NASA’s Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) Project: Additive Construction for Lunar Infrastructure

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R. G. Clinton, Jr., PhD, Principal Investigator, Moon to Mars Planetary Autonomous Construction Technology

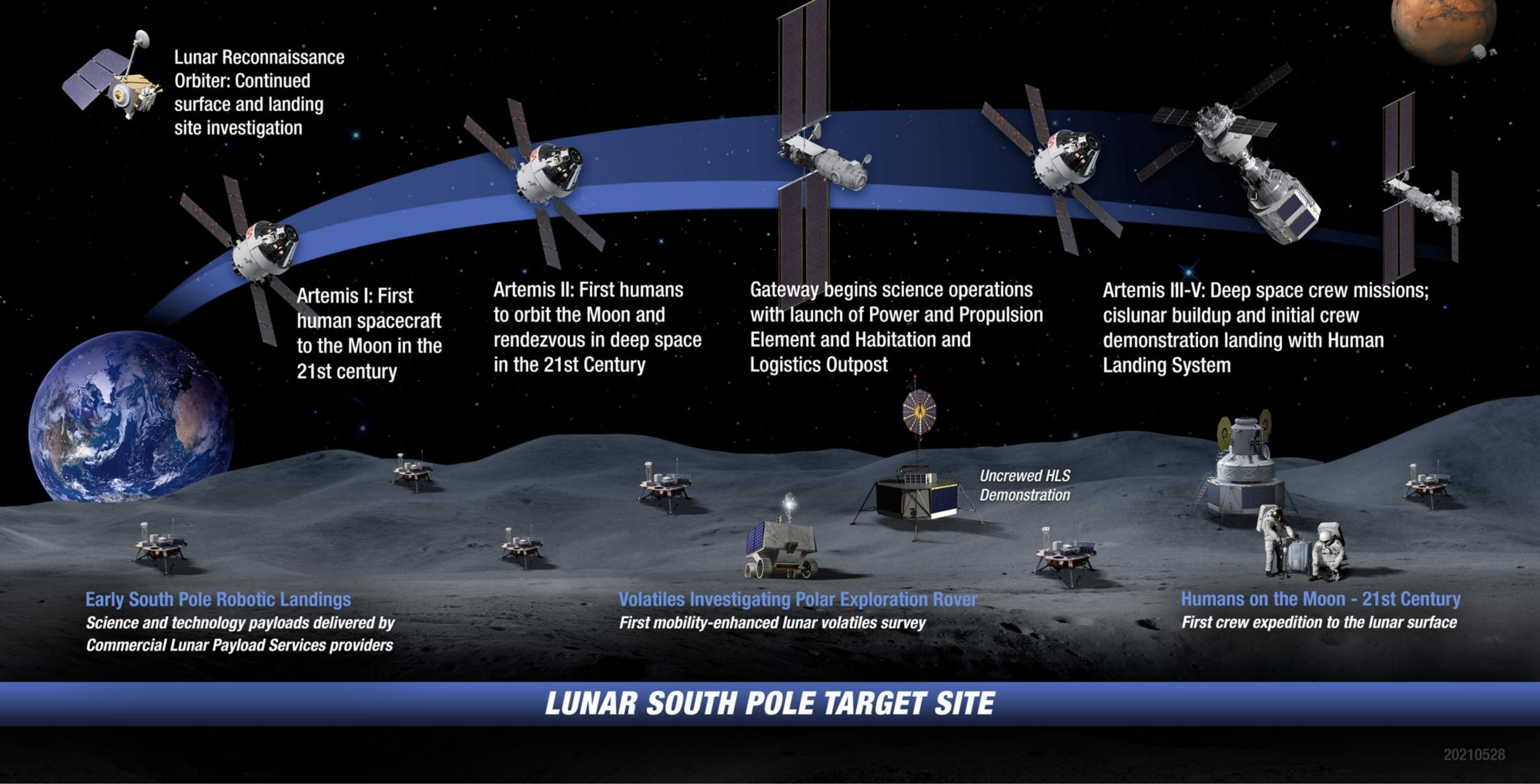
Co-authors

- Dr. Jennifer E. Edmunson - MSFC PM MMPACT
- Michael R. Effinger – MSFC MMPACT Element Lead
- Chelsea C. Pickett – MSFC MMPACT Test Lead
- Michael R. Fiske – Jacobs Engineering Group/MSFC MMPACT Element Lead
- Jason Ballard – CEO ICON Technologies
- Evan Jensen – ICON PM MMPACT
- Melodie Yashar - ICON
- Michael Morris – Space Exploration Architecture
- Christina Ciardullo - Space Exploration Architecture
- Rebeccah Pailes-Friedman - Space Exploration Architecture
- Dr. Holly Shulman – Alfred University
- Quinn Otte – Radiance Technologies

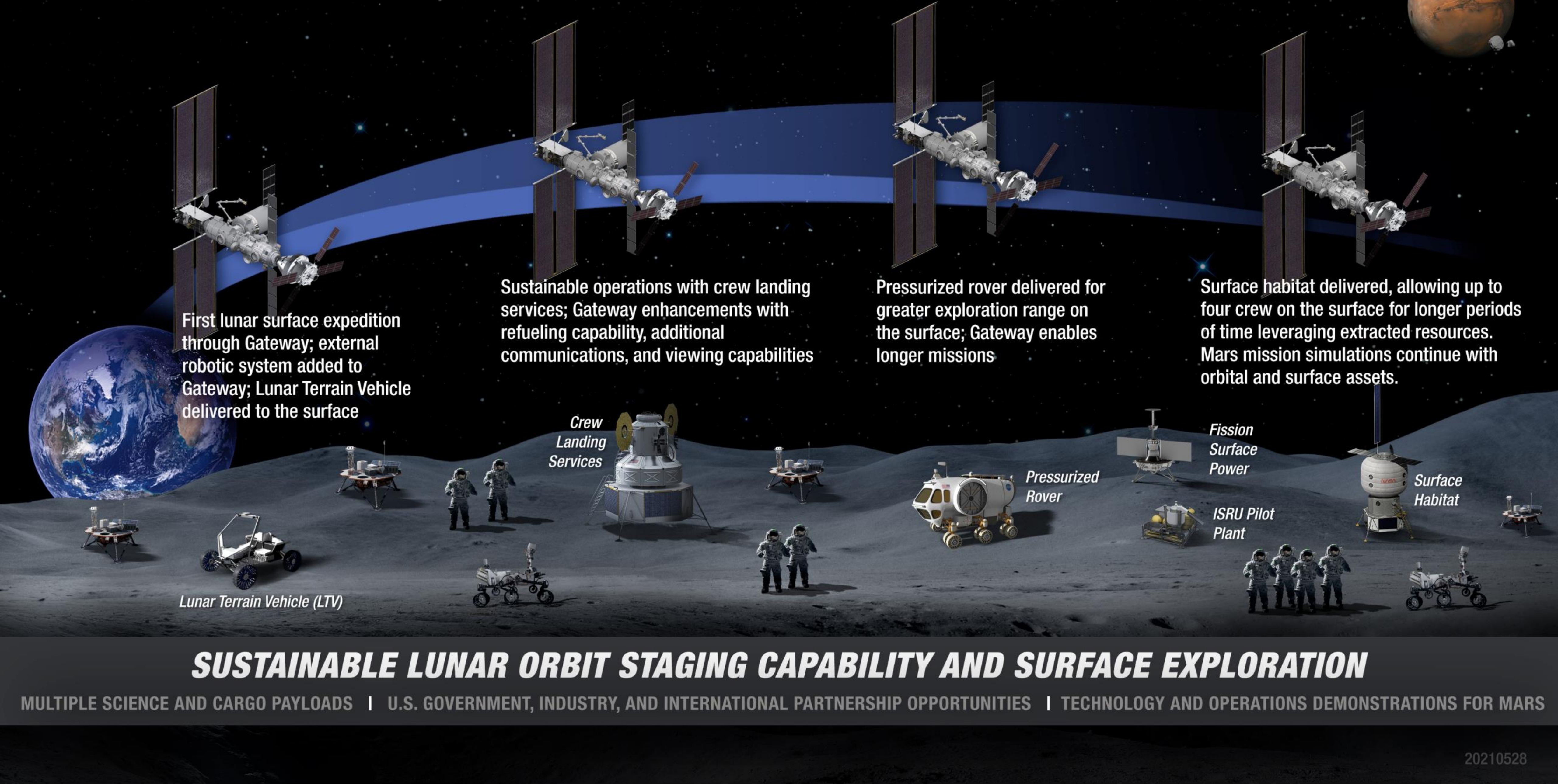
Agenda

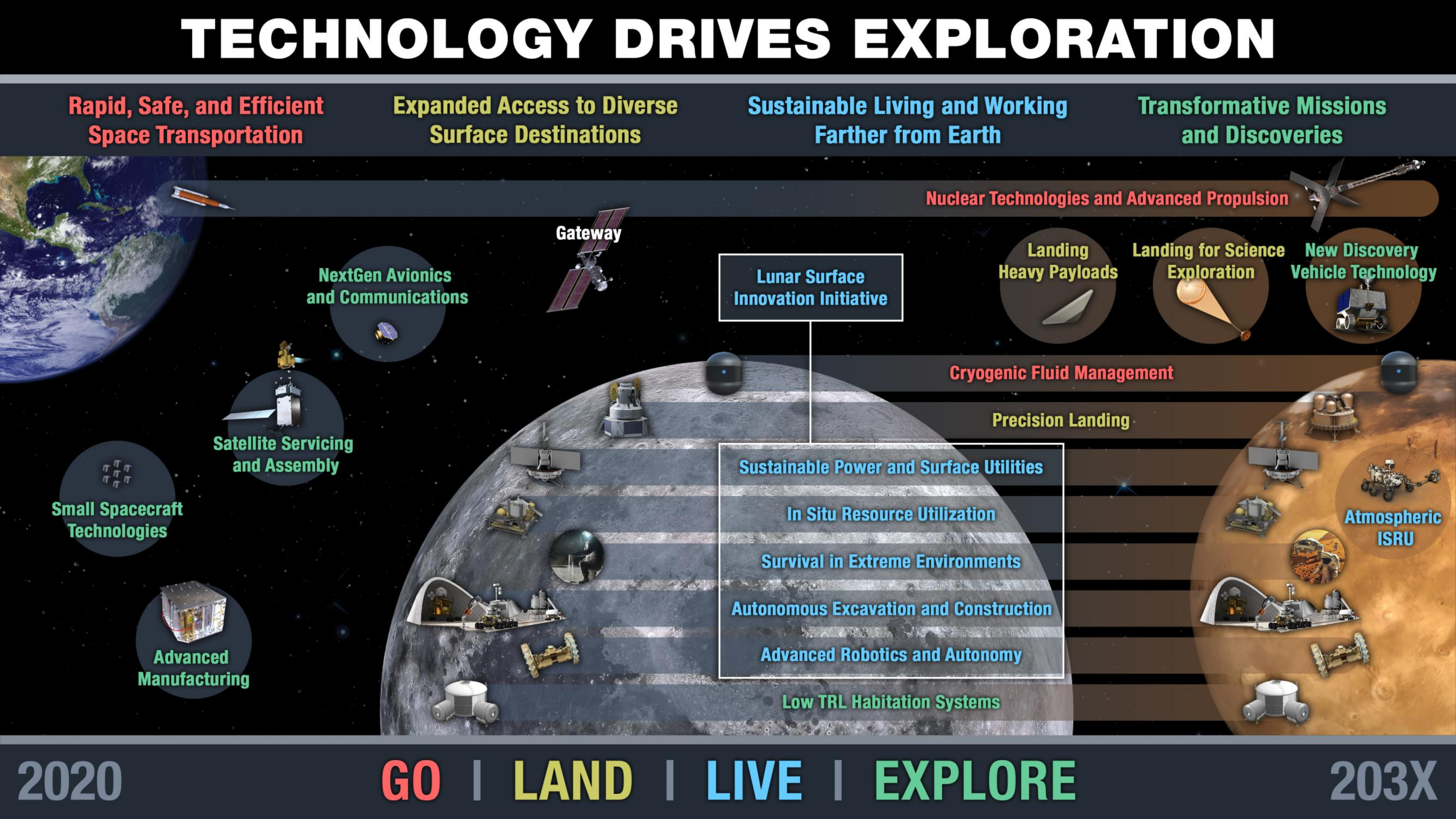
- Artemis: Phases 1 and 2
- Space Technology Mission Directorate - Technology Drives Exploration
- WHY: The Case for Lunar Infrastructure Construction
- Moon to Mars Planetary Autonomous Construction Technology (MMPACT)
  - Formulation
  - Partners
  - Materials and Processes
  - Materials Testing
  - Technology Demonstration Mission One (DM-1)
- Construction Technology Development Roadmap
- Outfitting
- Questions

Artemis: Landing Humans On the Moon



Artemis Base Camp Buildup




TECHNOLOGY DRIVES EXPLORATION
Rapid, Safe, and Efficient Space Transportation
Expanded Access to Diverse Surface Destinations
Sustainable Living and Working Farther from Earth
Transformative Missions and Discoveries
Nuclear Technologies and Advanced Propulsion
Gateway
NextGen Avionics and Communications
Satellite Servicing and Assembly
Small Spacecraft Technologies
Advanced Manufacturing
Lunar Surface Innovation Initiative
Landing Heavy Payloads
Landing for Science Exploration
New Discovery Vehicle Technology
Cryogenic Fluid Management
Precision Landing
Sustainable Power and Surface Utilities
In Situ Resource Utilization
Survival in Extreme Environments
Autonomous Excavation and Construction
Advanced Robotics and Autonomy
Low TRL Habitation Systems
Atmospheric ISRU
2020
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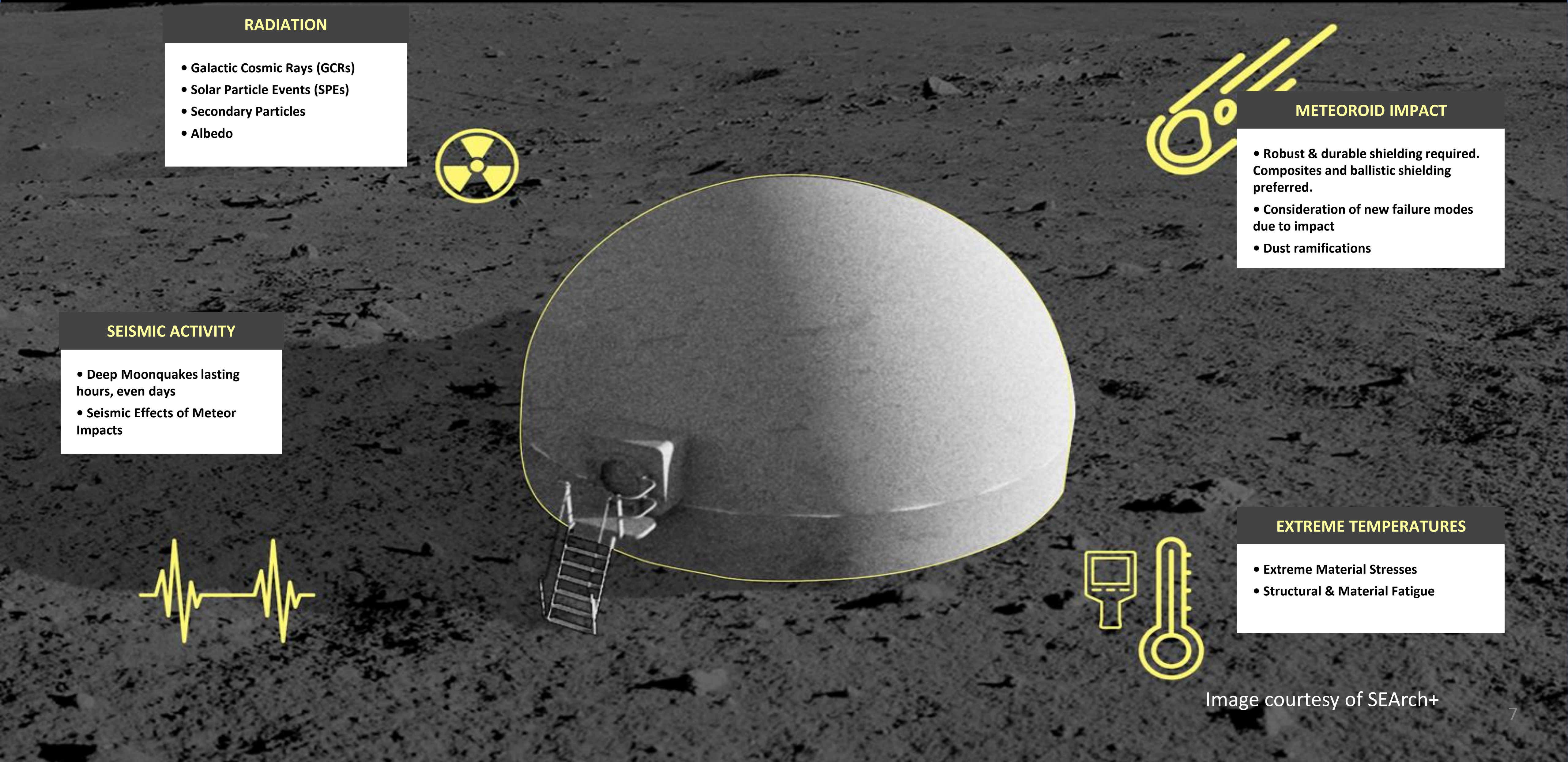
WHY- The Case for Lunar Surface Construction: (1) PROTECTION: Lunar ISRU-based infrastructure is expected to provide protection from a wide variety of environmental hazards.



RADIATION

- Galactic Cosmic Rays (GCRs)
- Solar Particle Events (SPEs)
- Secondary Particles
- Albedo

METEOROID IMPACT

- Robust & durable shielding required. Composites and ballistic shielding preferred.
- Consideration of new failure modes due to impact
- Dust ramifications

SEISMIC ACTIVITY

- Deep Moonquakes lasting hours, even days
- Seismic Effects of Meteor Impacts

EXTREME TEMPERATURES

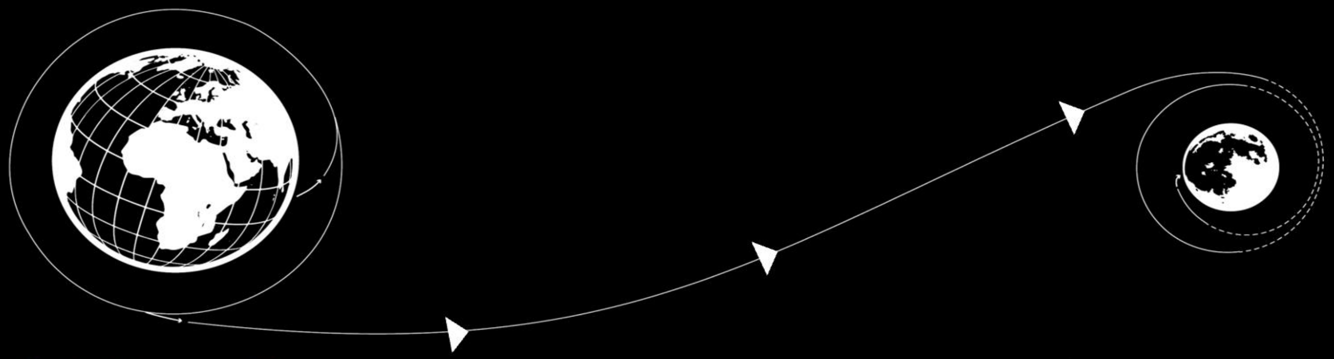
- Extreme Material Stresses
- Structural & Material Fatigue

Image courtesy of SEArch+

WHY- The Case for Lunar Surface Construction: (2) COST

Rockets are not ***efficient*** movers of building materials.

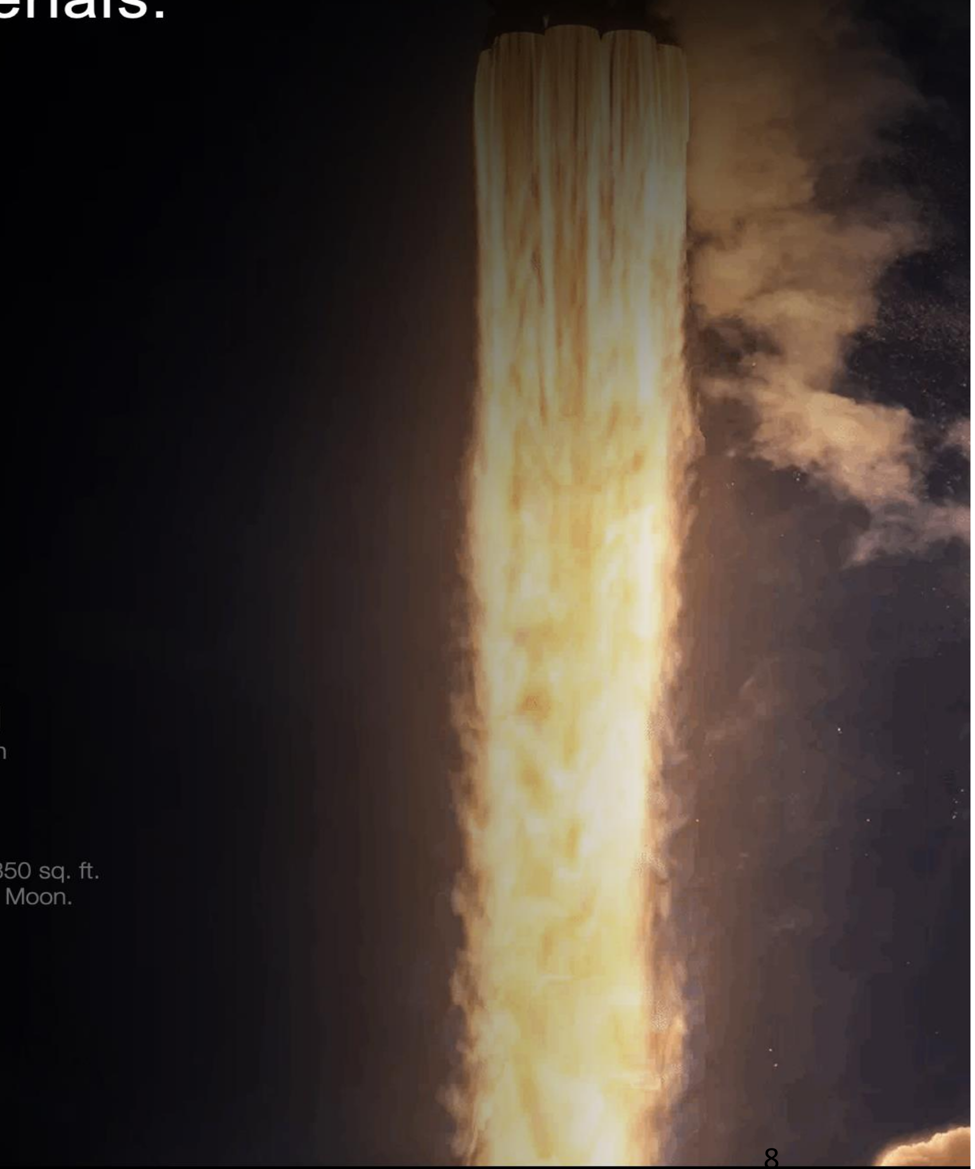
Even with commercial space flight dramatically dropping the launch costs to all-time historic lows, flying pre-built structures doesn't make financial sense. Even flying building materials from Earth to the Moon is costs prohibitive.



$ 0.11 per Kg
Costs of dry concrete on Earth

$ 1,200,000 per Kg
Cost to transport concrete to the Moon

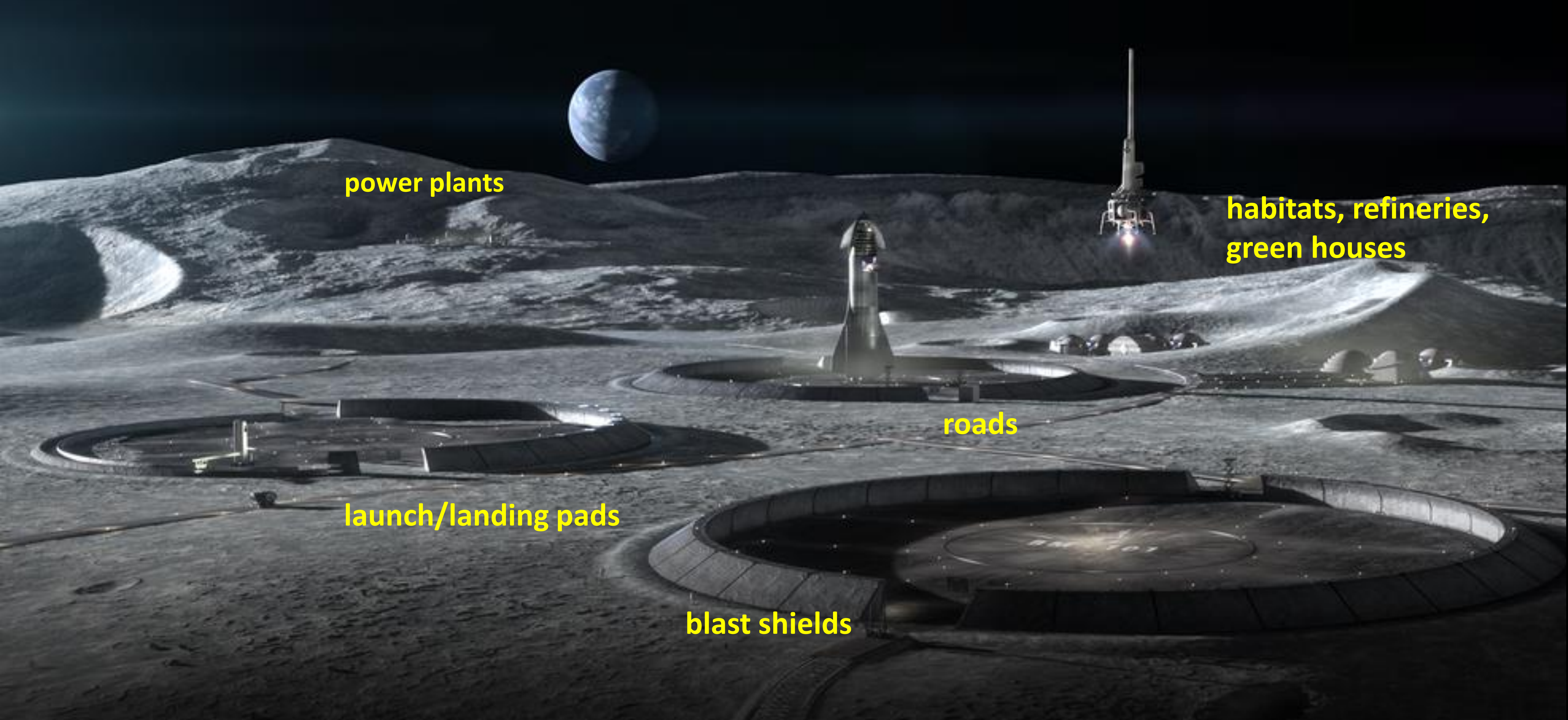
$ 96,000,000,000
Just the dry concrete costs to print a 350 sq. ft. structure like the Chicon House on the Moon.



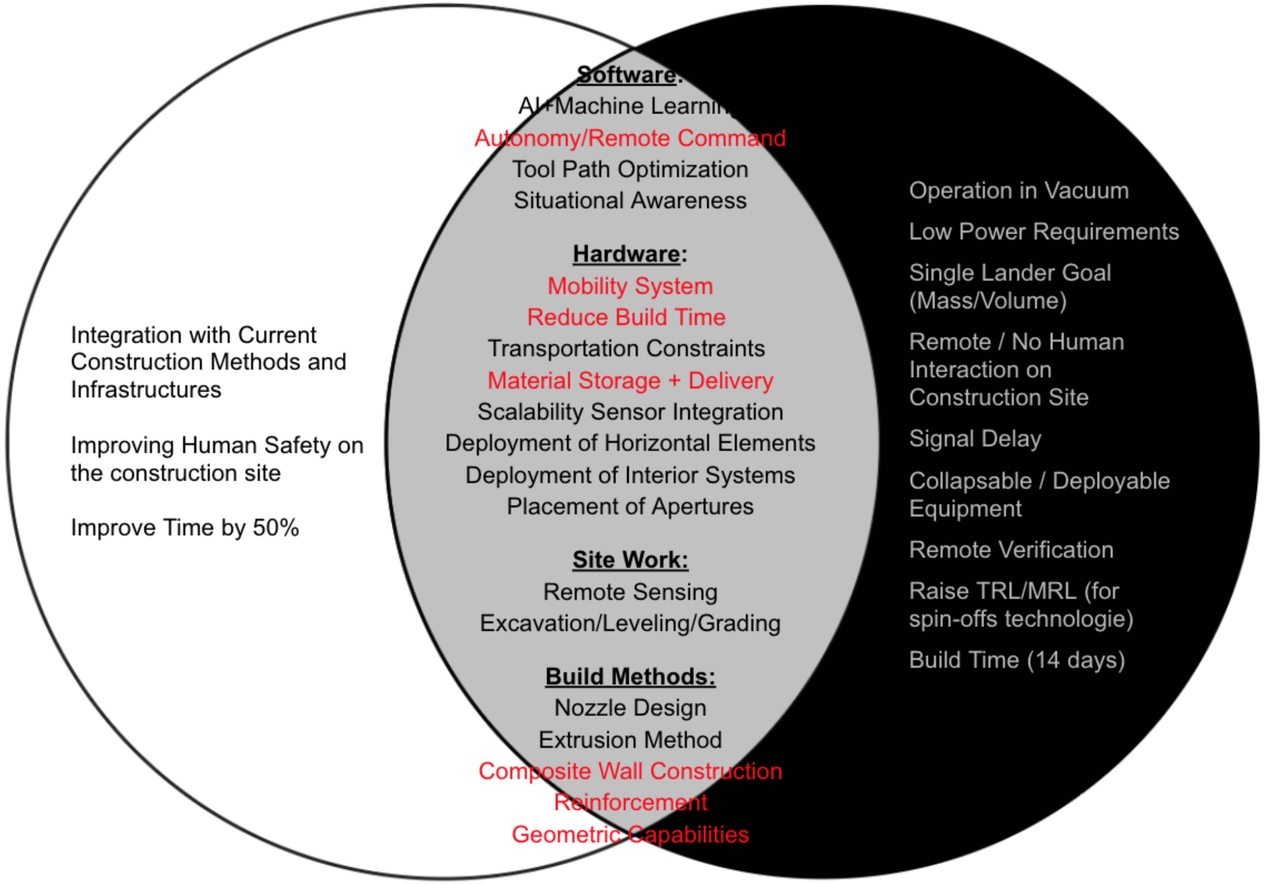
Source: Astrobotic Peregrine Lunar Lander Payload User's Guide: https://explorers.larc.nasa.gov/2019APSMEX/MO/pdf_files/Astrobotic%20-%20Payload%20User%20Guide%20v3%202018-10.pdf

Building a Sustainable Presence on the Moon

- What infrastructure are we going to need?



Initial MMPACT Formulation – Capabilities for Multi-Use Technology

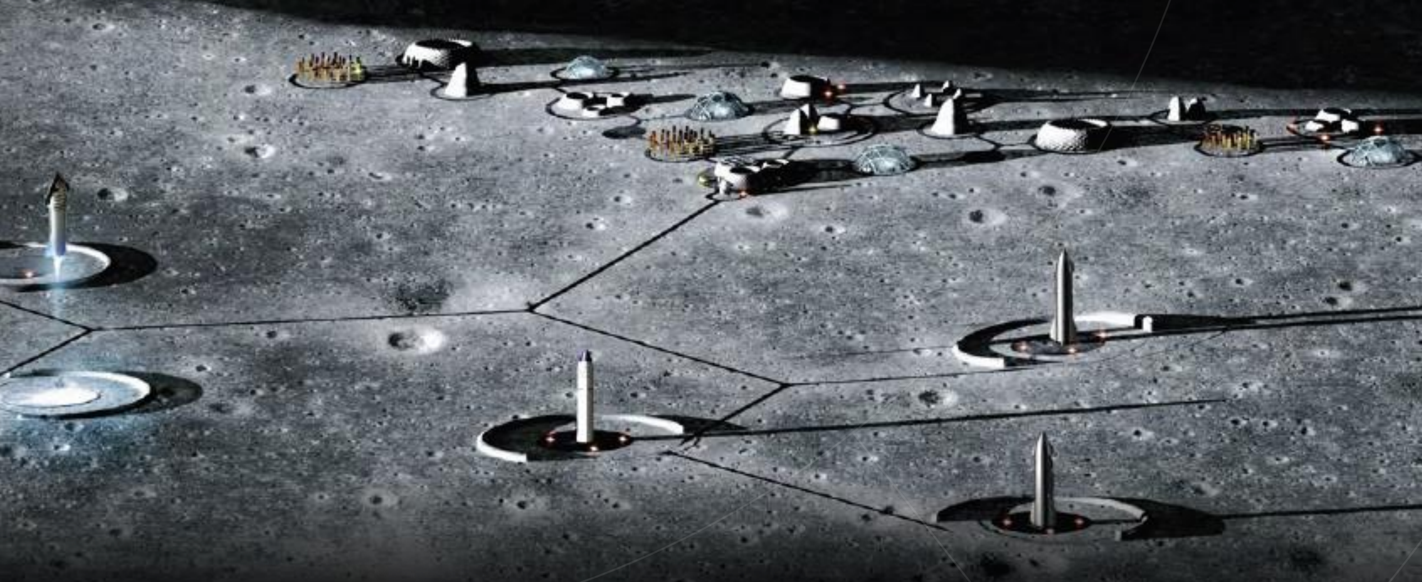


Exemplar Venn Diagram: Construction Means and Methods: Technology Drivers

Common Key Functional Requirements Development

- Developed individual requirements for Earth-based and Lunar construction with SEArch+
- Identified Common Technology Development Interests with SEArch for Earth-based and Lunar Construction Capabilities (Venn Diagram)
- Followed similar approach with ICON and DoD organizations for SBIR Proposal
- Results yielded shared set of key functional requirements that would benefit the goals of NASA, ICON, DoD, and SEArch+
    - Long-distance communication, monitoring, and control
    - Increased autonomy/automation of operations
    - Increased transportability / mass reduction
    - Expanded environmental range
    - Design for field reparability
    - Dust mitigation
    - Shielding / Ballistic Protection
    - Job-site Mobility
    - Off-foundation construction / foundation delivery
    - Multi-material printing & related control systems
    - Improved user experience/ease of operation (i.e. reduced training load)
    - Software Design Platform

Moon-to Mars Planetary Autonomous Construction Technologies (MMPACT) Overview



GOAL

Develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, and blast shields using lunar regolith-based materials.

OBJECTIVES

- **Develop and demonstrate additive construction capabilities for various structures as materials evolve from Earth-based to exclusively *In Situ* Resource Utilization (ISRU)-based.**
- **Develop and demonstrate approaches for integrated sensors and process monitoring in support of *in situ* verification & validation of construction system and printed structures.**
- **Test and evaluate materials from candidate processes for use in the lunar environment.**
- **Validate that Earth-based regolith simulants and testing environments are sufficient analogs for lunar operations**

MMPACT – Current Partners

NASA Centers
- MSFC
- LaRC
- KSC
- JPL

OGA Leveraging

Potential:
- Innovation Unit US Air Force (AF)

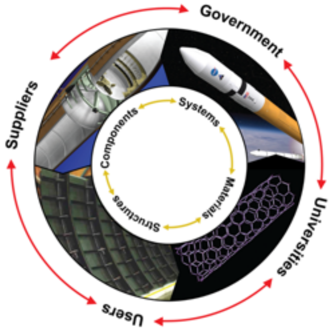
Contributing:
- AF Civil Engineering Center
- AF Special Operations Command
- Defense Innovation Unit
- Texas Air National Guard
- USAF

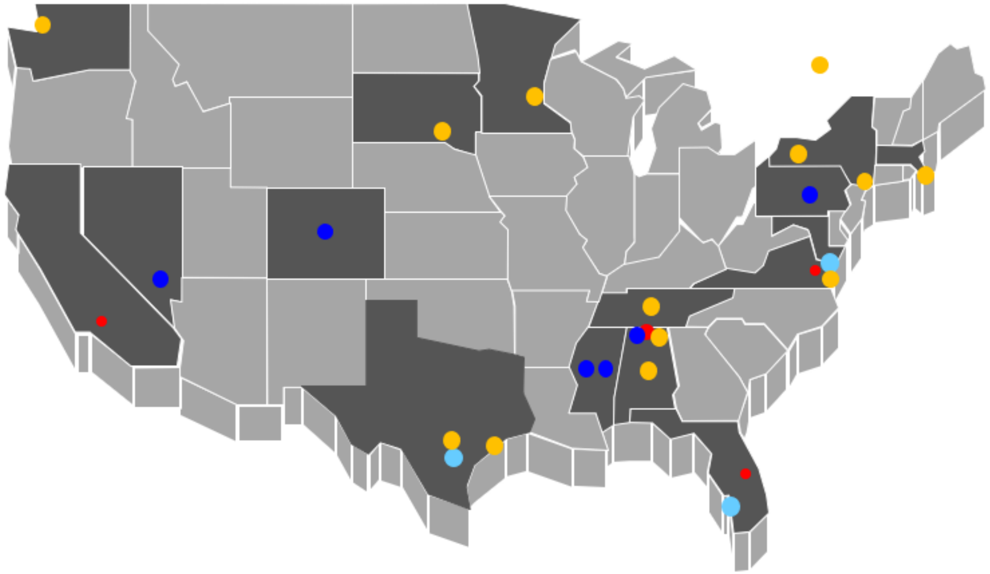
Public/Private Partnerships
- Dr. Holly Shulman
- ICON Build
- Radiance Technologies
- RW Bruce Associates, LLC
- Blue Origin
- Jacobs Space Exploration Group
- JP Gerling
- Logical Innovations
- Microwave Properties North
- MTS Systems Corp.
- Southeastern Universities Research Association
- Southern Research
- Space Exploration Architecture (SEArch+)
- Space Resources Extraction Technologies
- Sioux Tribes
- Astroport

Technology Providers/ Contributing Partners: Academia
- Colorado School of Mines
- Drake State
- Mississippi State University
- Pennsylvania State University
- University of Mississippi
- University of Nevada Las Vegas

SBIR/STTR
- Construction Scale Additive Manufacturing Solution

Potential Customer
- Artemis



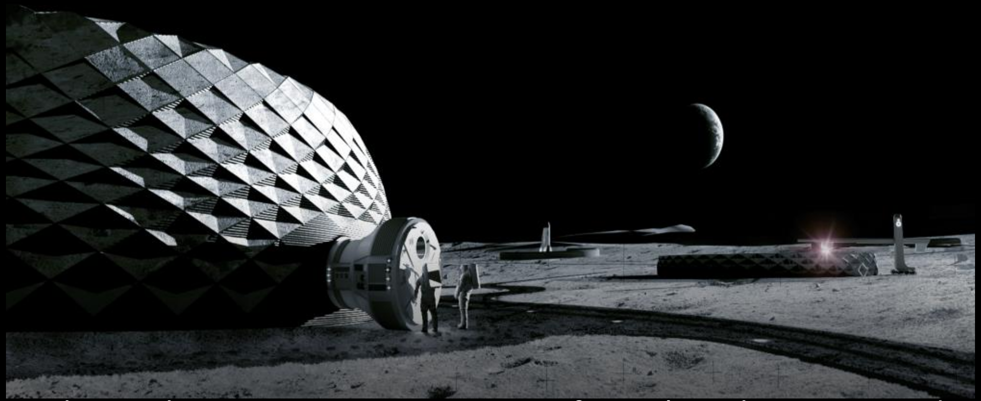


Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

Autonomous Construction: Materials and Concepts for the Lunar Outpost

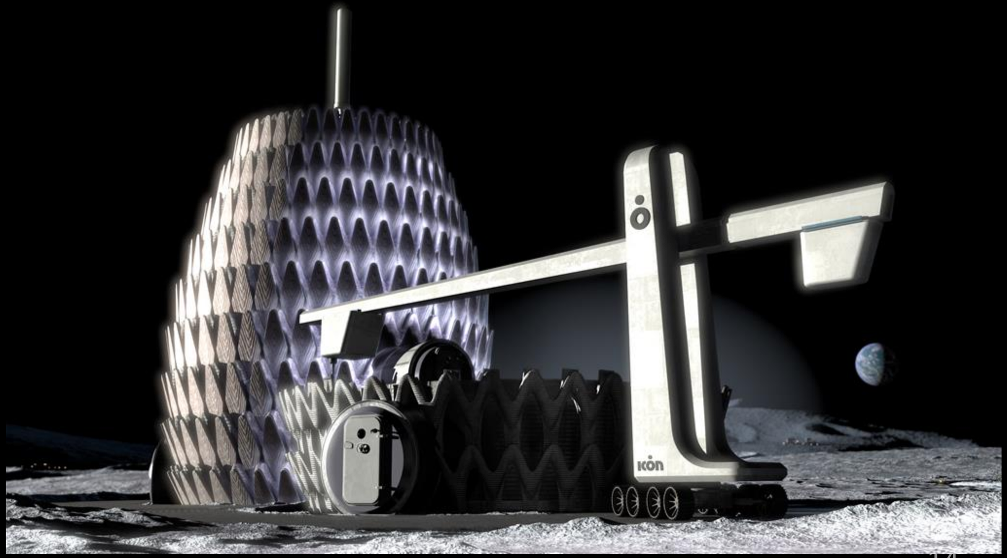
Regolith-based Materials and Processes:

- Cementitious
- Geopolymers/Polymers
- Thermosetting materials
- Regolith Melting/Forming
- Laser sintered
- Microwave sintered



Bjarke Ingels Group Concept courtesy of ICON's Architecture Study

Image courtesy of ICON



SEArch+ Concept courtesy of ICON's Architecture Study

Test Matrix for Selection of Demonstration Mission One (DM-1) Material/Process

Down-select Test Matrix for MMPACT DM-1

Rev A

Test Name	Material	Standard #	Standard Name	Test Enviro.	Test Qty.	Test Specimen[1]
Compression Strength	Mortar	ASTM C0109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)	STP	3	2" cube
	Ceramic	ASTM C1424	Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature	STP	3	1"D, 2"H
Compression at Cold Temperature	Mortar	ASTM C0109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)	-192°C	3	2" cube
	Ceramic	ASTM C1424	Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature	-192°C	3	1"D, 2"H
Compression at Hot Temperature	Mortar	ASTM C0109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)	57°C	3	2" cube
	Ceramic	ASTM C1424	Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature	57°C	3	1"D, 2"H
Compression After Thermal Cycling Under Vacuum[2]	Mortar	ASTM C0109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50 mm] Cube Specimens)	STP	3	2" cube
	Ceramic	ASTM C1424	Standard Test Method for Monotonic Compressive Strength of Advanced Ceramics at Ambient Temperature	STP	3	1"D, 2"H
Layer to Layer Adhesion	Both	ASTM C297	Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions	STP	3ea	1"D, .5" H
4 Point Bend Flexural Test	Mortar	ASTM C78	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)	STP	3	8" x 2" x 2"
	Ceramic	ASTM C1161	Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature	STP	3	Config. B
Ablation[3]	Mortar	EM40-OWI-013	EM40 Non-Metallics & Advanced Manufacturing Division Plasma Torch Test Facility Operation Procedure	TBD	6	1"D, 1.75"H
	Ceramic			TBD	6	1"D, 1.75"H

[1]All test specimens will have more than 1 horizontal layer, with the knitline(s) perpendicular to the loading axis. D = Diameter, H = Height, W = Width, L= Length.

[2]One thermal cycle is defined as room temperature to -192°C, -192°C to 57°C, 57°C to -192°C and back to room temperature. Vacuum level used will be 10-4 to 10-3. Specimens will be weighed before and after thermal cycling, before the compression test.

[3]Two configurations of ablation specimens will be tested: an as-built surface facing the plasma torch and a machined surface facing the plasma torch.

Early Process Development Results

- Controlled molten extrusion under vacuum from ICON’s molten regolith extrusion system.

- Vacuum-cast specimens, using ICON’s molten regolith extrusion system.

- Laser direct energy deposition process building a layer of a test specimen (brick).
- Laser direct energy deposition, additively constructed test specimen (brick).

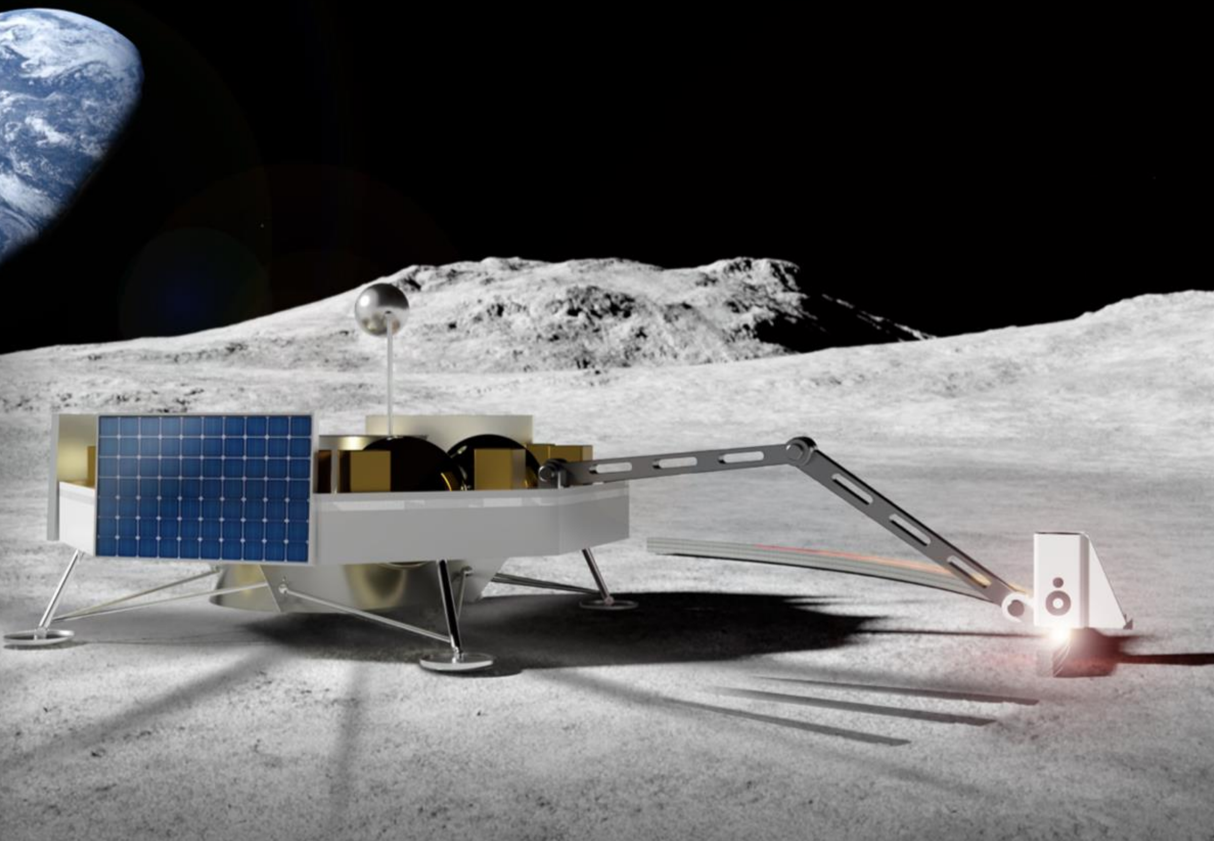
- First high vacuum microwave sintering result showing solid sintered CSM-LHT-1G tile

Initial Construction Technology Demonstration Mission (DM-1) Concept

Objectives:

- Demonstrate "proof of concept" for downselected construction technology utilizing ISRU materials at small scale from lander base
- Characterize ISRU and ISRU-based materials
- Demonstrate remote/autonomous operations
- Demonstrate instrumentation operations
- Validate that Earth-based development and testing are sufficient analogs for lunar operations
- Anchor analytical models
- Address technology gaps and inform construction processes for future construction of functional infrastructure elements

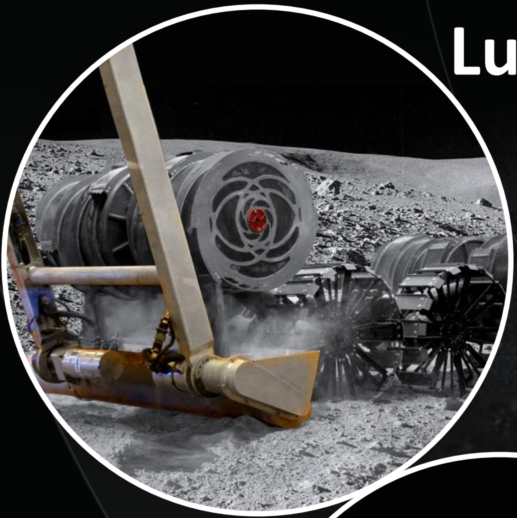
- ***Rationale:*** *Must prove out initial construction concept in lunar environment*

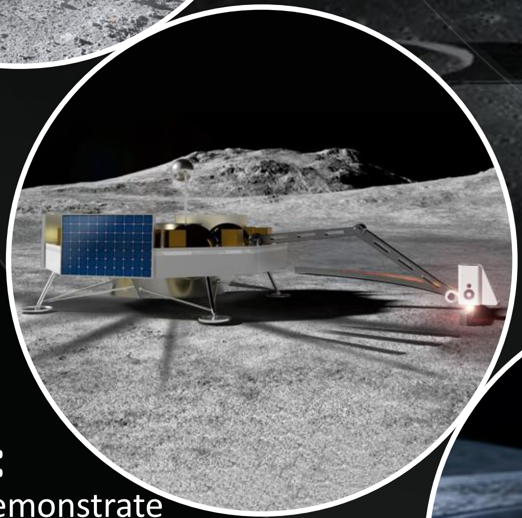


Outcomes

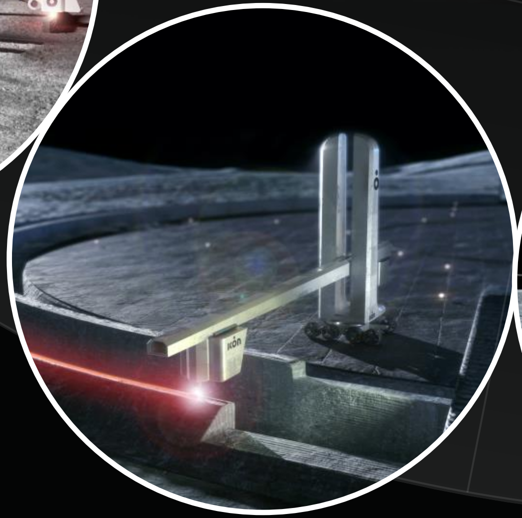
- **TRL 6** achieved for ISRU consolidation into densified, subscale structural elements
- **TRL 9** for specific hardware and instrumentation to be used on later missions

Lunar Construction Capability Development Roadmap

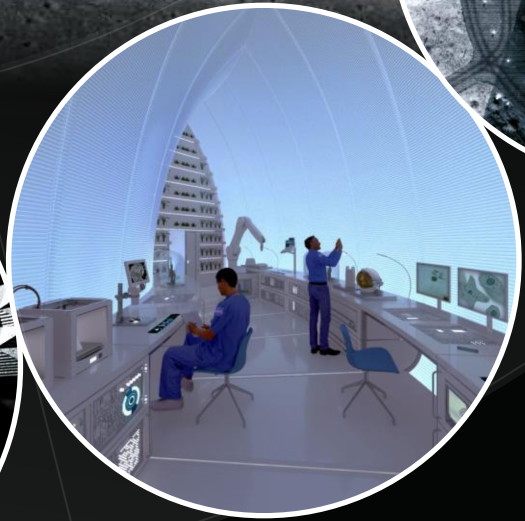




Phase 1:
Develop & demonstrate excavation & construction capabilities for on-demand fabrication of critical lunar infrastructure such as landing pads, structures, habitats, roadways, blast walls, etc.



Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.

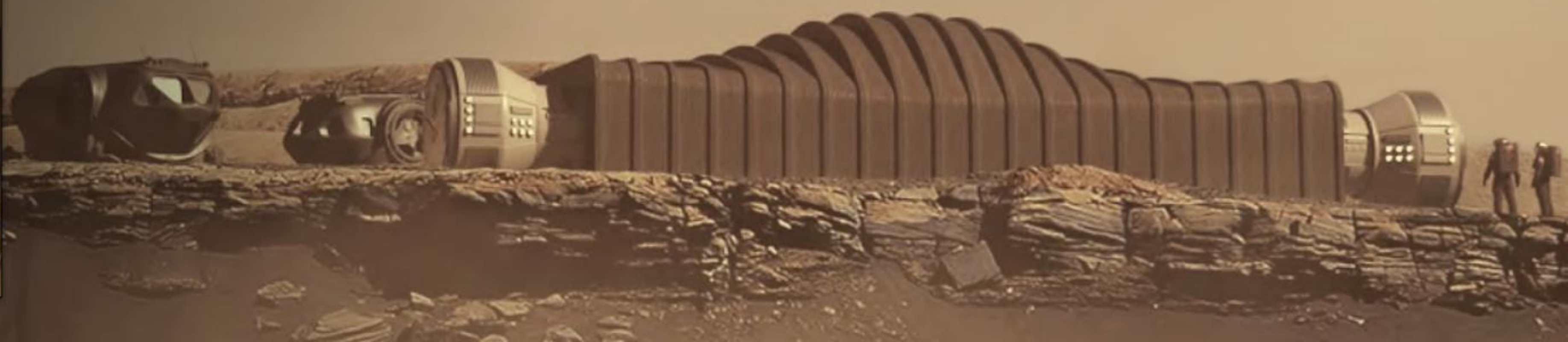


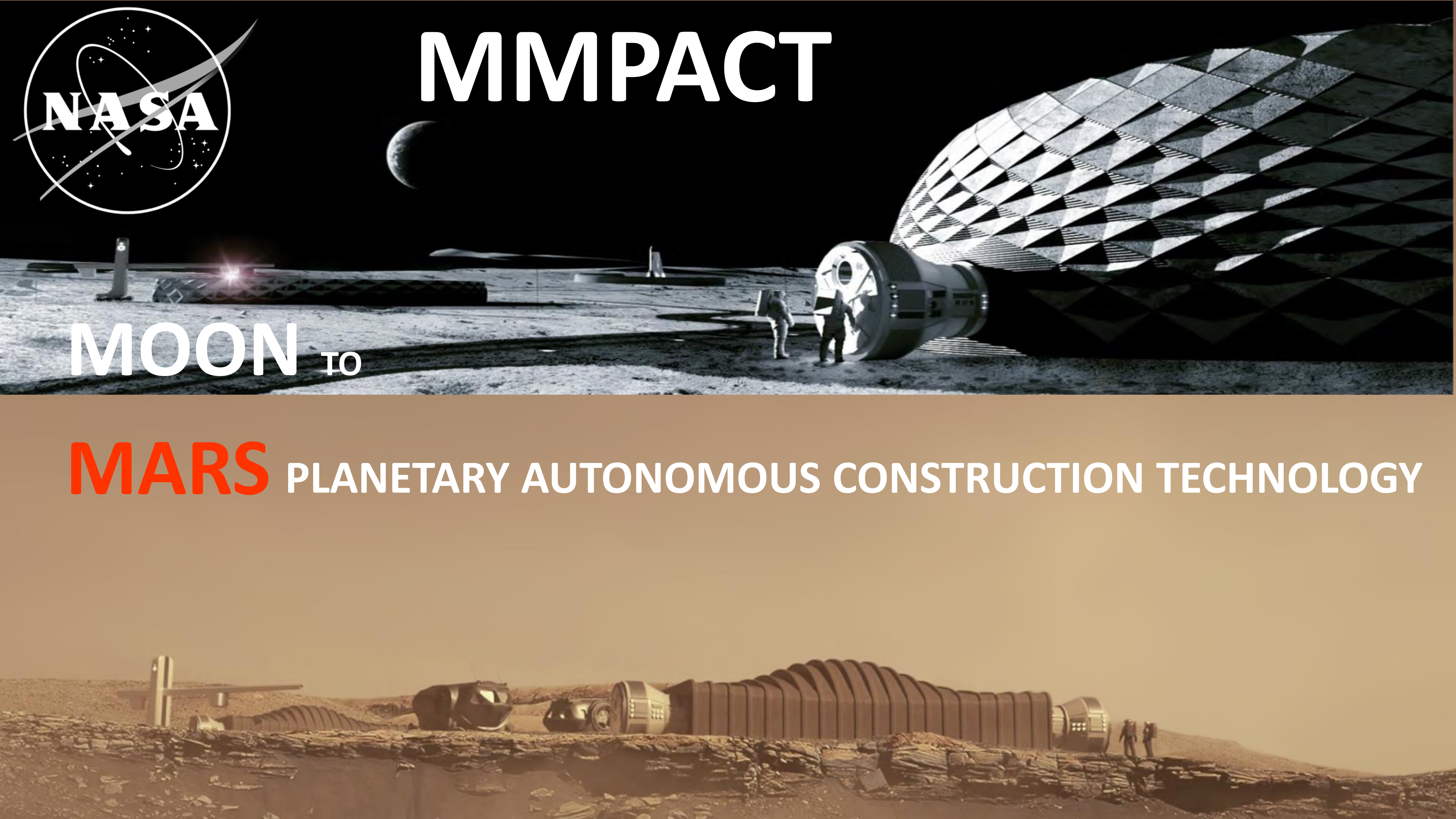
Phase 3: Build the lunar base according to master plan to support the planned population size of the first permanent settlement (lunar outpost).

Phase 4: Complete build-out of the lunar base per the master plan and add additional structures as strategic expansion needs change over time.

CHAPEA / Mars Dune Alpha

To prepare for long-duration missions to Mars, ICON constructed a Martian analog habitat designed by BIG at Johnson Space Center. The 1,700 ft^2 structure will be home to four crew members in year-long missions as part of the Crew Health and performance Exploration Analog (CHAPEA) program beginning in 2022.




MMPACT
MOON TO
MARS PLANETARY AUTONOMOUS CONSTRUCTION TECHNOLOGY


NASA
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