TRL 6 Testing Results for the Mason Tool Suite

For In-Situ Lunar Construction by Microwave Sintering

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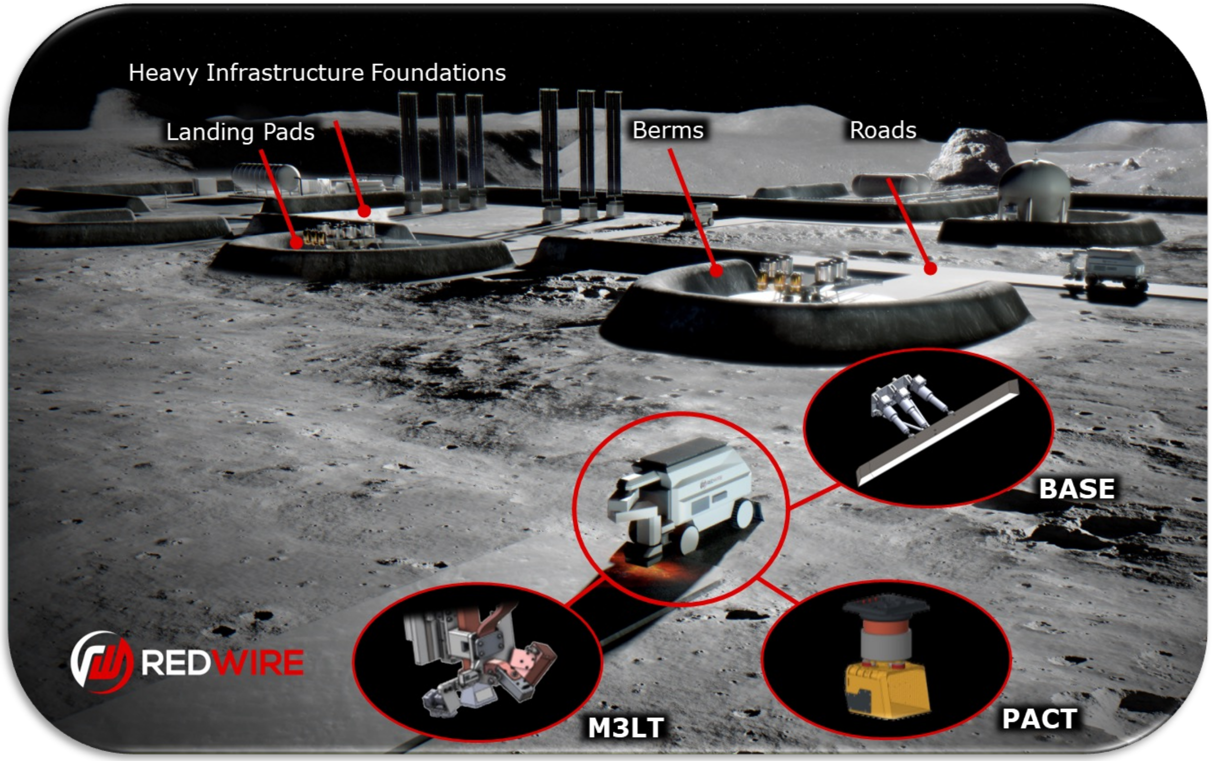
Presented by Lin Rossmann Moss 06.04.2026

Introduction

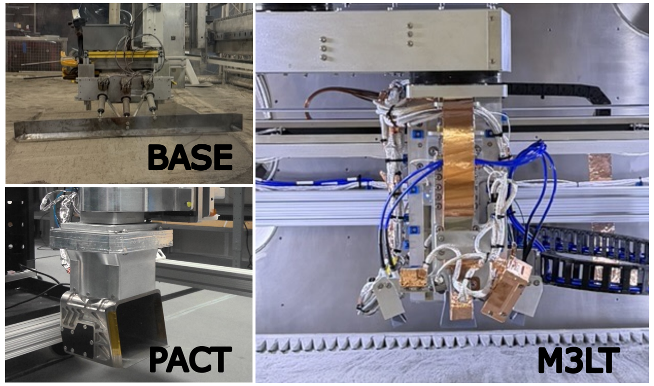
- Lunar infrastructure (landing pads, roads, berms, etc.) will be critical to lunar operations and long-term lunar presence
- In situ resource utilization (ISRU) will be necessary, due to the extreme cost of transporting material from the Earth to the Moon
- Mason is a platform-agnostic tool suite for in-situ lunar construction:
  - BASE (Blade for Autonomously Surfacing Environments) smooths and grades the lunar surface and removes rocks
  - PACT (Planetary Autonomous Compaction Tool) compacts the smoothed regolith to 80% relative density or greater
  - M3LT (Microwave Melter of Martian and Lunar Terrain) sinters the compacted regolith into a solid via microwave (MW) radiation
- This work presents early results from TRL 6 testing of PACT and M3LT on a highlands type lunar simulant relevant to the lunar south pole region targeted by the Artemis program



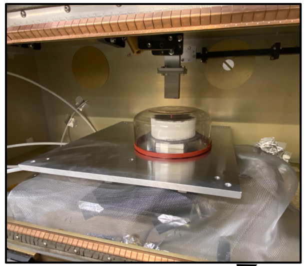
Mason: a tool suite for ISRU lunar construction

Mason's Progression

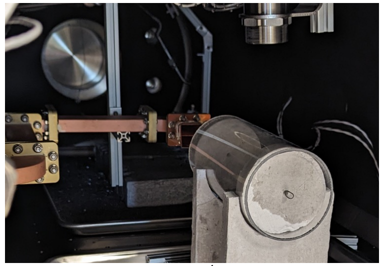
TRL 6 testing
Mar – May 2026



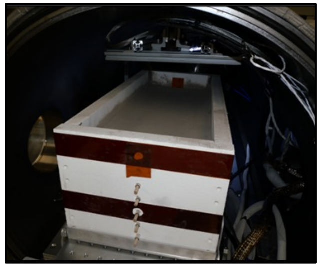
Initial vacuum testing



Early TVAC testing



TRL 5 sintering testing
July 2024 – Sept 2025



July 2023 Kickoff — May 2024 PDR — Apr 2025 CDR — Mar 2026 — Jun 2026 — Jul 2026

Ambient COTS microwave sintering of JSC-1A simulant

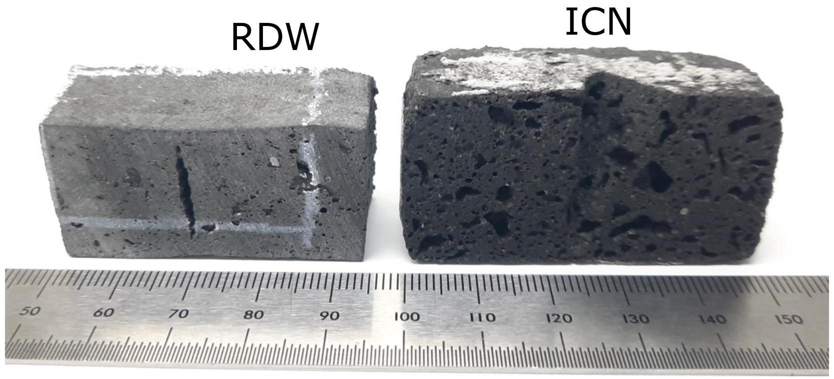
Demonstrated capability to produce 'potato' samples to validate ConOps

- *Demonstrated extension from 0D "potatoes" to 1D "baguettes"*
- *Demonstrated non-contact process control*

- *Demonstrated extension from 1D "baguettes" to 2D slab*
- *Demonstrated process at TRL 6*

Regolith Simulant

- Preliminary testing used JSC-1A, then Exolith Labs basalt; TRL 5 testing used ICN-LHT-1G purchased from ICON and heat treated by Redwire to remove nonlunar volatiles
  - Consulted NASA simulant advisory committee
  - LHT-1G represents compromise between availability and relevance to Artemis region
- ICON could not produce enough simulant for TRL 6 test campaign; Off Planet Research (OPR) was commissioned to create a simulant as closely matching as possible
  - Same mineral composition and same heat treatment applied; different mine was necessary for anorthosite component, details of glass fabrication unclear
  - Resulting simulant named RDW-LHT-1G (shortened to RDW here)
- Resulting simulant exhibits differences in compaction and heating behavior relative to ICN-LHT-1G:
  - Lower density, both loose and maximally compacted (loose: 1.28 vs 1.6 g/cc; compacted: 1.74 vs 1.93 g/cc)
  - Higher maximum sinter temperature window
  - Much greater contraction upon cooling
  - MW sintered samples have distinctive semi-circular cracks that did not appear in earlier tests using ICN-LHT-1G, Exolith Labs basalt, or JSC-1A.



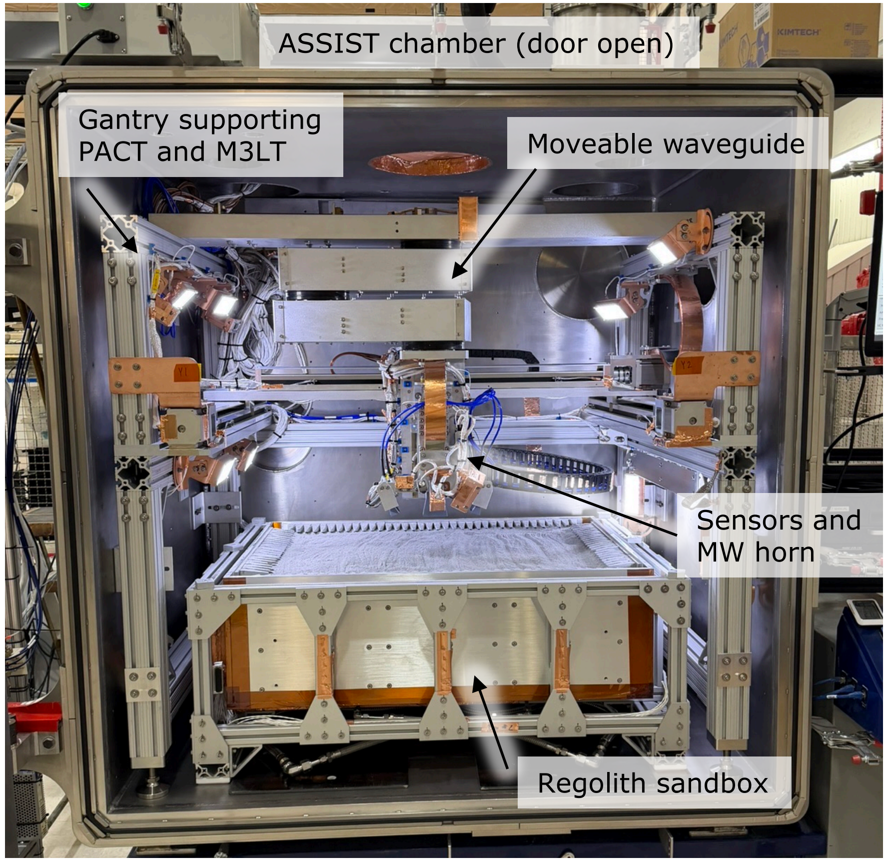
Bricks sintered side-by-side in crucibles in vacuum furnace at 1200 °C.

MW sintered RDW simulant (bottom right) has semi-circular cracks around hot spot while other MW sintered simulants do not

Supply chain challenges necessitated adapting to new simulant

TRL 6 Hardware Overview

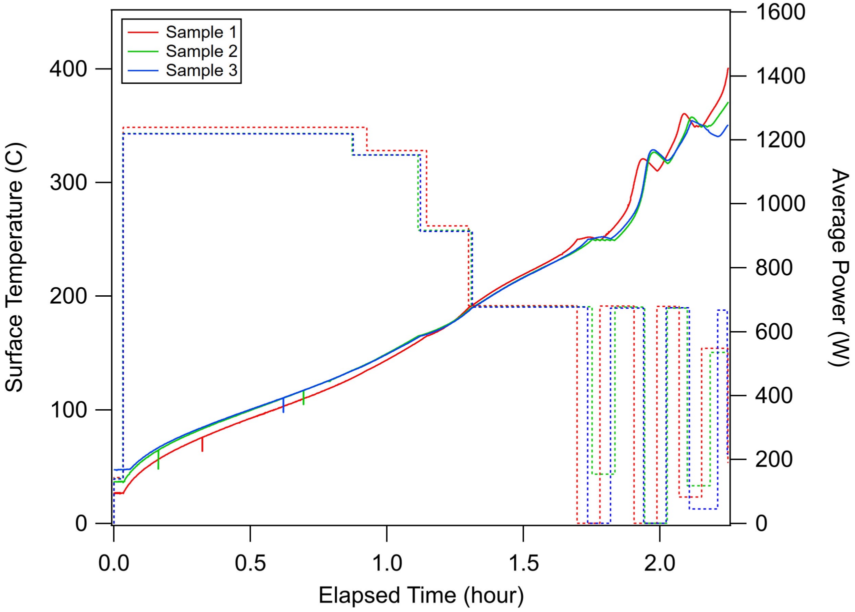
- PACT and M3LT integrated together inside the Atmospherically Sealed Simulator for In-situ System Testing (ASSIST) at Swamp Works
  - Compaction and sintering done in the same vacuum cycle – no repressurization in between that might disturb the regolith
  - Starting chamber pressure around 1e-5 Torr and kept below 1 mTorr during testing
- Regolith bed "sandbox" lined with microwave absorber panels to reduce effects of spurious MW reflections
  - Sandbox reflectivity attenuated by -29.4 dB with absorber panels added (99.9% attenuation)
- Sandbox and cold trap cooled with LN2
- Terminology:
  - "Run": One discrete microwave sintering test
  - "Cycle": One session of sandbox operations, consisting of pumpdown, compaction, multiple sintering runs, and repressurization; 5 cycles were conducted

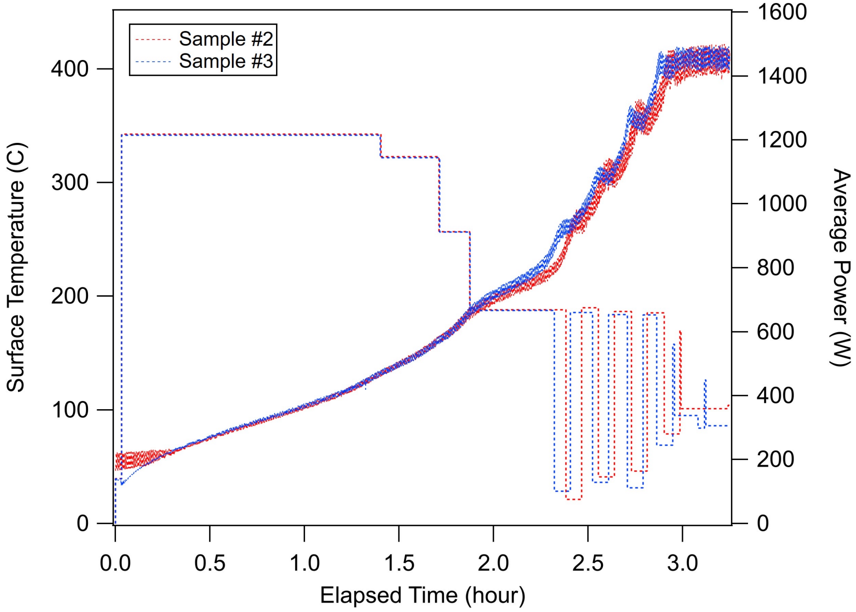


Compaction and sintering integrated into single vacuum test cycle

Sintering Repeatability

- Regolith heating response was highly repeatable for both stationary and pseudo-stationary (circles-in-place) ramping



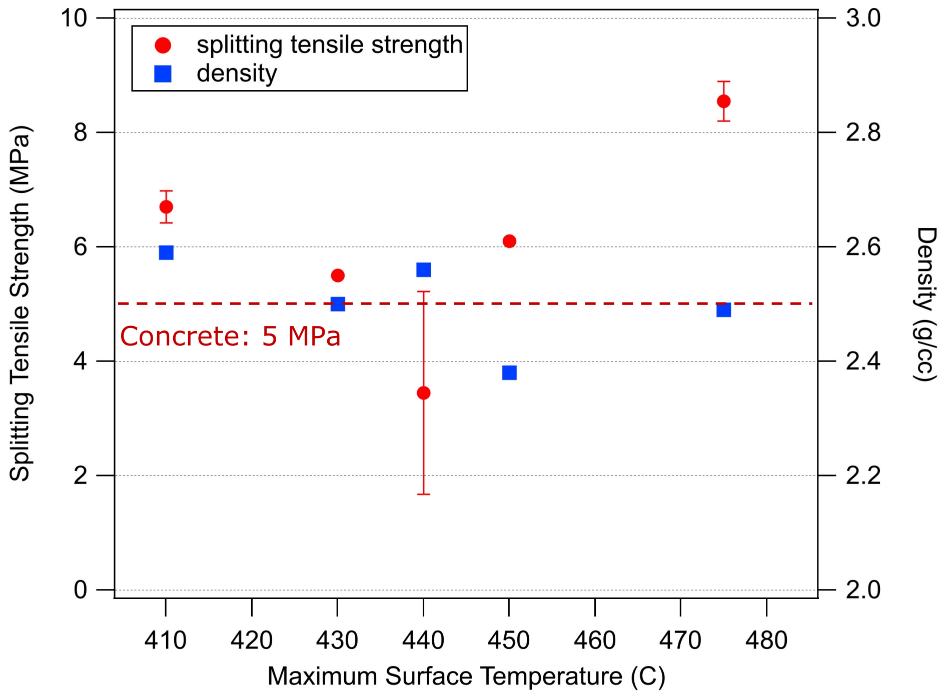


Surface temperature and average power plots during ramping while stationary (left graph) and while repeatedly moving around a 50 mm diameter circle (right graph), showing repeatable heating response.

Highly reproducible heating response

Initial Temperature Tuning

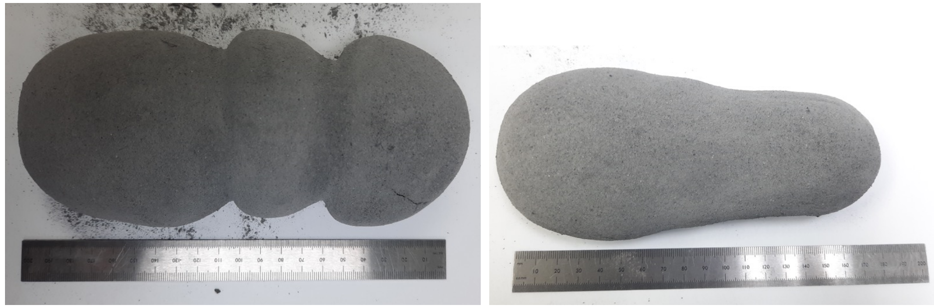
- Initial set of samples sintered at various temperatures, then splitting tensile strength (ASTM D3967) testing performed on them to identify best surface temperature to dwell
  - These were "pseudo-stationary" tests in which the MW horn continuously moved in a 50 mm diameter circle (increases heated zone, creates larger sample)
  - Sample at 475 °C was ramped until the regolith surface glowed (as seen by visual cameras) but did not dwell; others dwelled for 1 hour each
- Splitting tensile strengths ranged from 2.2 to 8.8 MPa
  - Compare to 5.0 MPa for ordinary concrete (Jehn and Dreyer, 2025, "A design methodology for flat slab lunar landing and launch pad systems")
  - Compressive strength is typically 10 – 12 times greater than splitting tensile
- 410 °C and 475 °C dwell temperatures targeted in subsequent tests



Preliminary strength results are encouraging

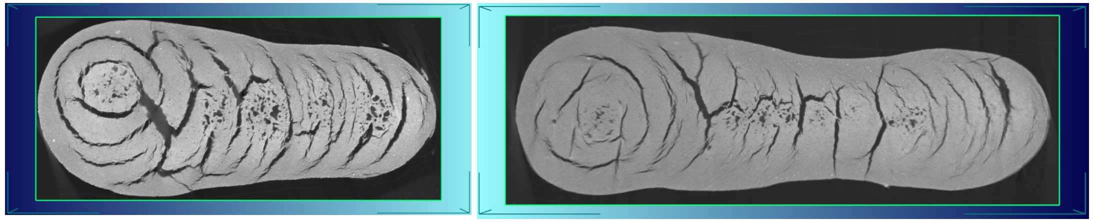
Motion Parameter Tuning

- Motion pattern: overlapping circles (varied circle diameter, circle overlap)
  - Compared to pseudo-stationary tests, higher power to dwell but also higher efficiency
  - New defect observed: semi-circular cracks
- Motion pattern: slow linear travel (varied speed, constant vs intermittent motion, dwell temperature, dwell power)
  - Semi-circular cracks were not prevented (suspected cause is this simulant's large volume change with temperature)
- Motion parameter: Row spacing
  - Hairpin turn tested with 2 row spacings



Circular motion overlap parameter had large effect on sample shape.

Hairpin turns demonstrated with 2 row spacings.

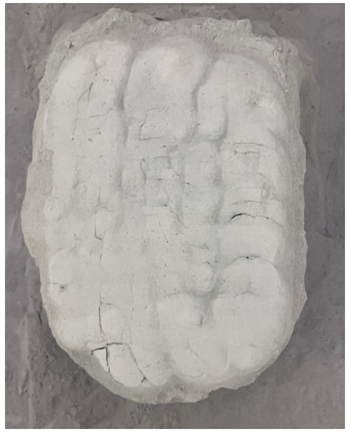


Examples of semi-circular cracks in both circular motion (left) and linear motion samples.

Motion parameters selected for large slab fabrication

2D Motion: Large Slab (1 of 2)

- 73-hour serpentine path test resulted in a 9 kg slab dubbed the Regoloaf
  - Length: 33.5 cm
  - Width: 24 cm
- Semi-circular cracking was still present
- Bulbous protrusions on underside are likely sites of re-ramp after resuming test after pauses
  - Test pauses were required to avoid chamber overpressure during switching of LN2 dewars



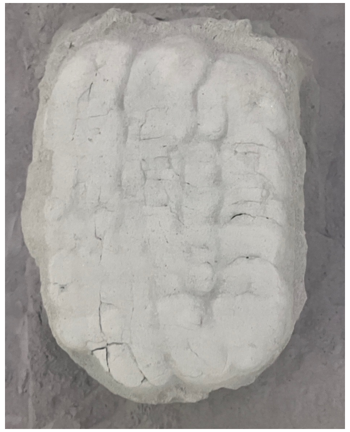
Top surface (partially excavated)

Bottom surface

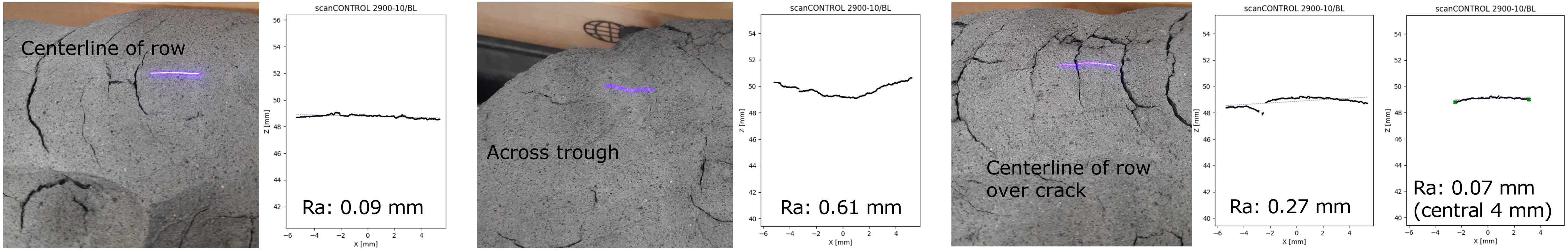
The Regoloaf is over 9 kg!

2D Motion: Large Slab (2 of 2)

- Top surface is mostly flat with gently rounded rows separated by troughs
- Parallel to rows: roughness Ra ~0.15 mm excluding cracks (by laser profilometer); variation in height over entire row length typically 2 – 4 mm (by ruler)
- Perpendicular to rows: roughness Ra ~0.40 mm excluding cracks (by laser profilometer); variation in height up to 6 mm between crests and troughs (by ruler)



Top surface (partially excavated)



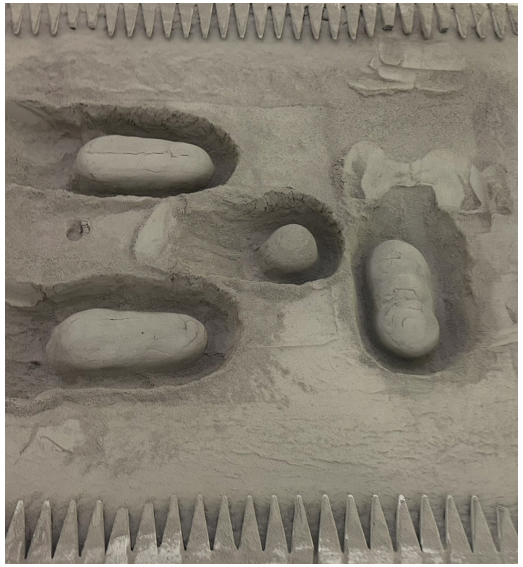
Example surface profiles by laser profilometer

Flat top surface

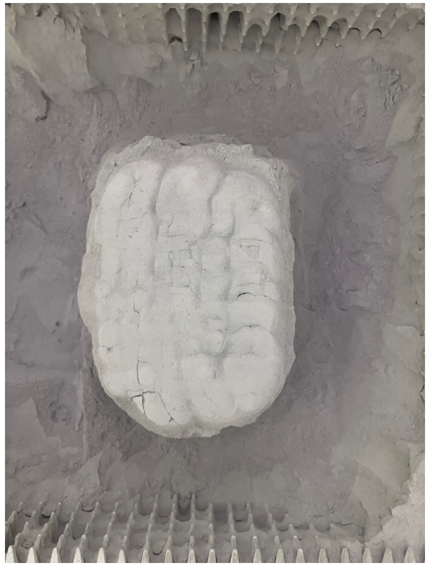
Efficiency Increase with Larger Samples

- Efficiency increased significantly when extending from 0D to 1D to 2D motion
- Process parameters are not yet optimized – expecting continued improvement in efficiency and sample quality

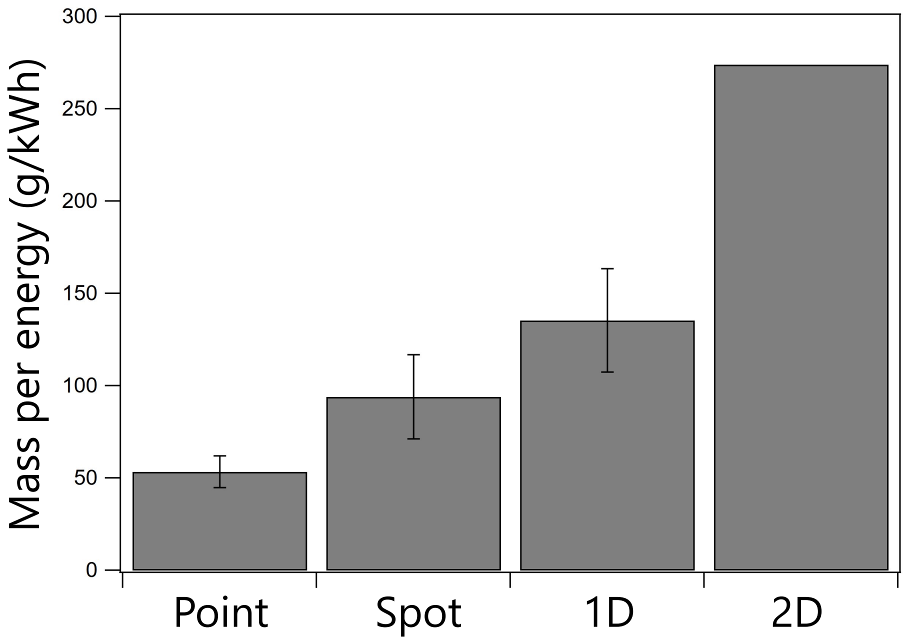
0D (circle or spot)



1D motion



2D motion



Efficiency increases as motion is extended from 0D to 1D and 2D. Data includes TRL 5 and TRL 6 tests using both ICN and RDW simulants.

Efficiency trend is encouraging for scaling up

In-Progress and Future Work

- **Mason has demonstrated:**
  - Highly repeatable in-situ sintering of regolith simulant in relevant environment with noncontact process control
  - Versatility of process by successful sintering of multiple regolith simulant types
  - Production of sintered regolith samples with strength greater than concrete
  - Increasing efficiency as parameters are tuned and sample sizes increase
- **In progress:** Characterization of TRL 6 samples
- **Planned:** MW sinter testing with other regolith simulants to demonstrate enhanced sample quality (reduced/eliminated internal cracking) by using simulants of higher fidelity/relevancy
- **Planned:** Expanding Mason's capabilities to demonstrate multi-layer construction, bricks/pavers, and grouting/joining tiles

Dec 2023

May 2024

May 2026

Characterization is in progress and further capabilities are planned

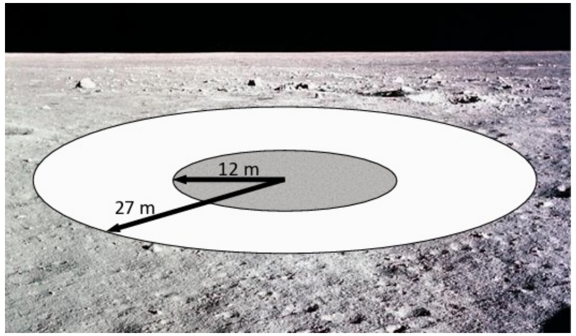
Future Outlook

- Estimated construction times for an inner landing pad with 12-meter diameter and 50 mm thickness shown for various power levels available
- Greater speed and efficiency improvements are expected as process is optimized
- Greater efficiency expected with Artemis-region regolith due to increased MW susceptibility with increased iron content
  - 4.53 wt% iron content in TRL 6 simulant (RDW-LHT-1G), 4.8 wt% in TRL 5 simulant (ICN-LHT-1G)
  - 5 – 10 wt% iron content expected in Artemis region (source: Lemelin et. al., 2022 “Compositional maps of the lunar polar regions derived from the Kayuga Spectral Profiler and the Lunar Orbital Laser altimeter data”)

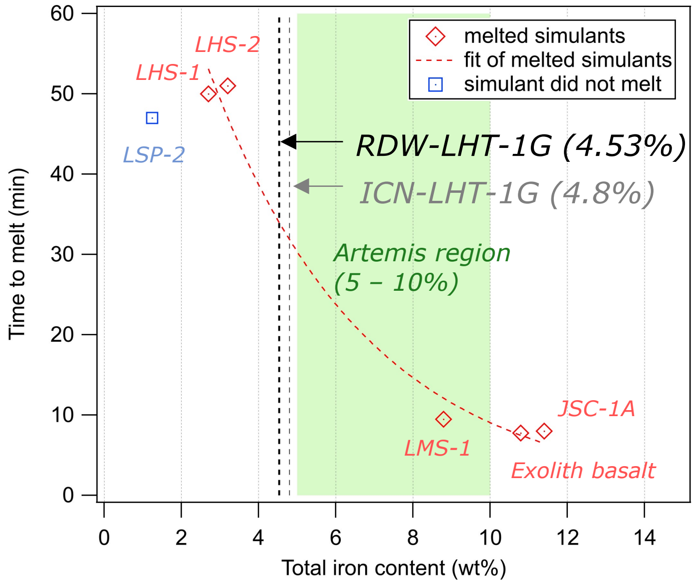
Conservative Landing Pad Construction Predictions

Power Availability	Conservative Construction Time Estimates*
436 W (same as the Regoloaf)	13.1 years
1000 W	5.7 years
5,000 W	1.1 years
10,000 W (projected power available at Lunar Innovation Park)	0.6 years

*Note: Actual construction times are expected to be significantly shorter for Artemis-region regolith due to increased microwave susceptibility



Baseline inner pad diameter and figure from Metzger and Autry, 2022, “The cost of lunar landing pads with a trade study of construction methods”; lunar surface image from NASA.



Dependence of time to melt on iron content for various simulants (Redwire data).

Construction time scales with available power; increased efficiency expected in Artemis region

Thank You

- We thank our collaborators at KSC Swamp Works and Colorado School of Mines
- Any questions?