



Please provide  
pictures specific to  
your project for each  
circle on this  
coversheet

## Space Technology Mission Directorate Game Changing Development Program

Nathan Gelino | Evan Bell | FY23 Relevant Environment Additive Construction Technology Annual Review Presentation | 09.22.23  
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# Project Overview



## Technology Development Needs Addressed by Project

|                |                                                                                                                                                                                |                                                                                       |
|----------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| <b>Artemis</b> | A sustained lunar presence will require ISRU based infrastructure to mitigate access and operational risks to enable a vibrant lunar economy and enhance scientific discovery. |                                                                                       |
| <b>STMD</b>    | Develop ISRU based construction technologies for infrastructure such as shelters, blast protection, landing pads, roads and habitats.                                          | Advanced Materials, Structures, and Construction (ASMC) Gaps: 425, 667, 669, 666, 416 |

## Project Goals

|                |                                                                                                                                                                                                                                                          |
|----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Goal #1</b> | To demonstrate construction of a civil engineered, unpressurized, protective shelter in simulated Lunar Dirty Thermal Vacuum (DTVAC) conditions using Regolith-Polymer Composites (RPC) in a Fused Filament Fabrication (FFF) additive process. (DRAFT)* |
|----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

## Project Objectives

|                     |                                                                                                                                                                                                                             |
|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Objective #1</b> | Develop regolith-polymer composites and characterize material/strength properties achieved under DTVAC. (DRAFT)*                                                                                                            |
| <b>Objective #2</b> | Develop the shelter's architectural and structural design based on protective needs, design criteria established from environmental conditions, and validation/optimization using terrestrial industry techniques. (DRAFT)* |
| <b>Objective #3</b> | Demonstrate additive construction of a sub-scale protective shelter in simulated lunar conditions. (DRAFT)*                                                                                                                 |

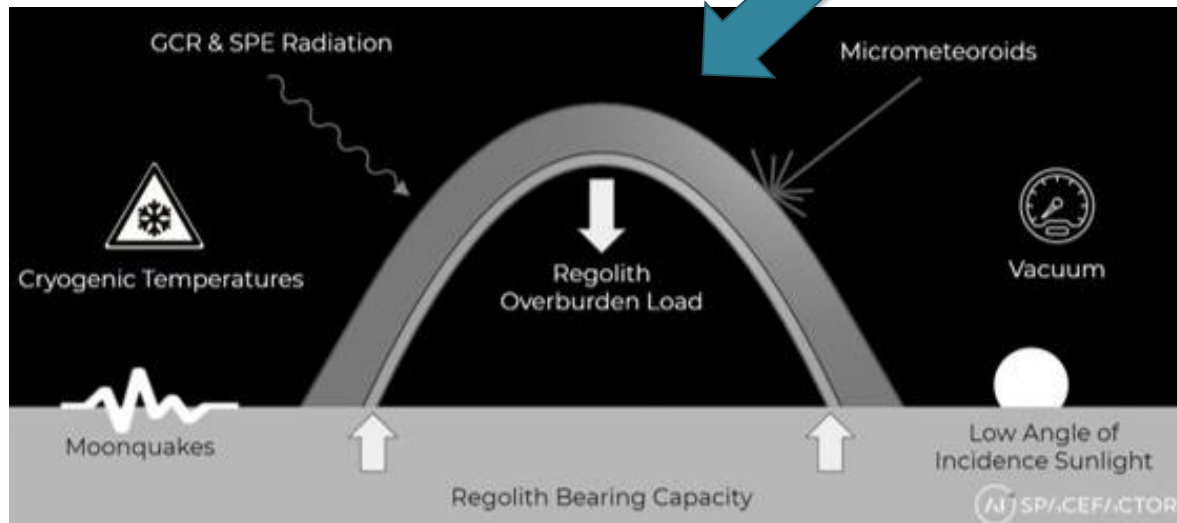
\*Announcement of Collaboration (ACO) projects do not require Goals and Objectives in the Project Plan.

# Project Overview

## Relevant Environment Additive Construction Technology (REACT)

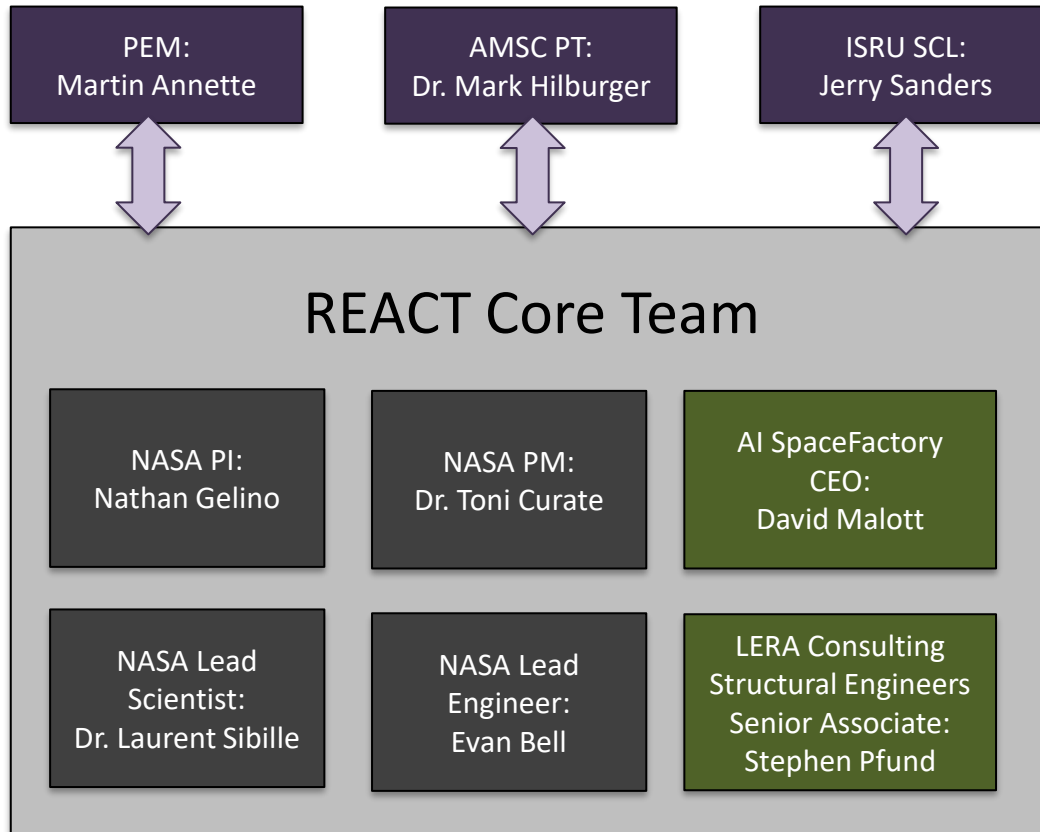


AI SpaceFactory won NASA' 3D Printed Habitat Centennial Challenge



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

# Team Members / Project Org Slide



David Malott



Stephen Pfund



Members of KSC's REACT team

# Collaborations & Partnerships

## ➤ Contributing partners

- AI SpaceFactory
- LERA Consulting Structural Engineers

## ➤ Target applications – In-Situ Construction

- Protective Shelters, Launch/Landing Pads, Blast Protection, Roads, Foundations, Habitats
- STTR Ph 1 (Awarded)
- ACO (Potential)
- Tipping Point (Potential)
- Flight Projects (Potential)

### Public/Private Partnerships

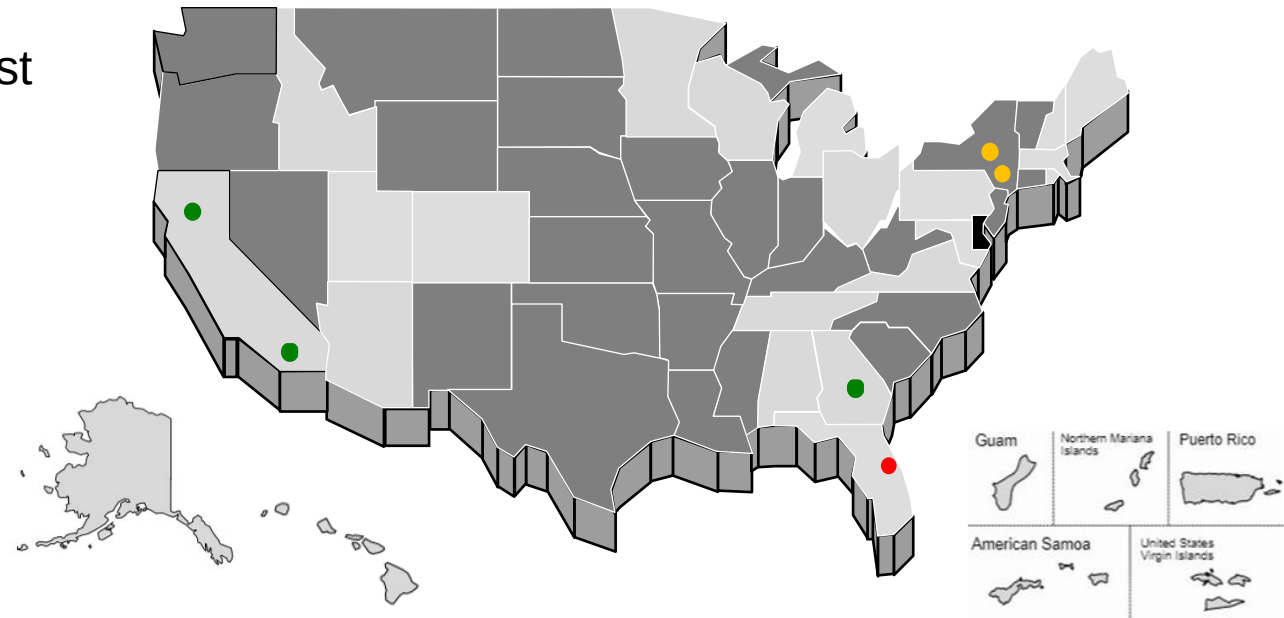
AI SpaceFactory  
LERA Consulting Structural Engineers

### NASA Centers

Kennedy Space Center  
Swamp Works

### Academic Interns

San Francisco State University  
California State University, Long Beach  
University of Georgia



Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

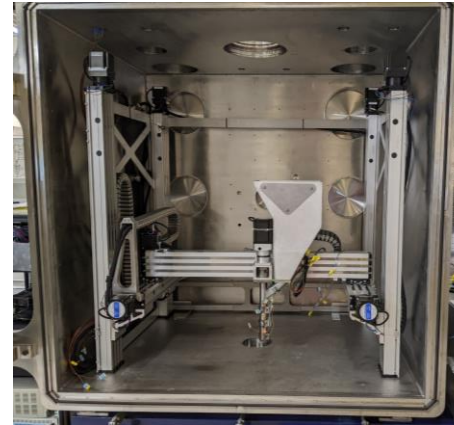
# Accomplishments – “Alpha” Materials



- Intent: To prove initial feasibility by printing in vacuum ( $10^{-3}$  torr)



RPC pellets are the feedstock for the construction system

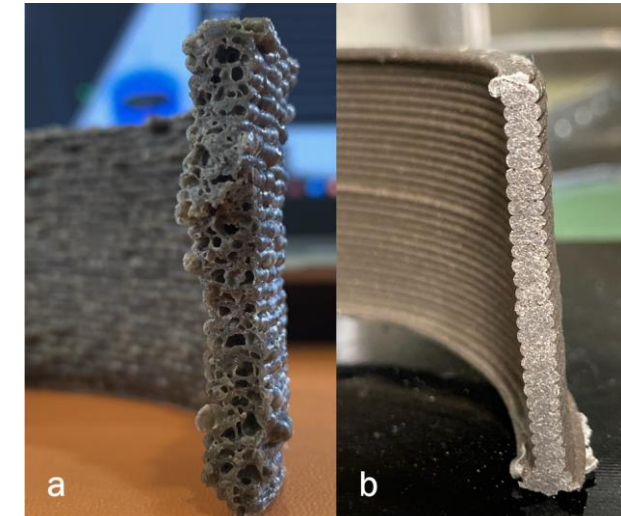


The construction system is installed in a vacuum chamber



Samples were printed under vacuum ( $10^{-3}$  torr)

| Regolith Simulant    | Binder                | Additive       | Result                                                            |
|----------------------|-----------------------|----------------|-------------------------------------------------------------------|
| Black Point-1 (BP-1) | Polypropylene (PP)    | Compatibilizer | Significant porosity due to compatibilizer                        |
| BP-1                 | PP                    | N/A            | Significant porosity believed to be from moisture in the simulant |
| BP-1                 | Polylactic Acid (PLA) | N/A            | Minimal porosity                                                  |



50:50 wt% BP-1:PP (a), and BP-1:PLA (b)

RPC pellets are produced on a compounding extruder

# Accomplishments - “Beta” Materials

- 5 formulations were printed at  $\sim 10^{-5}$  torr and  $\sim -170$  C



Test samples are printed in TVAC conditions



Printed test samples



Formulations undergo flexural testing

| Formulation            | Mass Ratio (wt%) | Ultimate Flexural Strength (Mpa)* | Flexural Modulus (Gpa)* |
|------------------------|------------------|-----------------------------------|-------------------------|
| BP-1: PLA              | 70:30            | 12.8                              | 1.8                     |
| BP-1: PLA              | 80:20            | 17.8                              | 2.8                     |
| BP-1: PLA: Process Aid | 80:18:2          | 14.9                              | 2.9                     |
| BP-1: PLA              | 85:15            | 7.3                               | 2.3                     |
| LHS-1: PLA             | 80:20            | 14.9                              | 3.7                     |

\*Data is from samples cut perpendicular to the grain which is the weakest orientation

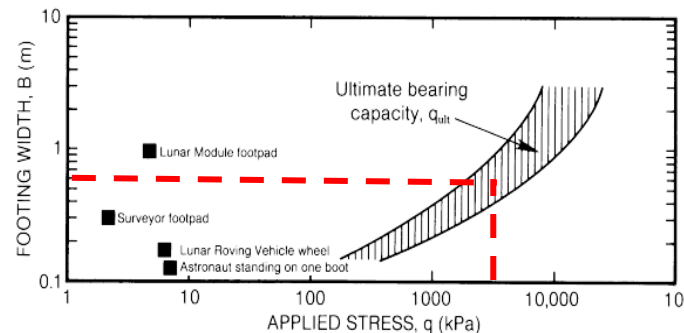
- Flexural strength and modulus control the shelter structural design
- Lunar Highlands Simulant-1 (LHS-1) formulation was selected for further development based on:
  - Sufficient ultimate flexural strength
  - Highest flexural modulus
  - Most relevant simulant for polar regions

# Accomplishments – Structural Design



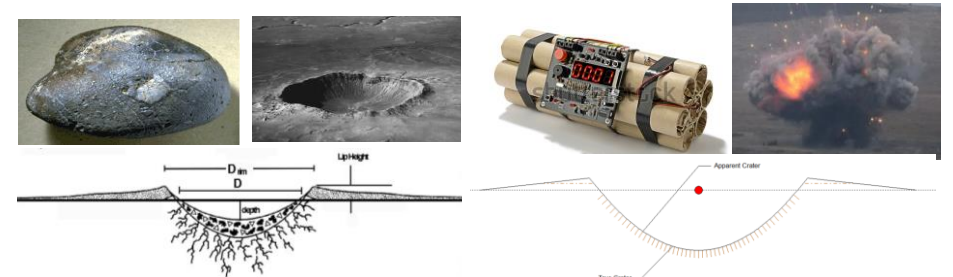
## ➤ Shelter Design Brief:

- Protect from radiation- OLTARIS Analysis
  - 2.3 m of  $1.3 \text{ g/cm}^3$  regolith overburden provides complete protection from SPE and significant protection from GCR
- Protect from meteoroids- ConWep-GShock Analysis
  - 1 cm impactor at  $70 \text{ km/s} = 74 \text{ lbs TNT}$
  - 2.3 m of regolith results in peak stress of  $355 \text{ kN/m}^2$  and Peak Impulse of  $0.46 \text{ kN/m}^2\text{-sec}$
- 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  $1000 \text{ kPa}$
- Polymer mass  $< 5 \text{ mt}$ 
  - Reasonable payload mass for HLS class vehicle

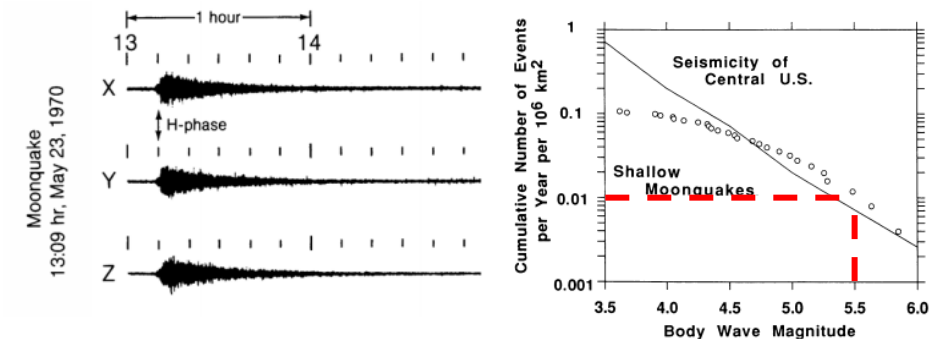


Lunar Source Book: "The lunar surface can support virtually any conceivable structure"

## OLTARIS On-Line Tool for the Assessment of Radiation In Space



Impact craters were assessed as TNT equivalent craters using Army Corp of Engineer's ConWep-GShock blast effects software

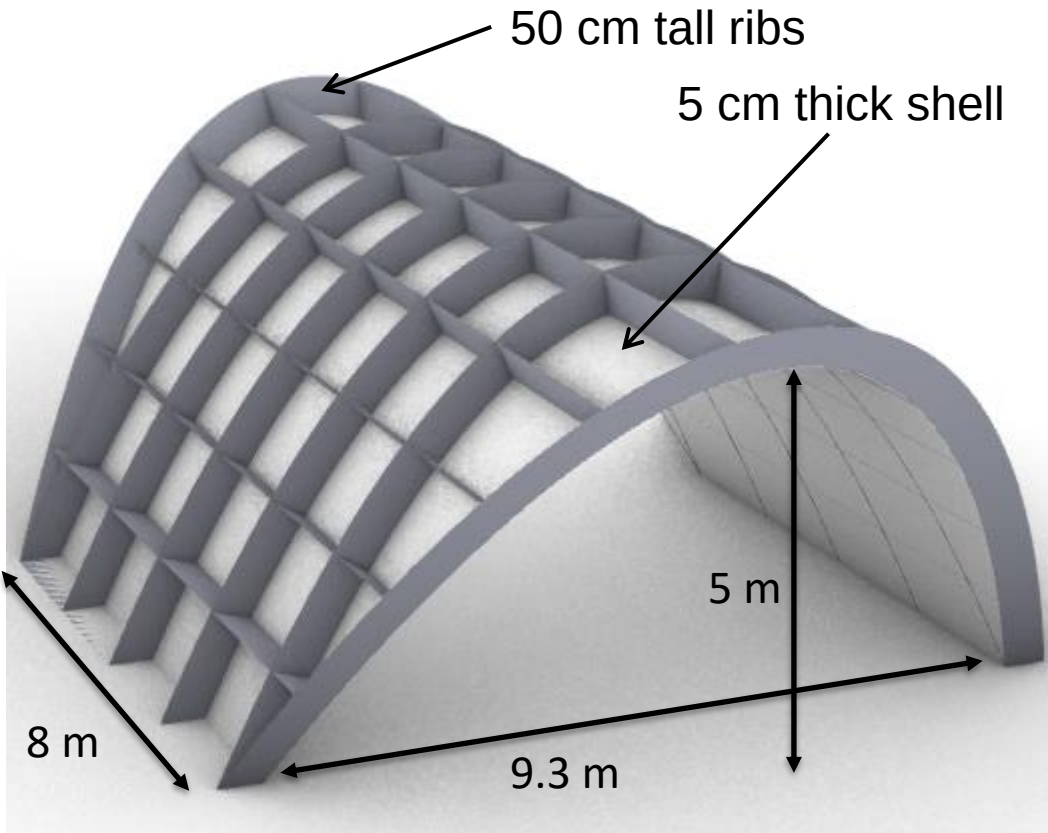


Ground acceleration data for moonquakes does not exist. ASCE 7-16 design criteria for the central U.S. was used.

# Accomplishments – Structural Design



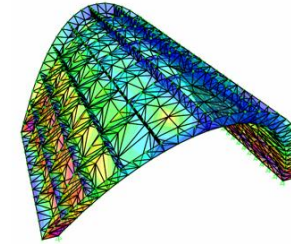
- SAP2000 Structural Analysis and Design
  - Resulting material stresses include SF > 2.0
  - Resulting bearing stresses include SF > 3.0



3D Rhino model of the parabolic arch structure

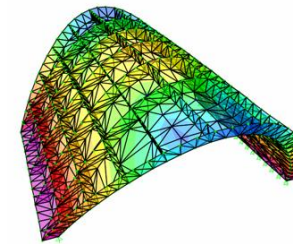
## Gravity Loads

1.4D Stress diagram



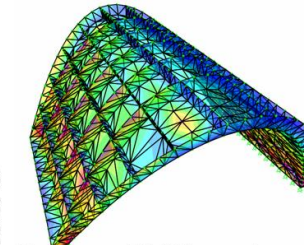
Max stress: **1.8 MPa** near base  
Bearing stress: **640 kPa** @ Footing  
1.0D buckling factor: **3.76**

1.0D Displacements (x60)

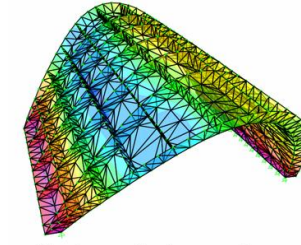


Maximum displacement:  
**0.58cm** vertical @ free edge

## Moonquake Loads



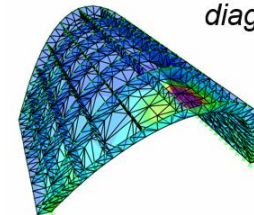
Max stress: **1.7 MPa** near base  
Bearing stress: **565 kPa** @ Footing  
1.0D + 1.0MQ buckling factor: **3.41**



Maximum displacements:  
**0.62cm** vertical @ free edge  
**1.45cm** horizontal @ 2/3 height

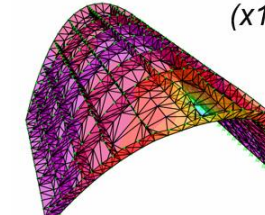
## Meteoroid Impact Loads

1.0D + 1.0MMI Stress diagram

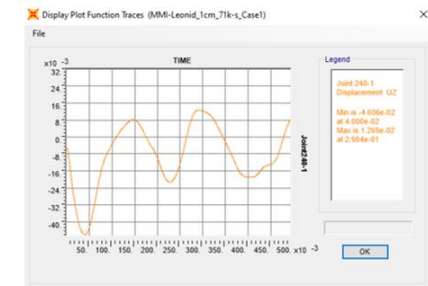


Max stress:  
**9.4 MPa** @ MMI  
Bearing Stress:  
**920 kPa** @ Footing

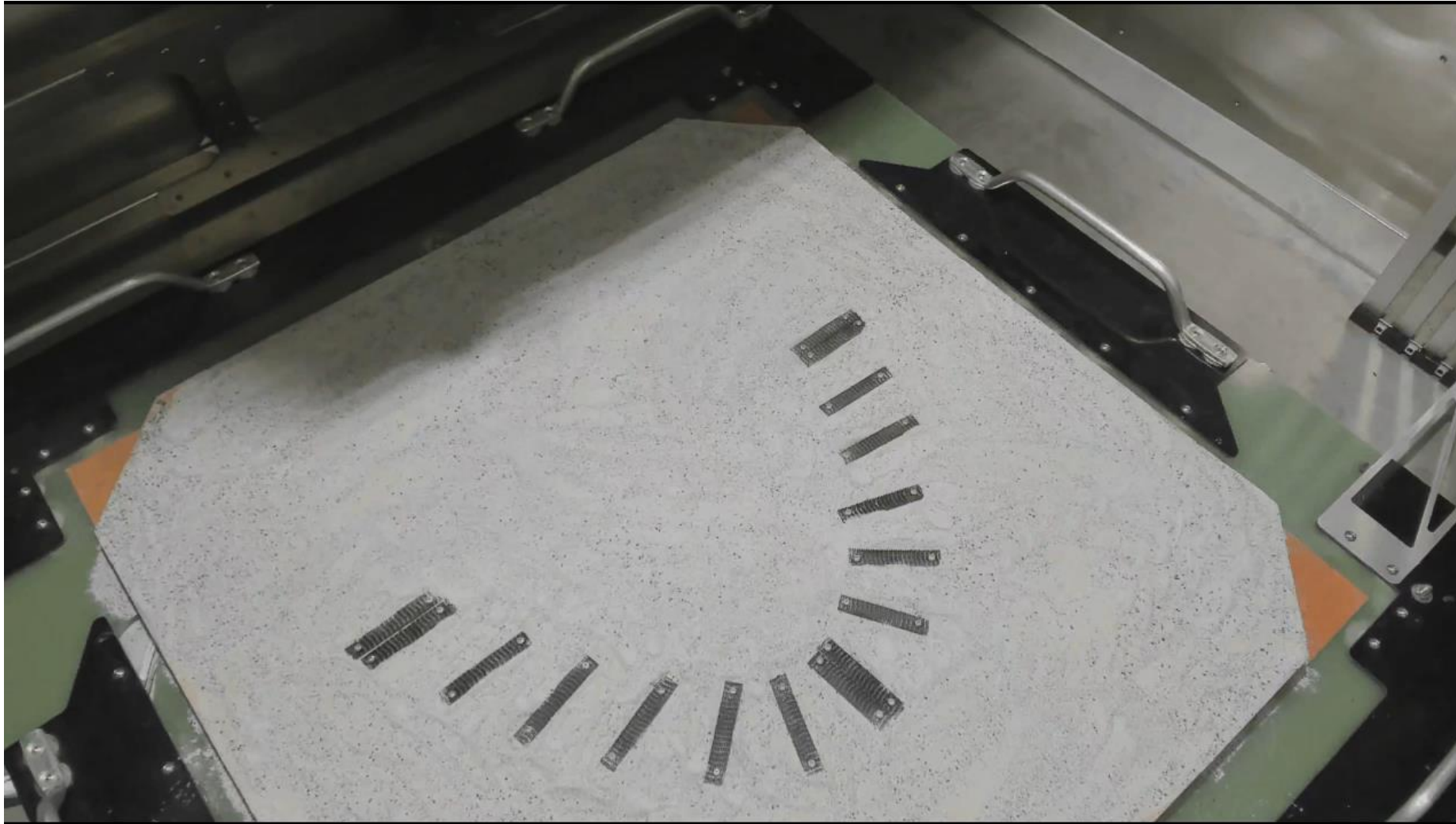
1.0D + 1.0MMI Displacements (x12)



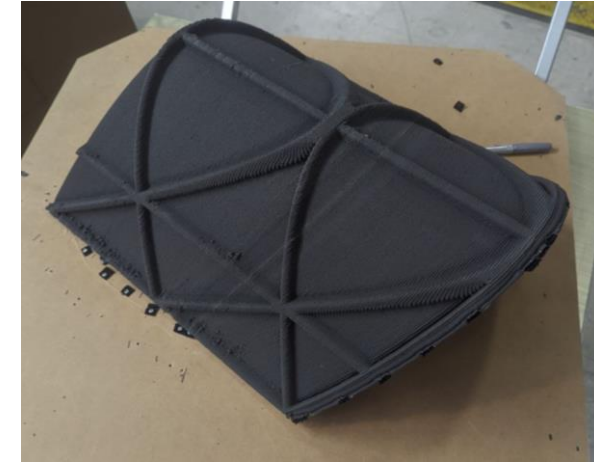
Maximum displacements:  
**4.61cm** vertical @ impact (L/200)



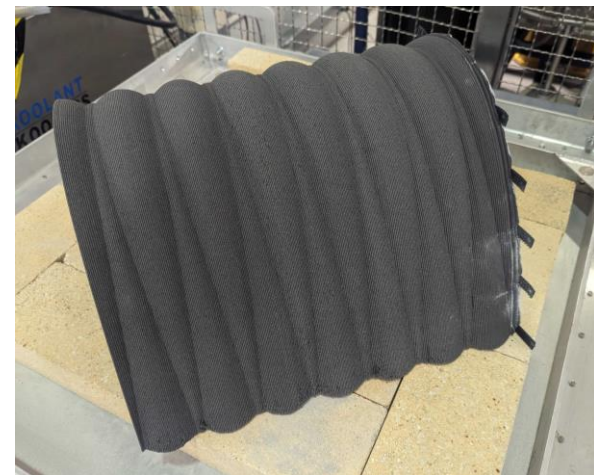
# Accomplishments – In-situ Construction



Second generation protective shelter is printed at  $\sim 10^5$  torr on LHS-1 Simulant



First generation shelter design



Second generation shelter design

# Full Scale Construction Concept of Operations



# Extendable Use Cases





# Project Assessment Summary



| REACT        | Performance |   |   |   | Comments                                                                              |
|--------------|-------------|---|---|---|---------------------------------------------------------------------------------------|
|              | C           | S | T | P |                                                                                       |
| Project Life | G           | G | G | G | Project has completed all goals, objectives, and milestones within cost and schedule. |

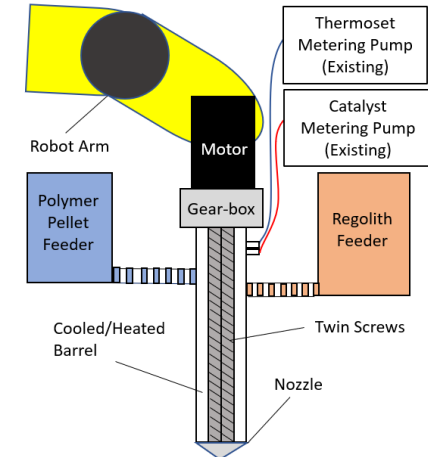
## ➤ Pending publications:

- “Development of lunar structural design criteria using terrestrial design practices and interpreted lunar conditions.”  
ASCE Journal of Architecture and Engineering
- “Building on the Moon- methods for structural validation and architectural design implications.”  
ASCE Journal of Architecture and Engineering
- “Selection, production, and properties of regolith polymer composites for lunar construction.”  
IEEE Aerospace Conference, 2024
- “Application of regolith polymer composite fused filament fabrication construction process in simulated lunar conditions”  
ASCE Earth and Space Conference, 2024

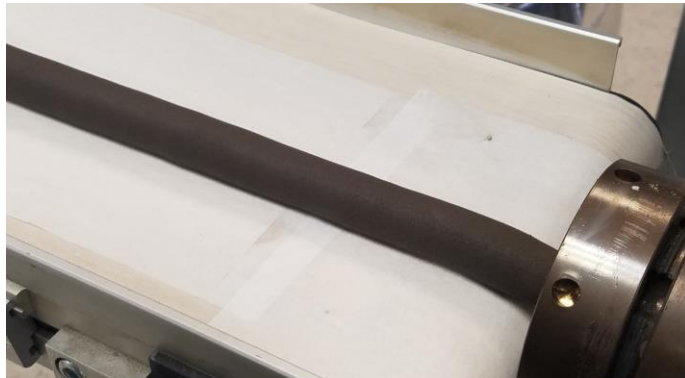
# Plans Forward and Transition / Infusion Plan



- AI SpaceFactory and LERA intend to commercialize by offering Lunar construction services to Artemis and other customers
- Mature towards CLPS lunar demonstration via follow on ACO, Tipping Point, and/or Flight Projects. Key next steps:
  - Develop flight TRL5/6 extruder
    - Compounding “on the fly” during additive operations without water in the process
    - Multi-material processing capability (thermoplastic and thermoset binders)
    - Applications in shelters, launch/landing pads, paver grouting, surface repairs
  - Develop and test materials for lifecycle considerations
    - Tailor polymers to lunar environment
    - Test strength at cold temps, thermal fatigue, etc.



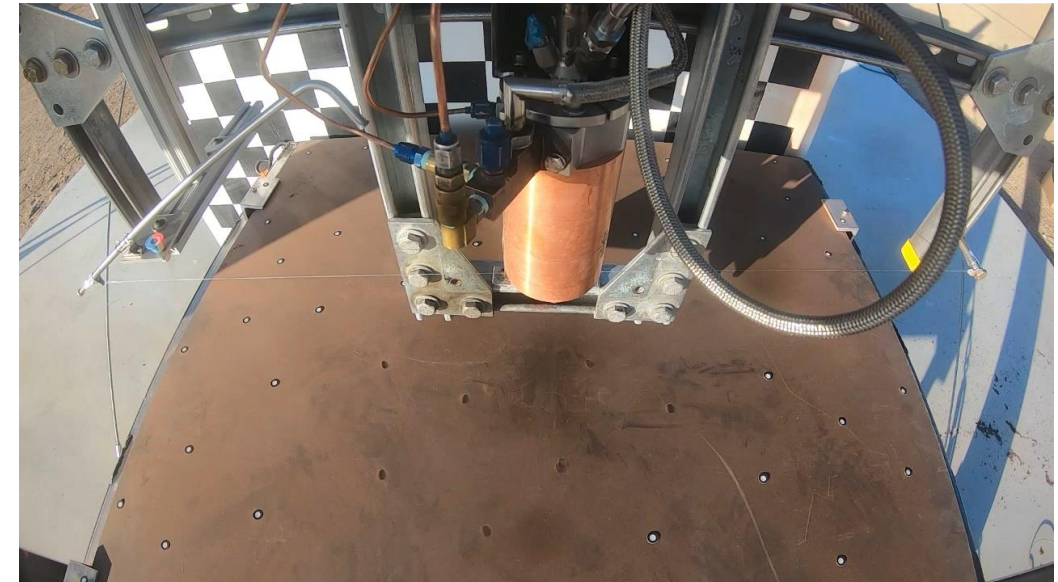
CLPS scale 3<sup>rd</sup> generation extruder concept



Extrusion of high temperature composite in lab



Paver grouting mitigates hot fire conditions



High temp composite mitigates plume environment (~3100 C)

# Education/Public Outreach

## EPO Involvement

- Posted an Instagram story on REACT:
  - [NASA's Kennedy Space Center on Instagram: “🤖🏠 How will #Artemis astronauts live on the Moon? The Relevant Environment Additive Construction Technology \(REACT\) project derives from N...”](#)
- Engaged underserved 4<sup>th</sup> and 5<sup>th</sup> graders at the Orlando Science Center as part of the National Engineering Design Challenge
- YouTube post:
  - <https://www.youtube.com/watch?v=22QlHZtwTSc>
- Internet press releases:
  - <https://www.prnewswire.com/news-releases/ai-spacefactory-and-nasa-kennedy-space-center-release-lunar-outpost-designs-301578951.html>
  - <https://www.designboom.com/technology/ai-spacefactory-nasa-lina-first-human-foothold-on-moon-07-04-2022/>
- Numerous interactions with industry and academia

## EPO Calendar Outlook (High Priorities):

### 6 Month Look-Ahead

|                                 |            |
|---------------------------------|------------|
| IEEE Aerospace Conference       | March 2024 |
| ASCE Earth and Space Conference | April 2024 |

# Summary & Concluding Remarks



- Accomplishments
  - Developed regolith-polymer composite construction materials and systems that are suitable for the moon.
  - Established the structural and architectural design of a protective shelter that mitigates risks associated with radiation, meteoroids, thermal cycling, and plume surface interaction ejecta.
  - Demonstrated construction of sub-scaled shelter in simulated Lunar dirty thermal vacuum conditions.
- REACT has achieved TRL 5 for:
  - Additive construction hardware and processes (non-flight)
  - Regolith polymer composite construction materials
  - Protective shelter structural and architectural design (Level of Development: 300)
- Concluding remarks:
  - Set out to prove a novel construction technology with multiple applications in simulated lunar environment
  - Intent was not to establish the “optimum” long term lunar construction method. It was to demonstrate feasibility of an in-situ construction technique that could be ready before other options become available.
  - REACT traded perceived development complexity, high power requirements, pressurize atmospheres, challenging process control, and scaling issues for the penalty of importing polymer mass.
    - Paths to polymer ISRU exist via apparent large deposits of carbon in Lunar PSRs and abundance of carbon in the Martian atmosphere.

The background is a dark, monochromatic topographic map. Overlaid on the map is a network of thin, light-colored lines that connect various points, some of which are marked with small dots. The lines and dots form a complex, web-like structure that spans across the map, suggesting a technical or engineering theme. The overall aesthetic is futuristic and technical.

# REACT

Relevant Environment Additive Construction Technology