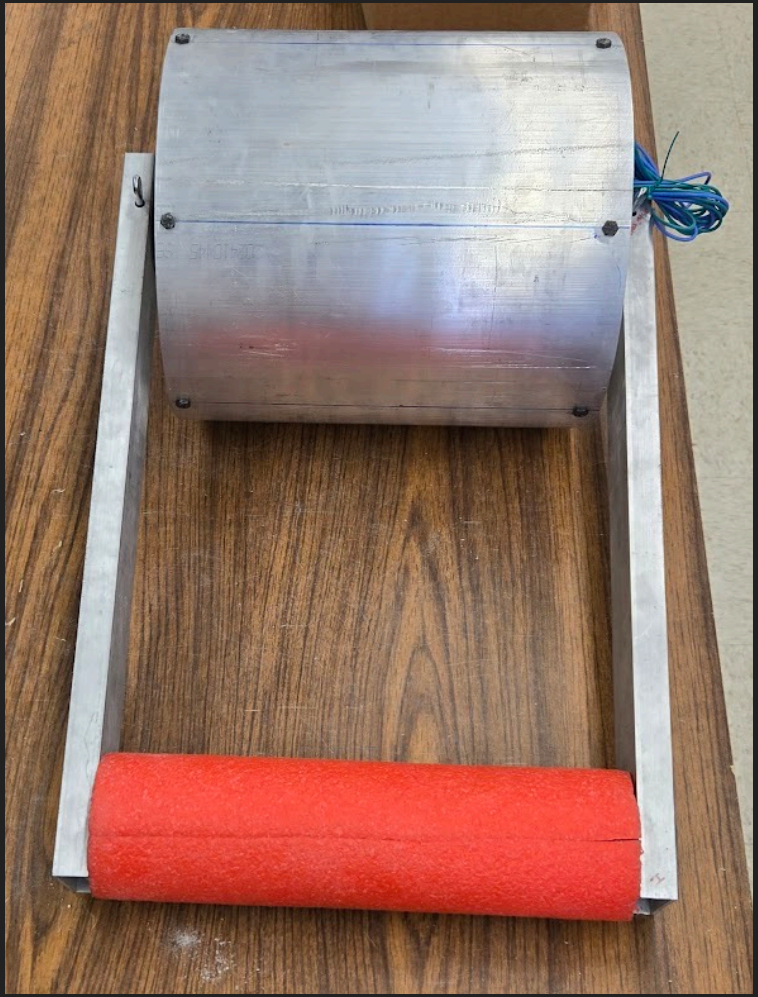
Rolling Vibratory Compactor

Materials
- 12.75” OD x 14” wide aluminum tube
- 2 – ¼” cover plates for support and dust mitigation
- MVE 200/3N-23A0-24V vibrator
- Welded ¼” thick steel motor crib
- 2 1” x 2” aluminum tube arms
- 2 solid lubricant sleeve bearings

Notes
- System struggled to roll in regolith







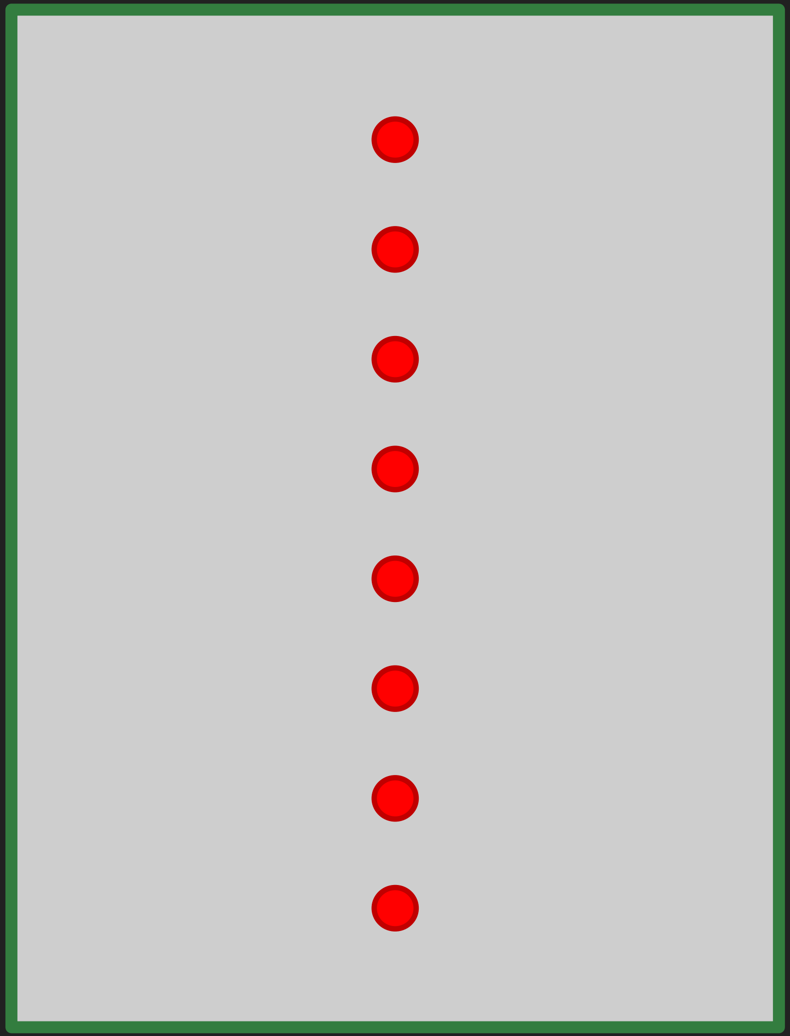
Test Parameters

Metric #	Metric Name	Metric Weight	Metric Type	Quantitative Metric Method
1	Mass (kg)	4	Quantitative	Lower is Better
2	Electrical Power (kW)	3	Quantitative	Lower is Better
3	Surface Quality	2	Qualitative	
4	Compacted Depth (cm)	5	Quantitative	Higher is better
5	Avg Penetration Resistance (kPa)	3	Quantitative	Higher is better
6	Pulling Energy (J)	3	Quantitative	Lower is Better
7	Pulling Force (N)	3	Quantitative	Lower is Better
8	Pulling Force Range (N)	3	Quantitative	Lower is Better
9	Avg Penetration Resistance Range	3	Quantitative	Lower is Better

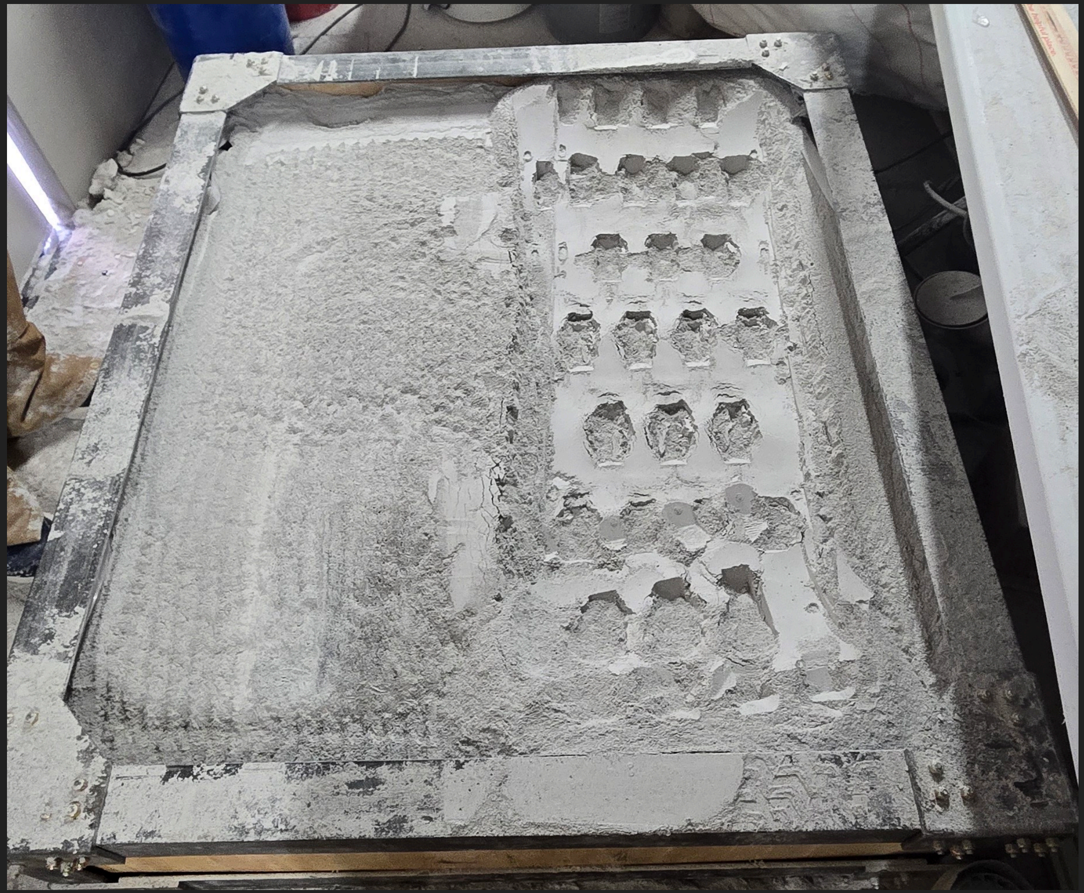
Single Compaction Test Overview

Regolith Bin

Pre-Test Penetrometer Readings



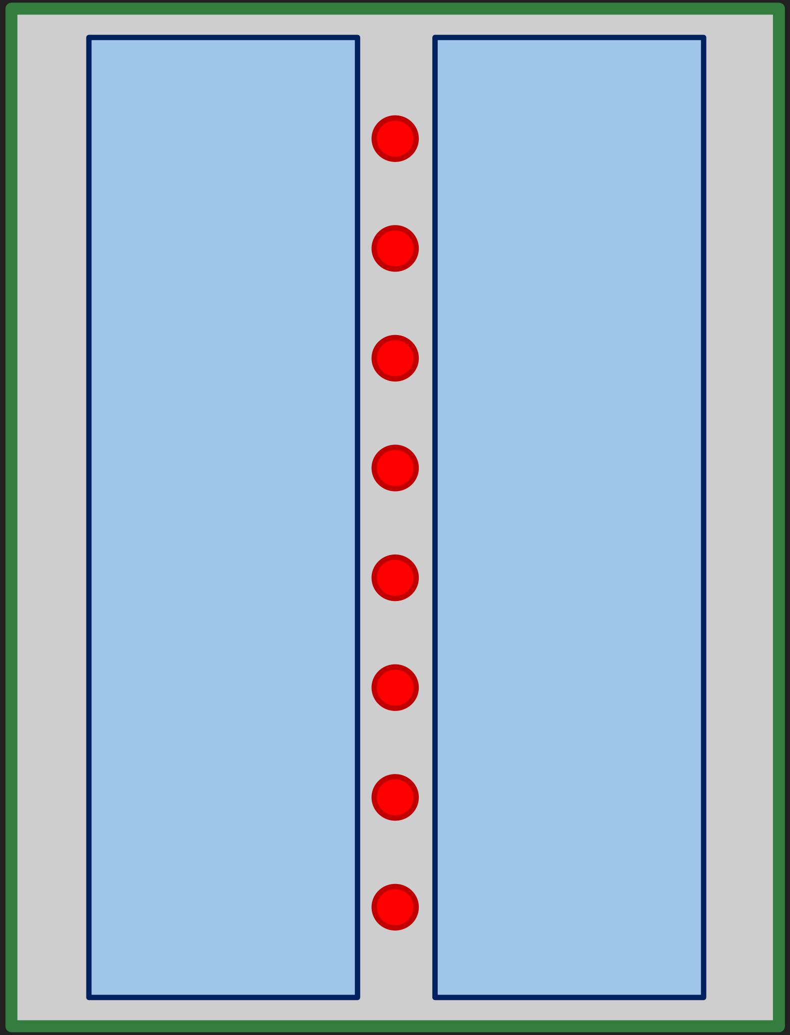
Single Compaction Test Overview



Regolith Bin

Pre-Test Penetrometer Readings

Tests 1 & 2



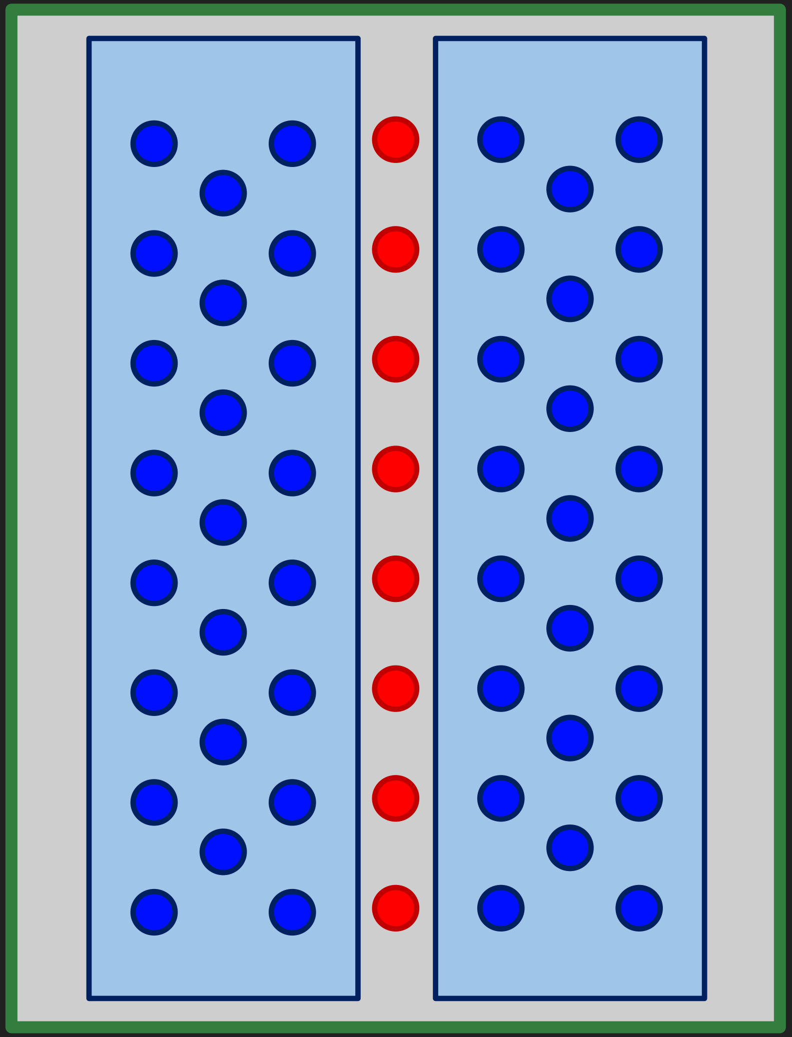
Single Compaction Test Overview

Regolith Bin

Pre-Test Penetrometer Readings

Tests 1 & 2

Post-Test Penetrometer Readings

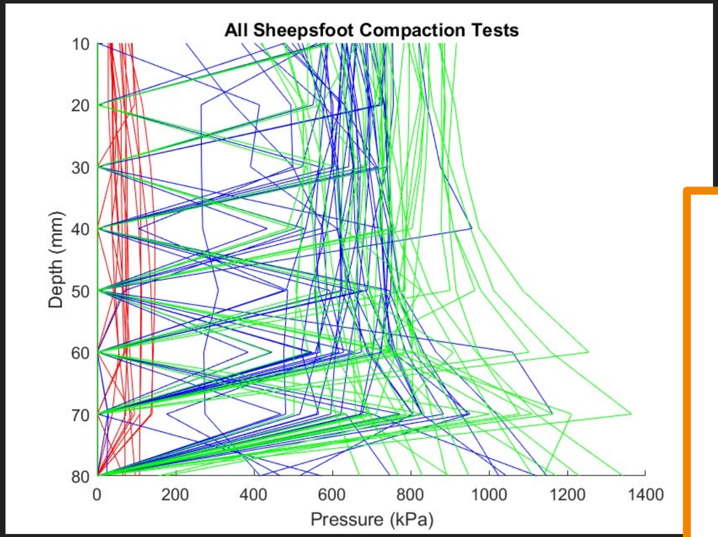


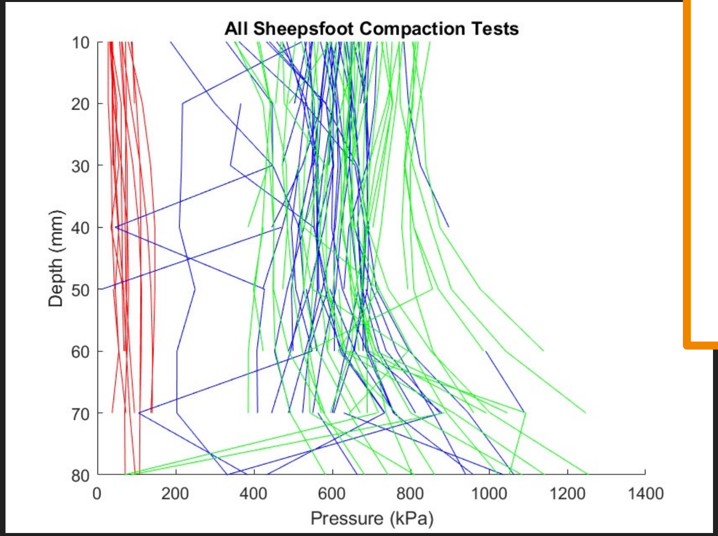
Notes on Penetrometer Tests

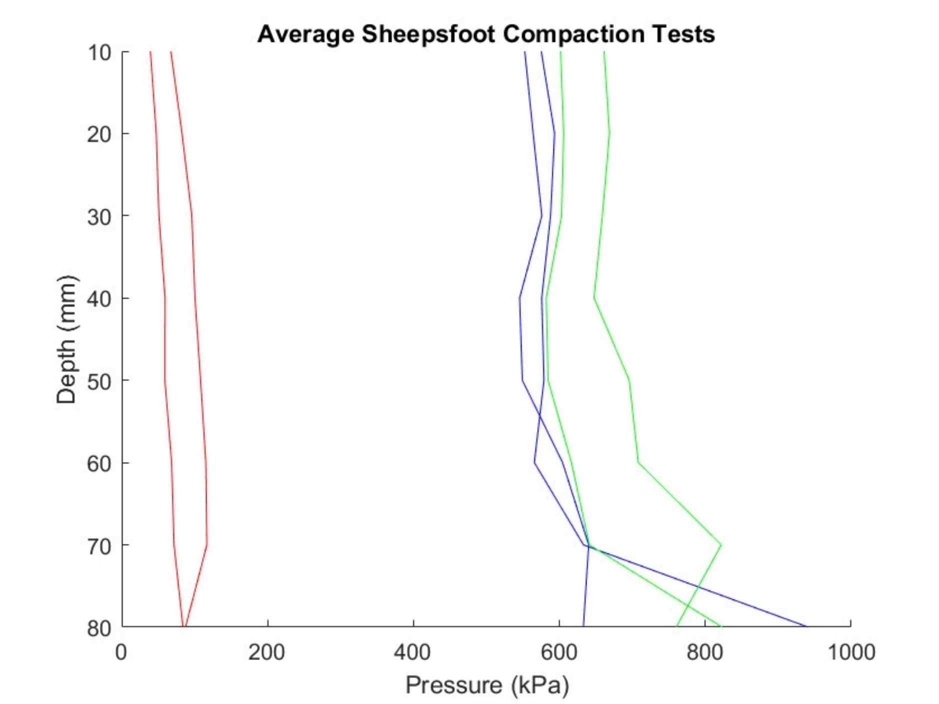
- Each compactor got 2 test beds of compaction data
- Measures pressure experienced by a cone being pushed into the ground vs distance from the surface in 10 mm increments
- Needs to be manually pushed into the ground
- Will record a 0 if the push rate is too fast or too slow
- Will occasionally completely fail on a measurement
  - Penetrometer beeps and displays “Too Slow! Keep Data? <Y> <N>”
- Leads to losing about 1 in 5 readings
  - Lots of redundancy

SPT Data and post-processing

- Set all 0's to NaN
- Remove any data sets highlighted by the SPT to have failed when collecting measurements
- Plot beds 1 and 2 in green and blue respectively, with pre-test for both in red
- Average each test of the system and plot
- Subtract corresponding pre-test average off averaged data to plot against other systems







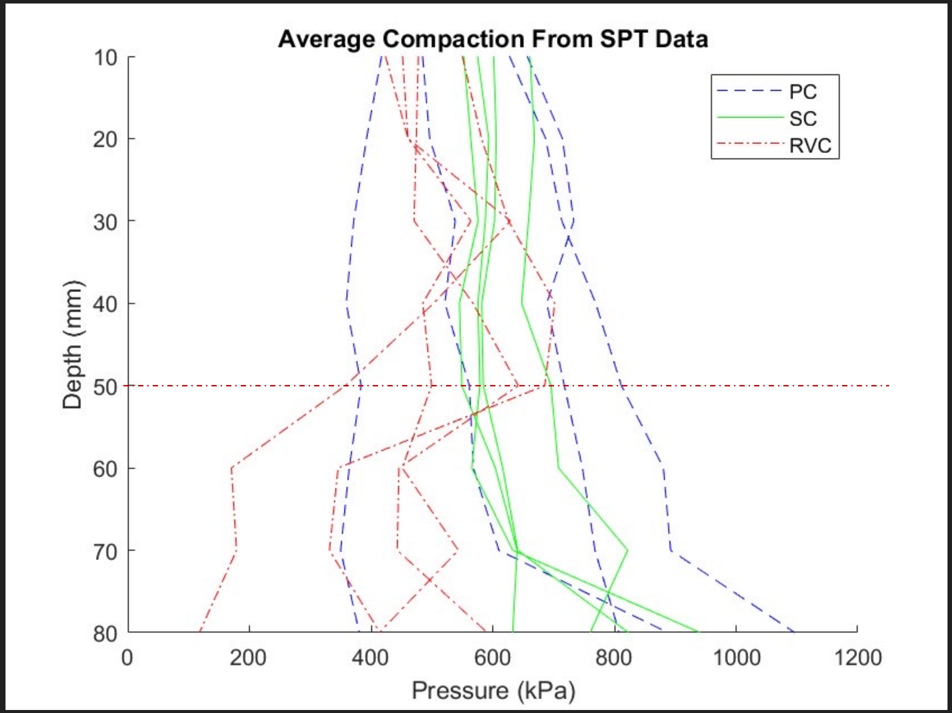
Processed Average Data from SC Test

Testing Observations

- RVC didn't roll very well in any regolith tests
- PC liked to dig itself in more than the other two systems
- SC and RVC pushed a lot of regolith up and out of the bin (figures on next slide)
- PC completed 4 passes per test, SC completed approx. 30 passes per test, RVC completed approximately 15 passes per test – Cumulative dwell time over each area is the same
- Some electrical issues led to loss of power data for 2 tests(1 RVC, 1 PC)
- Pulling Force tests occurred in a different, slightly more compacted bed than compaction tests did

Compaction and Compacted Depth

- Determined compacted depth from the plotted SPT data
- Averaged all data of every test up to compacted depth of each compactor type for “Avg Penetration Resistance”
- Took the min and max average values across all 4 tests of each compactor type to determine “Avg Penetration Resistance Range”



System	Avg Penetration Resistance (kPa)	Avg Penetration Resistance Range (kPa)	Compacted Depth (mm)
Plate	625.0	746.5	80
Rolling Vib.	530.6	584.1	80
Sheepsfoot	637.3	395.6	50

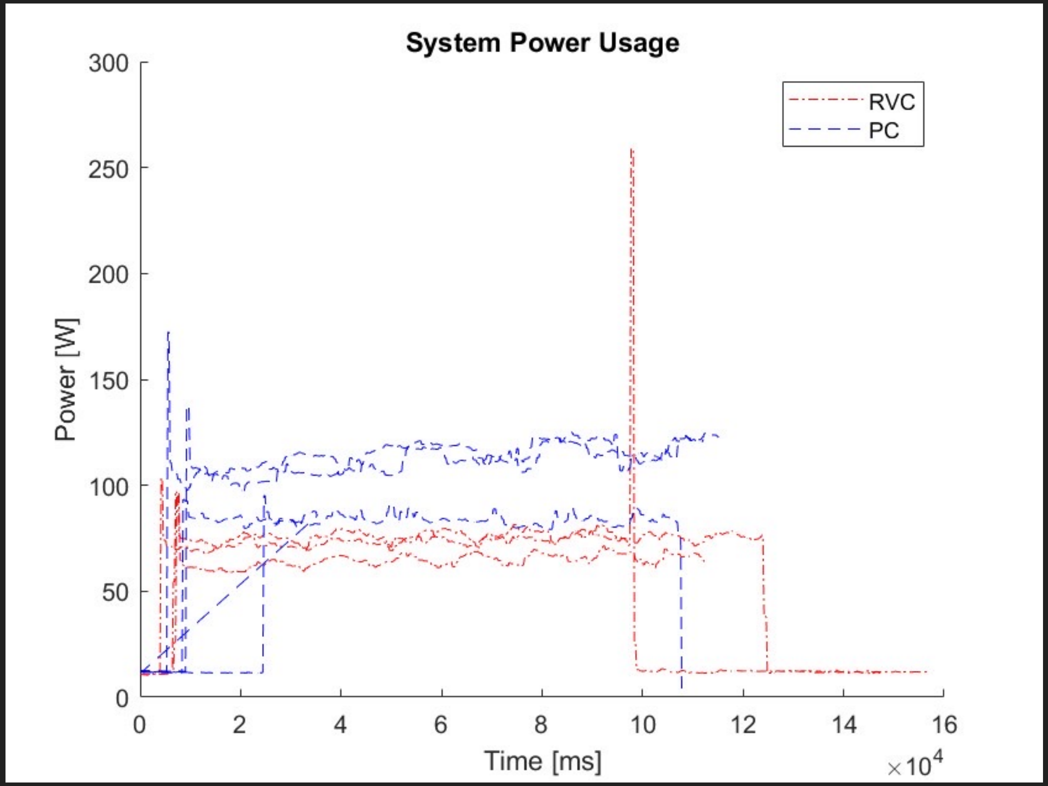
System Mass & Surface Quality

System	Mass (kg)	Surface Finish	Displaced Regolith
Plate	21.964	Average	Medium
Rolling Vib.	25.900	Semi-Smooth	High
Sheepsfoot	27.566	Rough	High

Surface finish was considered against uncompacted finish (small lines from raking)

Power and Energy Usage

- Sheepsfoot did not use any electrical power
- RVC and PC each had 3 successful runs of collecting power data (plotted)
- Averaged the power results from the systems
- Pulling Energy = Force to pull * Distance pulled (# passes * pass length)



System	Avg Electrical Power (W)	Pulling Energy (J)
Plate	103.3	416.0
Rolling Vib.	70.0	4,371.9
Sheepsfoot	0.0	1,040.2

Pulling Force and Force Range

Three - 1m pull tests were conducted of each system and averaged.

Notes:

- Pull force required for the SC has large variability
- Rolling systems were easier to pull than PC
- RVC did not want to roll

System	Pulling Force (N)	Pulling Force Range (N)
Plate	104.0	30.0
Rolling Vib.	74.3	30.0
Sheepsfoot	71.7	85.0

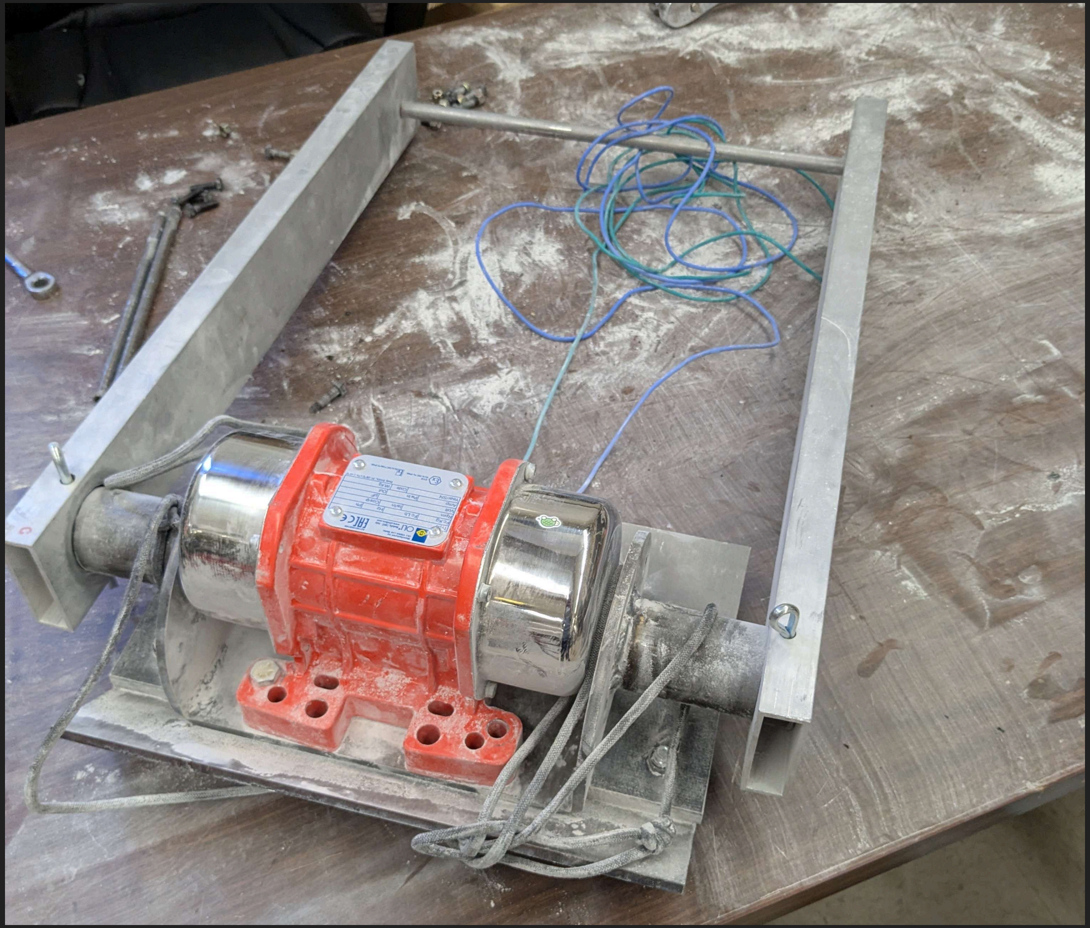
Experimental Summary Table

SPACE RESOURCES ROUNDTABLE

Rank	Total Score	System Name	Mass (kg)	Electrical Power (W)	Surface Quality	Compact. Depth (cm)	Average Pen. Resist. (kPa)	Pulling Energy (J)	Pulling Force (N)	Displaced Regolith	Pulling Force Range (N)	Avg Pen. Resist. Range
1	100	Plate	22 Score: 20	103 Score: 3	Average Score: 6	8 Score: 20	625 Score: 12	416 Score: 12	104 Score: 3	Medium Score: 9	30 Score: 12	747 Score: 3
2	89	Sheepsfoot	28 Score: 4	0 Score: 15	Rough Score: 2	8 Score: 20	637 Score: 12	4,372 Score: 3	72 Score: 12	High Score: 3	85 Score: 3	396 Score: 15
3	85	Vibrating Roller	26 Score: 12	70 Score: 9	Semi Smooth Score: 8	5 Score: 5	531 Score: 3	1,040 Score: 12	74 Score: 12	High Score: 3	30 Score: 12	584 Score: 9

Future Work

- Developing a Plate Compactor model to be more thoroughly tested
  - Changing parameters
    - Vibration frequency
    - Vibration mass
    - Plate size
    - Pull speed
  - In vacuum conditions in MTU DTVAC
  - On various starting compaction levels (bulk regolith relative densities)



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Questions