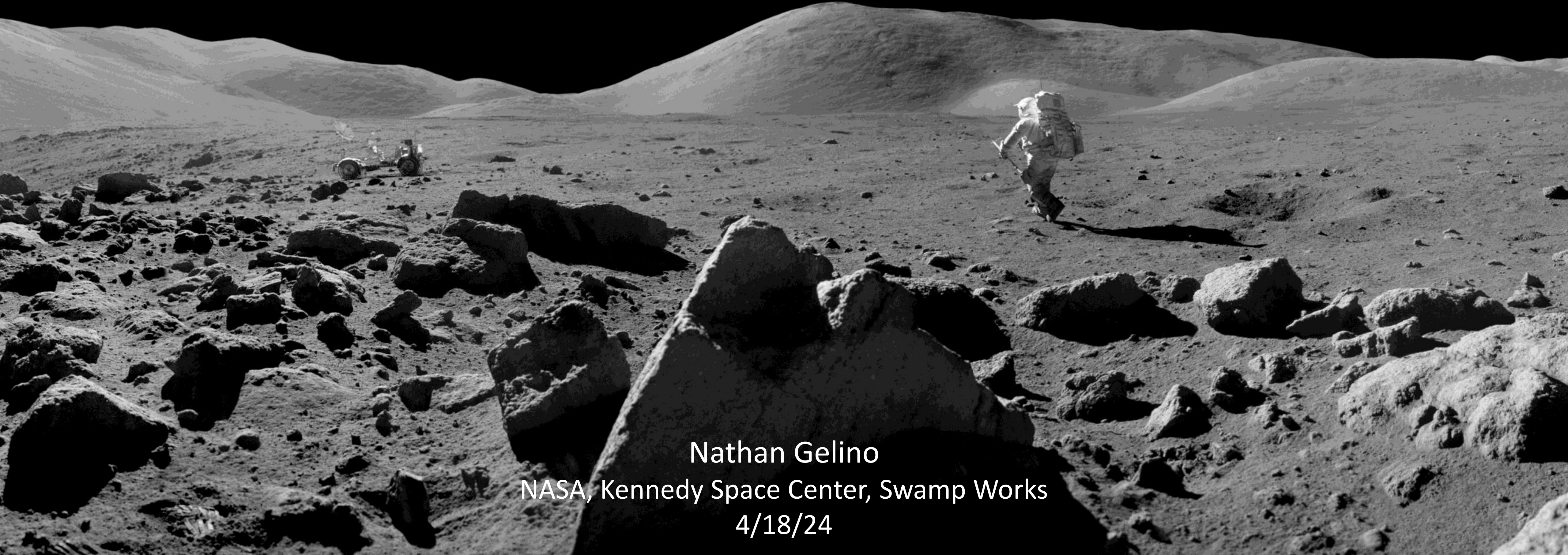
Innovation Through the Lens of Regolith Polymer Composites for Lunar Construction

2024 ASCE Earth and Space Conference



Nathan Gelino
NASA, Kennedy Space Center, Swamp Works
4/18/24

Introduction

- Motivation:
  - To showcase insights, lessons learned, and innovations from Regolith-Polymer Composite (RPC) development work
  - To share a story about the sometimes-chaotic development path of technology maturation

- Context:
  - NASA is developing construction technologies to build infrastructure on the Moon
  - Examples include launch/landing pads, blast mitigation, power/comm towers, roads, protective shelters, dust free zones
  - An objective is to use resources available on the Moon as construction feedstock
  - Many previous and ongoing efforts show promise

What is Regolith Polymer Composite (RPC)?

- Regolith and polymers are mixed and extruded typically using a compounding process
- Raw regolith is used as a filler (not melted)
- Polymers are used as a binder
  - Thermoplastics
  - Thermosets
  - Geopolymers
- Mixture rate is controlled to minimize polymer content while maintaining good strength characteristics
- Additives can be used to enhance performance
- RPC can be used in typical polymer processes such as injection molding, compression molding, and 3D printing.

RPC pellets are produced on a compounding extruder

Video Source: NASA

Influential Projects

2012 – Regolith Derived Heat Shields*

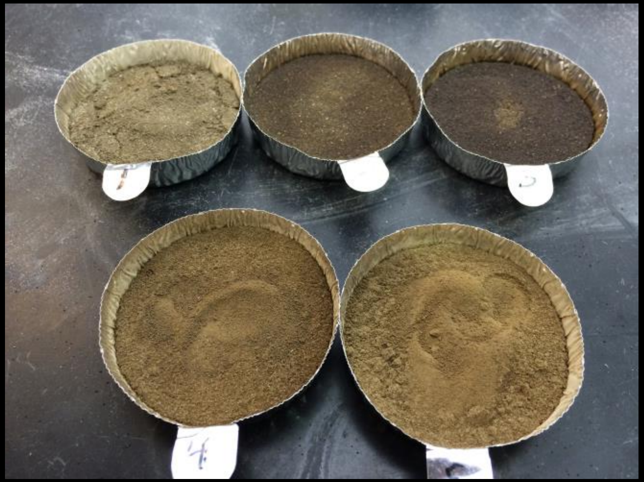
2014 – Additive Construction using Basalt Regolith Fines**

2015 – Additive Construction with Mobile Emplacement (ACME) Project***

*Hogue, Michael D., et al. "Regolith-derived heat shield for planetary body entry and descent system with in situ fabrication." Earth and Space 2012: Engineering, Science, Construction, and Operations in Challenging Environments. 2012. 526-536.
**Mueller, Robert P., et al. "Additive construction using basalt regolith fines." Earth and Space 2014. 2014. 394-403.
***Mueller, Robert P., et al. *Additive construction with mobile emplacement (ACME)*. International Astronautical Federation (IAF), 2017.

Photo Source: NASA

Early Ideation and Exploration


Premixed and heated regolith and plastic powder


Mixing regolith and plastic while hot shows promise


Extrusion is proven with low tech methods


Extrusion of premixed silicone and regolith

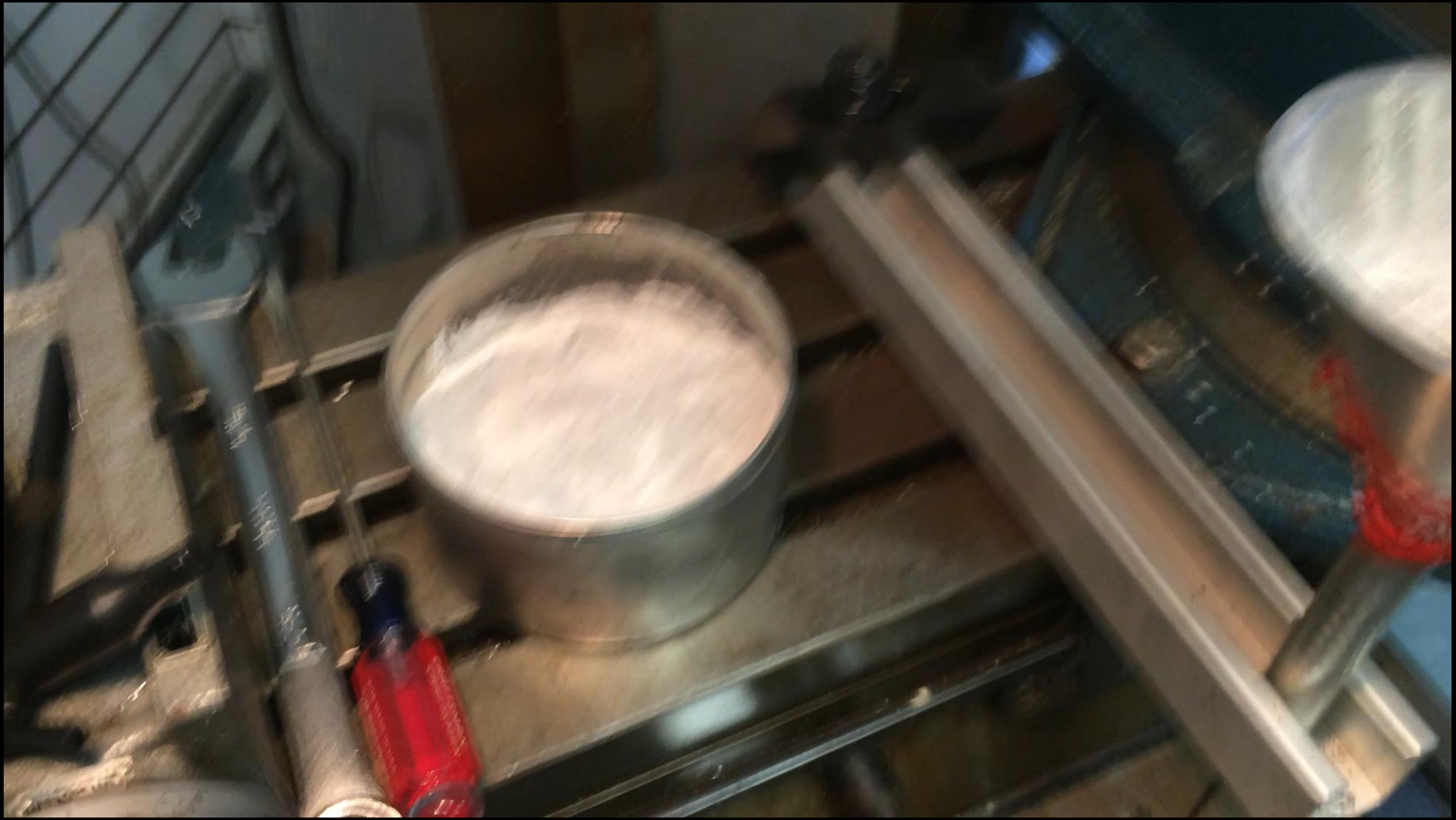
Various polymers and particle size ranges are evaluated


Machining RPC shows promise


RPC blocks are adhered by remelting adjacent surfaces

Photo Source: NASA

First “Print”



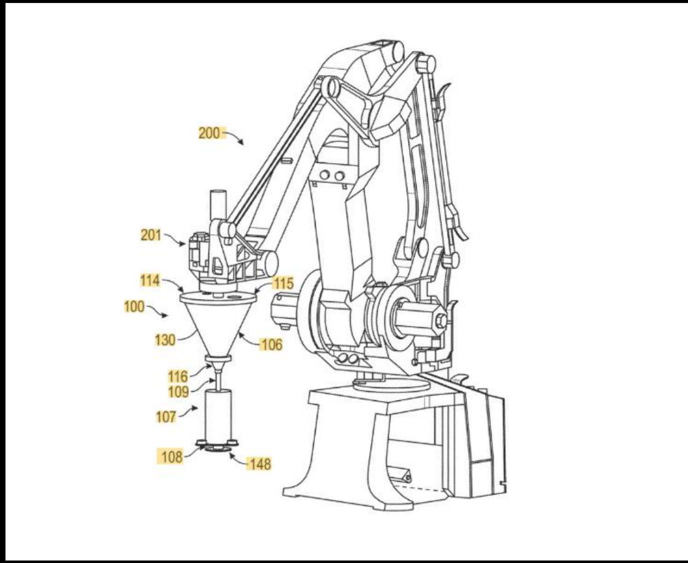
First generation RPC screw extruder works well despite the crude form

“Poor man’s” 3 dof 3D printer

First RPC structure is printed showing feasibility

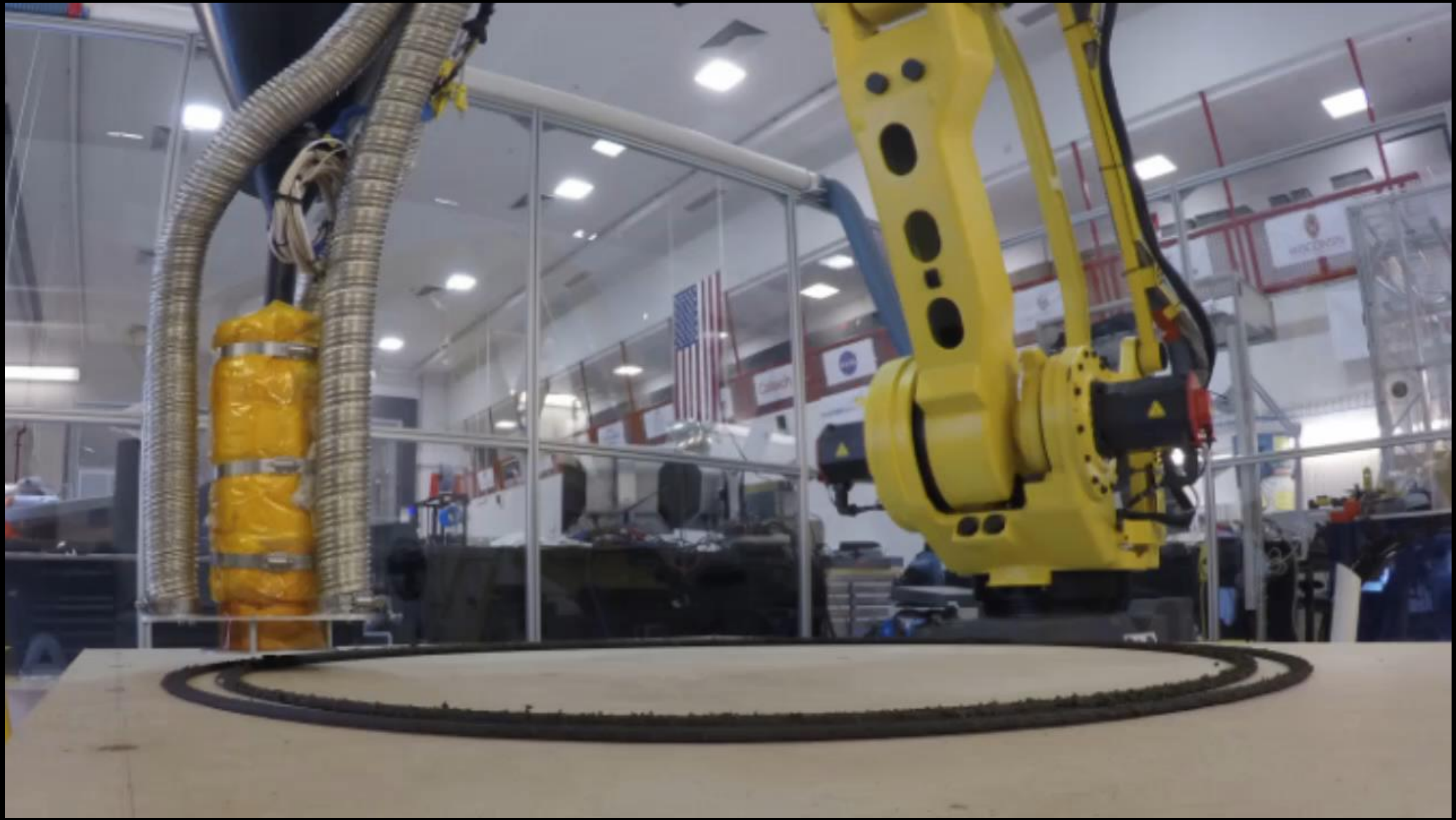
Photo/Video Source: NASA

Zero Launch Mass (ZLM) 3D Printer



U. S. Patent No. 11,260,589

First “Print” on ZLM



Printing a subscale habitat prototype

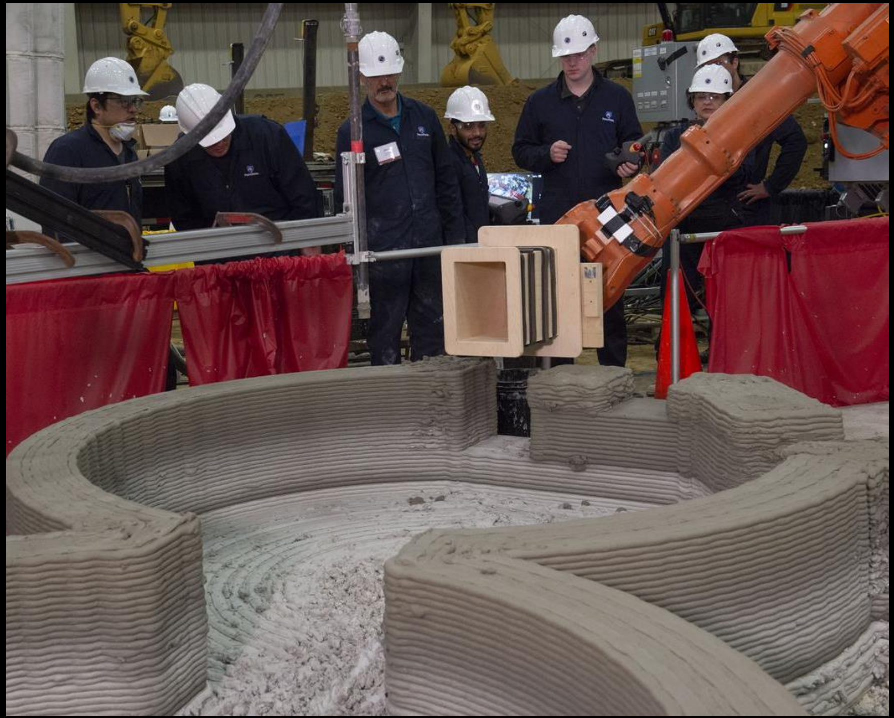
Mueller, R. P., Gelino, N. J., Smith, J. D., Buckles, B. C., Lippitt, T., Schuler, J. M., ... & Townsend, I. I. (2018, April). Zero launch mass three-dimensional print head. In 16th Biennial International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (pp. 219-232). Reston, VA: American Society of Civil Engineers.

Photo/Video Sources: NASA

3D Printed Habitat Centennial Challenge

AI Space Factory 3D prints a polymer-basalt fiber habitat prototype*

Foster + Partners and Branch Technology's structure defied gravity before load testing



Penn State 3D prints a cementitious habitat prototype

Photo Sources: NASA

Keep Alive Mode

A partnership with Autodesk develops toolpath algorithms and 3D prints barricades/blast walls

A partnership with NASA's Exploration Ground Systems Project produces 3D printed concrete formwork

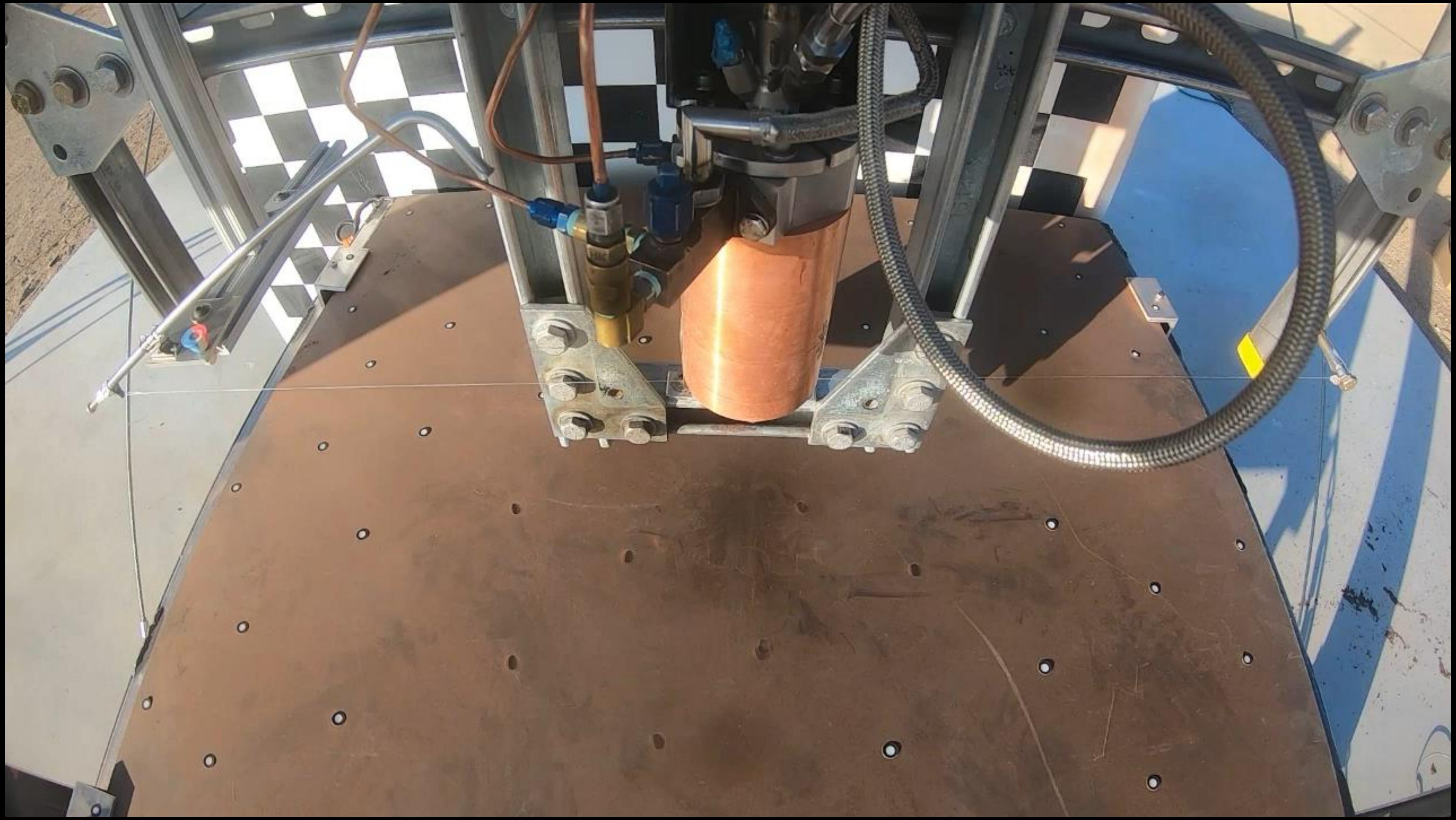
A partnership with KSC's Institution 3D prints a picnic table out of 100% recycled materials

Photo Sources: NASA

Thermosetting Variant is Effective in Launch/Landing Conditions

Extrusion of high temperature composite

Paver grouting mitigates plume effects



High temp composite mitigates plume effects (~3100 C)

Gelino, Nathan J., et al. "In Situ Lunar Launch and Landing Pad Construction with Regolith-Thermoset Polymer Composite Materials." Earth and Space 2022. 2022. 789-803.
Mueller, R. P., Gelino, N. J., Dixon, K. L., Sibille, L., & Vu, B. T. (2021). Large vehicle lunar landing surface interaction and in-situ resource based risk mitigation: Landing & launch pads. In ASCEND 2021 (p. 4071).

Photo/Video Sources: NASA

REACT

Relevant Environment Additive Construction Technology

SWAMP WORKS NASA KENNEDY SPACE CENTER

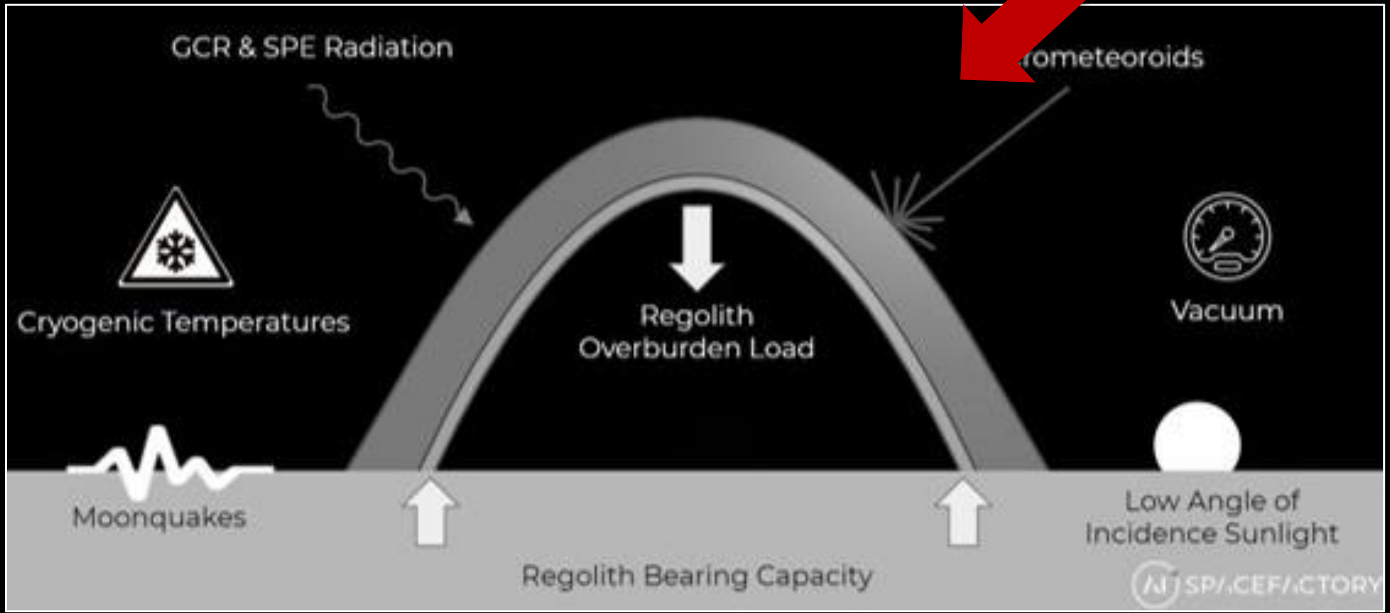
AI SPACEFACTORY

LERA Consulting Structural Engineers

Photo Source: AI Space Factory

REACT Overview

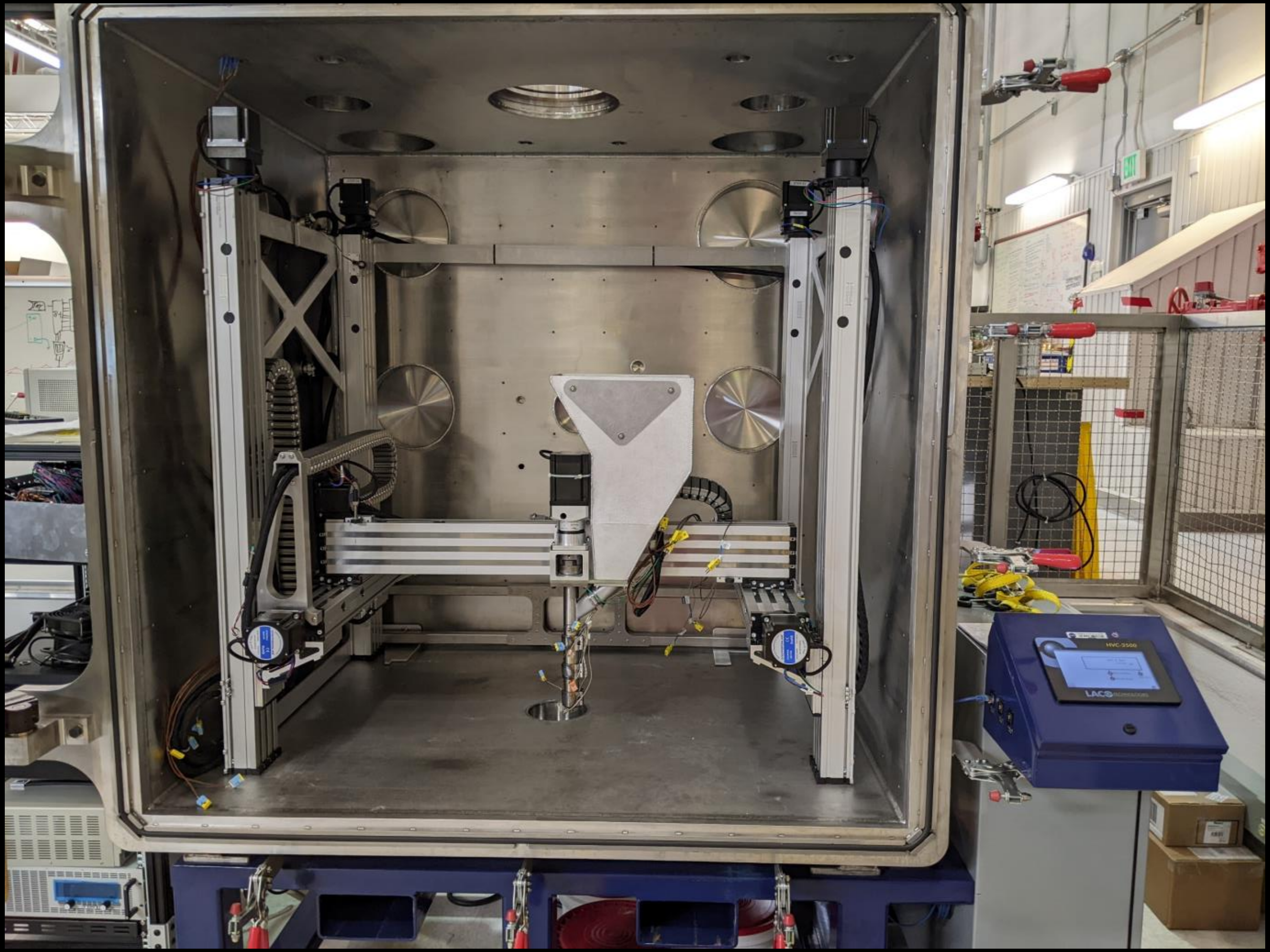

Swamp Works and AI SpaceFactory join forces



Intent is to mature this technology by exercising it in simulated lunar conditions and building a sub-scale unpressurized protective shelter

Photo Sources: NASA and AI Space Factory

Advanced Ground Operations (ARGO) Test Bed



ARGO 3D Printer is installed in the ASSIST vacuum chamber

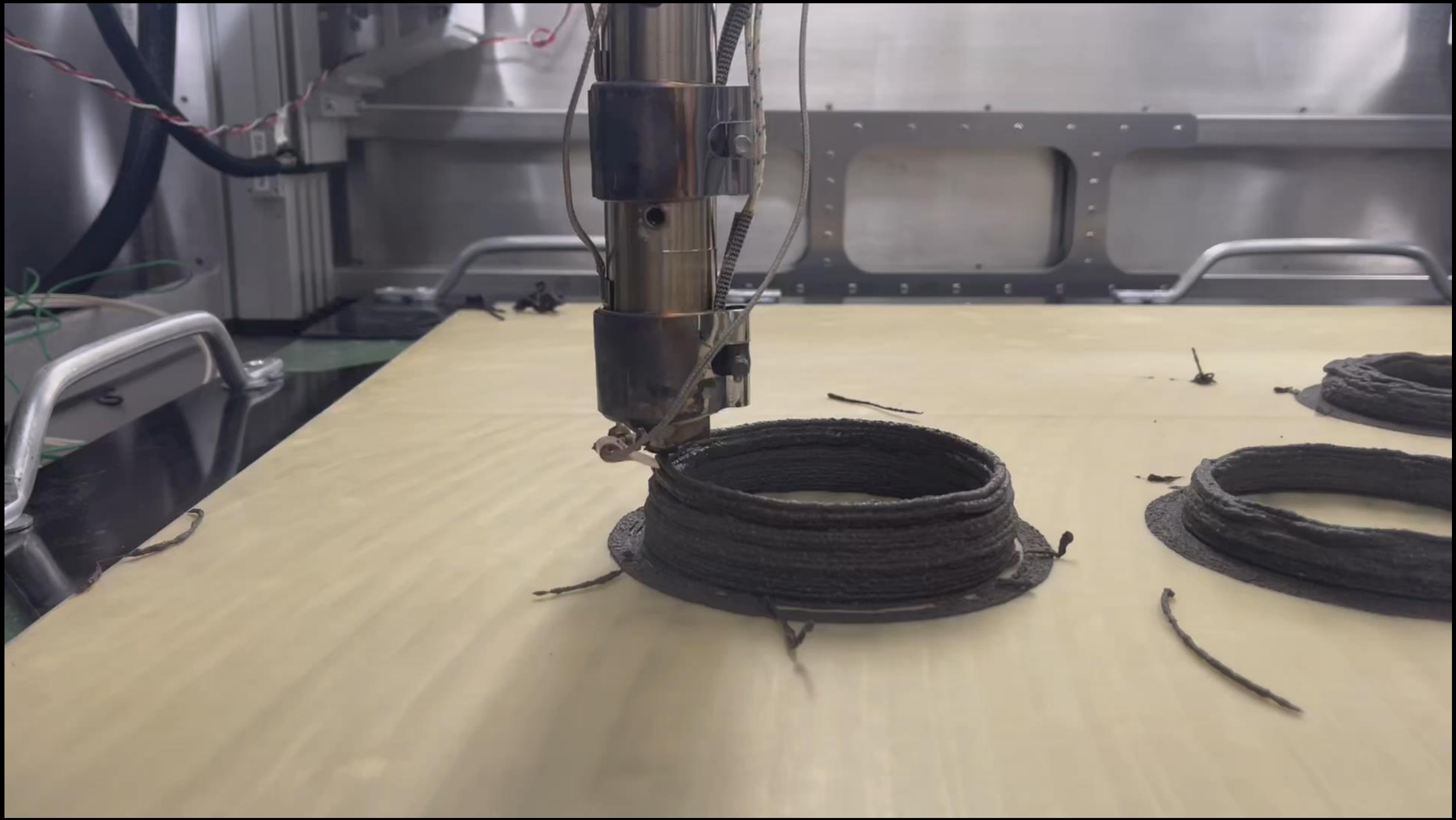
Software functionality is tested

Print quality is inspected

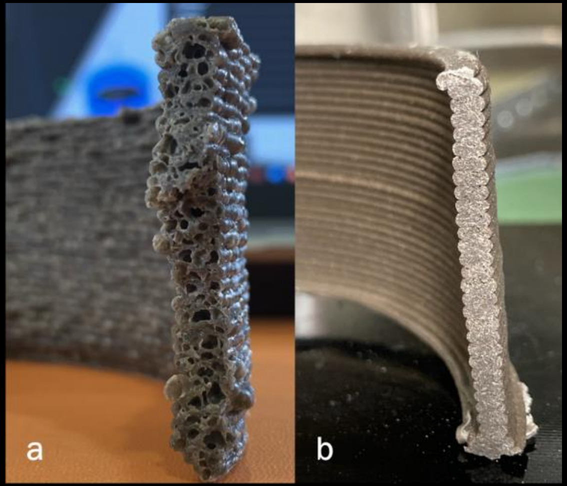
Bell, Evan A., Nathan Gelino, and Matthew Nugent. "Development of the Advanced Regolith Ground Operations (ARGO) Test Bed–A Robotic Excavation and Construction Test Facility with Simulated Lunar Environments." ASCEND 2023. 2023. 4796.

Photo Sources: NASA

First Experiments Printing in Vacuum



RPC is printed at 0.250 torr on a heated build plate

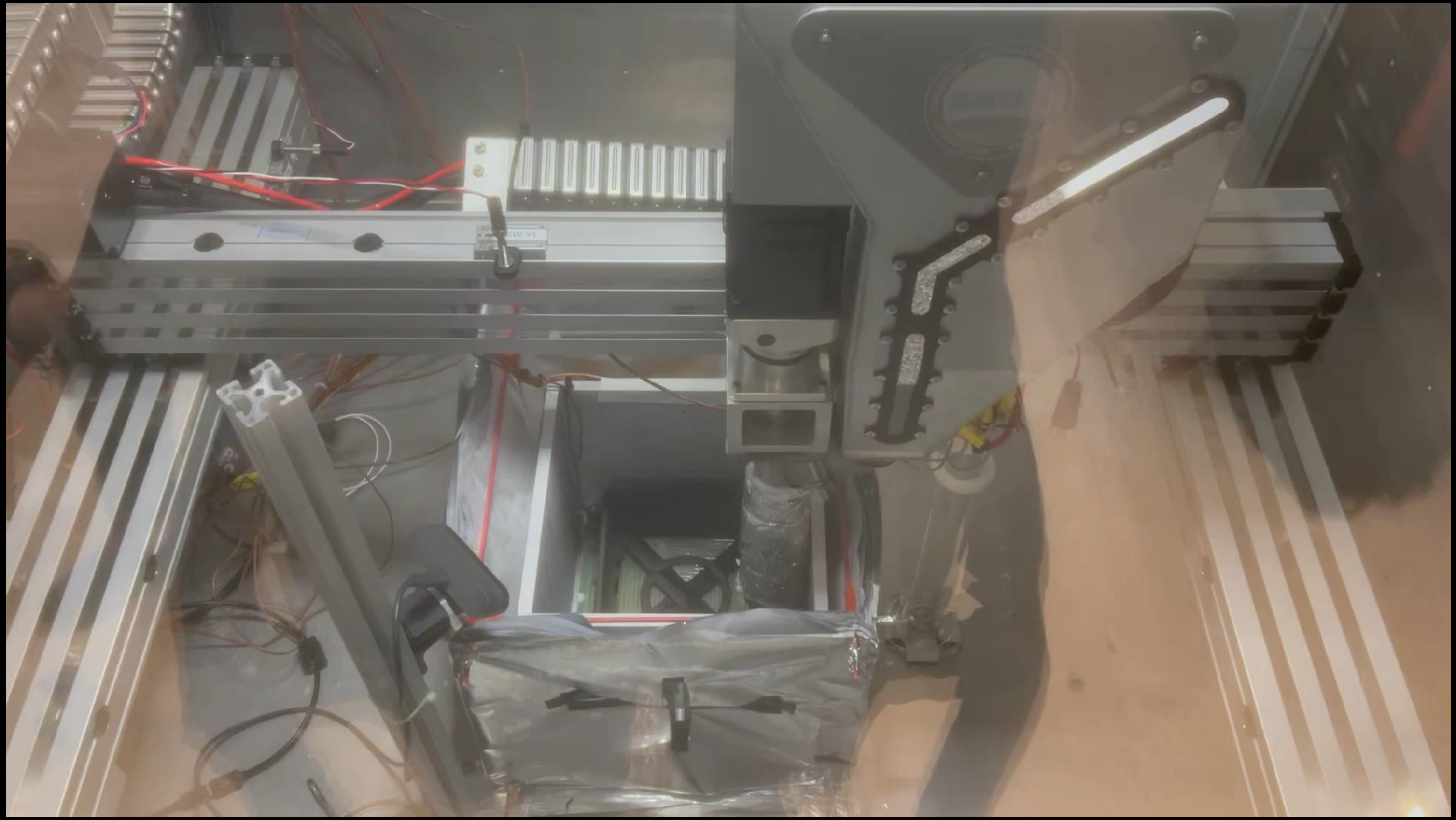


Polypropylene has porosity issues
PLA does not

A compatibilizer additive
contributed to porosity

Photo/Video Sources: NASA

TVAC Testing



A thermal shroud surrounded the build volume and was kept below -190C. Vacuum pressure started at ~10-3 torr ends at ~0.8 torr likely due to water sublimation off the shroud when warmed by the extruder and printed structure

Printed test samples prior to water-jetting

N. Gelino et al., “Applications of Regolith Polymer Composite FGF Construction in Simulated Lunar Conditions,” Proc. Am. Soc. Civ. Eng. Earth Space Conf., In Press

Photo/Video Sources: NASA

Primary Results Summary

ISRU Construction of Vertical Structures Metric	Value
Energy consumption	~3 MWh/m^3
Deposition Rate	0.6 kg/hr
Construction System Mass	~175 kg
ISRU Weight Percent	75% (Targeted 80%)
Height	~0.5 m

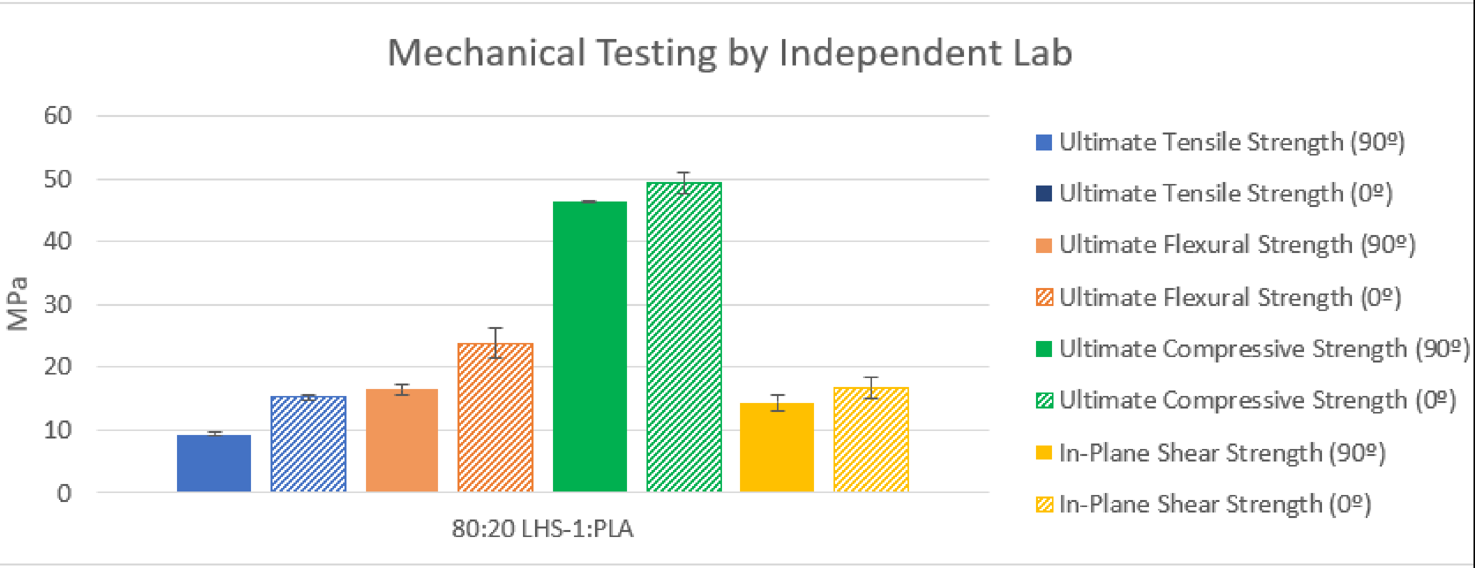


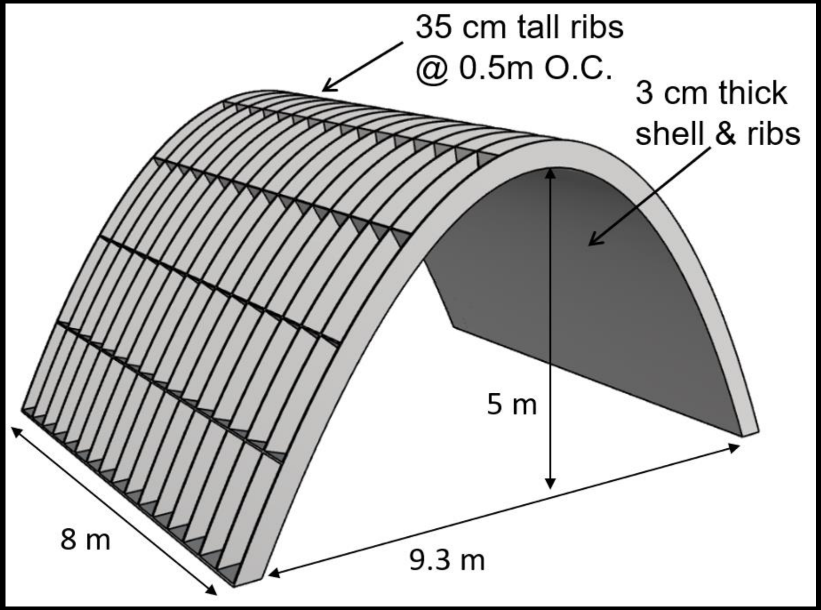
Image Source: NASA

- Vacuum pressure and temperature had minimal (if any) effects on construction process and resulting material characteristics
- 80:20 LHS-1:PLA had superior properties:
  - Flexural Modulus = 5.3 Gpa @ 0˚
  - Flexural Strength = 24 MPa @ 0˚
- Typical lumber properties
  - Flexural modulus of 6-10 GPa
  - Flexural strength of 4-8 Mpa
- Typical unreinforced concrete:
  - Flexural strength 3-5 GPa.
- Potentially suitable for lunar construction
- High performance polymers will likely improve performance
- Mechanical properties across the expected lunar thermal range must be determined
- Material lifecycle must be characterized

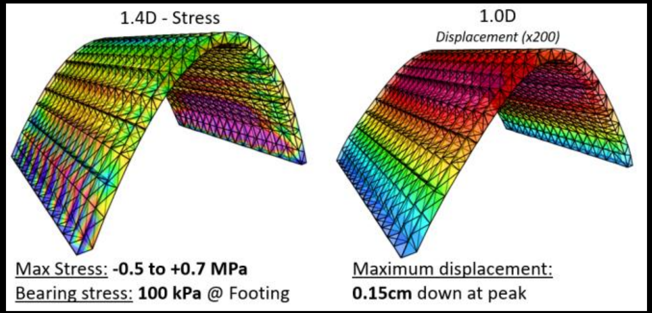
Gelino, N. J. et al., (2024, March). "Selection, Production, and Properties of Regolith Polymer Composites for Lunar Construction." IEEE Aerospace Conference, Big Sky, MT.

Lunar Infrastructure Asset (LINA) Structural Design

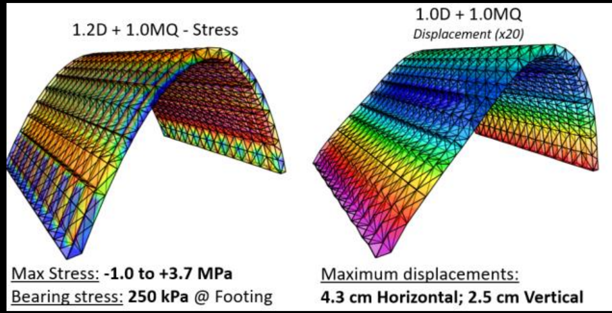
- Shelter Design Brief:
  - Protect from radiation- OLTARIS Analysis
    - 2.3 m of 1.3 g/cm^3 regolith overburden
  - Protect from meteoroids- ConWep Analysis
    - 1 cm impactor at 70 km/s = 0.084 kg TNT (ConWep-Cratering)
    - 2.3 m of regolith stress results (ConWep – G-Shock)
  - Withstand moonquakes- ASCE 7-16 Design Criteria
    - A randomly located lunar base would see 1 event of body wave magnitude 4.5 within 100 km every 400 years
    - Current moonquake ground acceleration data is not sufficient!
  - Regolith bearing strength - Allowable bearing of 1000 kPa
  - Polymer mass < 5 mt - Reasonable payload mass



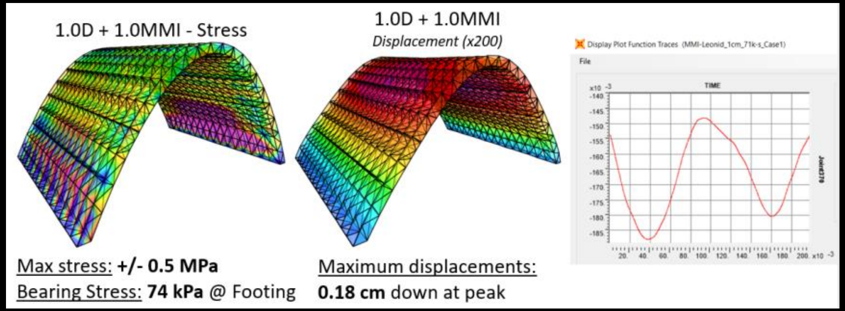
3D Rhino model of the parabolic arch structure



Gravity Load



Moonquake Load

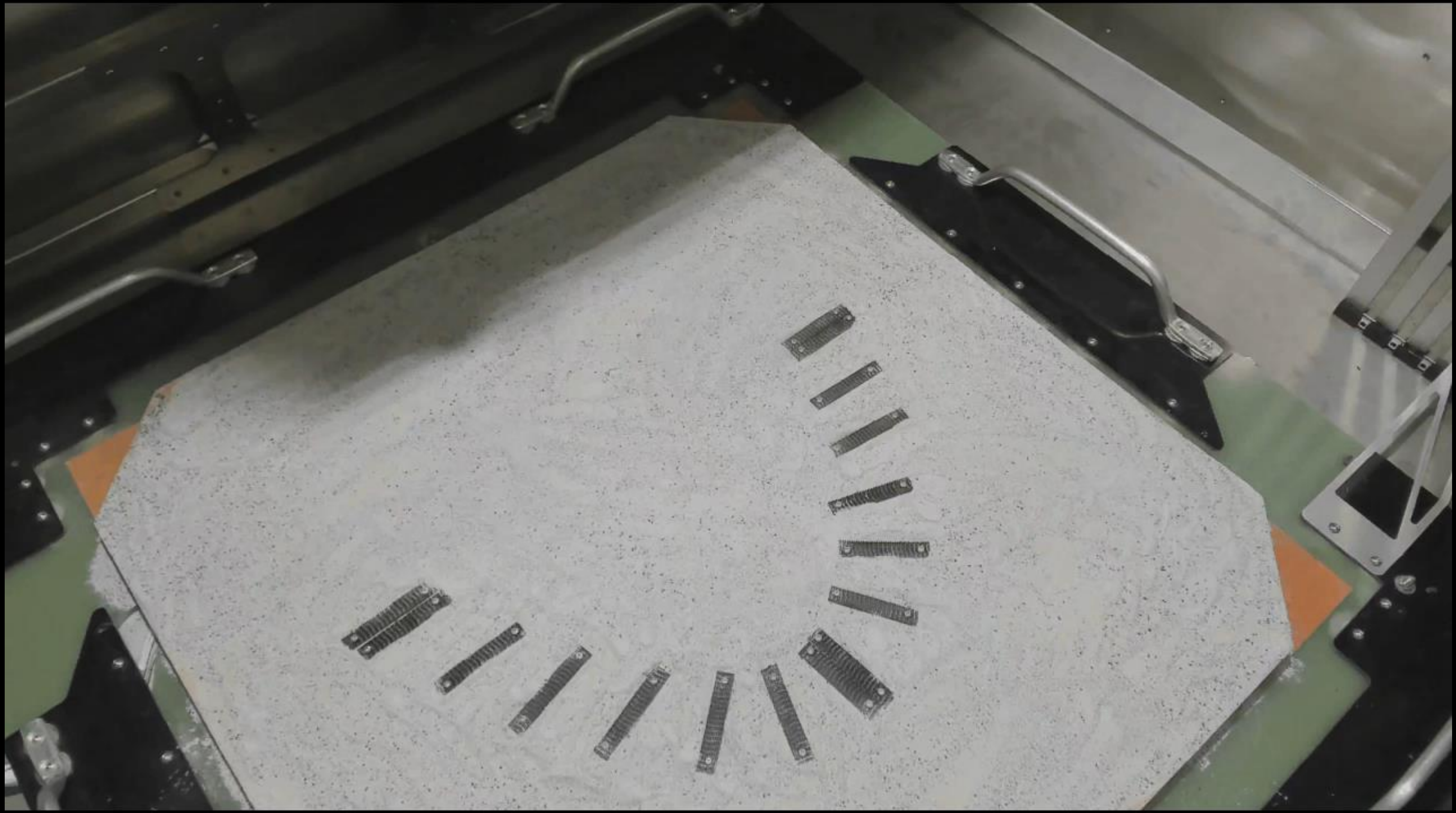


Meteoroid Impact Load

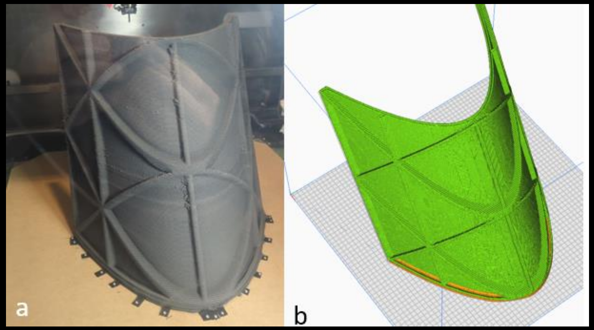
Sibille, L., Gelino, N. J., Pfund, S., J., McCarthy, A., Malott, D. I. (2024). “Development of lunar structural design criteria using terrestrial design practices and interpreted lunar conditions,” J. Aerosp. Eng., Manuscript in Preparation.
Pfund, S. J., Malott, D. I., McCarthy, A., Cornelius, B., Sibille, L., Gelino, N. J., (2024) “Building on the Moon- Methods for Structural Validation and Architectural Design Implications,” J. Aerosp. Eng., Manuscript in Preparation.

Image Source: LERA Consulting Structural Engineers

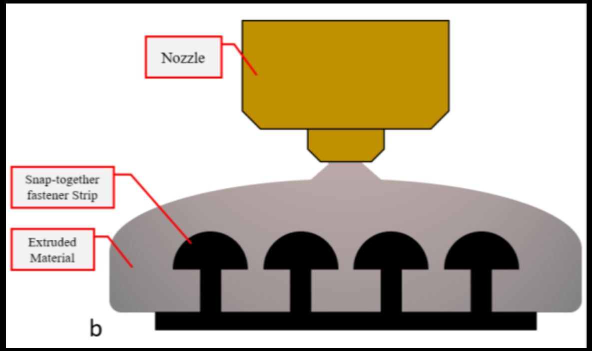
Subscale LINA Construction



Second generation protective shelter is printed at ~10^{-4} torr on LHS-1 Simulant



First generation shelter design



Ground anchors secure the print

Photo/Video Sources: NASA

Full-scale LINA construction concept

Video Source: AI SpaceFactory

Low TRL Innovation Best Practices

- Understand state of the art and its limitations
  - Confront the problem in new ways
- Take advantage of existing tech for new applications
- Build early to explore the tech and learn from fast, cheap, and safe iterations – finding bad assumptions later is costly
- Produce something physical that proves feasibility – funding comes easier if you have more than slides and reports
- Don’t be too disappointed with early setbacks - its only a failure if you don’t learn from them
  - Evidence of how much you have learned
- Engage the community – it plants seeds that can grow in unexpected ways
  - Free lessons
  - Rising tide raises all boats
- Explore adjacent applications to expand your customer base
  - New use cases
  - More potential funding sources
  - Synergies emerge





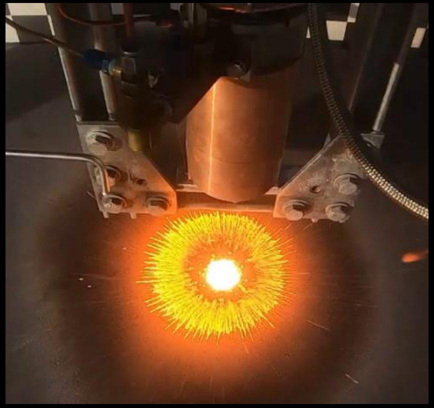



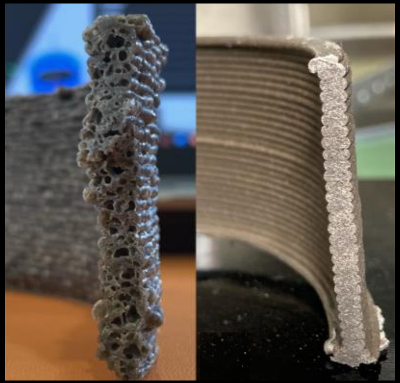
Photo Sources: NASA

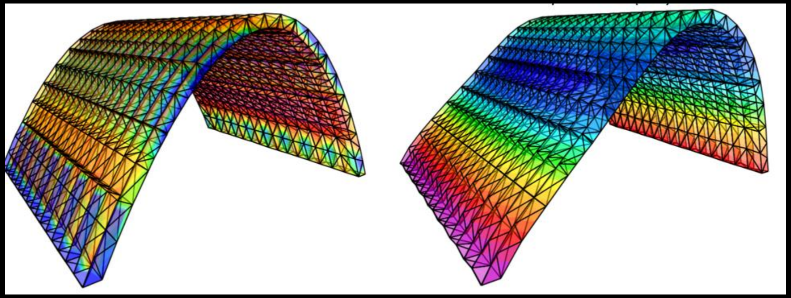
Mid TRL Innovation Best Practices

NASA

SPACEFACTORY

LERA
Consulting Structural Engineers





- Partnering is advantageous for complementary capabilities and access to experts
- Test in relevant environments as soon as possible, unexpected phenomenon happens
- Environments should be as close to real as possible, but they don't have to be perfect
- Don't be deterred by challenging problems, start working towards solutions early
- Formulate/communicate problems in a way that is actionable using terrestrial professional practices
- Understand your technology maturation path
- Share the results

Photo Source: NASA and LERA Consulting Structural Engineers

Mid TRL Innovation Best Practices

Have a vision for full scale implementation

Photo Sources: AI SpaceFactory and NASA