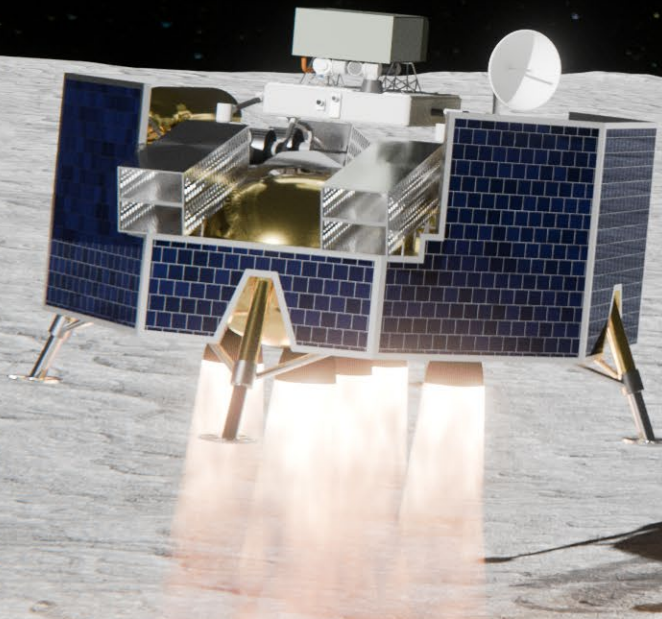




# Cosmic Capstone Challenge Pad Operations (C3PO)

Team C3PO 4/16/2026



## Problem Statement

Develop lunar landing pad to prevent damage to structures and vehicles caused by the displacement of lunar regolith.

## Mission Capabilities

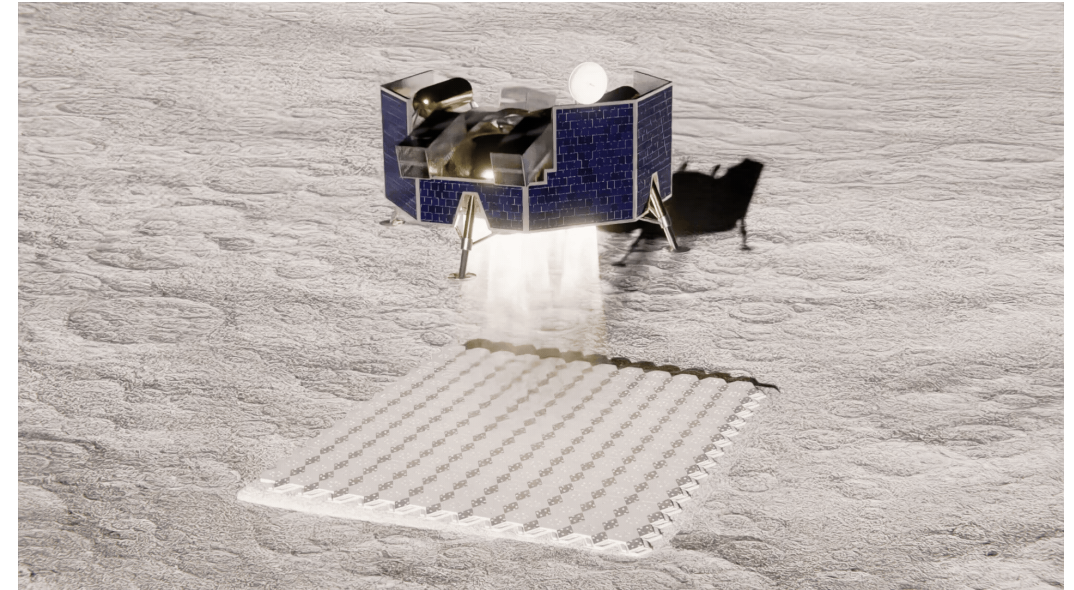
Develop small-scale landing pad using in-situ resources capable of withstanding loads from the Griffin Lunar Lander (GLL) Attitude Control System (ACS) thruster.

## Solution

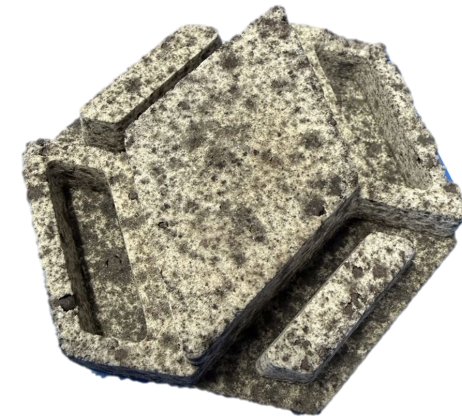
Manufacture interlocking tiles solely from in-situ resources capable of withstanding weight and thrust plumes of light to heavy class vehicles.

## Project Status

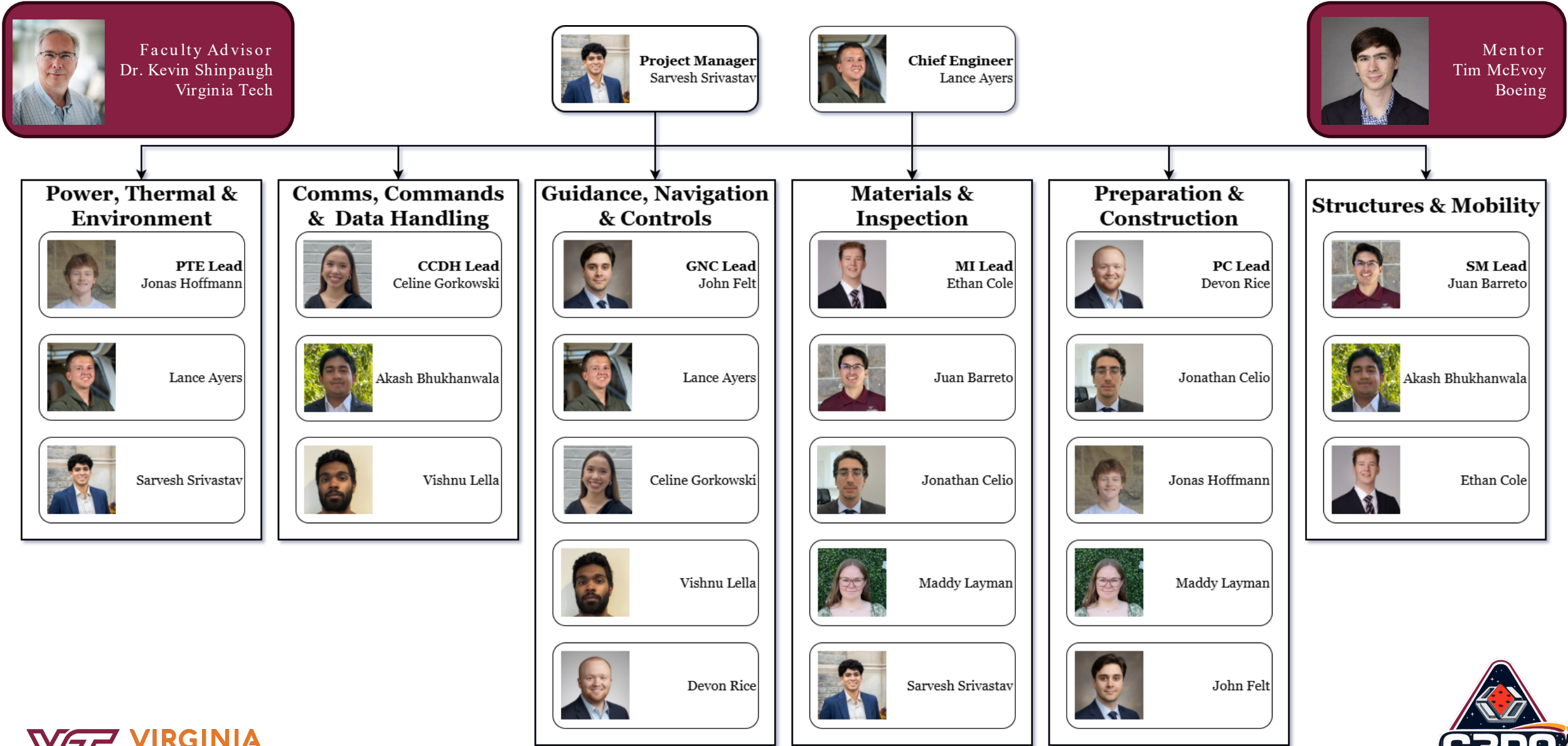
Half-scale tiles manufactured with LSP-2 simulant via thermal sintering. Supporting systems design at PDR level.



GLL landing on proposed lunar infrastructure



LSP-2 simulant sintered tile



# Program Management Milestones

Image taken from Artemis II [1]

**September**

Selected Program Manager

**October**

Defined mission scope and capabilities

**November**

Defined system requirements

**December**

Subsystem Requirements Review

**January**

Completed trade studies

**February**

Finalized conceptual design

**March**

Established path to PDR

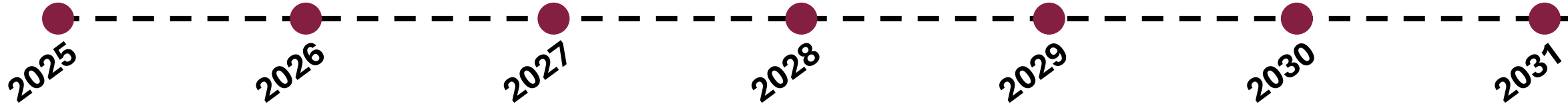
**April**

Present C3 Outbrief

**May**

Present PDR

# Program Timeline



**Conceptual Design & Prototyping**  
Completion 2027 Q4

**Manufacturing & Testing**  
Completion 2029 Q4

**Launch and Operations**  
Completion 2030 Q1

## Mission Start

## CoDR

## PDR

## CDR

## STR

## FMSR

## Operations

Identify Problem

Preliminary Research

Cost Budget

Finalized CAD models

Manufactured Systems

Fully Manufactured and Integrated System

Finalized Mission Decommissioning Plans

Identify Shareholders

Select Lunar Landing Location

Mass Budget

Updated Cost Budget

Updated Cost Budget

Finalized Cost Budget

Finalized Mission Continuation Plan If Applicable

Preliminary Mission Requirements

State Performance Metrics

Power Budget

Updated Mass Budget

Updated Mass Budget

Finalized Mass Budget

Identify Scope

Refine System Requirements

Expected Results

Updated Power Budget

Updated Power Budget

Finalized Power Budget

\*Design review should be scheduled for approximate time above review name  
\*All requirements should be complete prior to design review

Develop Subsystem Requirements

Success Criteria

Finalized Functional Block Diagram

Descope Underdeveloped Systems

Finalized Functional Block Diagram

Systems Analysis

Intermediate Functional Block Diagram

Manufacturing Plans

Subsystem Testing Results

Simulated Mission Lifespan Operations

Preliminary Functional Block Diagram

Identify and Manage Risk

Prototyping Results

Initial System Testing Results

Documented System Testing Results

Develop Concept of Operations

Identify Uncertainties

Testing Plans

ISTR schedule

Finalized Host Vehicle Integration Plan

Component Selection

Depict Minimized Risk

Updated Uncertainties

Launch and Operations timeline

Complete

Incomplete

Preliminary Prototyping Results

Descope Plan



# Mission Requirements

## Overall System Requirements derived from C3 RFP.

ID	Description	Source
SYS 1.0	The system shall have a mass less than 200 kg	RFP
SYS 2.0	The system shall have a volume less than 5.58 m <sup>3</sup>	RFP
SYS 3.0	The system shall survive the lunar night	RFP
SYS 4.0	The system shall interface with the GLL	RFP
SYS 5.0	The system shall communicate with the GLL	RFP
SYS 6.0	The system shall demonstrate ISRU manufacturing capability	
SYS 7.0	The system shall withstand lunar south pole environmental conditions	RFP

# Concept of Operations: Phase 1

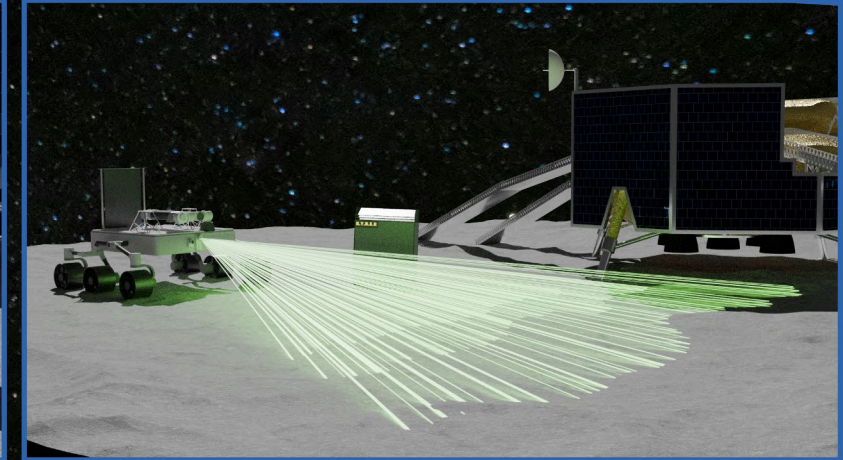
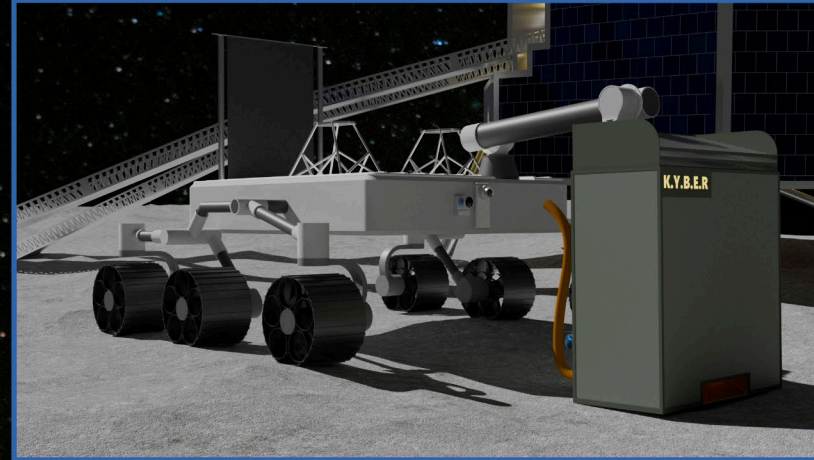
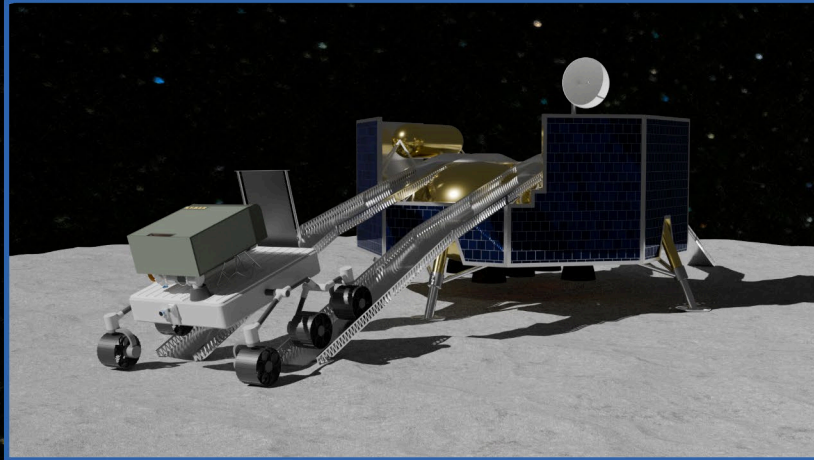
L&CRZ: FD0 - FD3

PHASE 1: FD4 - FD6

PHASE 2a: FD7 - FD45

LUNAR NIGHT: FD18 - FD31

PHASE 3: FD46



## 1 SABER Deployment:

1. Unfold ramps
2. Release from GLL
3. Traverse to lunar surface

## 2 KYBER Deployment:

1. Search vicinity for suitable site
2. Decouple KYBER from launch support
3. Position KYBER using robotic arm
4. Decouple KYBER from robotic arm

## 3 Site Mapping:

1. Waypoints set by Mission Control
2. SABER traverses waypoints
3. LIDAR + SLAM generates 3D local map

# Concept of Operations: Phase 2

L&CRZ: FD0 - FD3

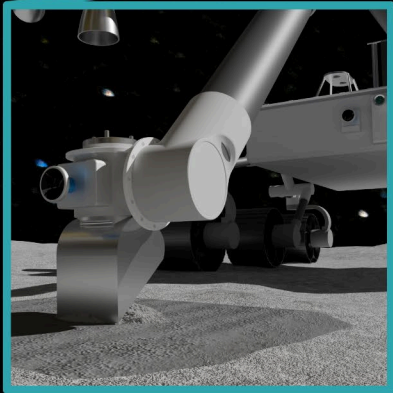
PHASE 1: FD4 - FD6

PHASE 2: FD7 - FD45

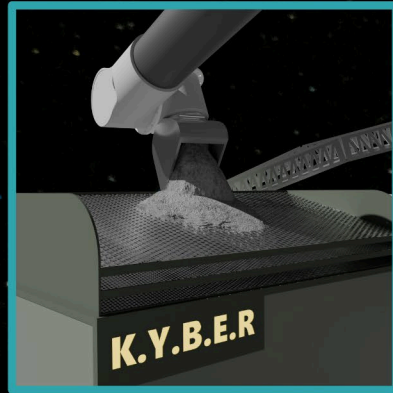
LUNAR NIGHT: FD18 - FD31

PHASE 3: FD46

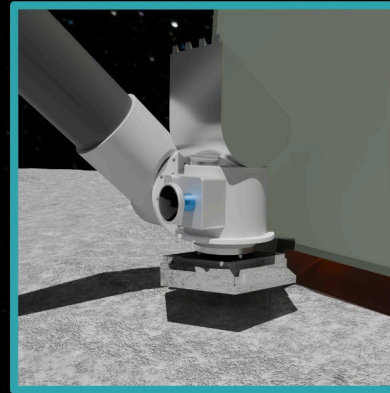
## PHASE 2: Operations 6-9 Loop



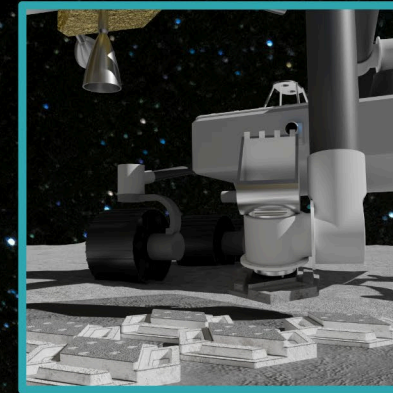
5a Flatten Site



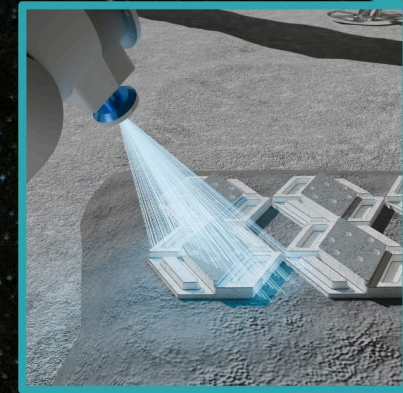
6a Deliver Regolith



7a Collect Tiles



8a Place Tiles



9a Inspect Placement

5b Warmup KYBER

6b Sift Regolith

7b Fill Mold

8b Sinter Tiles

9b Release Tile



# Concept of Operations: Phase 3

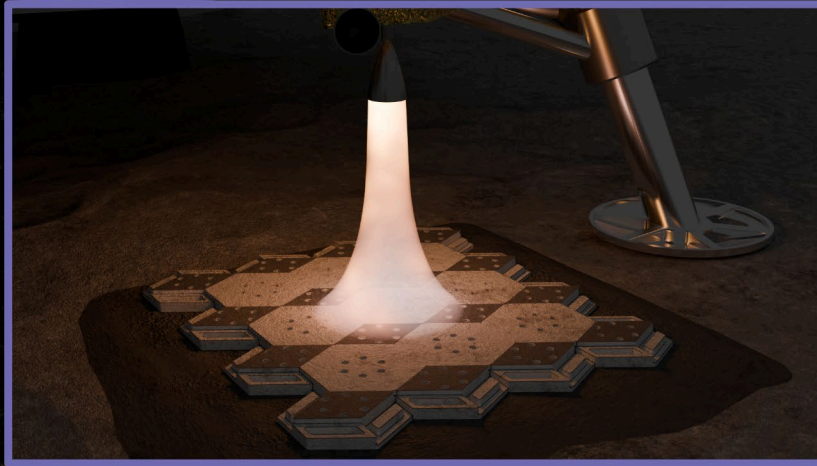
L&CRZ: FD0 - FD3

PHASE 1: FD4 - FD6

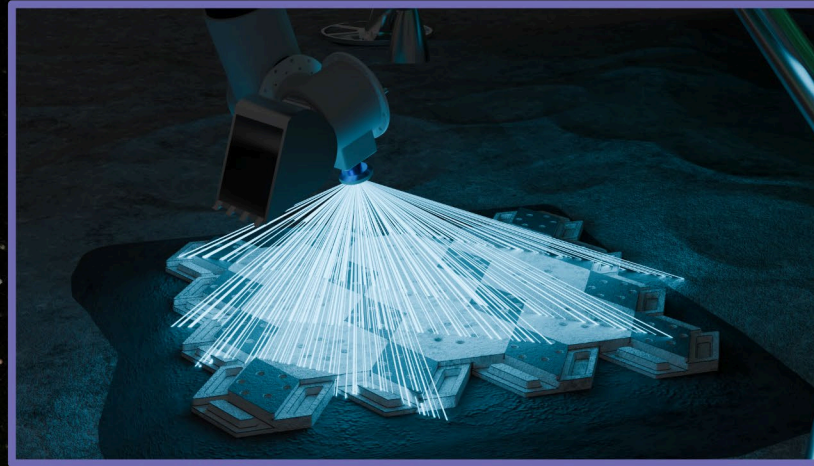
PHASE 2: FD7 - FD45

LUNAR NIGHT: FD18 - FD31

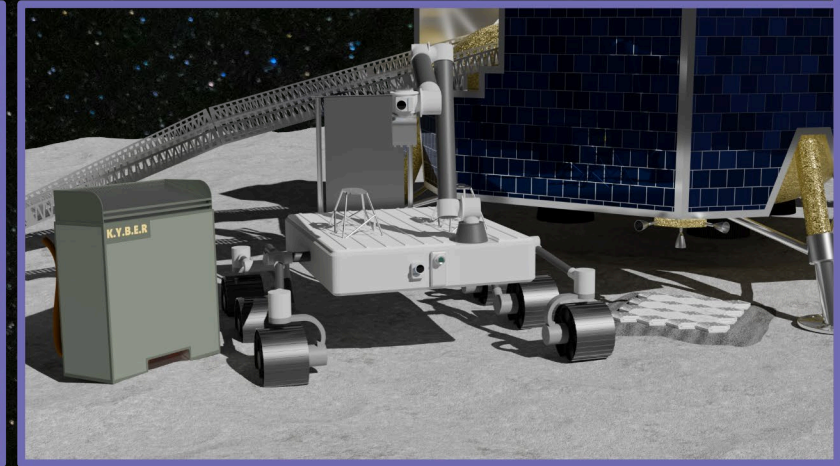
PHASE 3: FD46



- 10 ACS Test**
1. Fire thruster for 20s
  2. Record pad with thermal and optical cameras



- 11 Post Test Inspection**
1. LIDAR creates 3D model of pad
  2. Optical camera captures high resolution macro images



- 12 Results Analysis:**
1. Results are transmitted to the ground for analysis
  2. Mission Complete!
  3. Continue production and assembly till failure

## Lunar Landing Pads

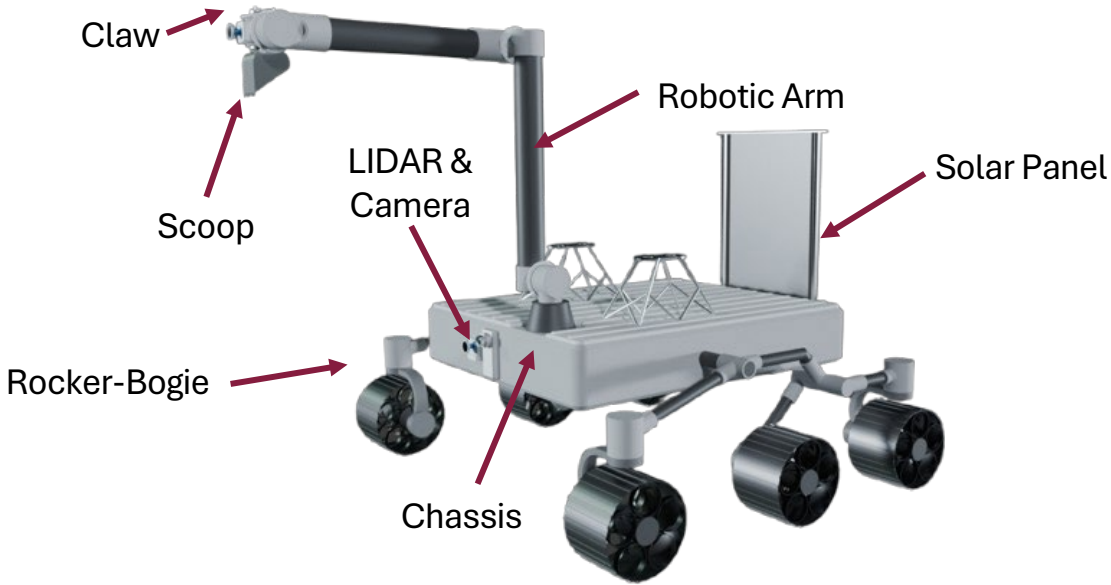
- Mitigate regolith plumes
  - Reduced damage to nearby infrastructure
- Known safe landing site
  - Provides clear and flat surfaces
- Allow heavy-class vehicles
  - Ensures stable platform for landing

## Alternative Use Cases

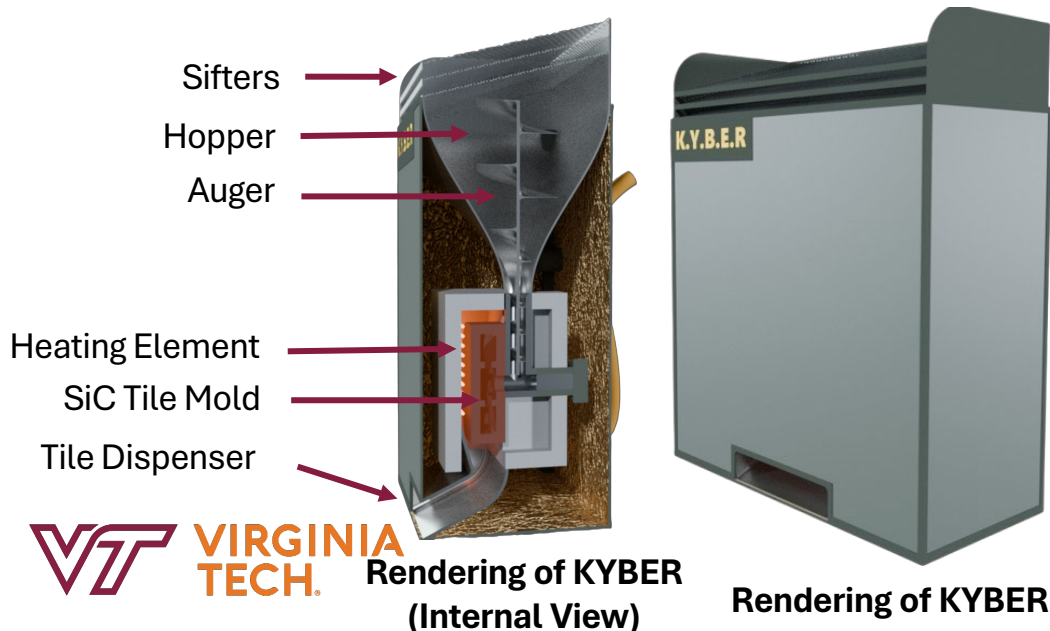
- Roads / Walkways
  - Increased traction
  - Reduced power draw during vehicle travel
  - Reduced risk of damage to spacesuits
- Foundation
  - Structural foundations for habitats and infrastructure
- Radiation Shielding
  - Combine with material such as aluminum to improve radiation shielding [2]



# Mission Feasibility



Rendering of SABER



Rendering of KYBER  
(Internal View)

Rendering of KYBER

## Surface-Prep, Analysis Building and Excavation Rover (SABER)

- Rover used to prepare pad area, collect regolith, place tiles, and inspect landing pad
- Consists of a robotic arm with a scoop and claw for excavation and tile placement
- Employs array of sensors to navigate and inspect landing pad including LiDAR, thermal and optical cameras, a sun sensor, an IMU, and wheel encoders

## Kiln for Yielding Building Elements from Regolith (KYBER)

- Sinters tiles from lunar regolith using a thermal oven
- Sifts and dispenses lunar regolith particles  $< 100 \mu\text{m}$
- Capable of manufacturing one tile every  $\sim 14$  hours

# Mission Innovation

## Typical Tile Designs:

- Symmetric tile designs do not interlock
- Interlocking pads require 2 tile designs
- Often requires additional binder to be transported from Earth

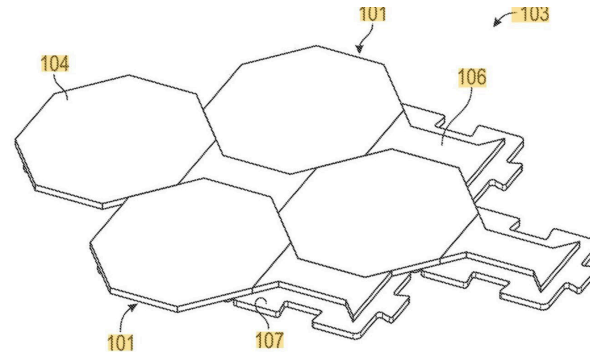
## C3PO's Tile Design:

- Single interlocking tile design
- Manufactured solely with lunar regolith
- Capable of withstanding compressive and thermal loads from heavy-class landers

## Current Tile Designs

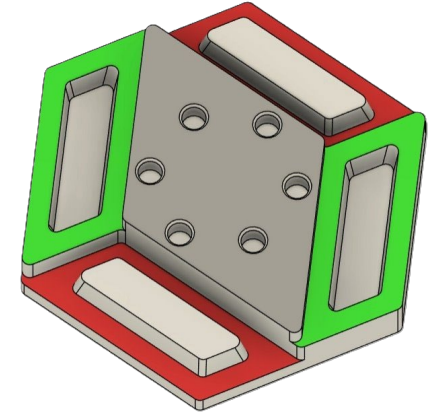


ESA Sintered Tiles [4]

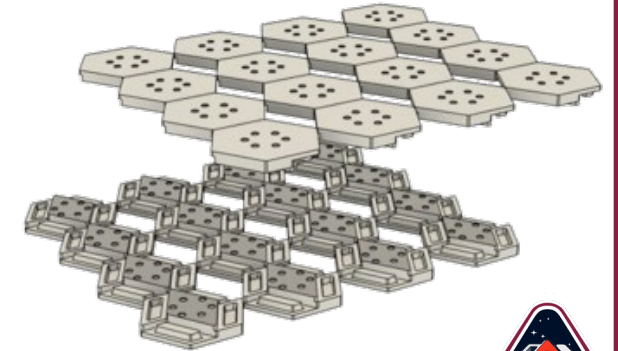


Proposed NASA Tile Design [5]

## Proposed Tile Design



Proposed Tile Design:  
Red outlines Protruding  
Green outlines Recessing



# Advancing High Value Missions

## Moon-Mars Architecture: NASA [6]

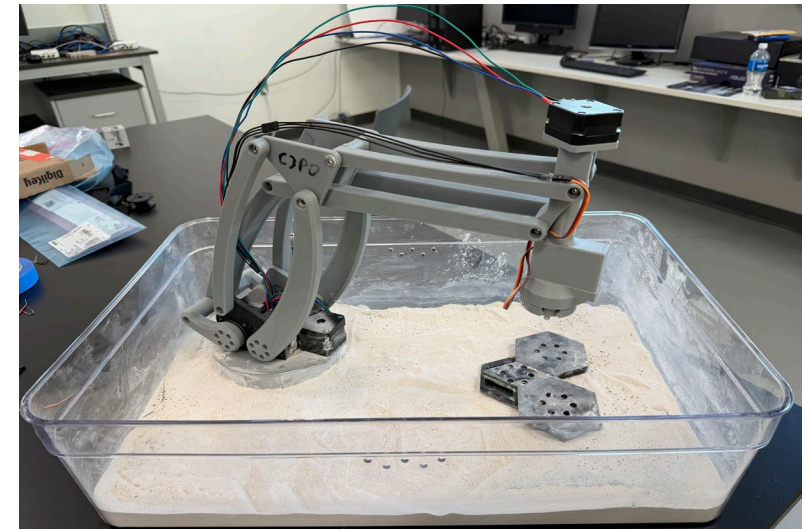
- Lunar infrastructure
  - Foundation for global lunar infrastructure
- Transportation and Habitation
  - System of systems allowing repeatable lunar landings

## Advancing from Successful Demonstration:

- Increased vehicle size would enable:
  - Manipulating larger tiles
  - Allow for faster transport of tiles and regolith
- Scaling up tile design would enable:
  - Higher thermal/structural loads
- Larger scale mission would enable advanced sintering techniques



**NASA Moon-Mars Illustration [7]**



**Tile Placement Demo: Moving arm and placed tiles**

# In-Situ Testing and Validation

## Test Setup

### Test Bed

- Prepare 1.0 m<sup>2</sup> area under the GLL ACS thruster to serve as a pad foundation
- 0.25 m<sup>2</sup> landing pad consisting of 25 tiles under the GLL ACS thruster

### Test Duration

- Fire ACS thruster for 20 s

## Inspection & Validation

### Thermal Inspection

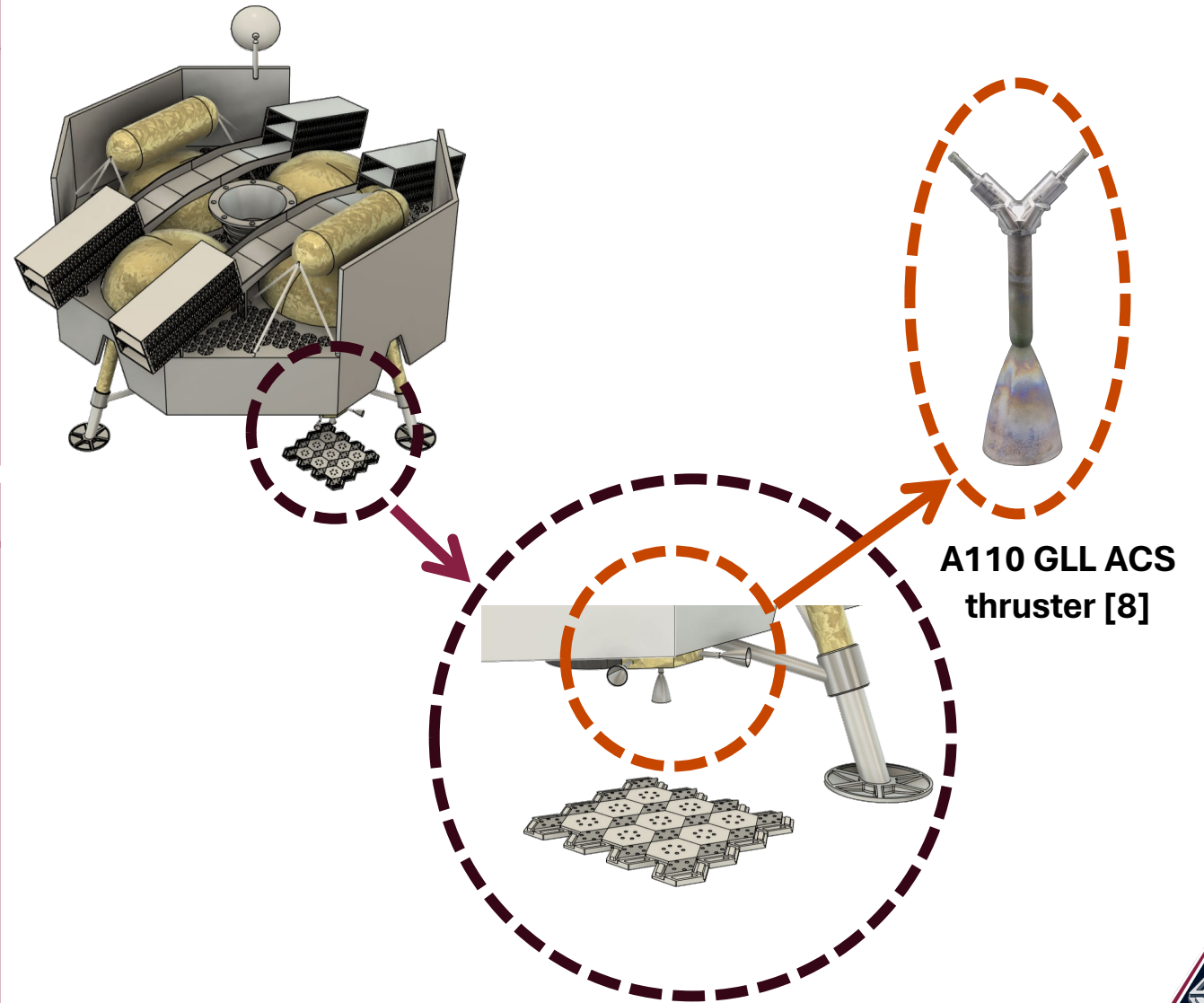
- Observe temperature distribution across pad during and after firing

### Particle Shadow Velocimetry

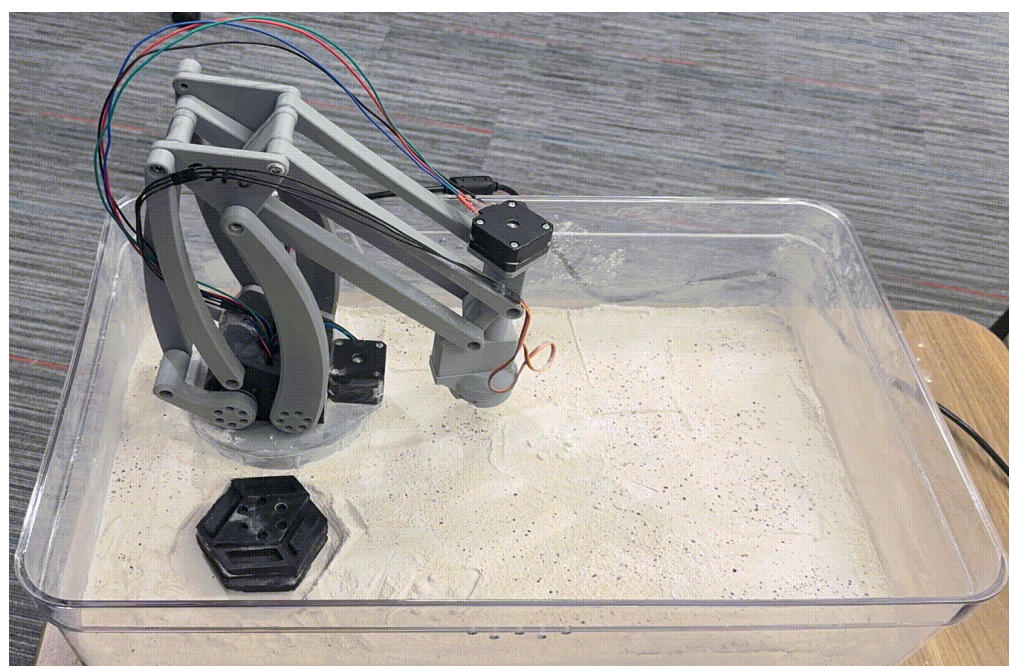
- Estimate velocity of ejected regolith particles

### Visual Validation

- Inspect pad for tile fracture or separation and GLL for damage



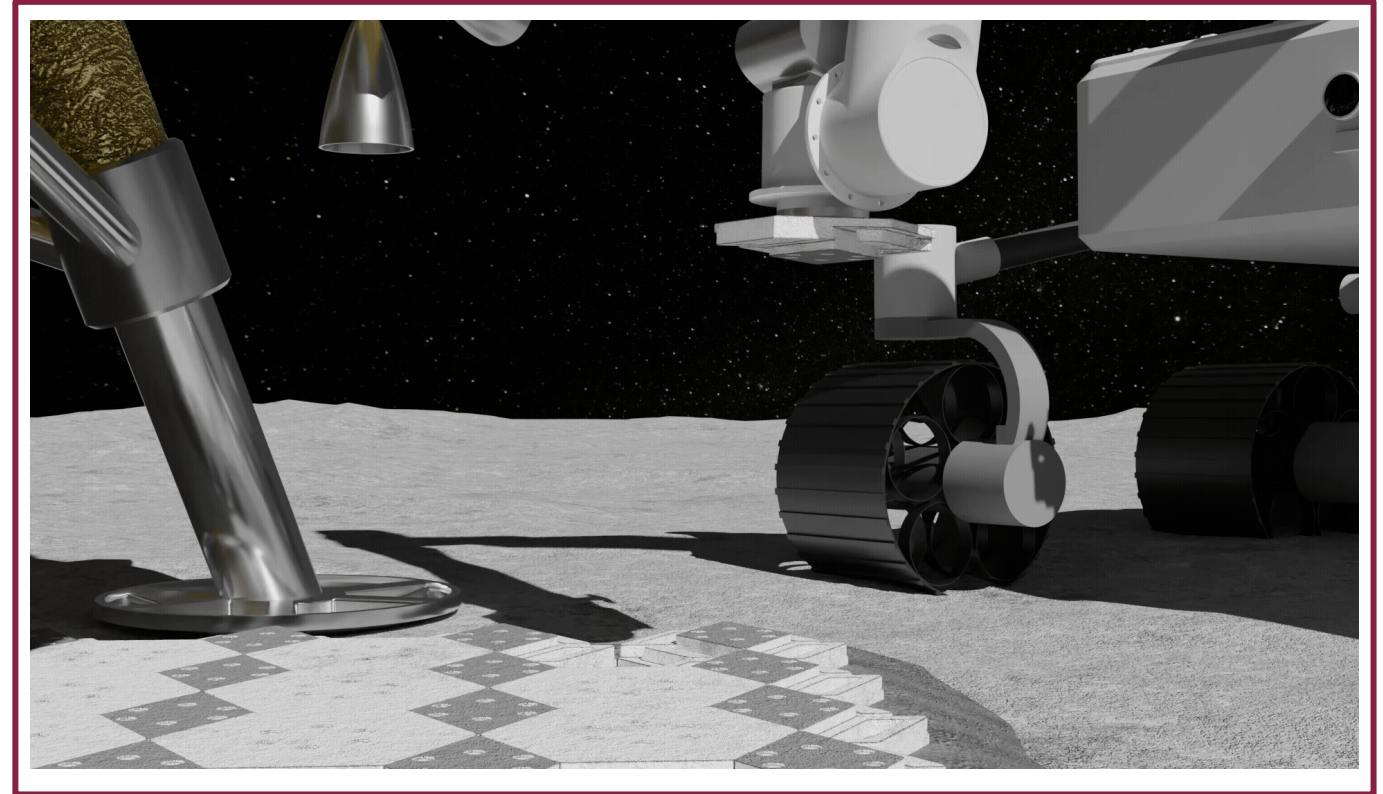
# Animation of Key Operating Sequences – Tile Placement Demonstration



Tile Placement Demo: Robotic arm places 3D-printed tiles



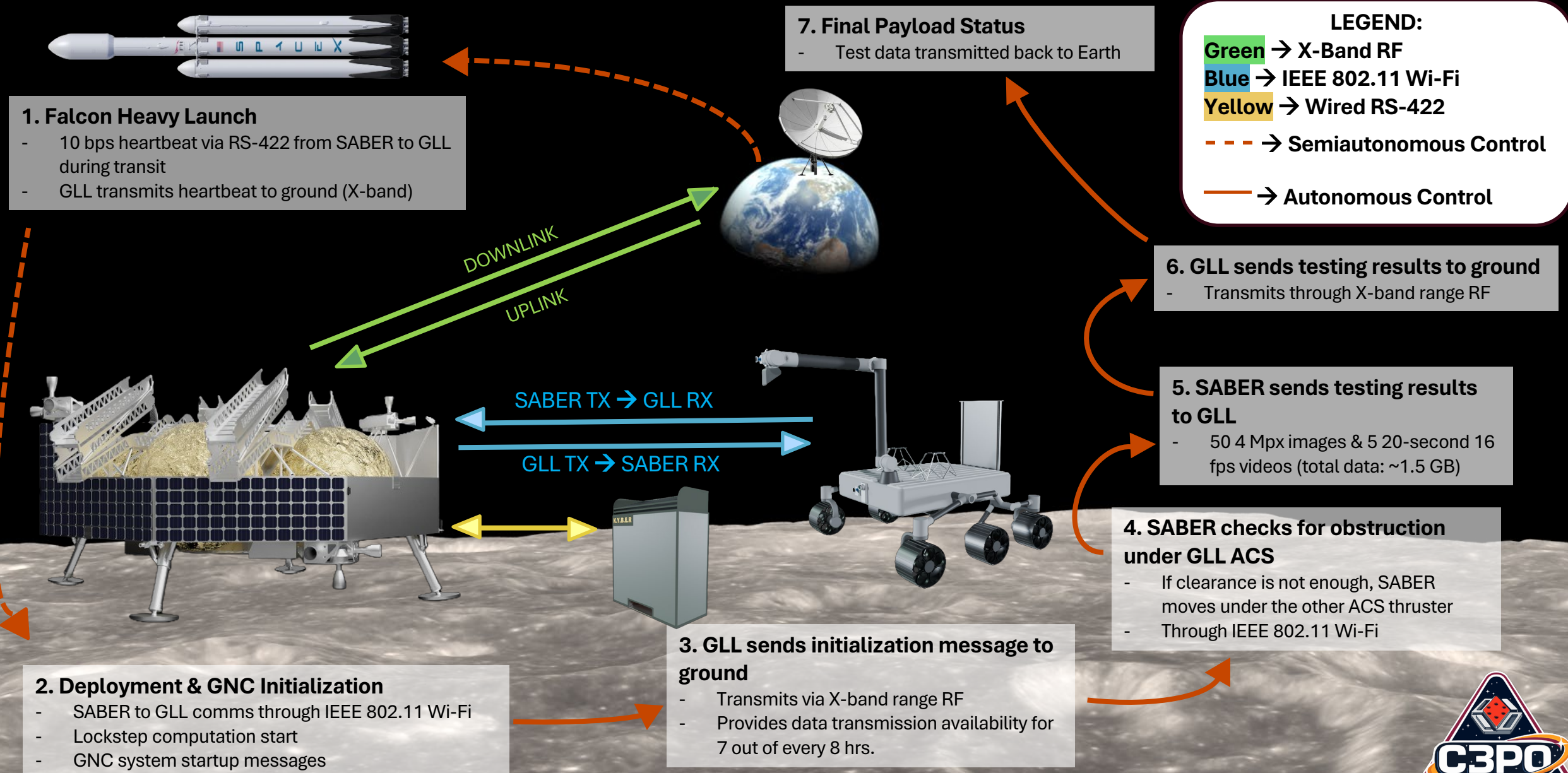
Required tile placement order



Render of tile placement process



# Communication and Data Handling ConOps



# Mobility and Structural Design

## Mobility features

- Max. velocity: 0.1 m/s
- Max. power consumption: 35 W
- Max. obstacle height: 56 cm
- Max. terrain slope: 30°

## Rocker-bogie

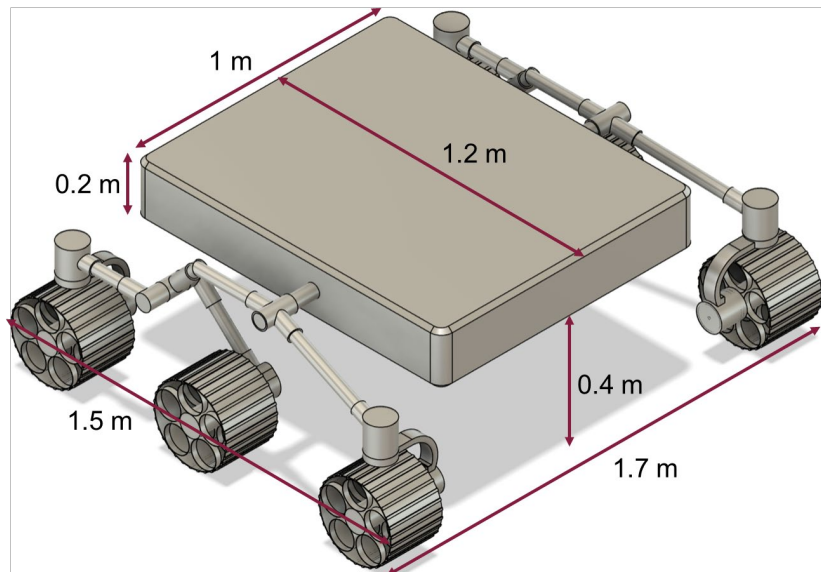
- Flight tested
- Differential mechanism
- Chassis maintains average pitch angle of both rockers

## Materials

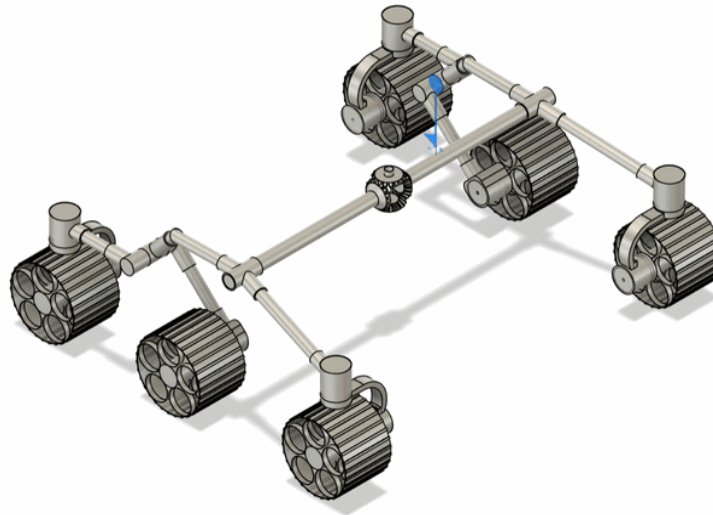
- Aluminum chassis and suspension
- Chromium Carbide-Nickel Chrome (Cr<sub>3</sub>C<sub>2</sub>-NiCr) coating
- Steel wheel rim and spokes

## Wheels

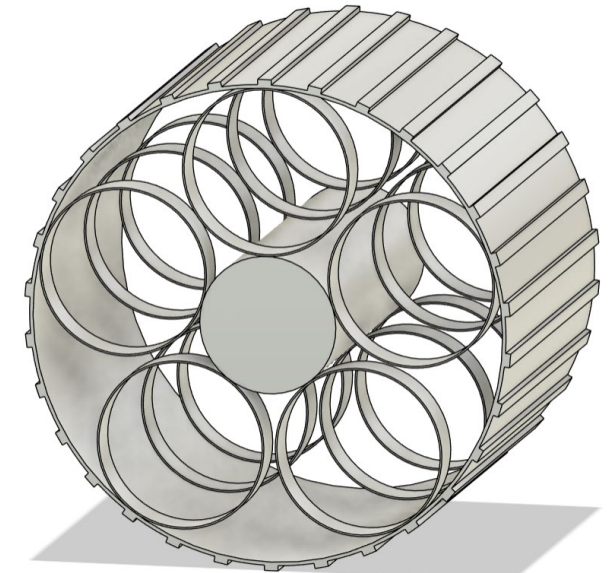
- Rigid inner cylindrical hub surrounded by 3 rows of spring loops
- Maximizes contact area



Dimensions of the rover's main body



Rocker-bogie suspension with differential gears



Flexible wheels

## Sintering Methods for Tile Assembly

Sintering Methods	Power (W/kg regolith)	Mass (kg)	Time (min)	Cost (M USD)	Score
	Minimize				
Criteria Weight	0.4	0.45	0.1	0.05	
<b>Oven [9]</b>	<b>355</b>	<b>35</b>	<b>600</b>	<b>0.5</b>	<b>0.225</b>
Microwave [10]	1852	52	180	20	0.208
Geopolymerization [11]	800	60	1440	0.5	0.195
Laser [12]	12000	3000	60	5	0.186
Flash [13]	3000	40	30	50	0.186

### Thermal Oven



Traditional Thermal Oven at Virginia Tech

### Microwave Furnace



Commercial Microwave Sintering Oven [9]

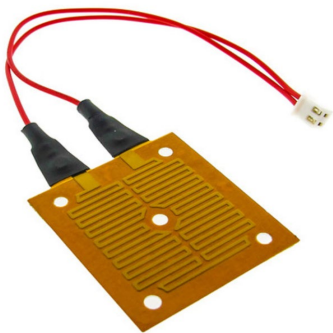
# Thermal Control System

Lunar south pole peak day and end night temperatures [14]

Lunar South Pole Low Night Temperature (°C)	Lunar South Pole Peak Day Temperature (°C)
-198	60

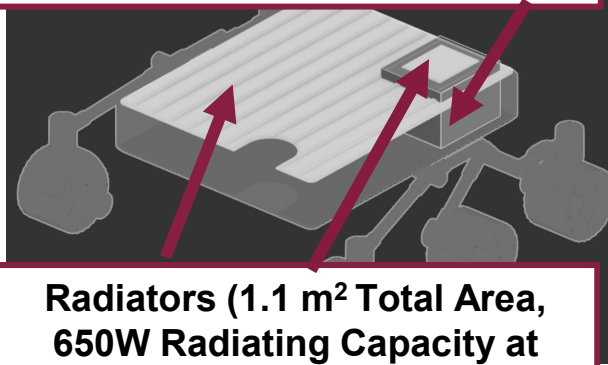
## Active Thermal Control:

Flexible Polyimide Resistance Kapton Film Heater [15], 10W Heating Capacity During Lunar Night



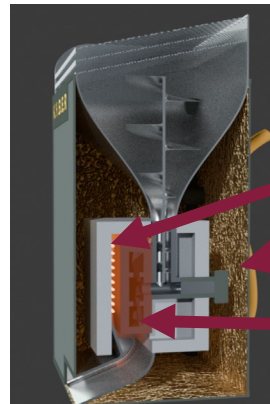
## Passive Thermal Control:

Warm Electronics Box (WEB)



Radiators (1.1 m<sup>2</sup> Total Area, 650W Radiating Capacity at Maximum Allowable Internal Temperature of 60°C)

SABER Thermal Control System

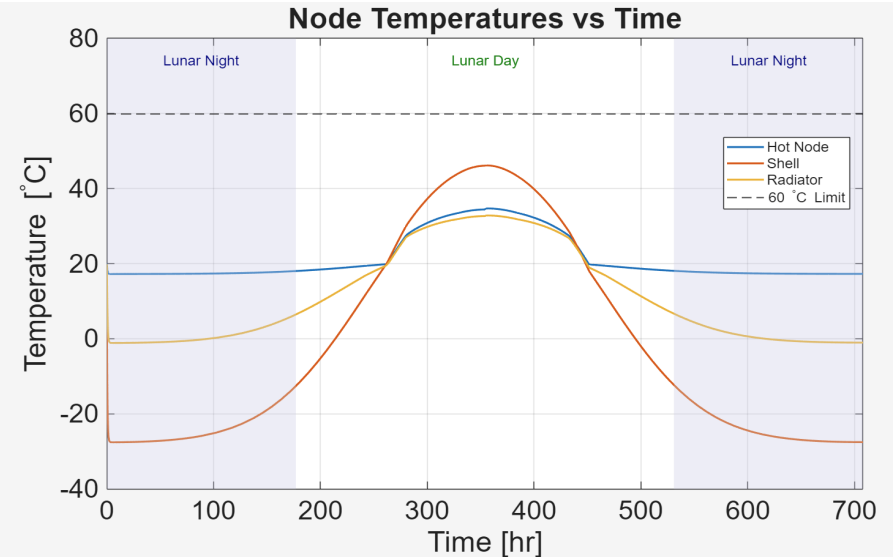


1200°C Heating Unit

MLI

Silicon Carbide Mold

KYBER Thermal Control System



- Results of transient thermal simulations of the WEB over a full lunar day/night cycle.
- Heater ran at 3 W continuously during lunar night, and radiator opened and closed linearly with internal temperature during lunar day.
- Hot node centered around sensitive electronics.

SABER Operational Temperature Range (°C)	SABER Survivable Temperature Range (°C)
0 - 40	-20 - 60

Operational and Survivable Temperature Ranges of SABER



# Power Budget and Methods

## GLL Power Methods

Mode	Max Power (W)	Application
Nominal	200	Sinter
Peak	500	Ramp-Up

## SABER Power Methods

Source	Max Power (W)	Energy (Wh)
Solar	278	-
Battery	282	249
<b>Total</b>	<b>560</b>	<b>249</b>

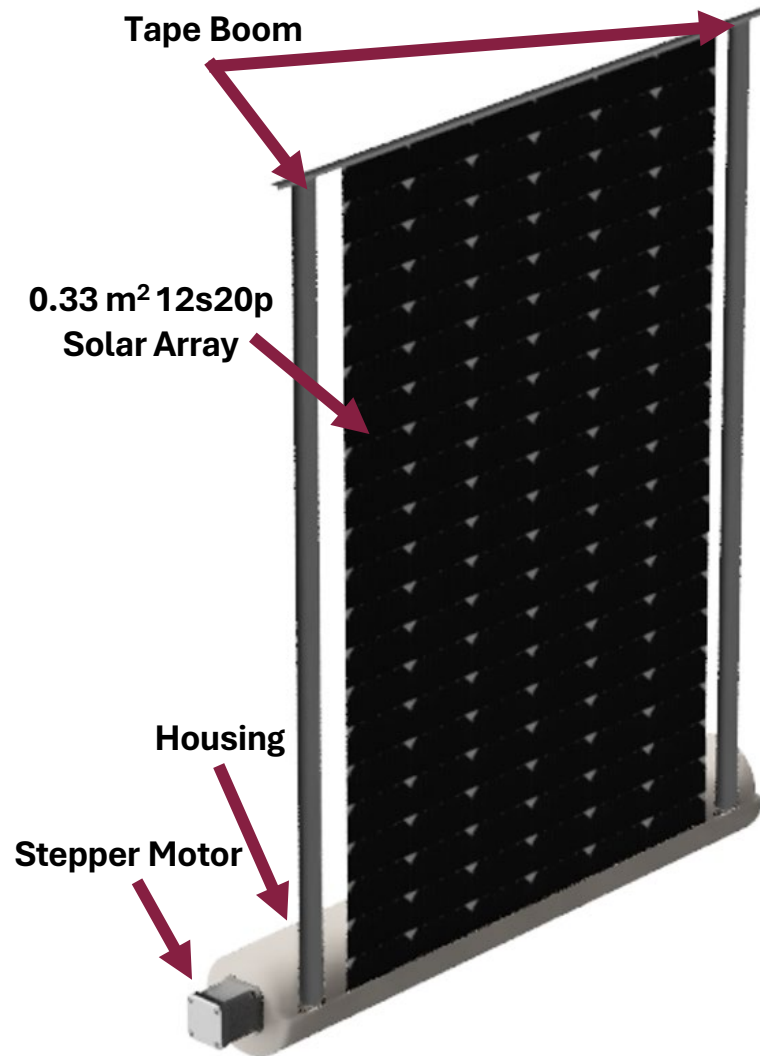


ASBL LiPo Battery [16]



Sharp IMM3J Solar Cell [17]

## Solar Array Design

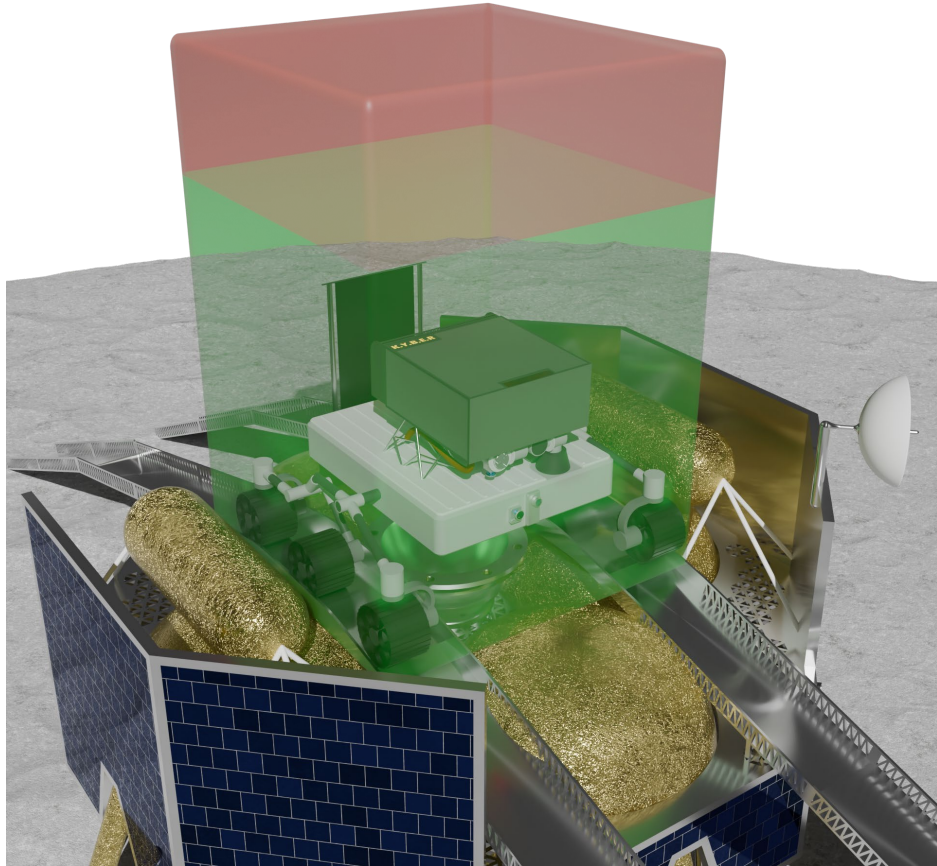


## Power Requirements

Subsystem	Action	Power (W)
KYBER	Ramp-Up	425
	Sinter	15
	RS-422	1
SABER	Material Delivery	4
	Tile Placement	4
	Drive	35
	Sensors	36
	FC & Comms	4



# Mass, Volume, and Cost Budget



SABER on top of GLL inside the volume restriction

## Hardware Mass and Cost

Component	Mass (kg)	Cost (M USD)
Robotic Arm	20.00	10.00
Chassis, Suspension, & Wheels	94.20	20.00
Flight Computer	0.50	0.50
Navigation Sensors	4.65	0.25
Thermal Control System	16.5	0.50
Power	5.00	0.50
KYBER	35.00	2.00
<b>Total</b>	<b>175.8</b>	<b>33.75</b>

GLL Volume ( $m^3$ )

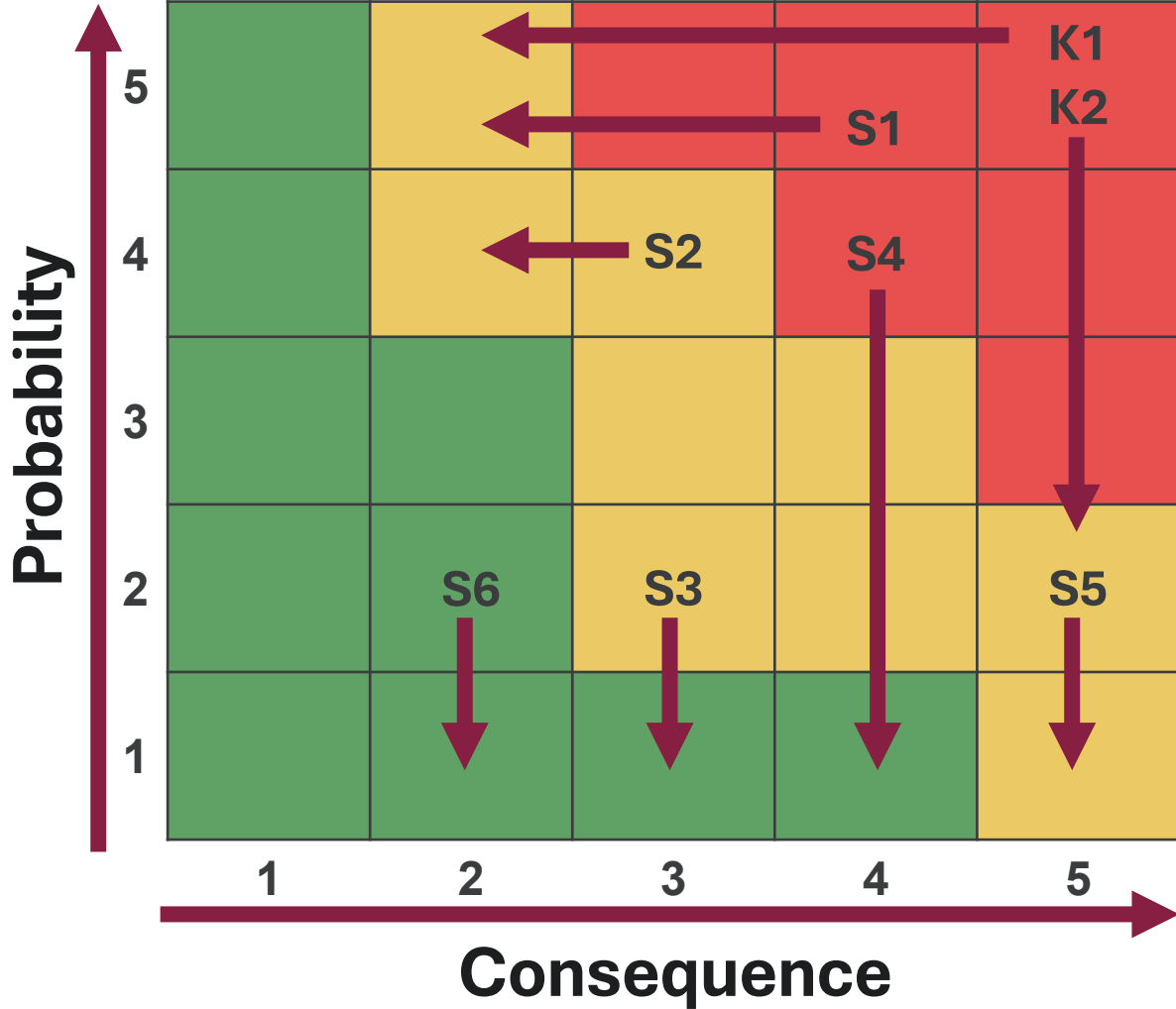
5.58

Payload Volume ( $m^3$ )

3.2

# Risks

## Risk Table



	No.	Risk	Consequence	Mitigation Technique
SABER	S1	Dust getting into actuators	Reduced actuator life	Making components dustproof
	S2	Radiation effect on processor	Bit flips cause computations to be incorrect	2 active dual-core processors using TMR lockstep processing with majority voting logic
	S3	Dust scratching lenses	Degraded navigation accuracy	Utilizing protective lens coating
	S4	Traction issues	SABER is unable to traverse the terrain	Rocker-Bogie suspension evenly distributes weight among wheels & wheels flex to increase contact area with the lunar surface
	S5	SABER thermal control failure	Damaged electrical components	Using a radiator, heater, and WEB to regulate temperature
	S6	Comms failure	Loss of data and control	Utilizing 2 idle processors in case of active processor failure
KYBER	K1	KYBER mold degradation	Improper tile manufacturing	Using a Silicon-Carbide mold for increased thermal conductivity
	K2	Damaged sifting mechanism	Improper regolith particle size	Utilizing 3 sifting layers

# Prototype - Tile



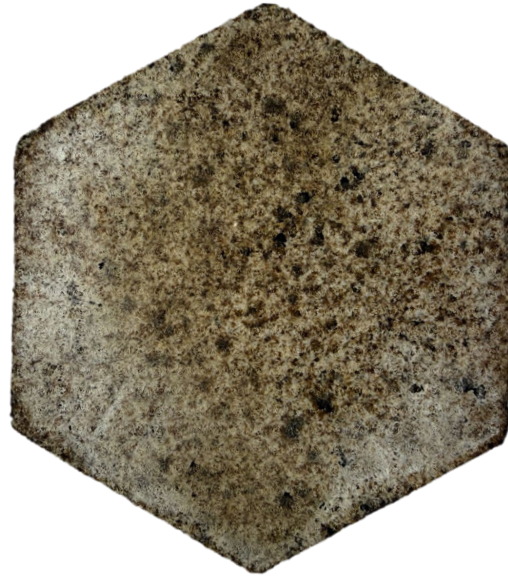
Diamond-up tile view

## Manufacturing

6hrs @ 1200°C

Graphite mold

±1mm tolerance



Diamond-down tile view

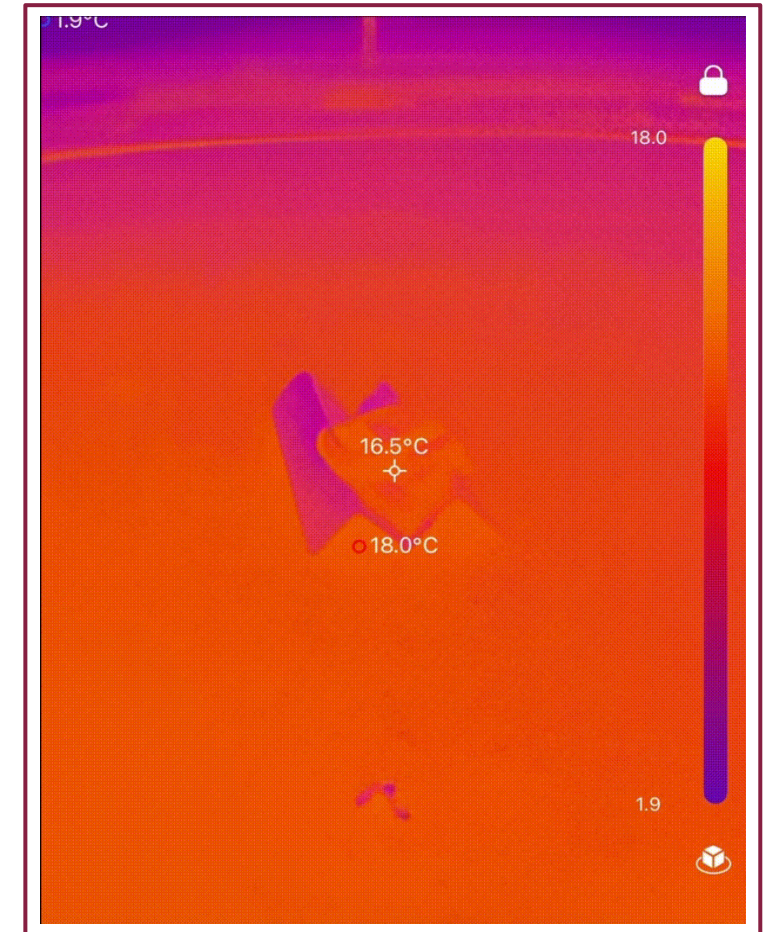
## Testing

ASTM C39 compression test coupons

- 12.5mm $\phi$  x 25mm
- 2.44 MPa max stress

2000°C torch test

- 2-minute burn
- Max diamond-up: 650°C
- Max diamond-down: 70°C



Sintered tile thermodynamic load test

# Most Innovative Concepts Considered

## Single Tile Design

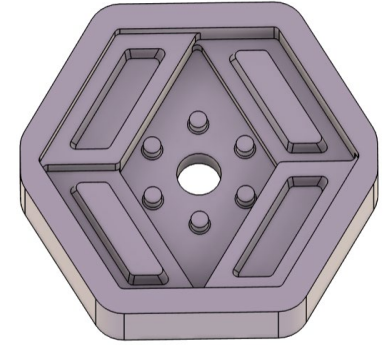
Ability to manufacture a landing pad from one tile design with one mold simplifies manufacturing process and required equipment.

## Solar Mirrors for Sintering

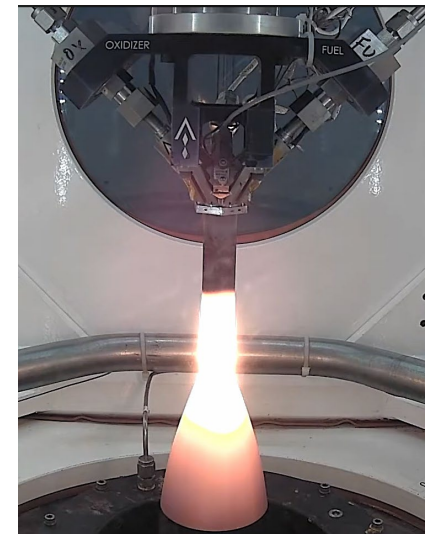
Considered as an alternative sintering method due to reduced power requirements, the mass and size of the design led to it being descoped.

## Using GLL ACS Thruster on Landing Pad

Implementing the testing capabilities to include firing GLL's ACS thruster extended pad evaluation to include compressive and thermal performance



**One Piece of Tile Mold**



**A110 GLL ACS thruster [18]**

# Most Important Technology Gaps

## Gap ID: 0801

### Lunar Dust Tolerant Systems and Dust Mitigation

- Lunar dust is highly abrasive and electrostatically adhesive, degrading components and sensors
- Lunar dust accumulation can reduce mobility of the rover and arm, as well as impair the thermal control system
- Lunar dust mitigation is critical for maintaining rover reliability during excavation and tile placement

## Gap ID: 0605

### Lunar Regolith Excavation, Manipulation, and Transportation

- Current methods have demonstrated regolith maneuverability using tools less than 10 kg
- Regolith excavation can expedite ISRU capabilities
- If successful, infrastructure can be scaled to a full-size mission, rather than a technology demonstration

## Gap ID: 0602

### In-Situ Resource Identification, Characterization, Mapping

- Regolith material properties vary across the lunar surface
- Sintering performance requires extensive analysis on regolith material properties
- Accurate site mapping allows for selection of optimal sites for excavation and construction

# Biggest Challenges Encountered

## Tile Design

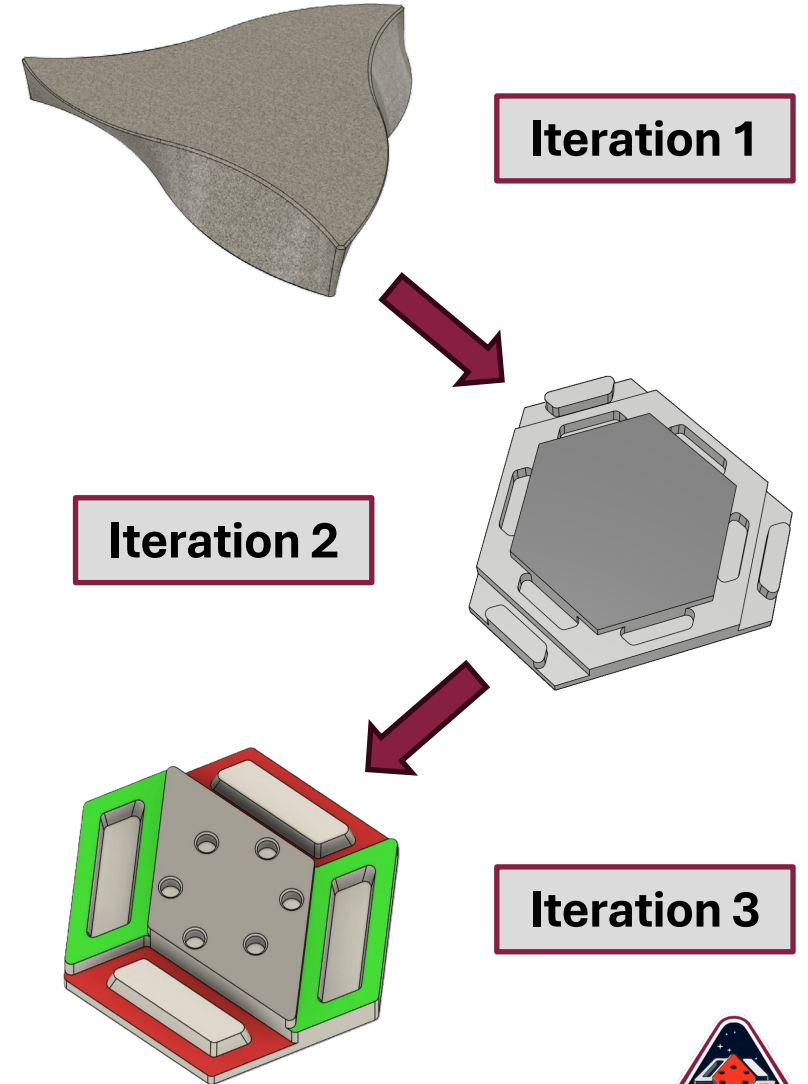
Designing a landing pad with one tile proved to be difficult, requiring several iterations of the tile design to achieve the necessary performance.

## Mass Budget

Developing a system capable of manufacturing a landing pad within the allotted 200 kg proved to be difficult, so the scale of the landing pad and tiles were reduced.

## Lunar Night Survivability

10 W of power from GLL limited heating capabilities during lunar night, requiring the development of the WEB to protect temperature sensitive components.



# Paper Information

Image taken from Artemis II [1]

Abstract Length: 142 words

Paper Length: 20 pages

References: 49

Potential publishers:

- AIAA SciTech
- AIAA Ascend
- IEEE



# Summary, Conclusion, and Highlights

## Problem

- Lunar dust can cause damage to nearby structures and the lander
- Limits sustainable lunar operations

## Solution

- Autonomous ISRU landing pad construction and In-situ tile fabrication and placement
- Integrated system: SABER + KYBER

## Methodology

- Excavation of lunar regolith (SABER) and sintering into structural tiles (KYBER)
- Autonomous placement to form landing pads

## Validation

- Thermal and power analyses completed, CAD models, and prototype developed
- Trade studies and risk mitigation performed

## Impact

- Reduces dust plume effects during landing, enabling reusable lunar landing zones
- Supports Artemis & future Moon-to-Mars missions

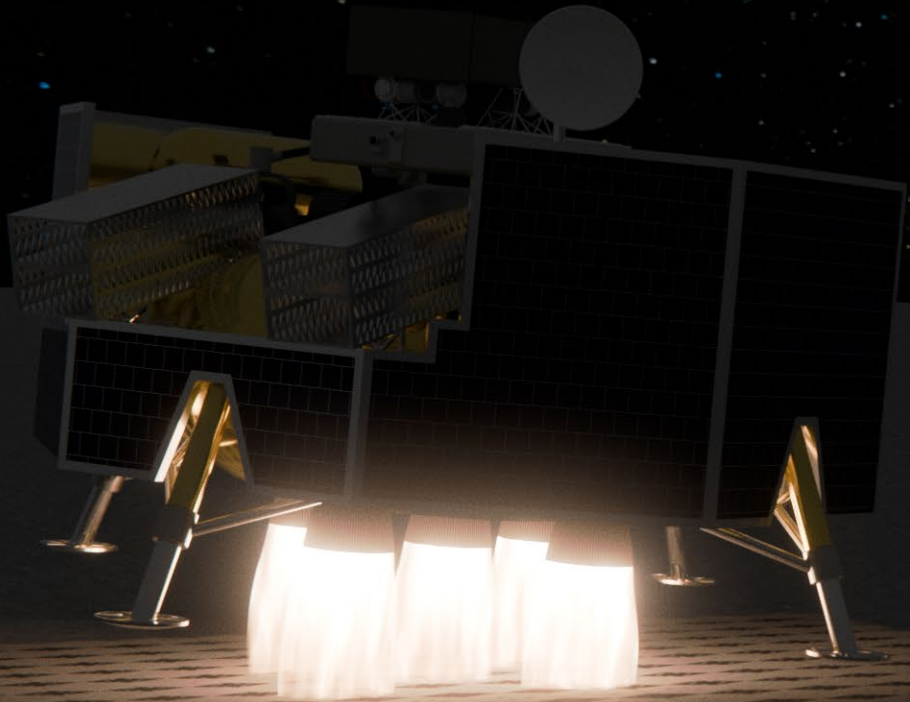


Render of KYBER



Render of Saber

Questions?



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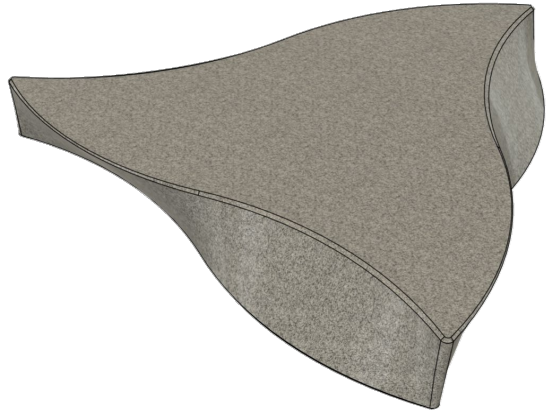
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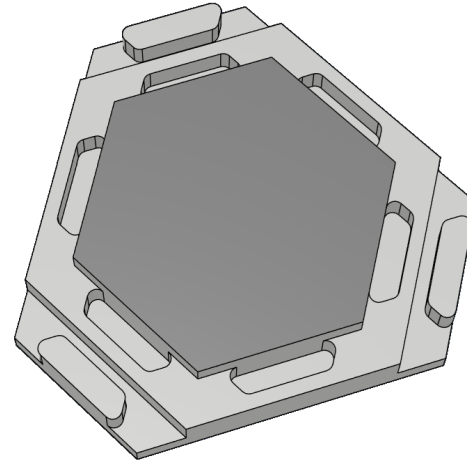
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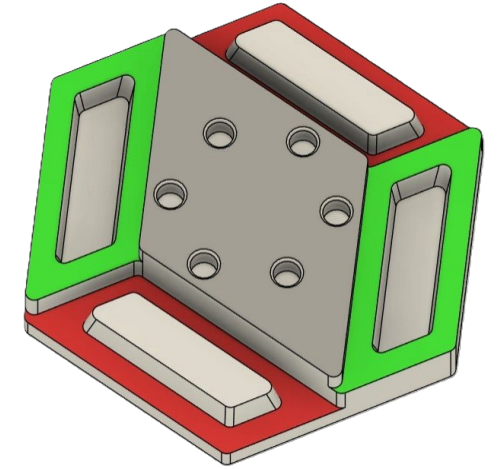
# Backup Slides: Materials & Inspection - Tile Geometry Shape Decision



Iteration 1



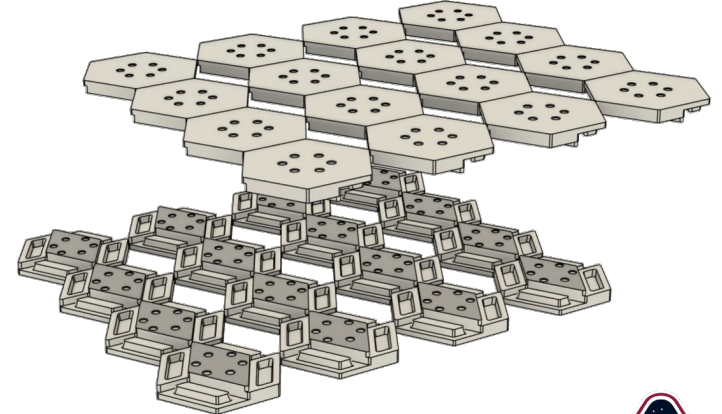
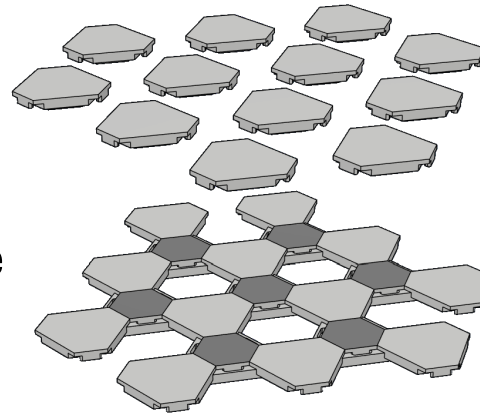
Iteration 2



Iteration 3

## For all tile Iterations:

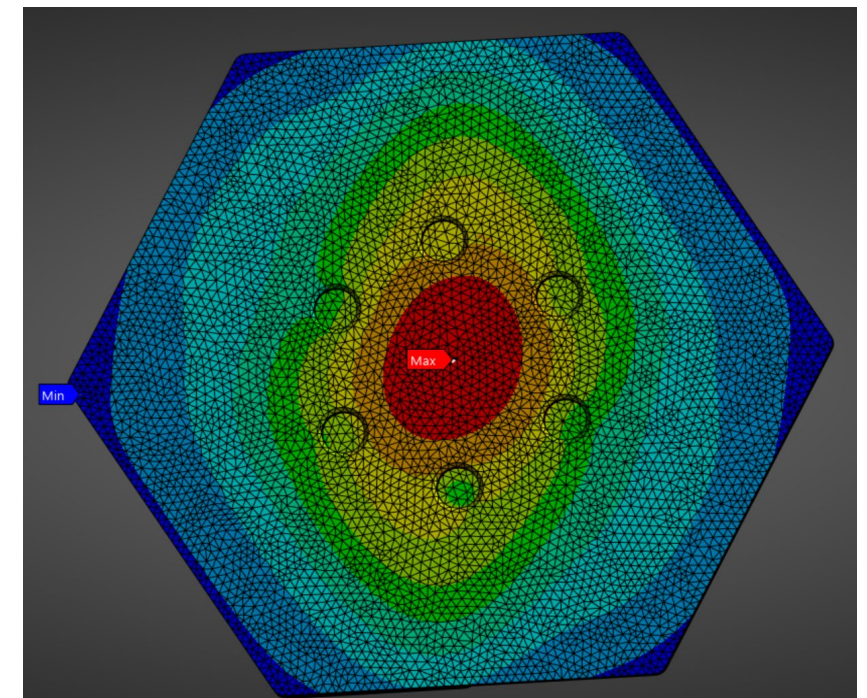
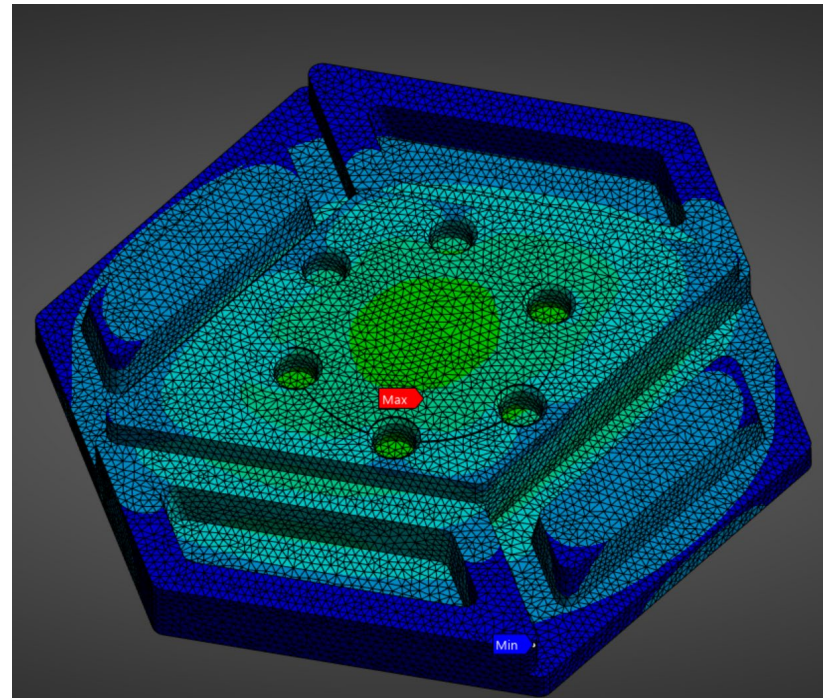
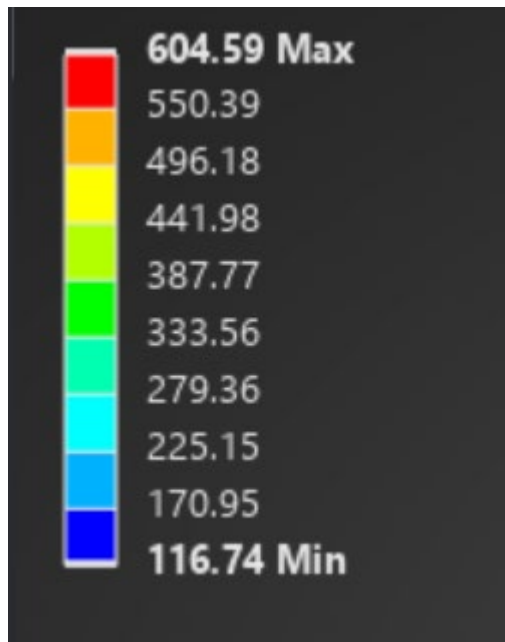
- One mold required
- Can be mirrored, flipped, rotated
- Tiles the plane
  - Iteration 2 only tiles one side of the plane
  - Iteration 3 completely tiles the plane



# Backup Slides: ANSYS Tile Cool Down Simulation

## Entire Tile Cooldown Profile:

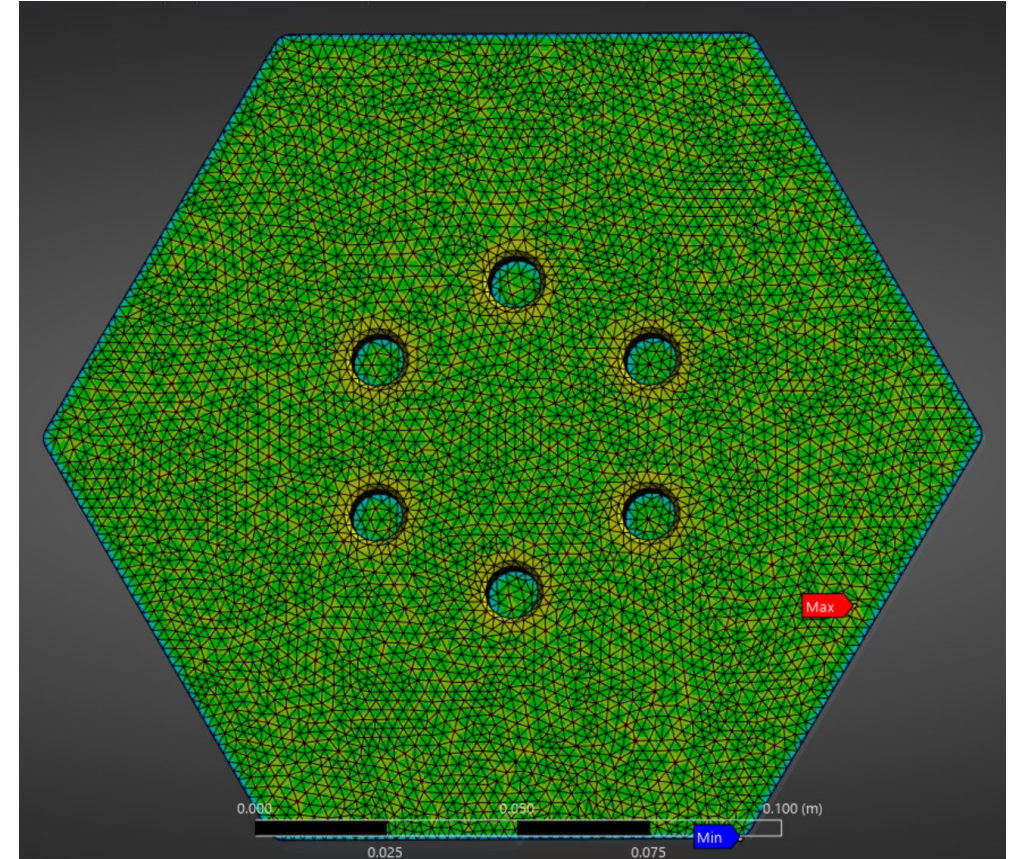
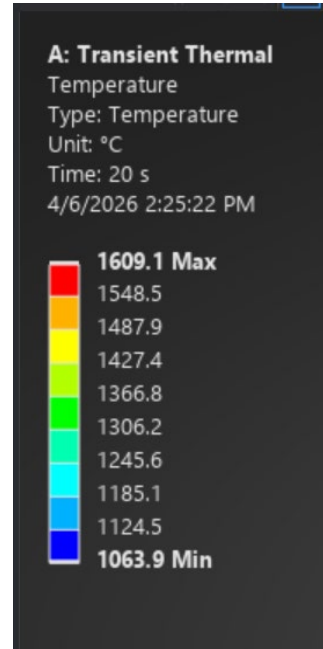
- Simulating cooldown after being dispensed by KYBER into ambient conditions after sintering
- Starting at 1200 °C, the diamond-up orientation achieves a cooler temperature after an hour, the diamond-down remains at a maximum of 604.59 °C directly in the center



# Backup Slides: ANSYS Transient Thermal Analysis

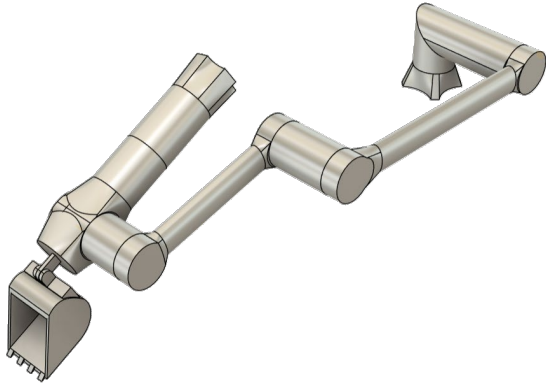
## Diamond-down orientation:

- Thermal analysis applied to simulate heat flux from the ACS thruster over 20 second period
- Tile experiences a general temperature of 1306.2 °C along the face
- Maximum temperature visually occurs around the tile placement holes
- Minimum temperature occurs only the edge of the tile



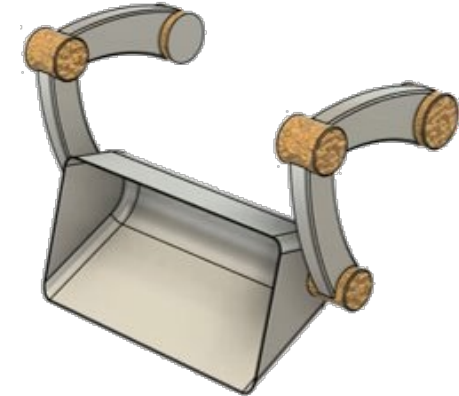
# Backup Slides: Trade Studies – Preparation and Construction

## Robotic Arm with Scoop:



Robotic Arm with Scoop CAD model

## Front-End Loader:



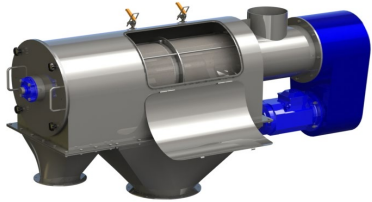
Front-End Loader CAD model

### Preparation and Construction Excavation and Material Delivery Trade Study

Excavation / Material Delivery	Mass Delivery Rate (kg/hr)	Mobility (DoF)	Power	Mass	Cost M USD	Score	Source(s)
<i>Criteria Weight</i>	0.15	0.2	0.3	0.3	0.05		
	Maximize		Minimize				
Robotic Arm with Scoop	60	6	75	20	10	0.55	[19, 20, 21]
Front-End Loader	400	2	100	35	1	0.45	[22, 23]

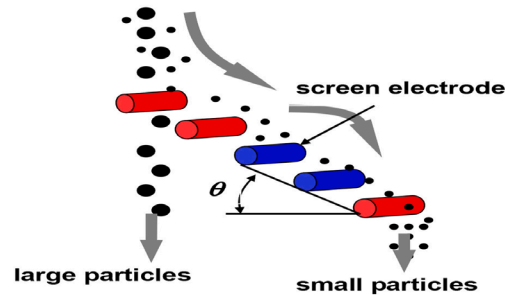
# Backup Slides – Sifting Trade Study

## Centrifugal



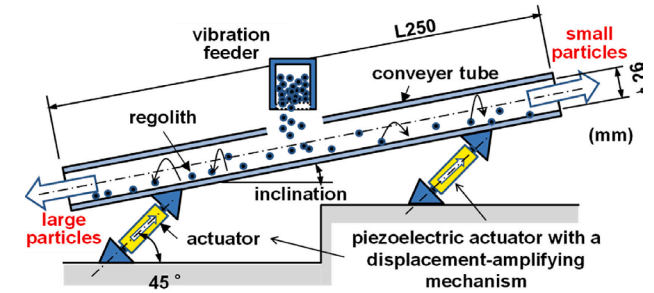
Example Centrifugal Sieve [24]

## Electrodynamic



Electrodynamic Sieving Example [25]

## Vibrational

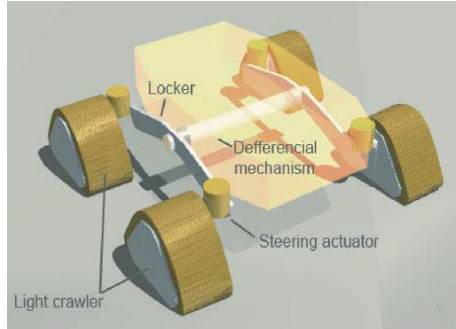


Example Vibrational Sifter [25]

## Sorting Trade Study

Sifting Subsystem	Regolith Sorting Rate (kg/hr)	Power (W)	Mass (kg)	Risk	Cost (USD)	Score	Source
	Maximize						
Weight	0.35	0.2	0.2	0.15	0.1		
Centrifugal	400	180	37.5	0.1	400	0.36	[24]
Electrodynamic	0.18	0.5	0.18	0.65	0	0.34	[25, 26]
Vibrational	10	10	1.72	0.25	610	0.30	[25, 27-29]

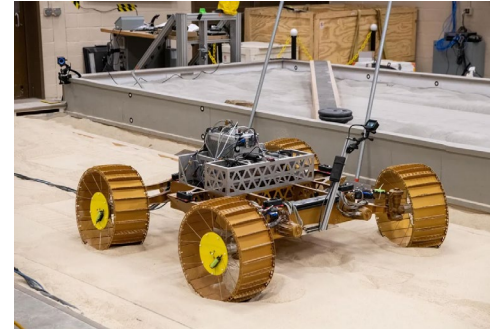
# Backup Slides: Suspension Trade Study



Locker-Crawler concept proposed by JAXA [30]



Zoë is a single-rocker rover designed by Carnegie Mellon researchers [31]



VIPER is a lunar rover that uses active articulation [32]



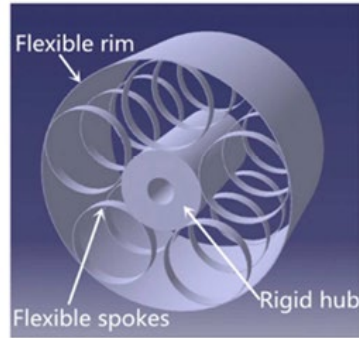
Curiosity is a Mars rover that uses rocker-bogie suspension [33]

## Suspension Mechanisms Trade Study

Suspension Mechanisms	Performance	Reliability	Mass (kg)	Power (W)	Cost (M USD)	Score	Source
	<i>Maximize</i>		<i>Minimize</i>				
Weight	0.4	0.21	0.2	0.15	0.06		
Rocker-Bogie	2	3	21	35	20	0.43	[33]
Actively Articulated	3	1	32	45	70	0.31	[32]
Single-Rocker	1	2	12	35	10	0.26	[31]

# Backup Slides: Wheel Trade Study

## Flexible wheel



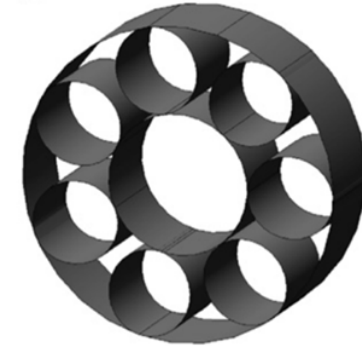
Jilin University flexible wheel design [34]

## Wire Mesh wheel



Mesh wheel on Lunakhod-1 [34]

## Elastic wheel

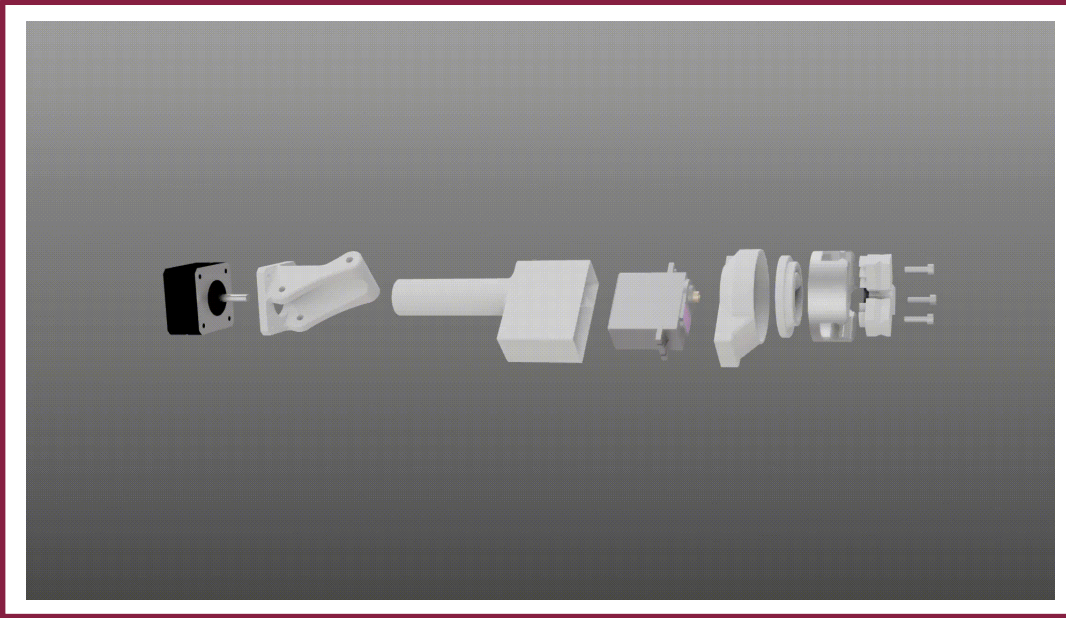


Model of an ellipse spring elastic wheel concept [34]

## Wheel design Trade Study

Wheel Design	Performance (Matrix Score)	Mass (kg)	Power (W)	Cost (\$)	Score	Source
	<i>Maximize</i>	<i>Minimize</i>				
Weight	0.35	0.33	0.24	0.08		
Flexible Wheel	0.5	3.08	0.64	36000	0.396	[34]
Wire Mesh Wheel	0.33	5.48	1.35	14000	0.319	[34]
Elastic Wheel	0.17	36.6	1.62	110000	0.285	[34]

# Backup Slides: Robotic Arm Chuck Mechanism



**3-jaw chuck end effector  
exploded CAD view (pictured  
left)**

**3-jaw chuck prototype  
(pictured right)**

