RENEST

REFURBISHMENT ENHANCED NON-SINTERED EXTRUDABLE SURFACE TECHNOLOGY

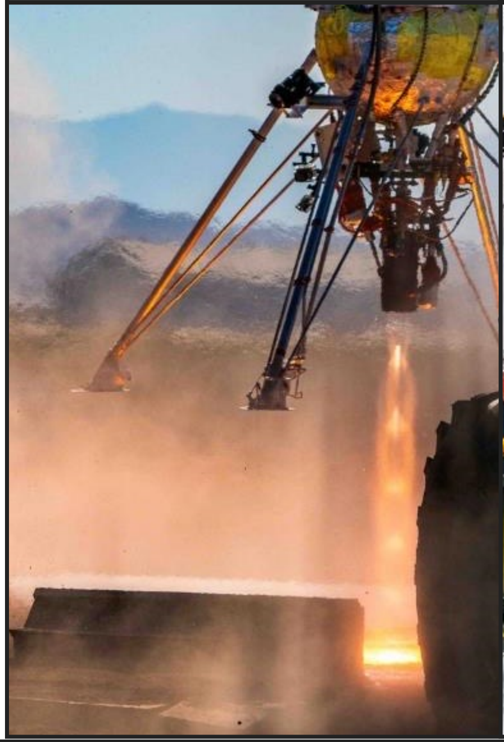
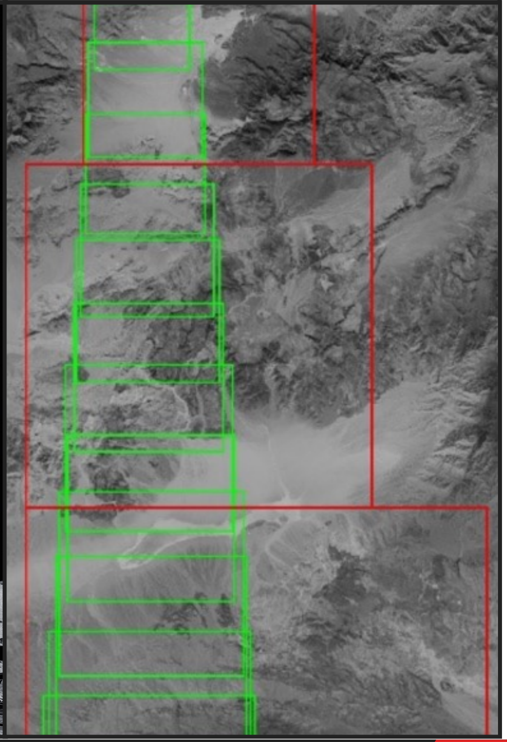
XXVI Space Resources Roundtable

6/4/2026

ASTROBOTIC

WHO WE ARE – ASTROBOTIC

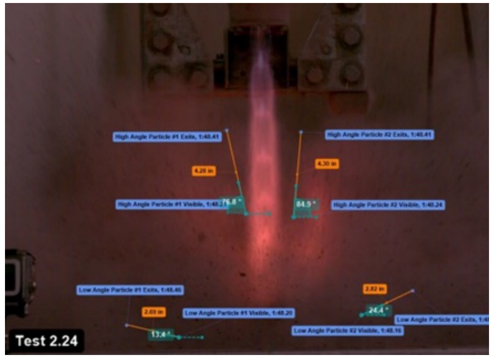
Astrobotic is a pioneering force in space exploration specializing in suborbital, lunar, and in-space systems. With a robust portfolio of over 60 contracts from NASA, the DoD, and commercial entities totaling more than $600 million, we cover a lot of ground (and space). Our expertise spans from lunar landers, rovers, and power infrastructure networks to reusable rockets and rocket test beds. We are developing power generation systems and distribution services that will deliver power by the Watt to landers, rovers, habitats, science suites, and other lunar surface systems.

ROCKETS	LANDERS	ROVERS	POWER	SENSORS
				

ASTROBOTIC ISRU & PSI STRATEGY

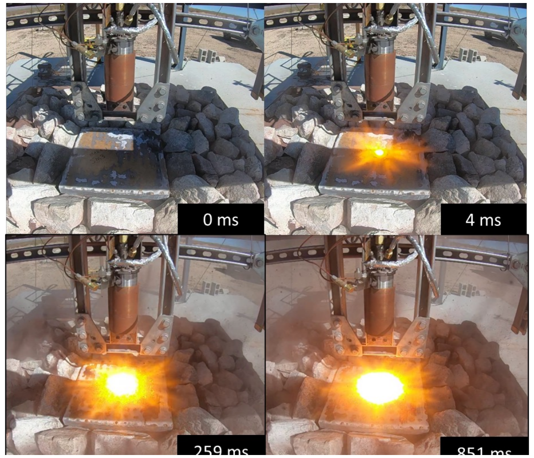
- Overview of Strategy
  - Use & enable ISRU applications
  - Understand plume-surface interaction (PSI) phenomena
  - Mitigate PSI hazards

- ISRU and ISRU-Enabling Projects
  - Direct ISRU
    - RENEST – Low energy pavers
    - RocketM – Rocket driven excavation
    - BUILD – Rover for construction using MRE slag bricks
  - Enabling
    - Floatinator – Reduced gravity PSI testing
    - NITE – Survive the night warming & power
    - FAST – Just-in-time landing pads



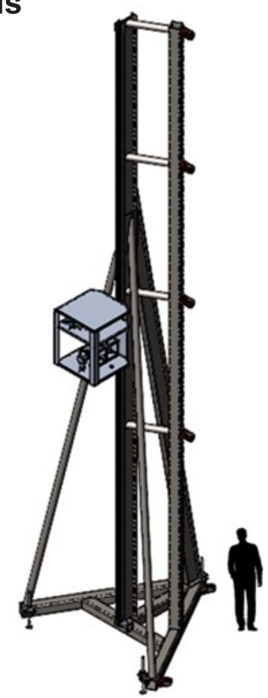
Ejecta Analysis

Subsurface Cratering Analysis



Landing Pad Testing

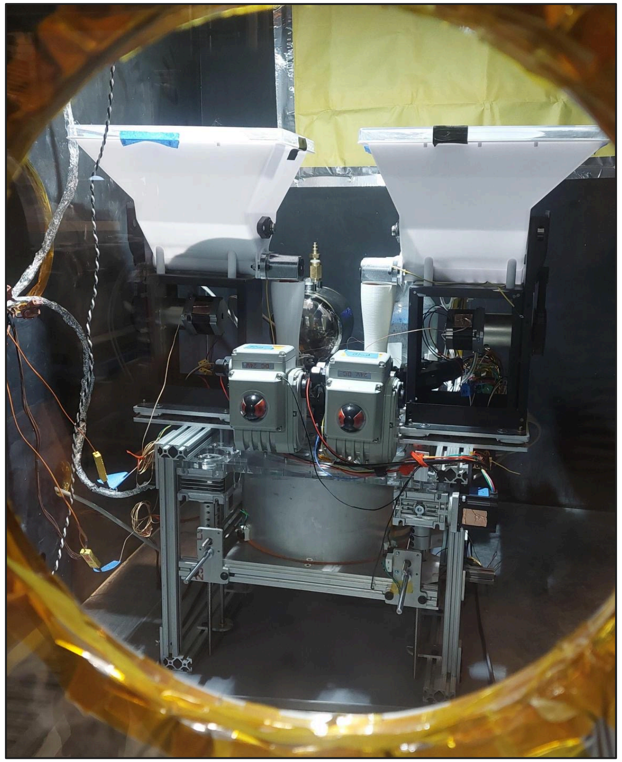
RocketM Excavation



Floatinator Test Platform

RENEST SYSTEM OVERVIEW

- RENEST – **R**efurbishment **E**nhanced **N**on-sintered **E**xtrudable **S**urface **T**echnology
  - Envisioned as a lunar landing pad fabrication technology for sites with no prior infrastructure
- Cures into a hardened surface using the following materials
  - Binder – Brought from Earth
  - Lunar regolith – In-situ
  - Water – In-situ ideally; Brought from Earth initially
  - Acid – Brought from Earth at high concentration and diluted with water in-situ)
- Low power requirements when compared with sintering



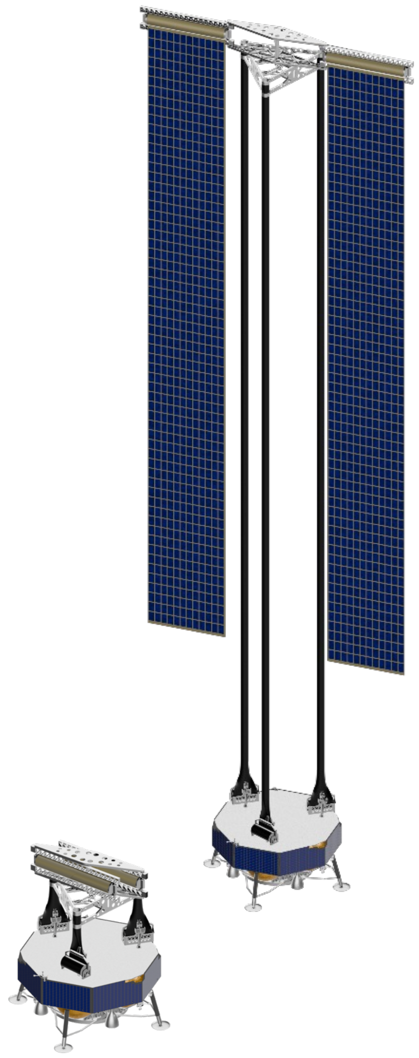
RENEST Paver System in DTVAC

Hot Fire Testing on RENEST Paver

RELEVANCE

- Why are landing pads needed?
  - PSI effects can put landers or other nearby assets at risk (P.T. Metzger and J.G. Mantovani 2021) [1]
    - Viscous erosion
    - Bearing capacity failure
    - Diffused gas eruption
    - Diffusion-driven flow
    - Shock impingement splashes/repeated shocking of the soil
  - Landers with larger payloads increase the risk

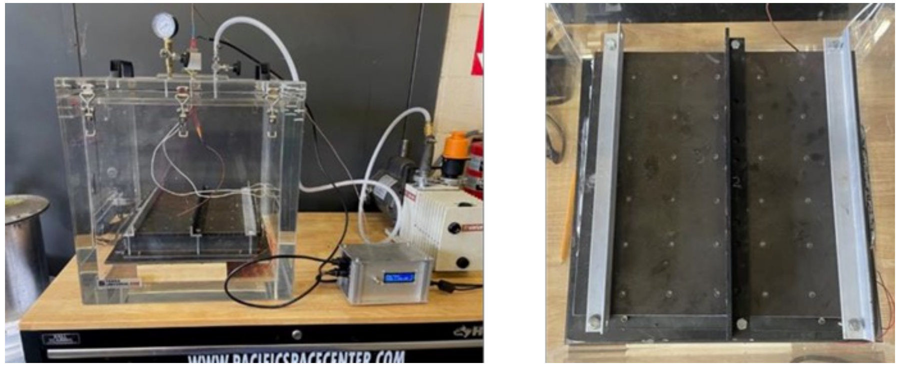
- Why are low power solutions needed?
  - Estimated power consumption for construction for a 40t capacity lunar landing pad is on the 10’s of mega-watt hour scale with peak power of 200 kW (P. T. Metzger and G. W. Autry 2022) [2]
  - RENEST’s objective is to provide the pad to land heavy power infrastructure in close proximity without the need for many dispersed landings



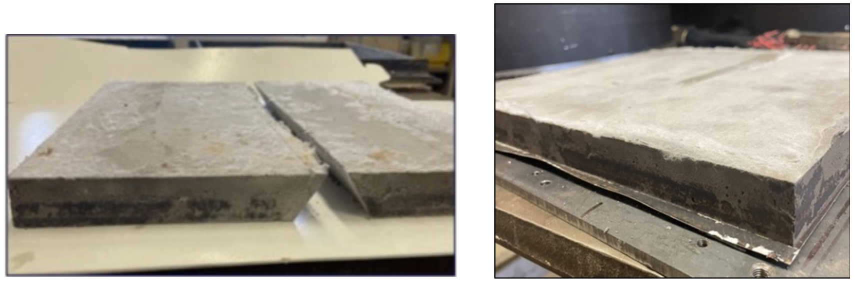
Astrobotic VSAT-XL 50kW

STTR PHASE I SUMMARY

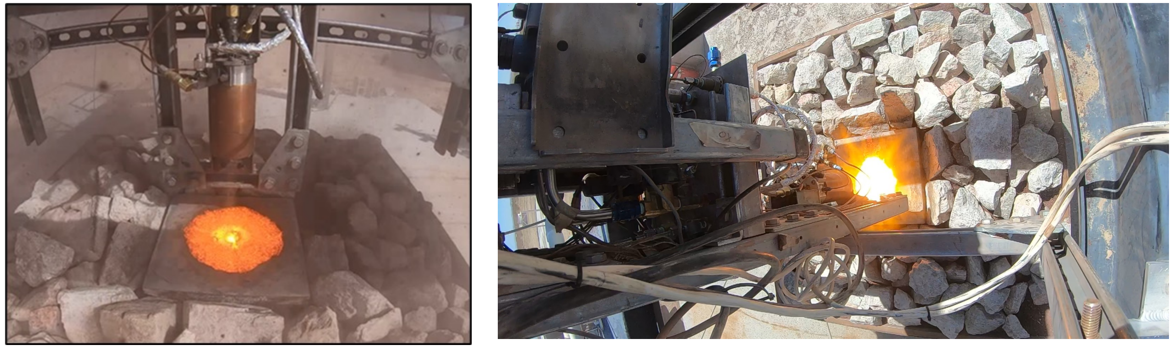
- Fabricate pavers in relevant environment and test under live rocket plume
  - Research Institute: PISCES (Pacific International Space Center for Exploration Systems)
- Mixture Development
  - Formula: 70% <100 μm basalt and 30% binder solution (40% concentration)
  - 70/11.1/18.9 Wt% Regolith/Binder/Water
  - Cured in perforated steel mold for ~30 hr in relevant environments
    - Lunar: 1.5x10^-3 torr, 70° C
    - Martian: 7.5 torr, 70° C, CO_2 environment
  - 30 cm x 30 cm x 2.5 cm paver dimension
- Tested cured pavers beneath a live rocket plume
  - 0.2 m above paver
  - 2 s test duration
  - 2200° C plume temp at stagnation point (estimated)
  - Refurbished and re-tested some pavers
- Strength Testing
  - Compressive Strength
    - Lunar: 13.71 MPa compressive strength pre hot fire, 5.15 MPa post hot fire
    - Martian: 14.25 MPa compressive strength pre hot fire, 9.09 MPa post hot fire
  - Bending strength 10-20% of compressive on all samples



Vacuum Chamber & Mold for Curing



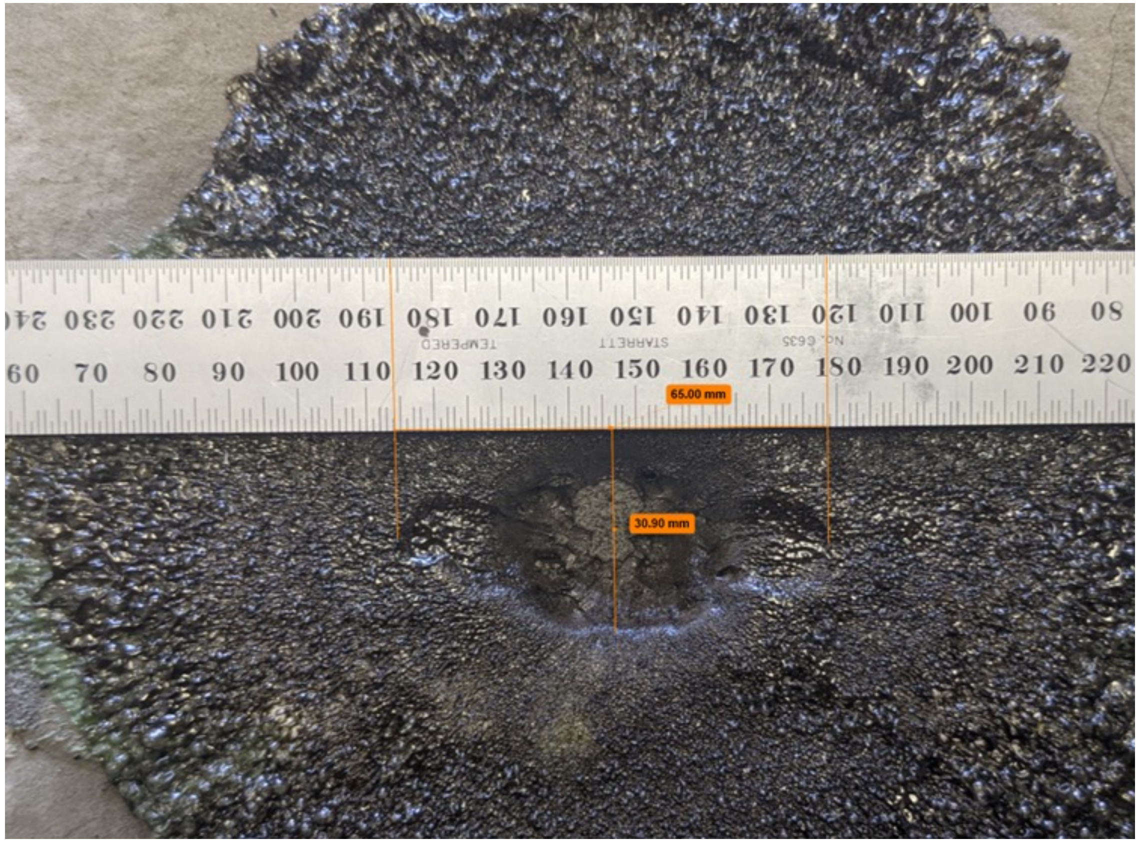
Cured Pavers



Paver Hot Fire Testing


GL2
GL2

STTR PHASE I HOT FIRE TEST RESULTS



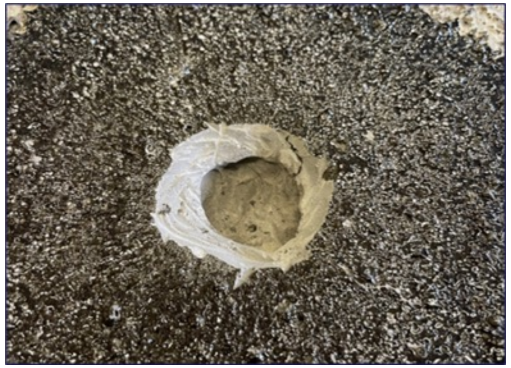
Degradation Width

Degradation Depth

Paver GL2 Post Hot Fire
Lunar Curing Conditions
Grouted Wedge Joint

STTR PHASE I HOT FIRE TEST RESULTS

Degradation After First Hot Fire


Refurbishment Surface Prep

Degradation After Refurbishment and 2^{nd} Hot Fire

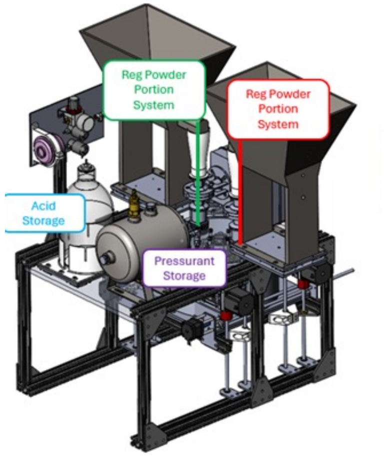
Paver SL3 Post Hot Fire
Lunar Curing Conditions
No Joint

STTR PHASE II SCOPE

- Develop RENEST production system
  - Mix and cure semi-autonomously
  - Test system in a relevant environment
    - Michigan Technological University (MTU) Dirty Thermal Vacuum Chamber (DTVAC)

- Continue mixture development
  - Investigate variations in regolith, binder, and water proportions
  - Investigate use of additives for improved workability and cure times

Mixture Development Samples



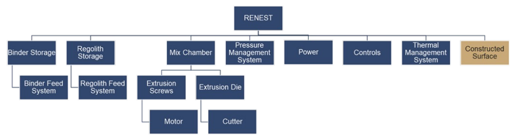
Paver Production System

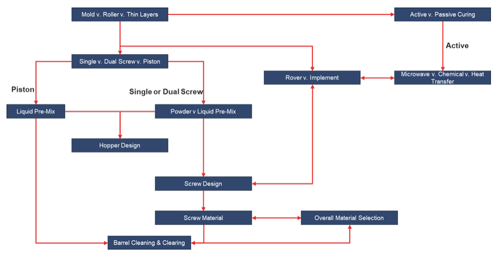
MTU HuskyWorks DTVAC Chamber

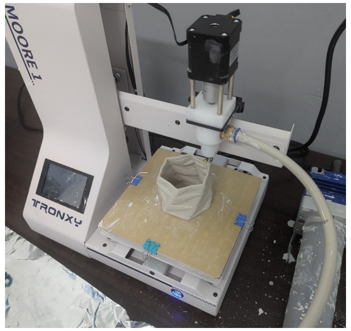
STTR PHASE II TIMELINE

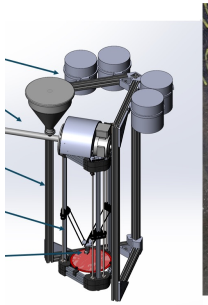
Sep 2023 – Mar 2024	Mar 2024 – Sep 2024	Sep 2024 – Mar 2025	Mar 2025 – Sep 2025	Sep 2025 – Feb 2026
Develop Requirements Analysis of Alternatives	Test COTS System Initial Extruder/Gantry Design Mixture Prototyping	Updated Extruder/Mold Design & Prototype Fabrication	Extruder Integration, Troubleshooting, & Challenges	Pivot to Mix-in-Mold Design DTVAC Testing

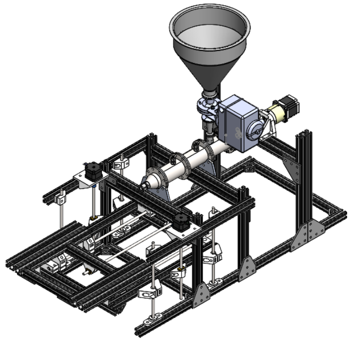
Sep 2023 | Mar 2024 | Sep 2024 | Mar 2025 | Sep 2025 | Feb 2026

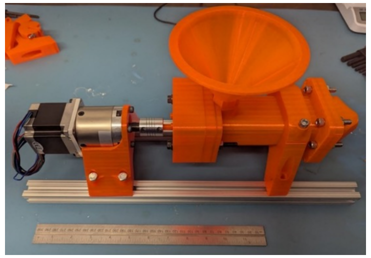


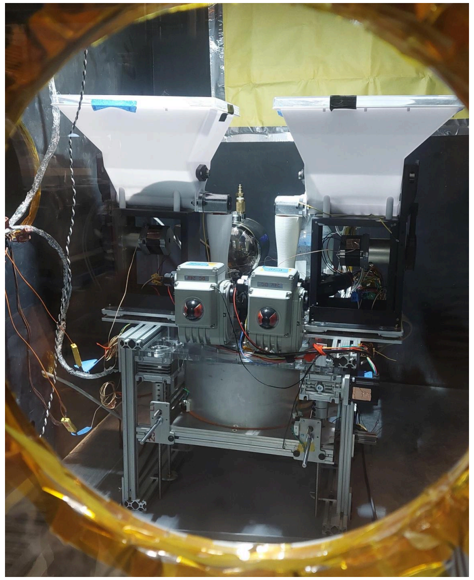










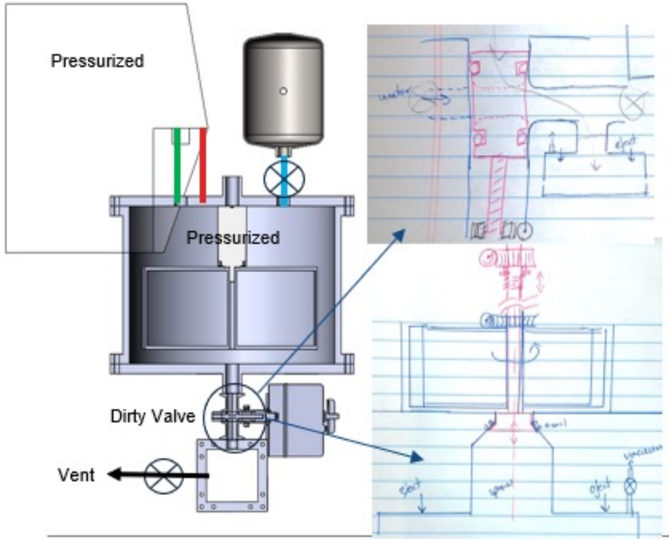


ARCHITECTURE TRADE STUDY

- The team considered alternative mixer designs later in the program after encountering continuing issues with the extruder
- Mix In Mold design was chosen to avoid the need for airlocks required to input material into the system and removed the need for wet binder to move through valves

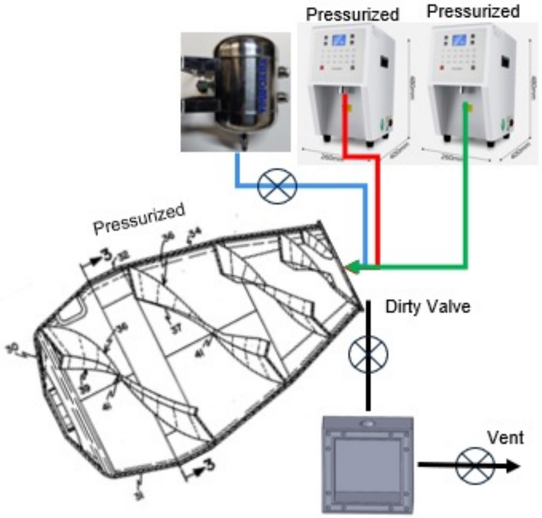
Mix In Vat

- Good mixing agitation
- Few moving parts and parts are available
- Very easy material input
- Reliance on gravity feed
- Dirty valve/seal problems (see below)
- Requires pressurized regolith storage



Cement Mixer Style

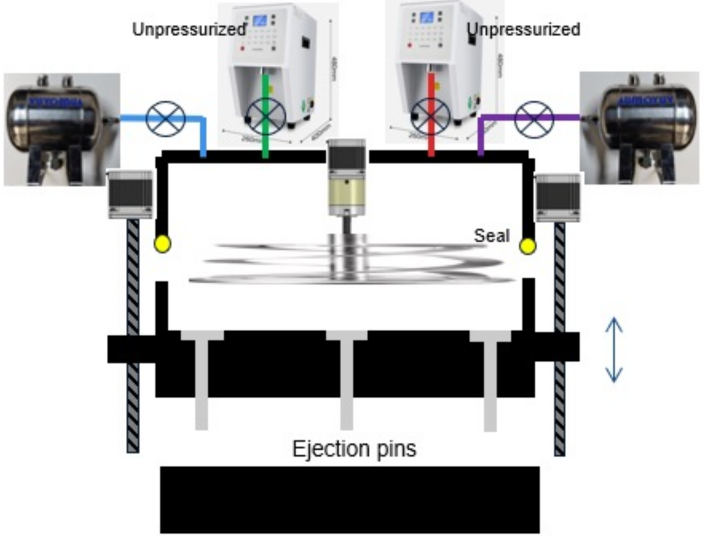
- Very good mixing agitation and lots of industry research and experience
- Actively conveyed into mold
- Similar dirty valve/seal problems as mix in vat
- More difficult material inputs
- Complex parts/geometry
- Requires pressurized regolith storage



Mix In Mold

Recommendation

- Ok mixing agitation
- No need for dirty valves
- Very easy material input
- Little to no reliance on gravity
- Does not require pressurized regolith storage
- Lots of moving parts
- Dynamic Seal

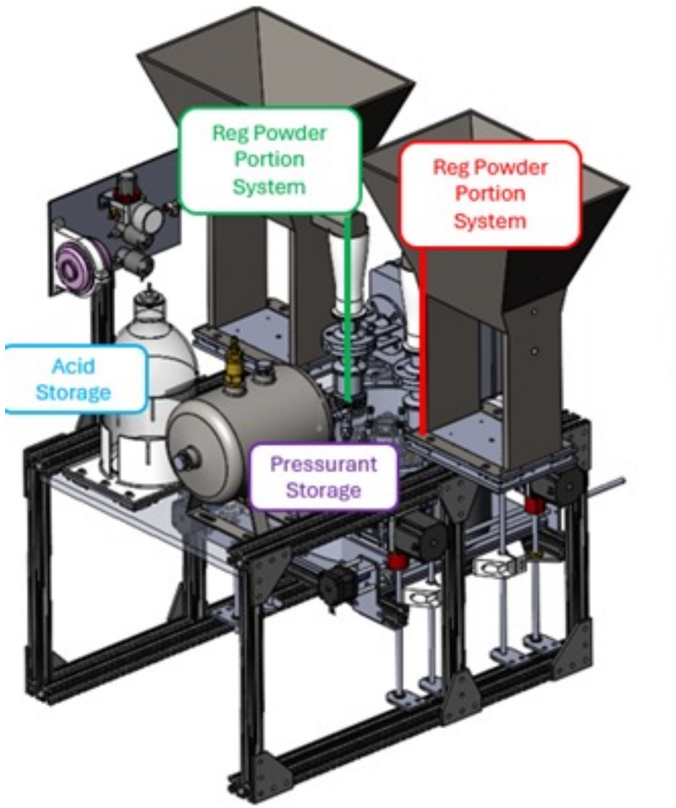


MIX-IN-MOLD DESIGN & CONOPS

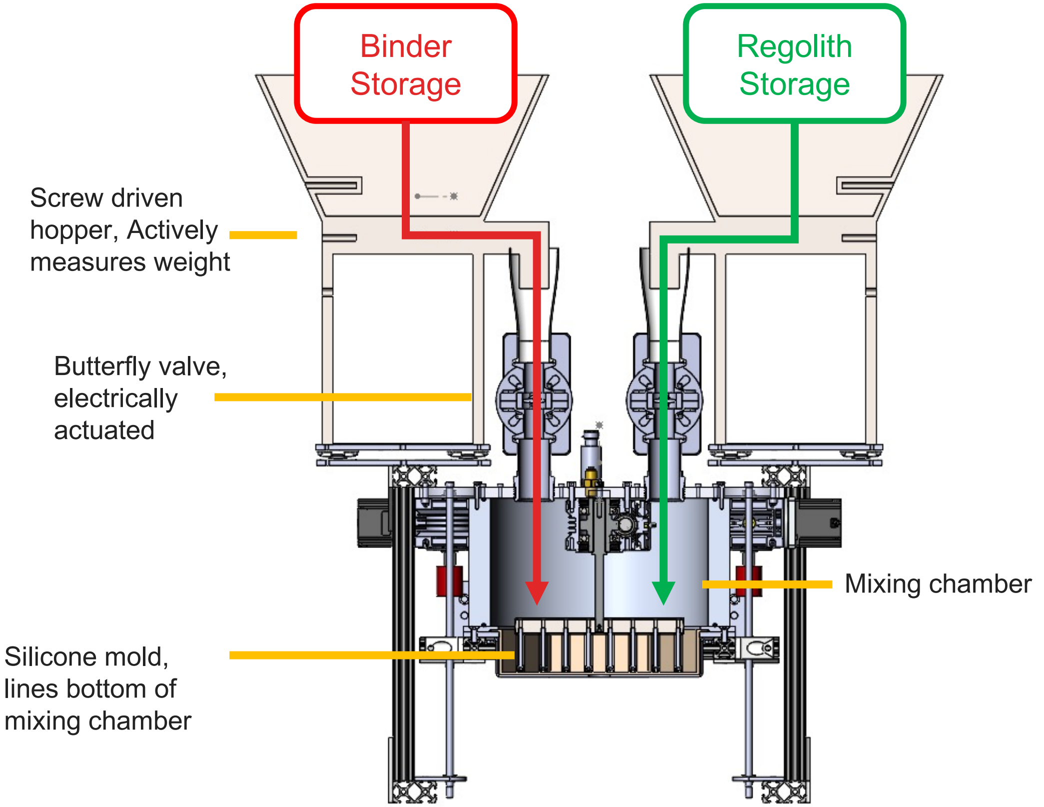
Simplified Operational loop:

1. Input powdered binder and regolith into the mixing chamber and mix.
2. Add pressurant and 0.1M acid solution to the sealed chamber and mix. Then open vent to slowly de-gas larger bubbles (10 minutes).
3. Lower mold gantry partway to break seal and expose mixture to vacuum for full curing process (5 hours).
4. Lower mold gantry fully onto ejection pins and use wiper stage to remove sample from system

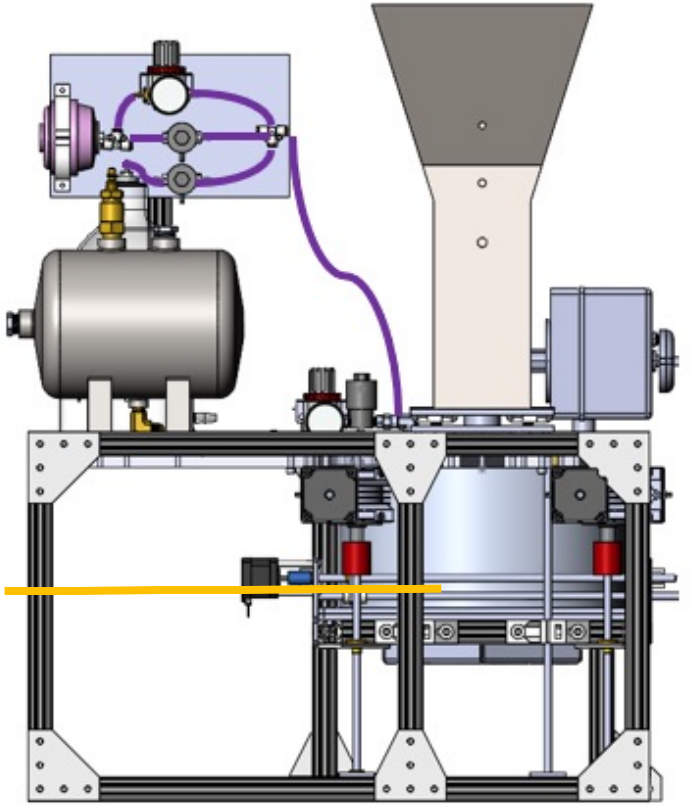
Ortho View



Cross-Section View (Raised Mold Gantry)



Side View



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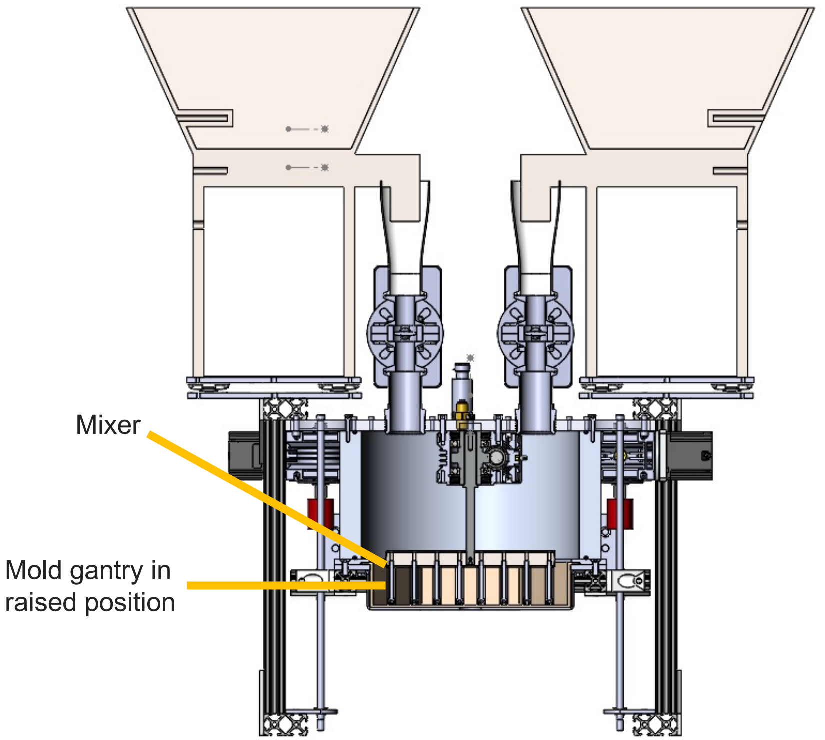
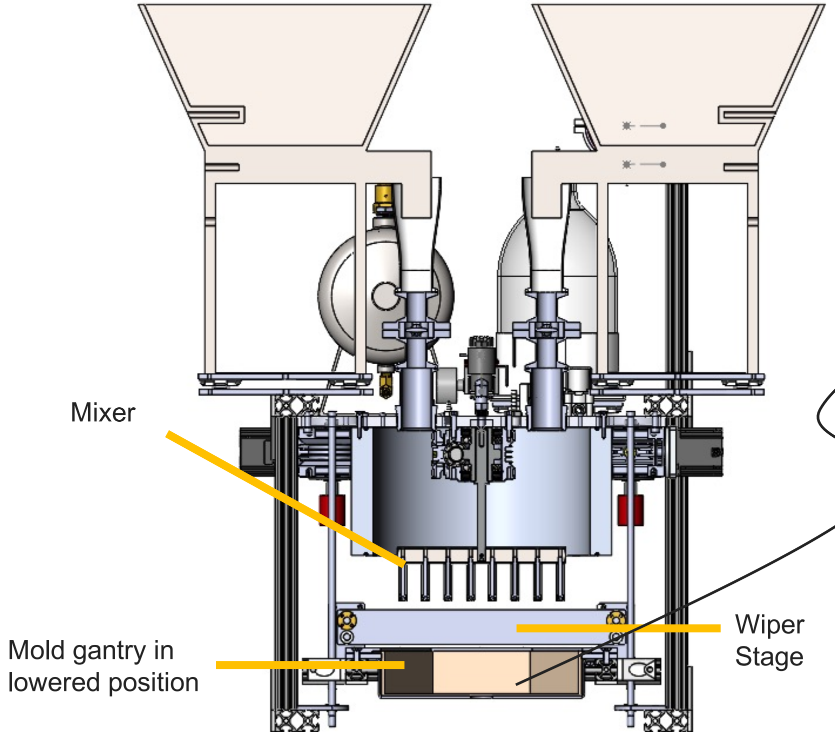
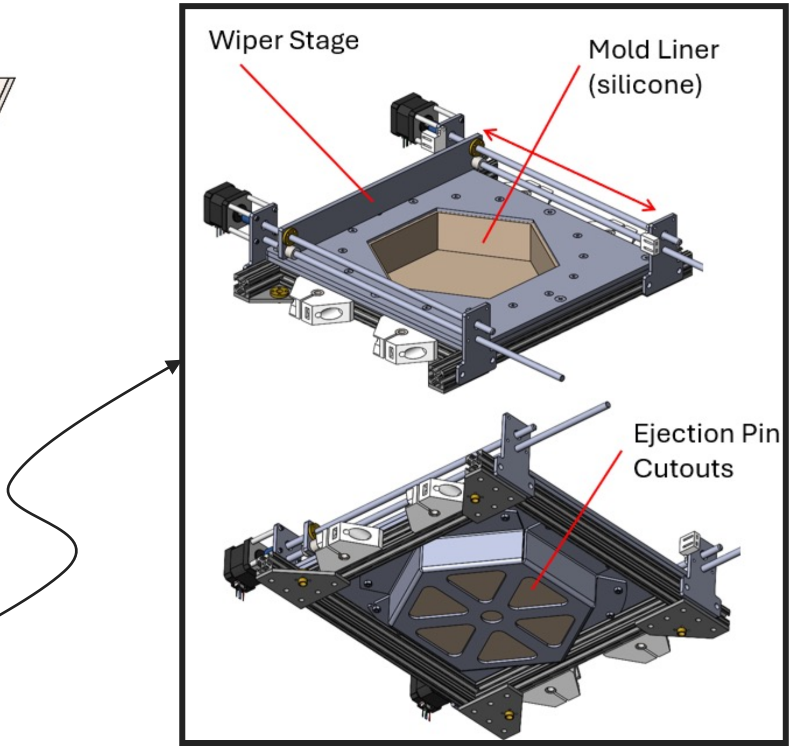
Raised Mold Gantry



Lowered Mold Gantry

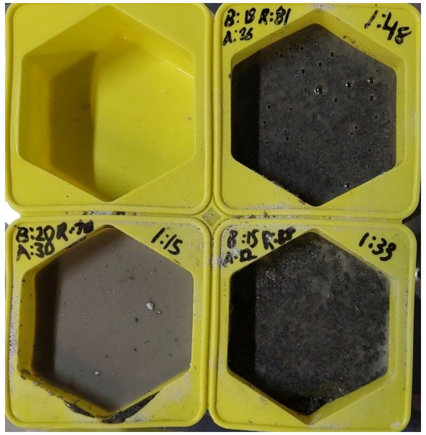


Mold Gantry Details

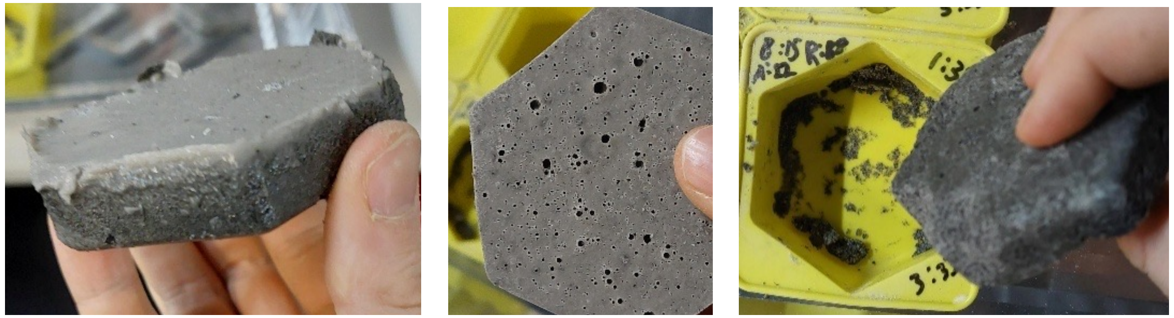


WHY ACID? ACCELERATING CURE TIMES

- One of the critical issues with the existing CONOPS was the duration of time required for a cure
  - 30 hrs in Phase I
  - Repeat tests could take even longer depending on ability of the vacuum pump (3 days in Astrobotic bake out oven)
- Accelerants for our binder are used in industry and include CO2 gassing and use of acids
  - CO2 curing was attempted in Phase I by nature of curing in Martian environmental conditions, but it needs to be injected into the center of the sample to be effective. Typically used with larger grain size material.
  - Acids were experimented with to some success
- Water replaced with 0.1M acid solution in RENEST system to accelerate cure times
- Acid does introduce corrosion concerns, requiring PTFE lined tanks, lines, and valves in the acid fluid loop
  - The acid is neutralized when added to the binder



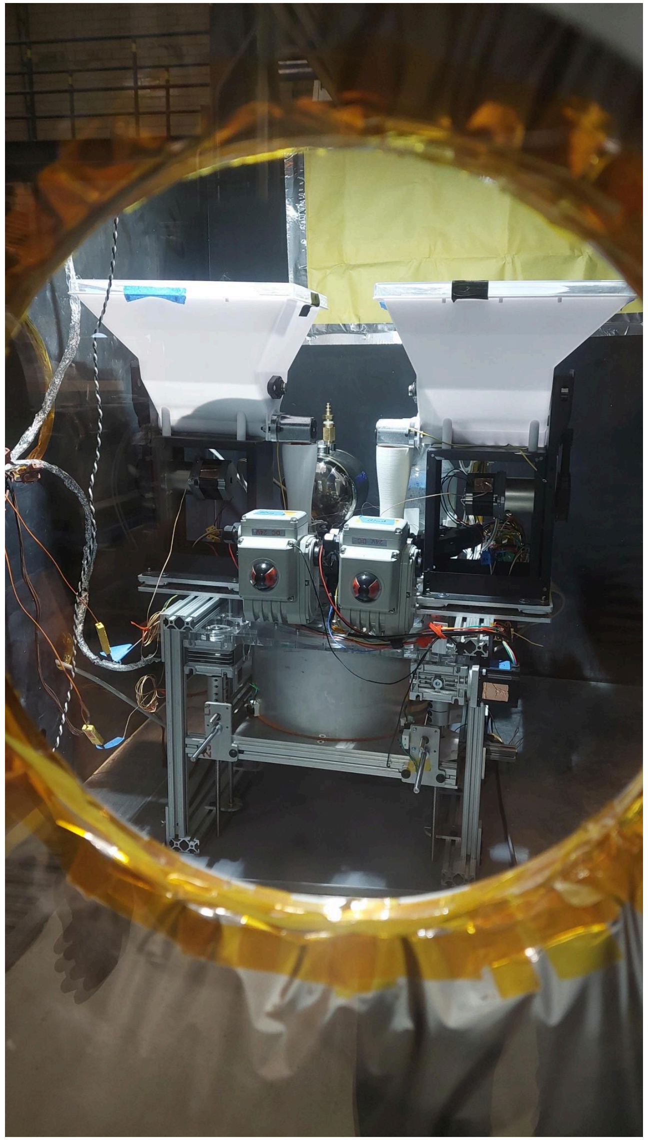
Test Samples to Investigate Acid Accelerant for Different Regolith Ratios



Cured Test Samples. 60% Regolith Left; 65% Center; 70% Right

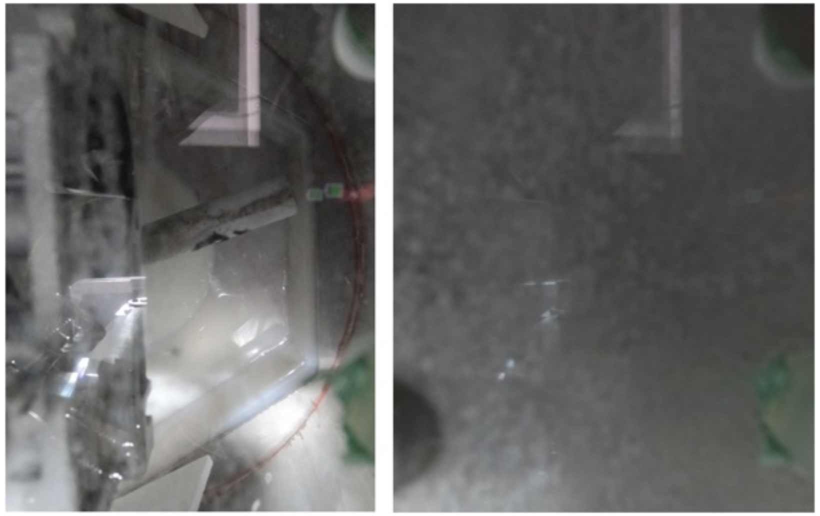
DTVAC TESTING

- Dusty Thermal Vacuum Chamber (DTVAC) at Michigan Tech
- 3 Test Runs Conducted
- Primary Test Objectives – All Achieved
  - Produce a paver in a relevant environment which can be strength tested
  - Measure the power draw required for dispensing and mixing operations
- Secondary Test Objectives – Did Not Achieve
  - Paver mold ejection
  - Continuous operation (i.e. making multiple pavers in one vacuum test session)
- Mixture Formula:
  - 65% LHS-1E Regolith Simulant – Space Resource Technologies
  - 21% 0.1M Acid Solution
  - 14% Binder Powder
- Environment Conditions
  - Temperature: 25°C
  - Pressure: Must be below 4 torr to guarantee solution is below it's triple point
    - Pressure peaked at 0.16 torr during volatilization



DTVAC TEST RESULTS – TEST #1

- Test #1 unsuccessful due to sample not curing
- Powder dispensing caused ejecta that clouded interior view
- Experienced inversion of pressure differential
  - Required a change in how chamber pressurization was conducted
- Residual acid solution in lines was prematurely dispensed onto powder and began curing early
  - Re-routed plumbing for fluid pressurant line
- Left sample to cure for 12 hours in 2psi sealed mix chamber to match integration test conditions
  - This was the slow pressure drop period just after mixing but before full vacuum



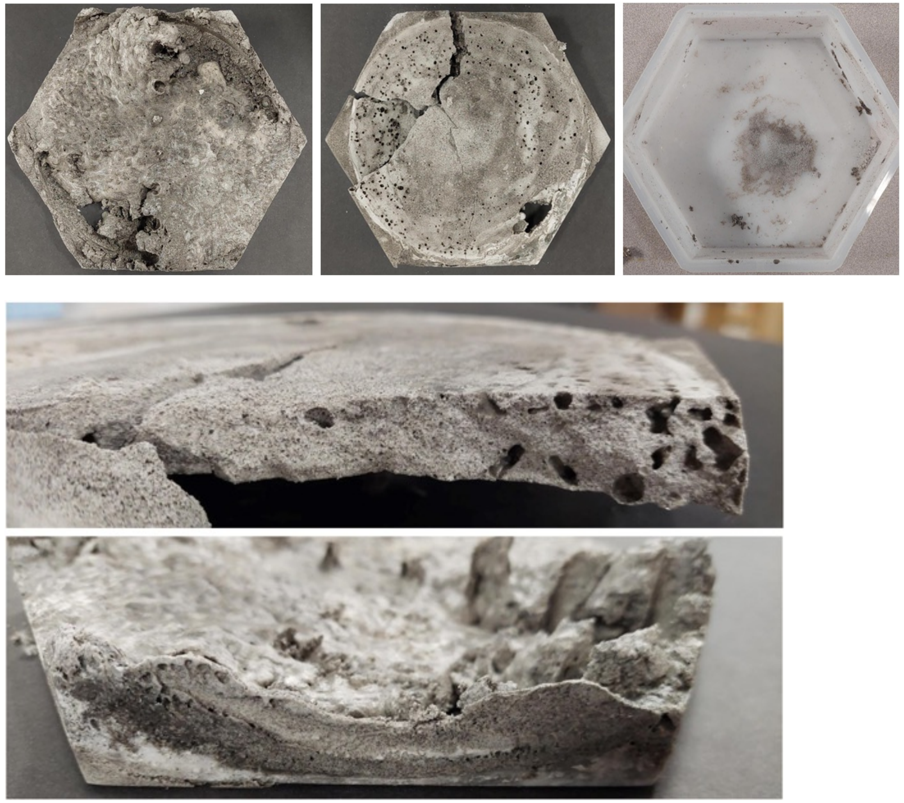
Interior View of Mix Chamber. Before Powder Dispensing (Left); After Powder Dispensing (Right)

Test #1 Product

DTVAC TEST RESULTS – TEST #2

- Test #2 partially successful
- Powder manually dispensed before vacuum ops began to avoid obscuring interior camera view
- Sample left to cure overnight for 11 hours in vacuum
- Attempted to eject paver, but crack formed from the pressure
- Overall crumbly texture, which appeared to stem from improper mixing

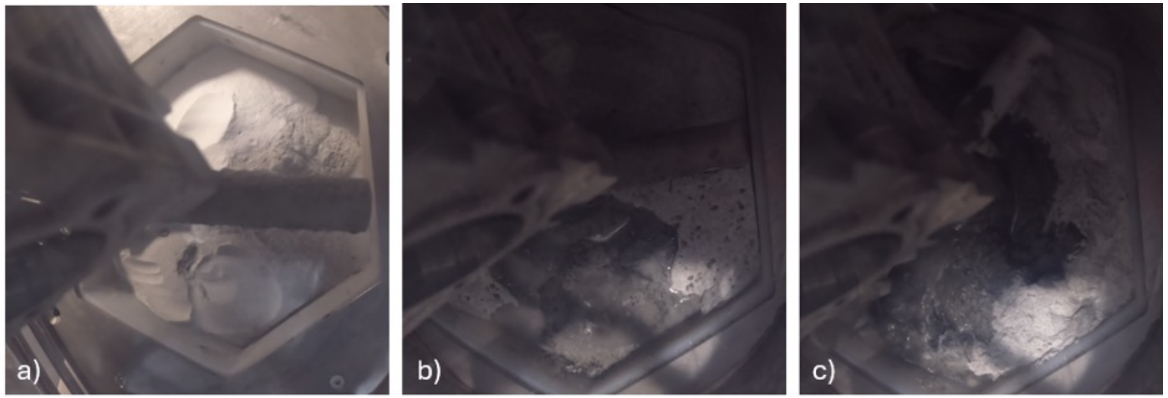
Test #2 Interior View of Mixing



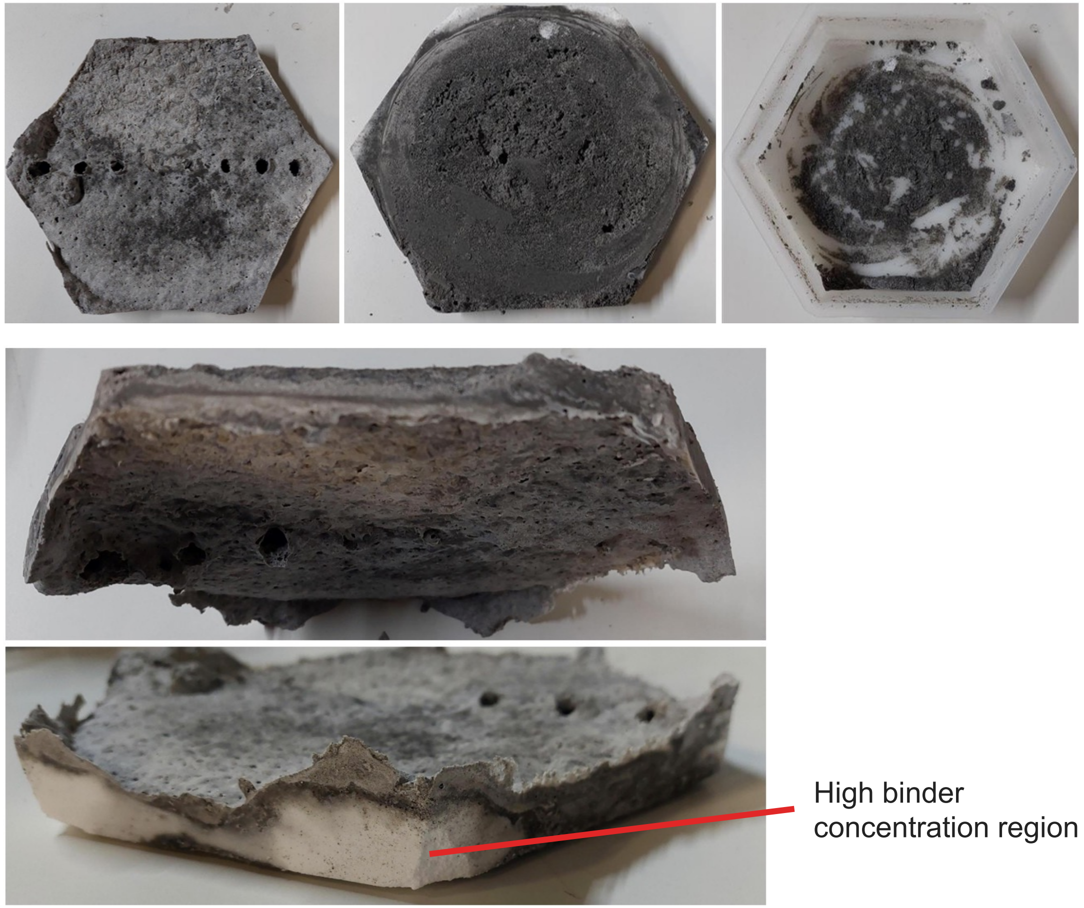
Test #2 Cured Paver

DTVAC TEST RESULTS – TEST #3

- Test #3 successful
- Added additional mixing cycles to CONOPS
- Residual acid deposited on top of the mixture during de-gassing
  - This was the slow pressure drop period just after mixing but before full vacuum
- 5-hour cure time
- Left sample in mold until returned to Astrobotic HQ
- Corner regions not fully mixed and had higher binder concentrations



Test #3 Interior View of Mixing

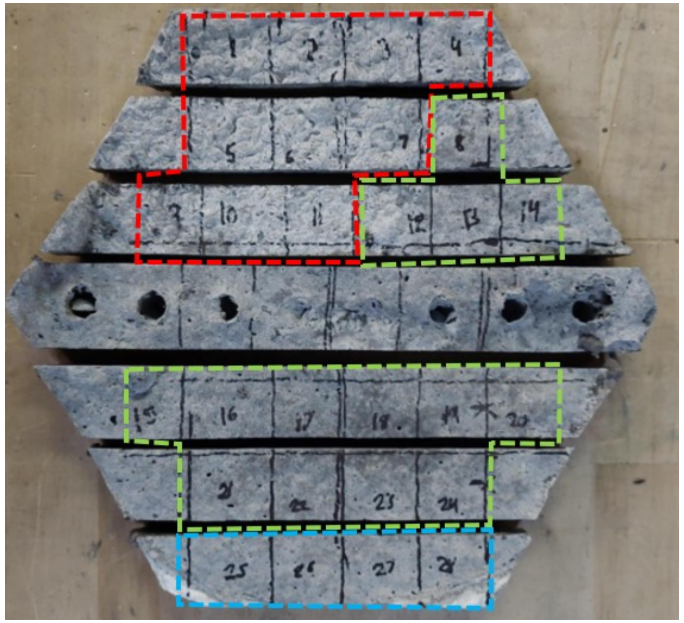


Test #3 Cured Paver

DTVAC TEST RESULTS – COMPRESSIVE STRENGTH

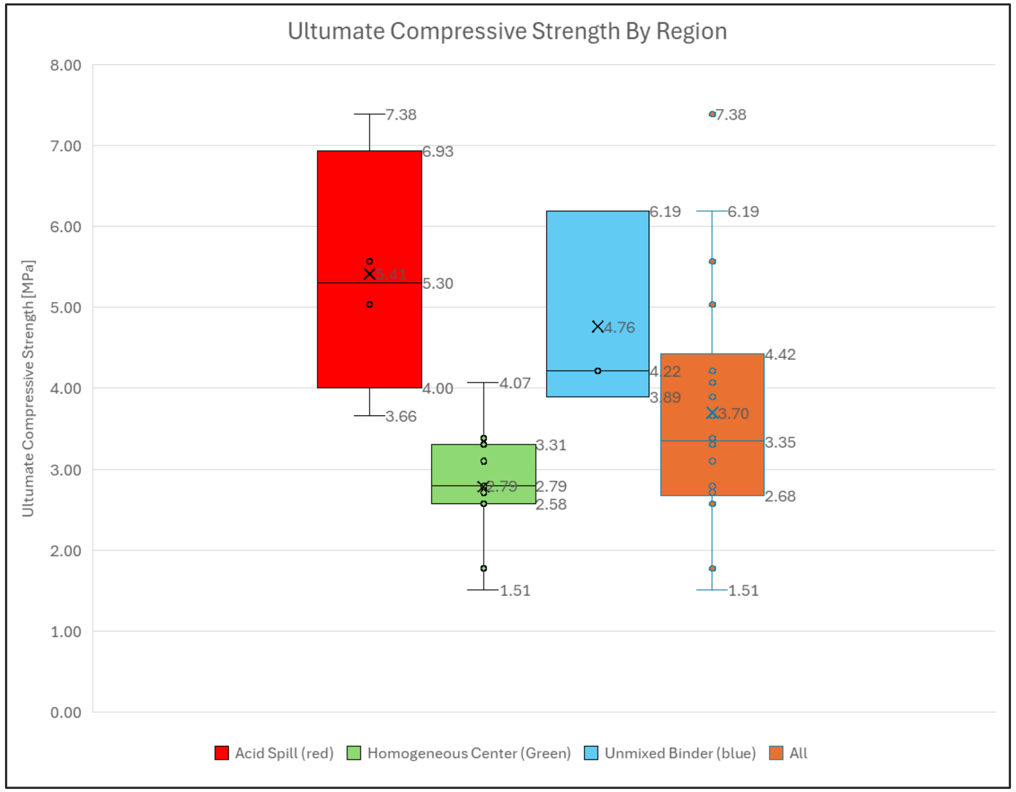
- Paver split into 3 regions based on material condition
  - Seemingly most homogenous region performed the worst
  - Accidental extra acid region performed best

- Overall average strength 3.7 MPa



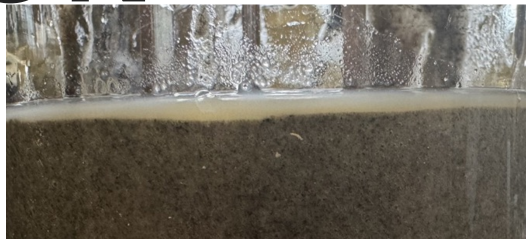
Test #3 Paver Sample Map; Acid Spill, Homogeneous Center, Unmixed Binder

Compressive Test



Ultimate Compressive Strength by Sample Region

MIXTURE OPTIMIZATION



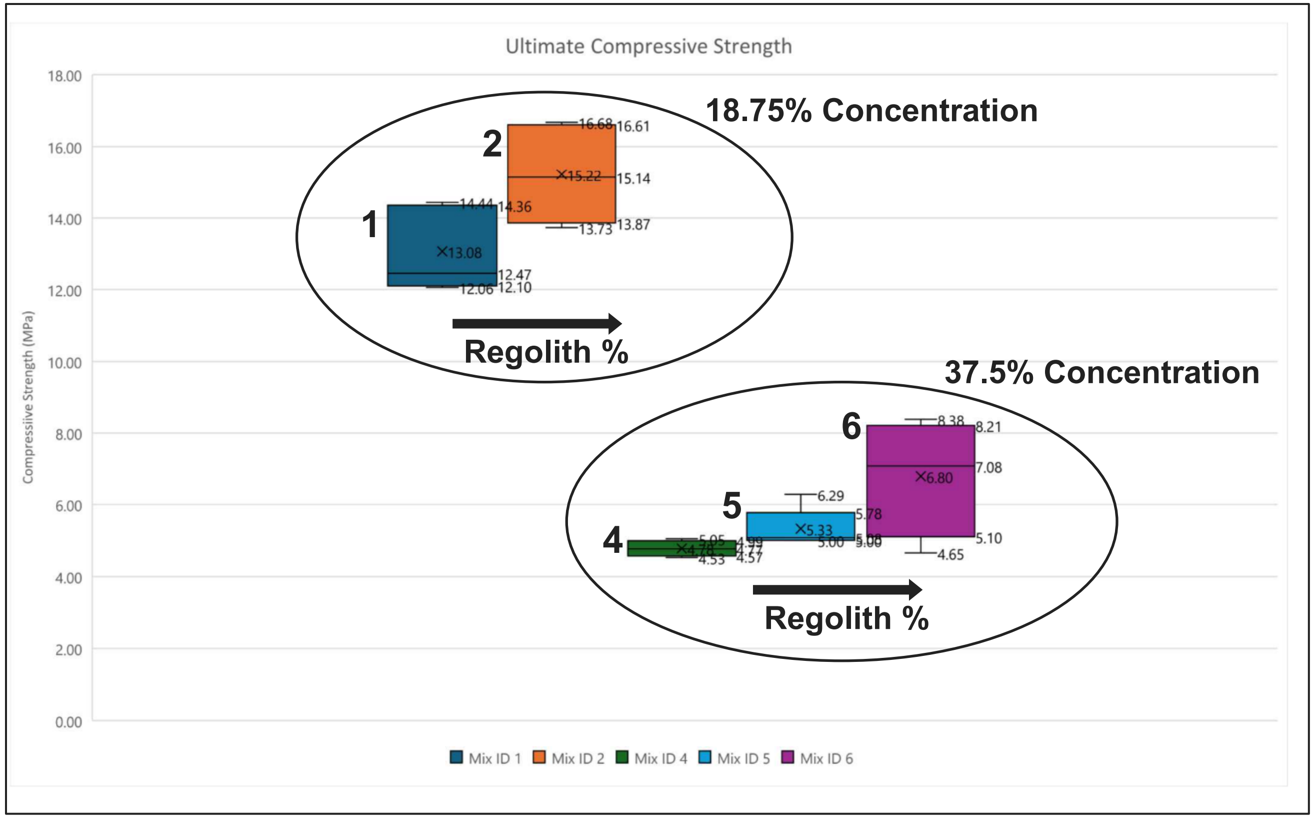
Visible Separation When Low Regolith% Used

Sample Slabs Curing in Kiln

- Tested various regolith:liquid:binder ratios
- Used two binder solution concentrations
  - Determined upper and lower bounds of regolith content for the two concentrations
- Cured at 65°C in ambient pressure

Mix Ratios					
		Mix ID	Regolith (% Mass)	Water (% Mass)	Binder (% Mass)
Binder-Water Concentration	18.75%	1	70.0%	24.4%	5.6%
		2	72.5%	22.3%	5.2%
		3	75.0%	20.3%	4.7%
	37.50%	4	65.0%	21.9%	13.1%
		5	67.5%	20.3%	12.2%
		6	70.0%	18.8%	11.3%

*Note: Mix 3 crumbled during sample prep cutting and was not tested



DTVAC TEST RESULTS – SYSTEM PERFORMANCE

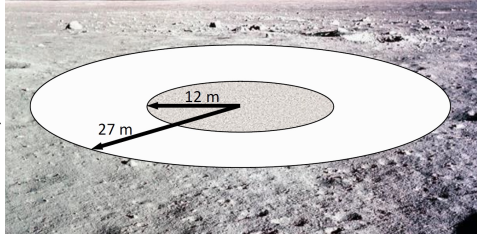
- Time history of power consumption was collected for each of the three DTVAC test runs
  - Power data should be interpreted as conservative maximum because stepper motors with constant current controllers were used

Test	Energy Consumed [Wh]
Single Paver Production Test #1	36.6
Single Paver Production Test #2	95.1*
Single Paver Production Test #3	44.0

*Gantry motors unintentionally left enabled for extended period on Test#2 during pump-down and contributed to higher energy consumption

Statistic	Value	Unit
RENEST System mass	40	kg
Paver area	415.5	cm^2
Paver thickness	1.2	cm
Average paver strength	3.7	MPa
Paver production time	8	hr
Paver production rate	62.3	cm^3/hr
Energy required per paver	44.0	W-hr
Peak power draw	60	W
Down mass per paver (binder and 10M acid accelerant)	0.1424	kg
Paver Formula	65/21/14	%Regolith / %0.1M Acid / %Binder

CONSTRUCTION METHOD COMPAR



Notional Landing Pad*

- Considers 27m radius landing pad consisting of inner and outer zones

Method	Description	Energy Expended (MWh)	Mass from Earth (tons)	Time to Construct (days)
Microwave Sintering* Inner Pad Only	• Can produce mechanically strong surfaces with single pass • Deep penetration into Lunar soil	19.7	5.8	4.3
Baking Pavers* Inner Pad Only	• Bake paver in oven and then deploy • Grouting joints also required after paver deployment	41.3	2.9	39.7
Polymer Infusion* Outer Pad Only	• Unknown if feasible to use as central landing pad material	0.075	8.7	1.2
RENEST Inner Pad Only	• One RENEST paver unit with one emplacement rover and one volatile recovery system • Grouting joints also required after paver deployment • Assumes volatiles are recovered during curing and recycled	0.219	8.9	9,073
RENEST Revised Inner Pad Only	• Reduced to 8-meter inner pad radius • Improved cure time from benchtop experiments vs. DTVAC • Used 5.6% binder formula from mixture optimization results • Added 3 RENEST systems in parallel	0.097	6.3	336

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* Source: P. T. Metzger and G. W. Autry, "The Cost of Lunar Landing Pads with a Trade Study of Construction Methods," New Space, vol. 11, no. 2, pp. 94–123, Jun. 2023, doi: 10.1089/space.2022.0015.

FUTURE WORK

- Investigate the exact chemical processes taking place during cure
- Conduct more investigation into the higher strength material that was tested during mixture optimization
  - Test those mixtures in relevant environments (temperature and pressure)
  - Introduce acid to accelerate curing
- Develop water recovery system
- Develop method for grouting and refurbishment in the field
- Optimize surface operations to reduce construction timeline

Hunter McGillivray (PI) Prepping RENEST for DTVAC Testing

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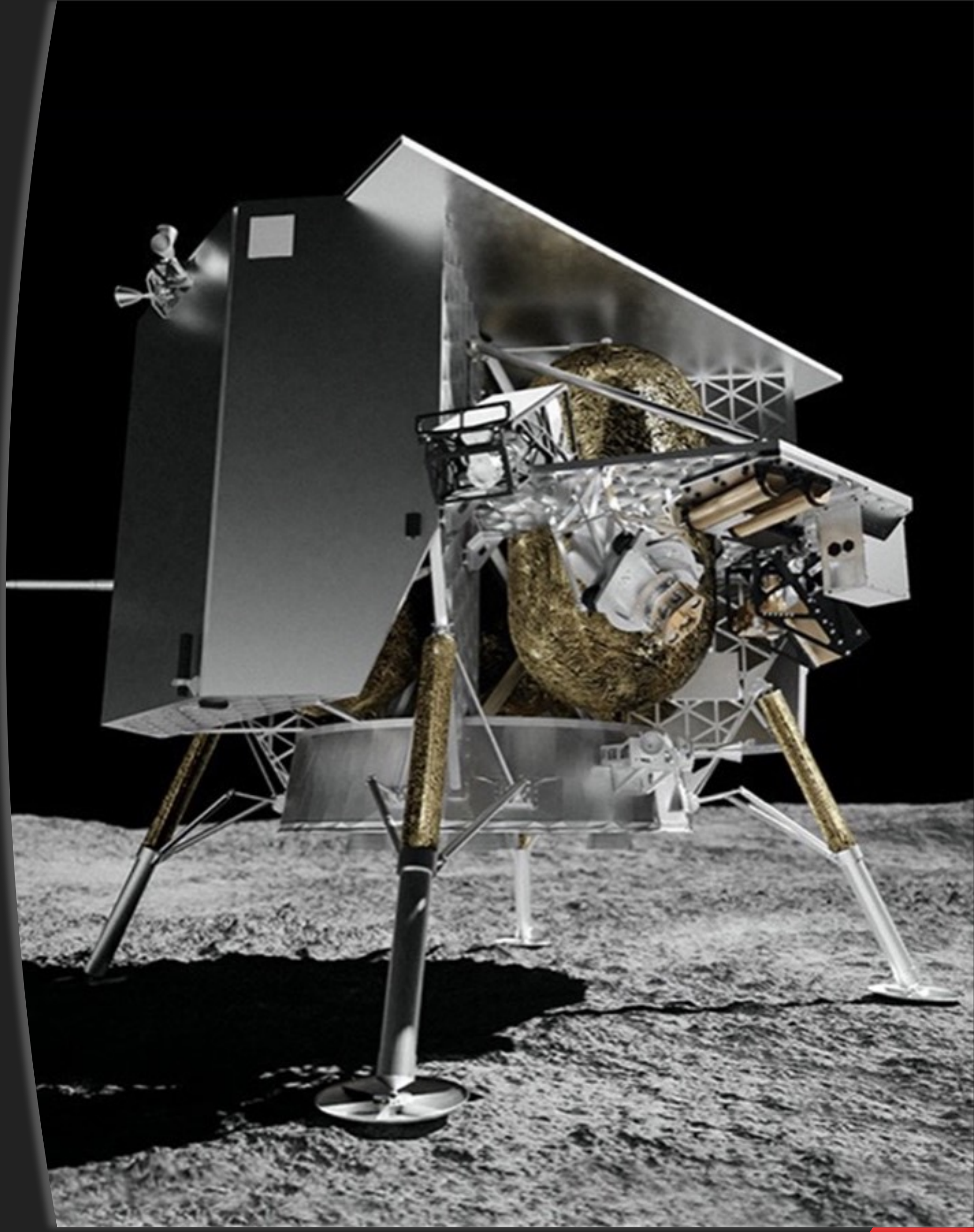

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[2] P. T. Metzger and G. W. Autry, "The Cost of Lunar Landing Pads with a Trade Study of Construction Methods," New Space, vol. 11, no. 2, pp. 94–123, Jun. 2023, doi: 10.1089/space.2022.0015.


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