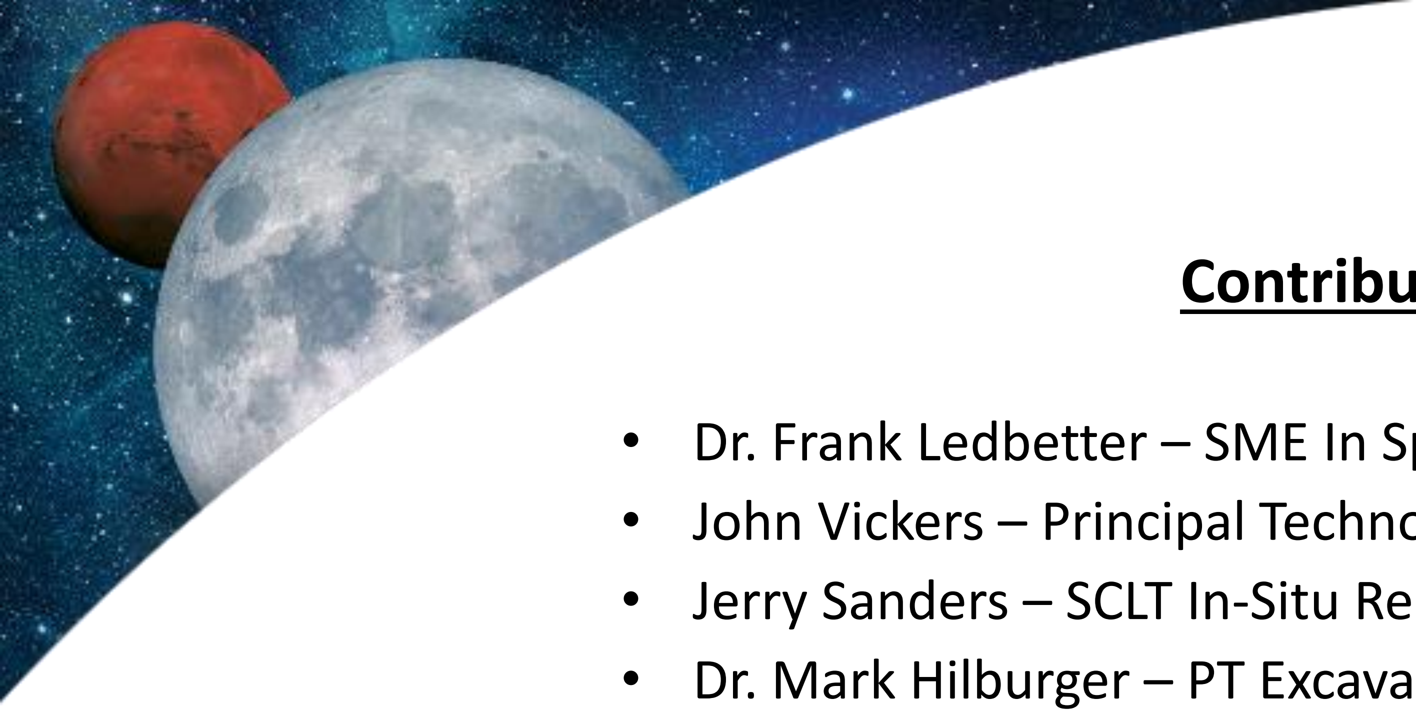
National Aeronautics and
Space Administration

Don’t Take It – Make It: NASA’s Efforts to Address Exploration Logistics Challenges through In Space Manufacturing and Extraterrestrial Construction

R. G. Clinton, Jr., PhD; Tracie Prater, PhD; Jennifer Edmunson, PhD; Mike Fiske; Mike Effinger

Novel Orbital and Moon Manufacturing, Materials, and Mass-efficient Design (NOM4D) Kick-Off

December 14-15, 2021



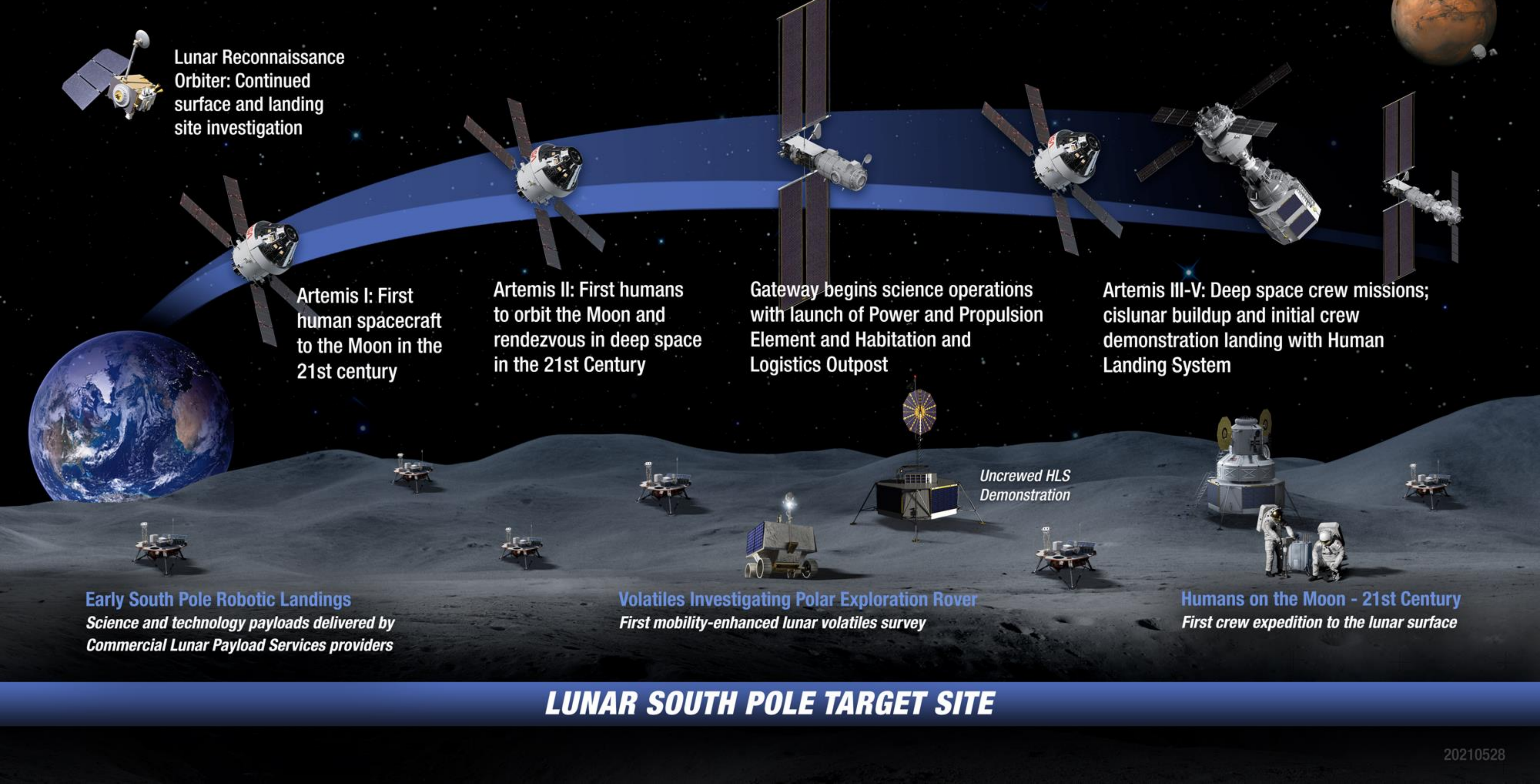
Contributors

- Dr. Frank Ledbetter – SME In Space Manufacturing (ISM) and MMPACT
- John Vickers – Principal Technologist (PT) Advanced Manufacturing
- Jerry Sanders – SCLT In-Situ Resource Utilization (ISRU)
- Dr. Mark Hilburger – PT Excavation, Construction, and Outfitting
- Jason Ballard – CEO ICON Technologies
- Evan Jensen – ICON PM MMPACT

Agenda

- Artemis: Phases 1 and 2
- Space Technology Mission Directorate: Technology Drives Exploration
  - Lunar Surface Innovation Initiative (LSII)
    - In Situ Resource Utilization (ISRU)
    - Excavation, Construction, and Outfitting (ECO)
    - Challenges and Capability Gaps
  - Advanced Manufacturing
    - In Space Manufacturing (ISM) – Portfolio and Challenges
- Questions

Artemis: Landing Humans On the Moon



Lunar Reconnaissance Orbiter: Continued surface and landing site investigation

Artemis I: First human spacecraft to the Moon in the 21st century

Artemis II: First humans to orbit the Moon and rendezvous in deep space in the 21st Century

Gateway begins science operations with launch of Power and Propulsion Element and Habitation and Logistics Outpost

Artemis III-V: Deep space crew missions; cislunar buildup and initial crew demonstration landing with Human Landing System

Uncrewed HLS Demonstration

Early South Pole Robotic Landings

Science and technology payloads delivered by Commercial Lunar Payload Services providers

Volatiles Investigating Polar Exploration Rover

First mobility-enhanced lunar volatiles survey

Humans on the Moon - 21st Century

First crew expedition to the lunar surface

LUNAR SOUTH POLE TARGET SITE

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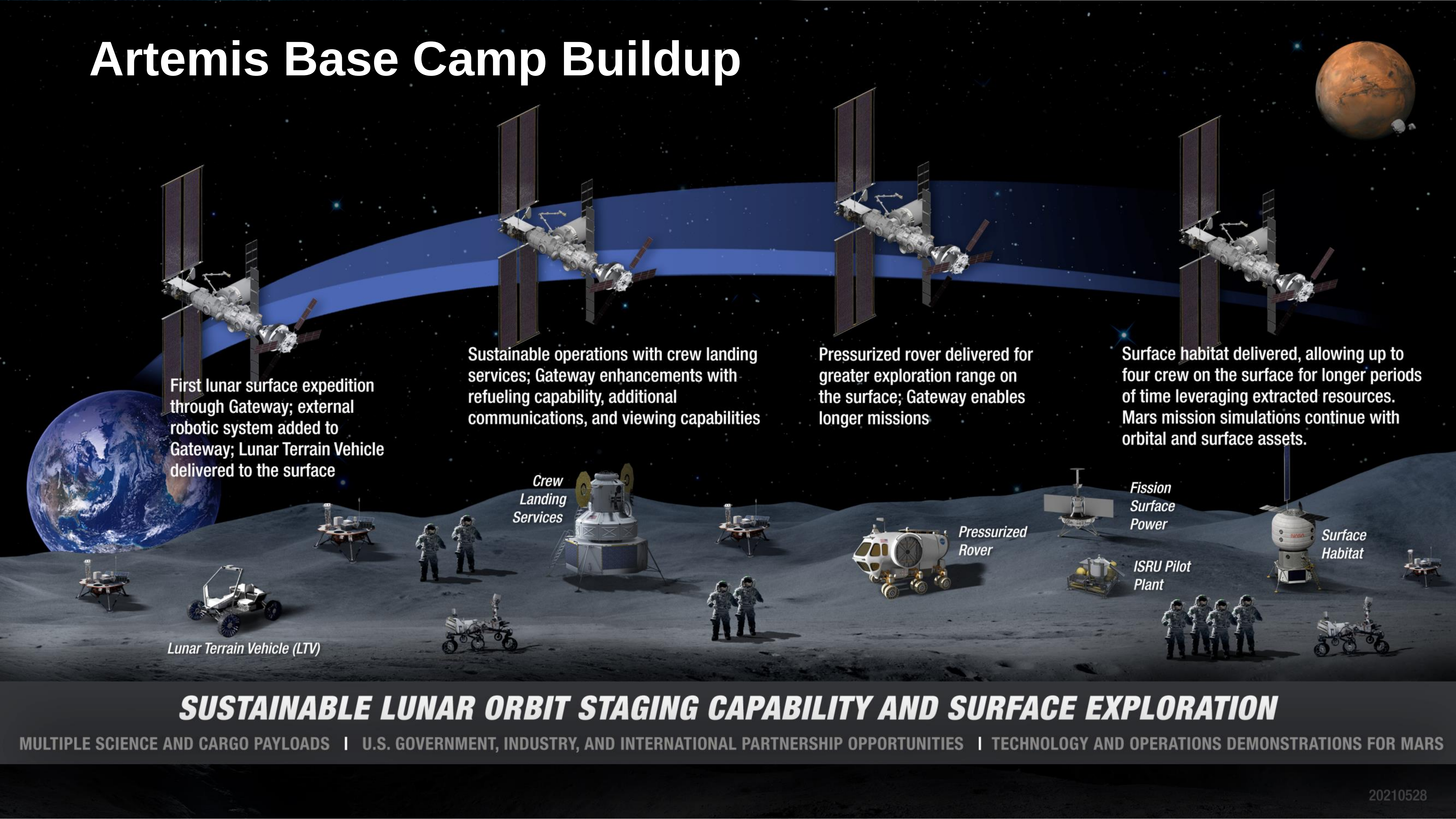
Artemis Base Camp Buildup



First lunar surface expedition through Gateway; external robotic system added to Gateway; Lunar Terrain Vehicle delivered to the surface

Sustainable operations with crew landing services; Gateway enhancements with refueling capability, additional communications, and viewing capabilities

Pressurized rover delivered for greater exploration range on the surface; Gateway enables longer missions

Surface habitat delivered, allowing up to four crew on the surface for longer periods of time leveraging extracted resources. Mars mission simulations continue with orbital and surface assets.

SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

20210528

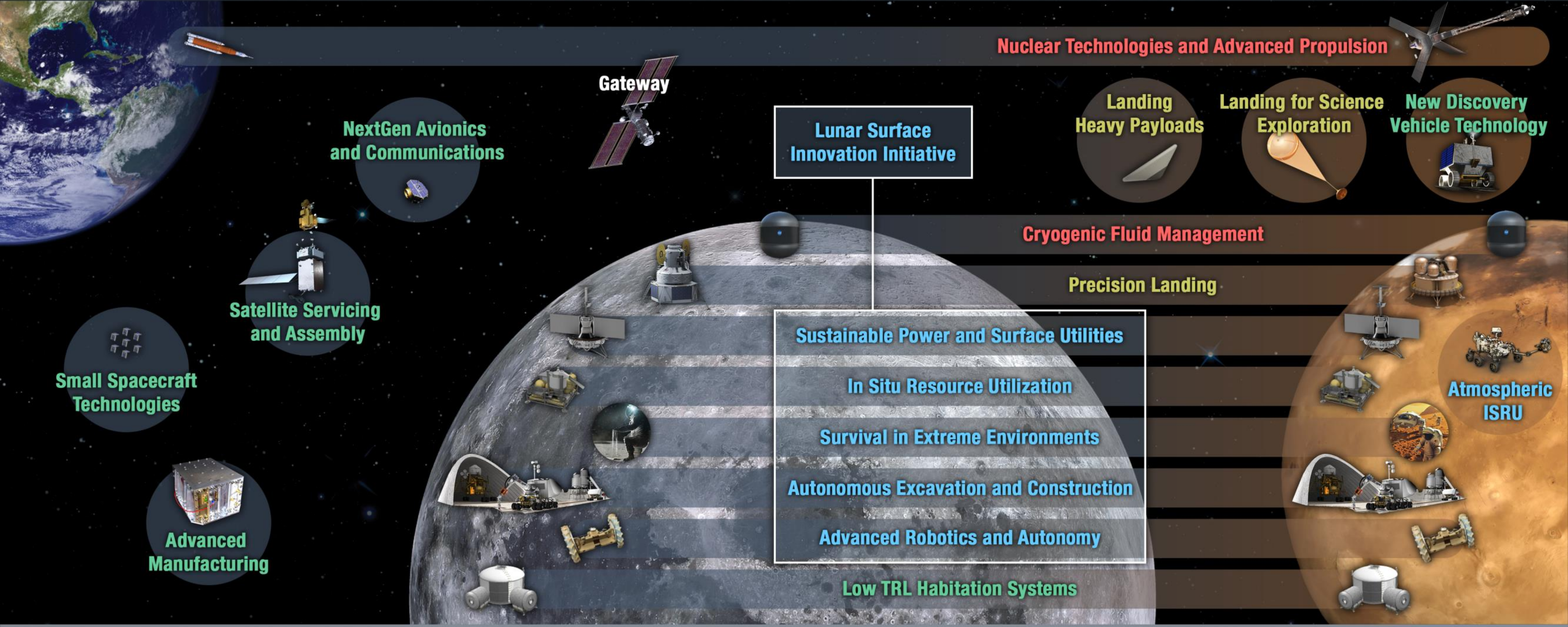
TECHNOLOGY DRIVES EXPLORATION

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

Landing Heavy Payloads

Landing for Science Exploration

New Discovery Vehicle Technology

Lunar Surface Innovation Initiative

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

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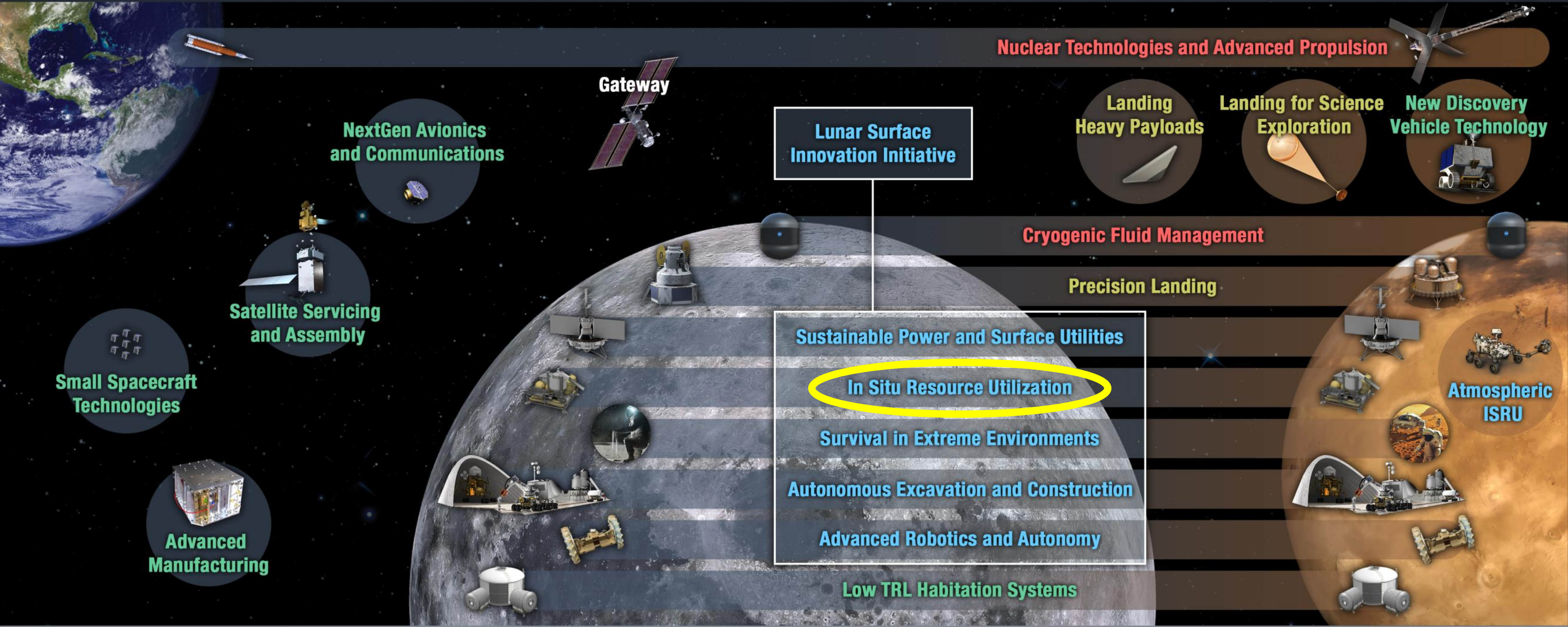

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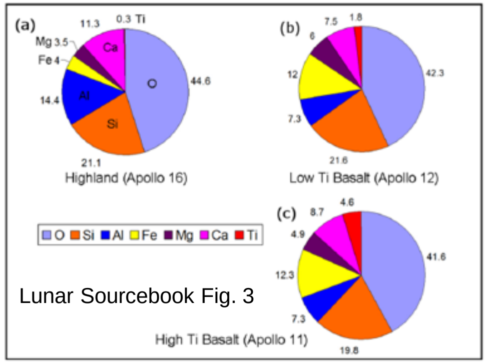
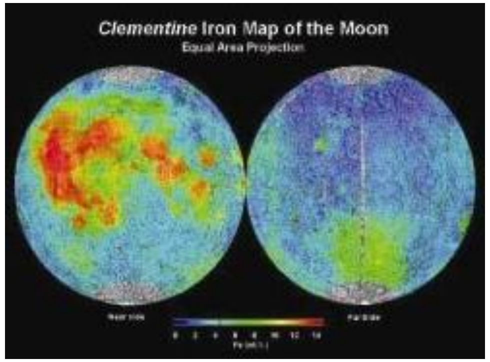
Lunar Resources: Regolith, Solar Wind Volatiles, Polar Water/Volatiles



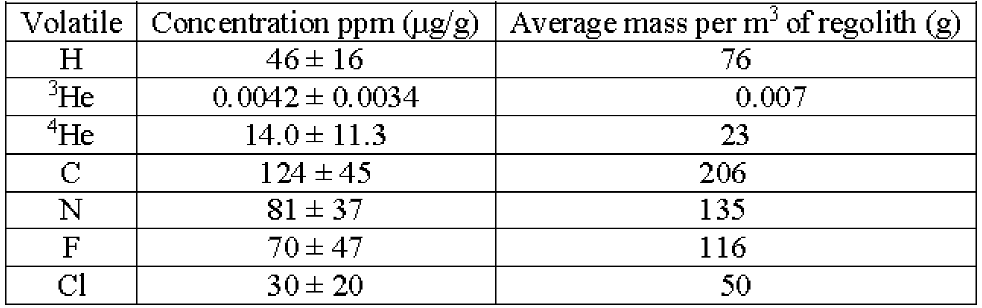
Lunar Sourcebook Fig. 3



Lunar Regolith

- **>40% Oxygen by mass**; numerous metals (Fe, Al, Ti)
  - Silicate minerals make up over 90% of the Moon
- Mare – Basalt
  - 15-20% Plagioclase, 15-24% Pyroxene, 3-4% Olivine, 2-10% Ilmenite, 45-53% Agglutinate glass
- **Highland/Polar area**
  - >75% Anorthite, Pyroxene, 7% Olivine
- Pyroclastic Glass
- KREEP (Potassium, Rare Earth Elements, Phosphorous)
- Solar Wind Implanted Volatiles

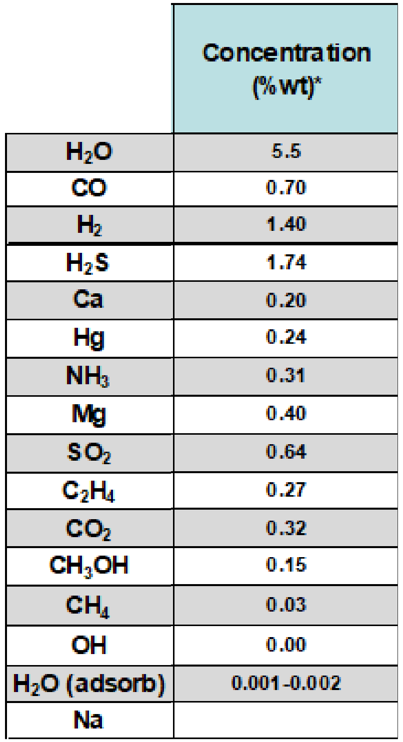
Fegley and Swindle 1993



Volatile	Concentration ppm (µg/g)	Average mass per m^3 of regolith (g)
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14.0 ± 11.3	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

Polar Water/Volatiles

- LCROSS impact estimated **5.5 wt%** water along with other volatiles
- Spectral modeling shows that some ice-bearing pixels may contain **~30 wt % ice** (mixed with dry regolith)
- *Without direct measurements, form, concentration, and distribution of water is unknown*



	Concentration (%wt)*
H_2O	5.5
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Products

- Oxygen
- Water and other volatiles
- Consumables for in-space and surface transportation and crop growth
- Feedstock materials for manufacturing, e.g. metals and silicates
- Feedstock constituent materials for construction
- Production of commodities for future lunar economy

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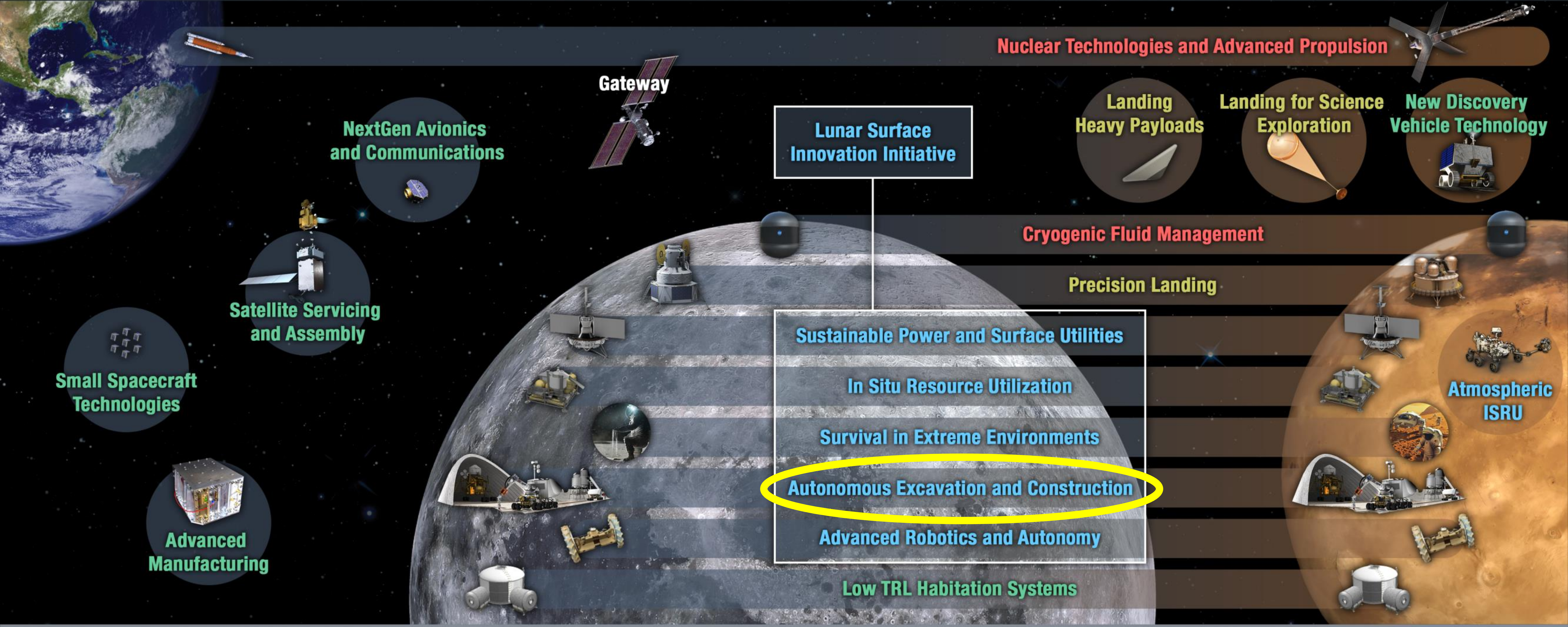

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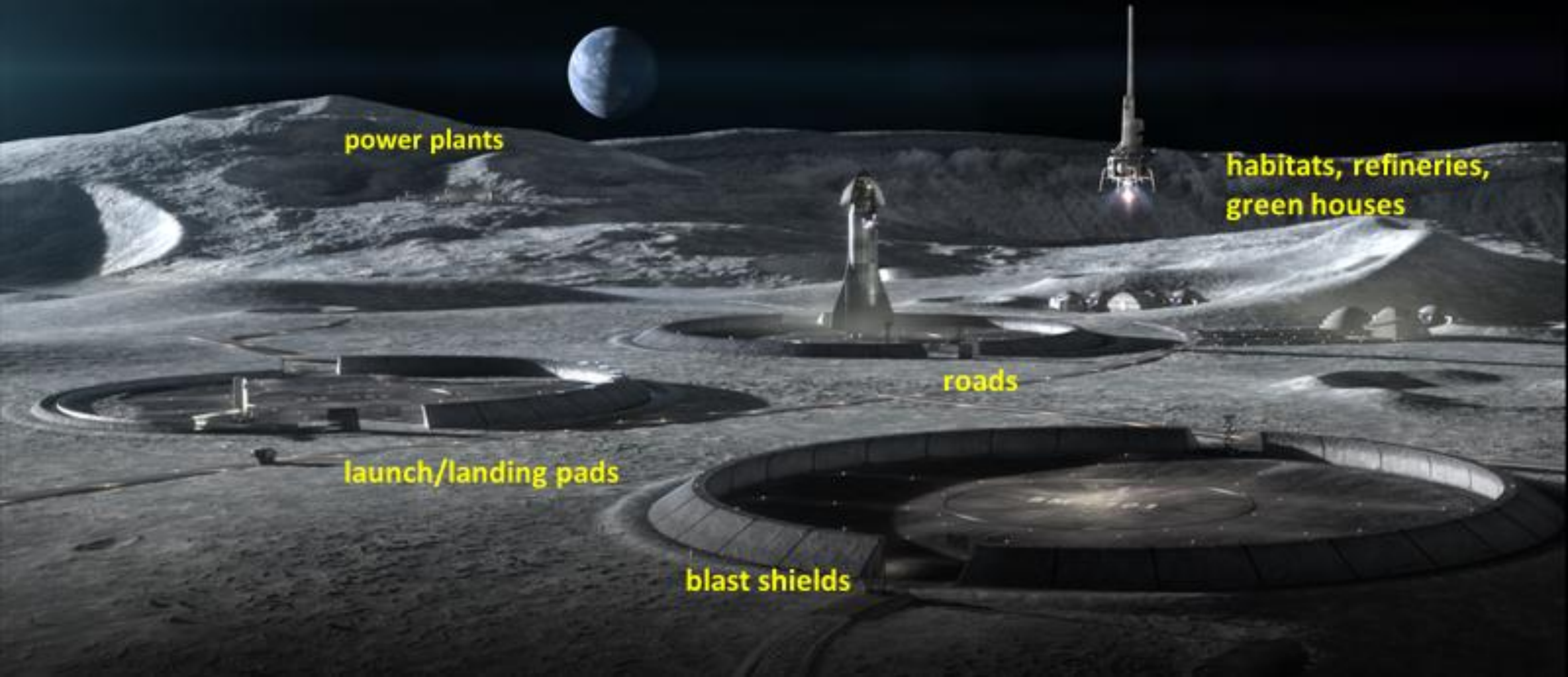
Building a Sustainable Presence on the Moon

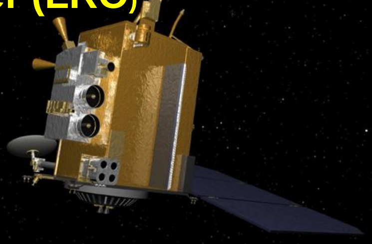
- What infrastructure are we going to need?

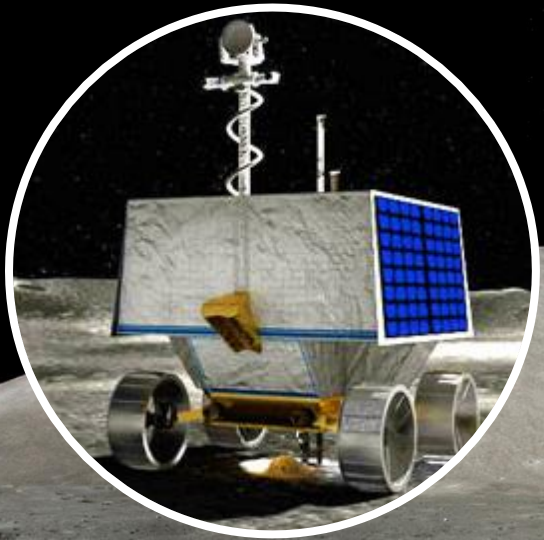


Excavation for ISRU and Construction:
Finding, Excavating and Transporting the Resources

Resource Prospecting – Looking for Resources

Lunar Reconnaissance Orbiter (LRO)





Volatiles Investigating Polar Exploration Rover (VIPER)
~2024 mission

Excavation & Processing for Aggregates and Binders

RASSOR Excavator
~2026 mission

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.

MMPACT is structured into three interrelated elements:

1. Olympus Construction Hardware Development
2. Construction Feedstock Materials Development
3. Microwave Structure Construction Capability (MSCC)

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 cementitious blends that can originate from *in situ* resources for Olympus.
  - Develop directed energy – based construction technologies
  - Develop molten regolith construction concepts
- 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 Olympus and MSCC products for use in the lunar environment.
- Validate that Earth-based development and testing are sufficient analogs for lunar operations

Autonomous Construction for the Lunar Outpost

Regolith-based Materials and Processes:

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

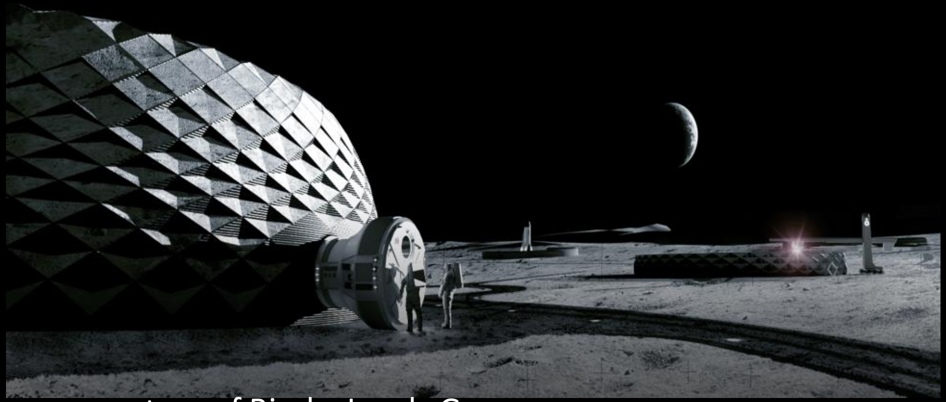


Image courtesy of Bjarke Ingels Group

Image courtesy of ICON

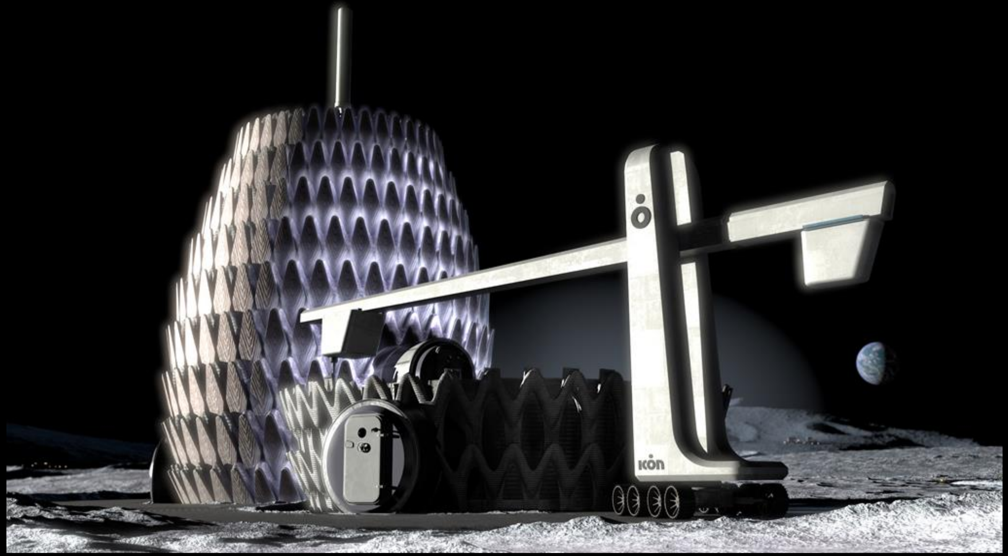


Image courtesy of SEArch+

Initial Construction Technology Demonstration Mission, DM-1 (2026)

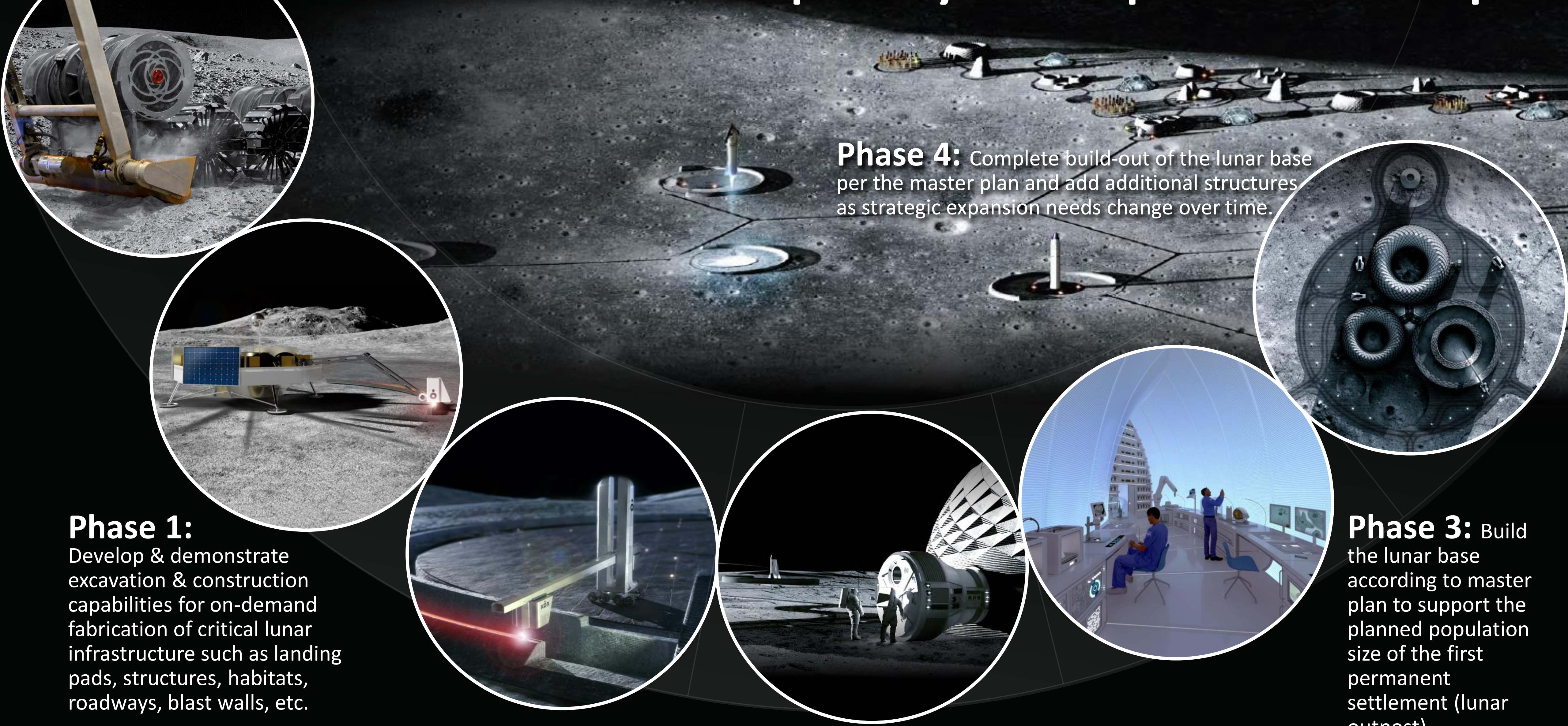
Construction Roadmap

- Demonstrate downselected construction technique utilizing ISRU materials at small scale from lander base (horizontal and vertical subscale “proof of concept” elements)
- Results are critical to inform future construction demonstrations & characterize ISRU-based materials and construction processes for future autonomous construction of functional infrastructure elements
- Demonstration of remote/autonomous operations
- Initial demonstration of instrumentation and material
- Validation that Earth-based development and testing are sufficient analogs for lunar operations
- Anchors analytical models
- ***Rationale:*** *Must prove out initial construction concept in lunar environment*

Outcome

- **TRL 6** achieved for autonomous ISRU consolidation into densified, subscale horizontal and vertical demonstration products
- **TRL 9** for limited hardware and instrumentation that will 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.

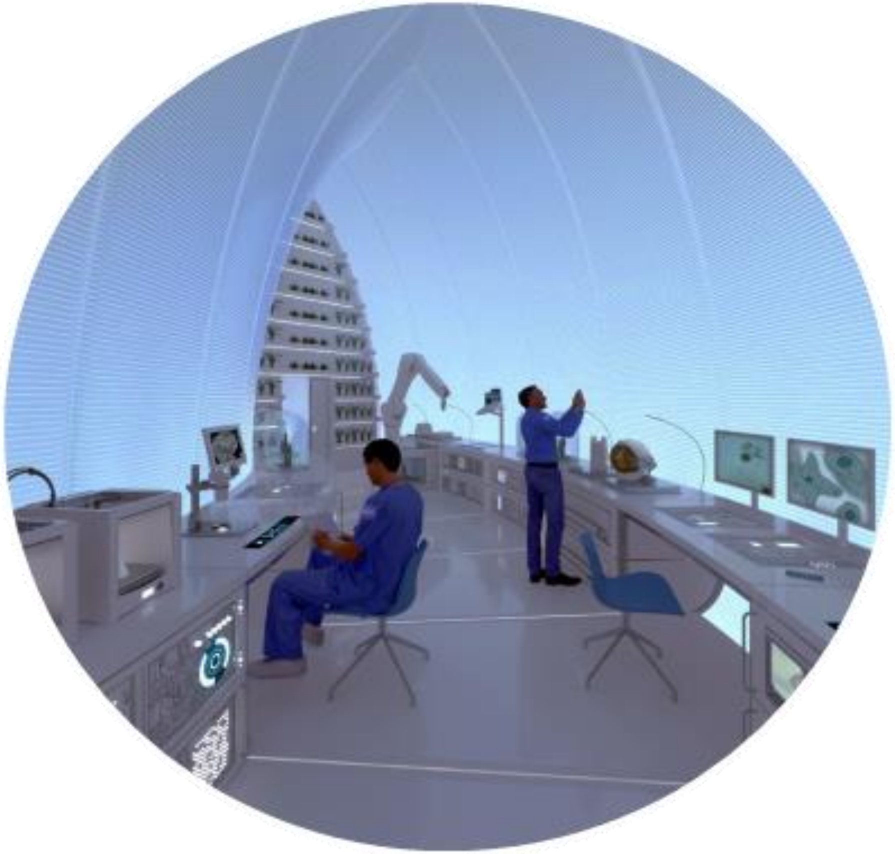
Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.

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.

Lunar Outfitting Capability Development

- Outfitting: Broad spectrum of capabilities – “Turning a house into a home”
- In-situ installation of subsystems
  - Mechanical
  - Electrical
  - Plumbing (ducting, piping, gas storage)
- Interior Furnishings Fabrication
  - Workbenches
  - Tables
  - Chairs
- Power, Lighting, Communications
- Enclosures (windows, hatches, bulkheads)
- Verification, Validation, and Inspection Technologies



Challenges and Capability Gaps

- Reduced gravity and low reaction forces – Excavation
- Inspection and Certification of as-built structure – Construction
- Material and construction requirements and standards - Construction
- Process Development and Demonstration
  - ISRU for extraction of basic products:
    - Consumables – water, oxygen, and volatiles capture
    - Feedstock materials – metals, alloys and binder constituents
  - Construction: Deposition processes and associated materials
- Scale Up
  - ISRU production (10's to 100's mT)
  - Excavation: (10's to 1000s mT); Trips/Distance traversed
  - Construction: Proof of concept to full scale landing pads and habitats
- Regolith excavation, transfer, and conveyance
- Long-duration operation of mechanisms and parts under lunar environmental conditions (Reliability and Maintainability)
- Structural Health Monitoring and Repair
- Dust Mitigation
- Increased Autonomy of Operations
- Power

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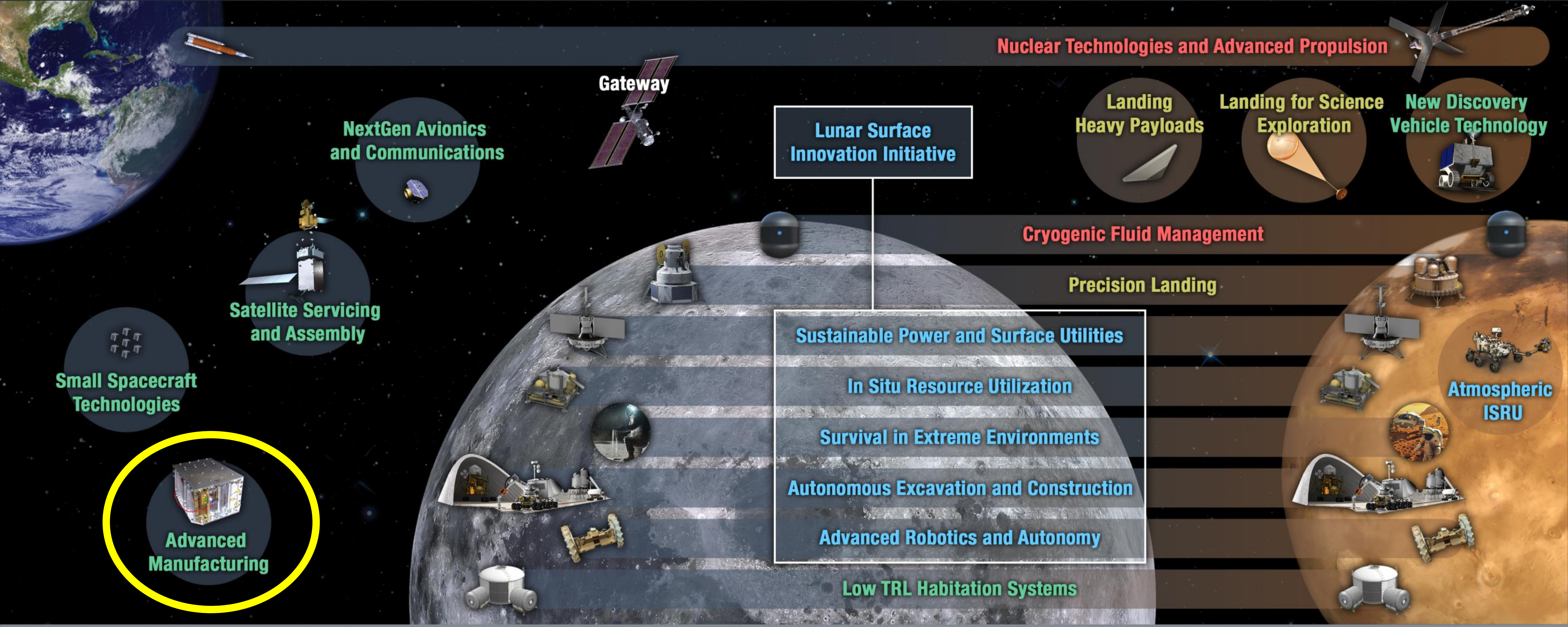

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In-Space Manufacturing Project Portfolio

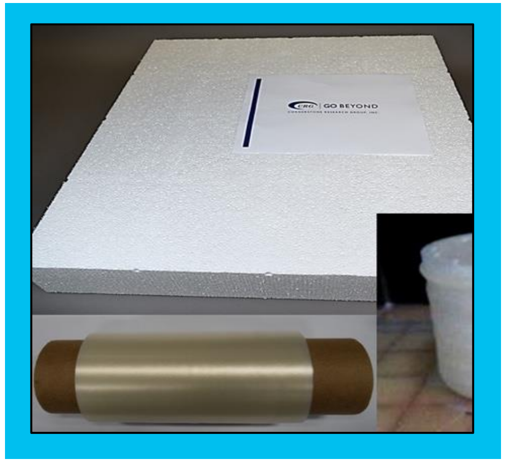
Objective: provide a solution towards sustainable, flexible missions through development of on-demand fabrication, replacement, and recycling capabilities

On Demand Metals Manufacturing

Provide a capability for on-demand 3D printing of metal parts

Image Courtesy of Made In Space

Recycling and Reuse



Develop materials and recycling technologies to create an on-orbit recycling ecosystem

Image Courtesy of Cornerstone Research Group

On Demand Electronics Manufacturing

Develop printed electronics, sensors, and power devices for testing and demonstration on ISS

Development and Testing of Capabilities for On-Demand Spare Component Manufacturing

Techshot Fabrication Laboratory ground-based prototype for bound metal deposition. Image from Techshot, Inc.

Vulcan wire+arc hybrid additive manufacturing system from Made in Space, Inc.

Systems in development for future initial ISS demonstrations: 3D printing of metals

Adapting Metal AM for ISS and Lunar Surface

Environments (ISS and the lunar surface) impose unique constraints for manufacturing systems.

- Scale/scalability of hardware
  - Power (max power for ISS payload is 2kW)
  - Mass
  - Volume
- Safety (feedstock management, chip debris capture)
- Limited crew interaction
- Remote commanding
- Range of materials within processing capability
- Feedstock materials available, via beneficiation, on Moon
- Ability to produce complex features
- Surface finish
- Operation in reduced gravity
  - Physics of deposition
  - Impact on material quality
  - Management of heat in absence of natural convective cooling

One of the pre-eminent ISM challenges is verification of parts produced on-orbit or on the lunar surface.

Recycling and Reuse (RnR)

The RnR project element develops materials and recycling technologies with the goal of creating an on-orbit ecosystem for repurposing waste products, such as packaging materials and defective components.

Cargo bags filled with trash on ISS for downmass in Cygnus cargo capsule. Image from NASA.

- Analyze historical waste streams and recycling technologies
- Development of “purpose-built” recyclable materials
- Development of in process monitoring technologies

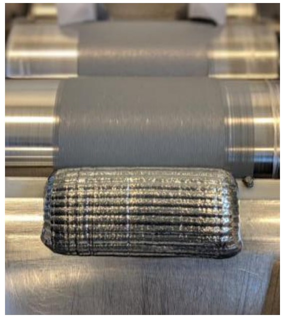
(LEFT) Thermally reversible packaging materials (which can also be used for 3D printing) and (RIGHT) in-process monitoring system for polymer filament production from Cornerstone Research Group (CRG). Images from CRG.

Potential Areas for Future Exploration

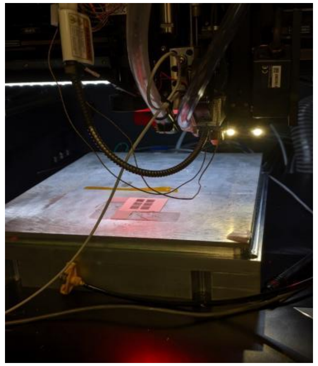
- Metals Recycling
- Sterilization and Sanitization Technologies
- Increased feedstock strength
- Validation and characterization of recycled feedstock
- In Situ Resource Extraction
- Cleaning Technologies (esp. food packaging)
- Disassembly of multi material products

On-Demand Manufacturing of Electronics (ODME)

ODME is developing printed electronics, sensors, and power devices for initial testing and demonstration on ISS. In parallel, deposition processes used with printed electronics (direct write and plasma spray) are being matured for future flight demos.



Development of electronic inks



Development of laser sintering process

nScrypt 3D Multi-Material Printer

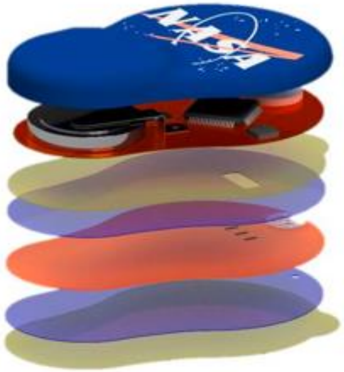
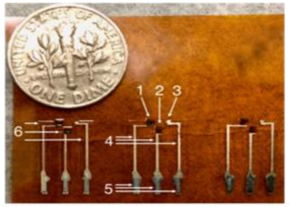


Diagram of AstroSense next-generation flexible, wireless, multi-sensor printed device for crew health monitoring. Image from Nextflex.

Development of photonic sintering process

Dimatix inkjet thin film printer

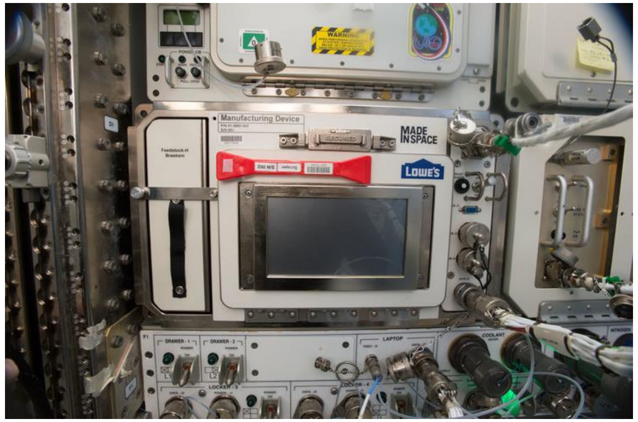


Printed cortisol (stress) sensor. Image from California Institute of Technology.

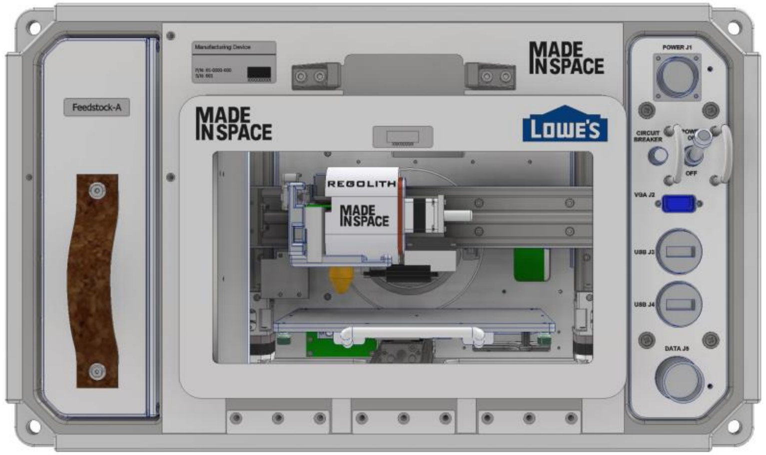
1st Generation Personal CO_2 Monitor

3D Printing and In Situ Resource Utilization (ISRU): RegISS demonstration

RegISS will be an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It will be the first demonstration of manufacturing with ISRU-derived feedstocks on ISS.



Made in Space (MIS) owns and operates the Additive Manufacturing Facility (AMF).

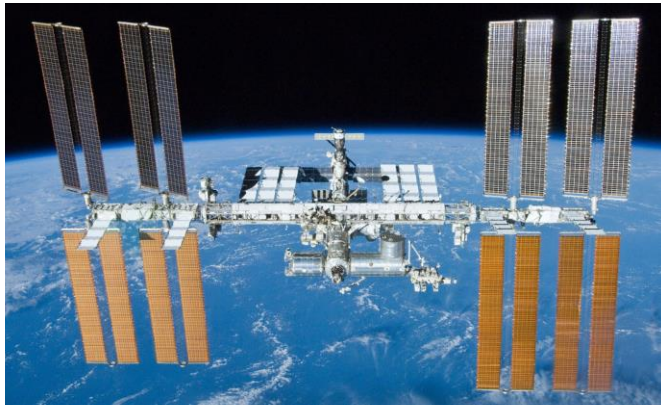


In this effort, a previously flown version of AMF will be modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.

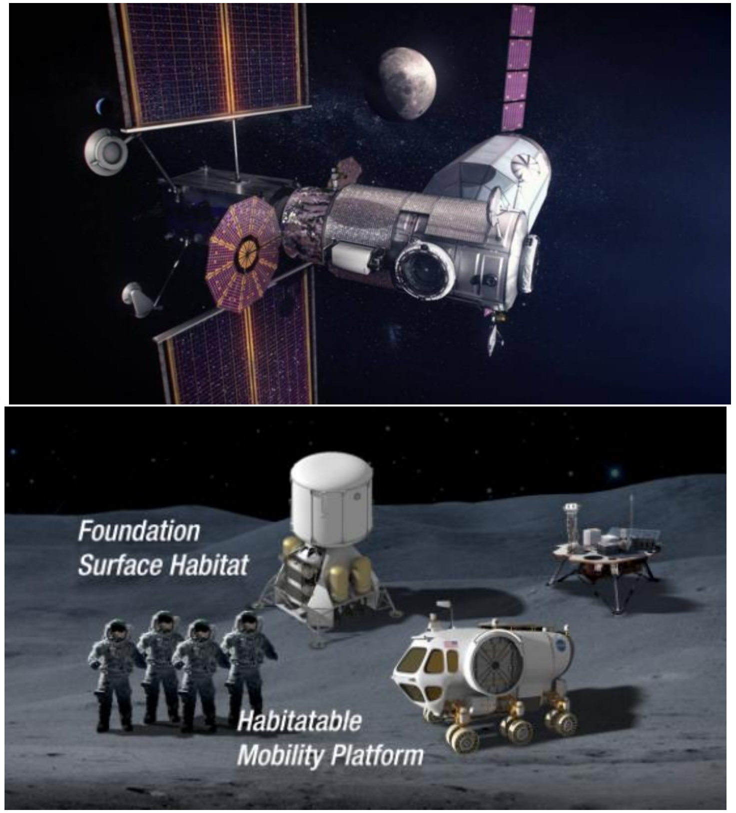
Printing (top) and testing (bottom) of a compression cylinder with a regolith simulant/polymer feedstock.

The Vision of Space Sustainability

Manufacturing in space is a destination-agnostic capability and has clear mission benefits beyond low earth orbit, where cargo resupply opportunities become more limited. These technologies are key enablers for sustainable space exploration.



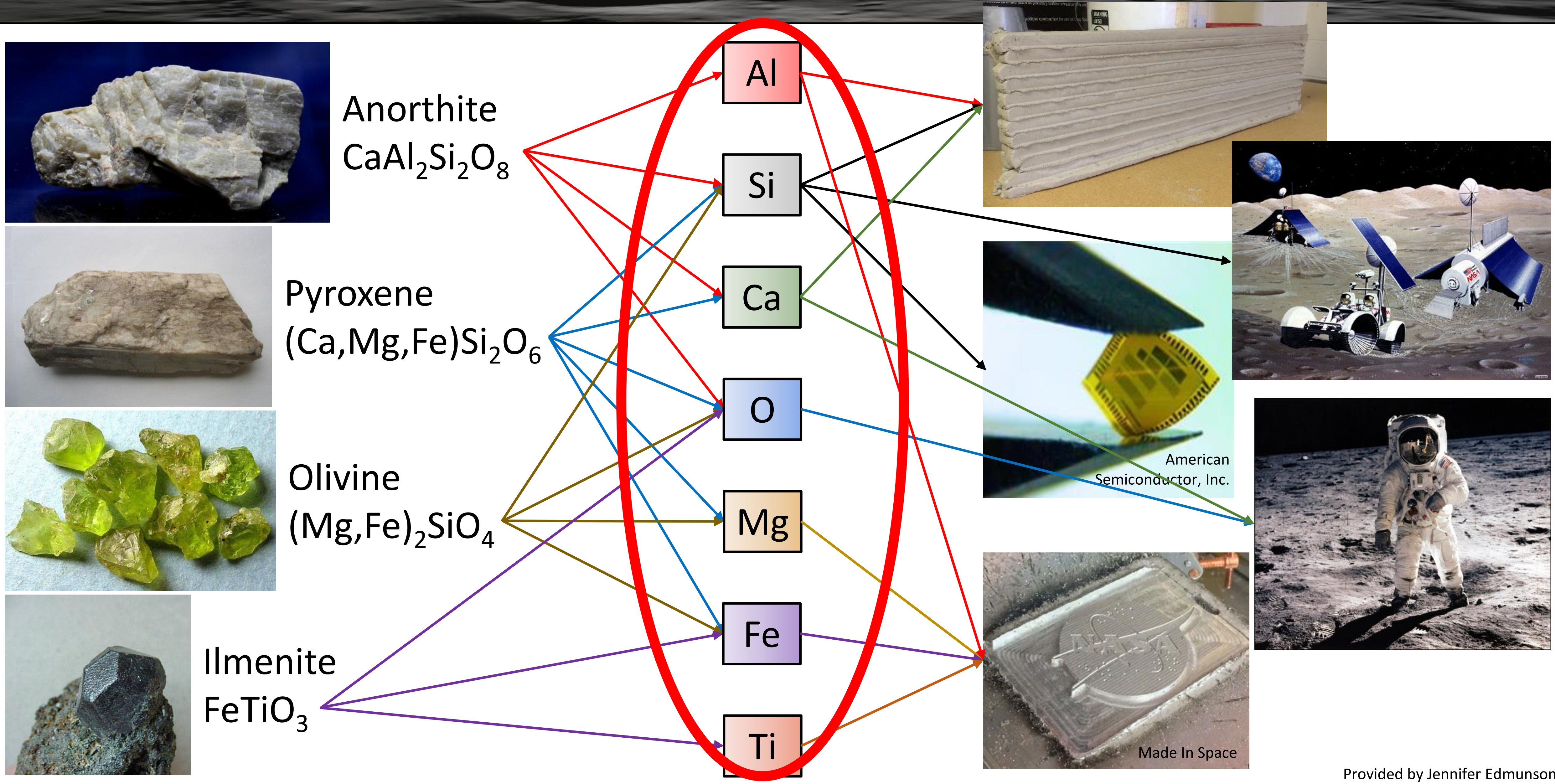
ISS is the testbed for ISM.



ISM capabilities demonstrated on ISS are applicable to Gateway and the lunar surface.

"Houston, we have a solution."

Lunar regolith must be used for multiple applications (consumables, manufacturing, infrastructure construction) to enable a sustainable human presence and future lunar economy



Anorthite
$CaAl_2Si_2O_8$

Pyroxene
$(Ca,Mg,Fe)Si_2O_6$

Olivine
$(Mg,Fe)_2SiO_4$

Ilmenite
$FeTiO_3$

American Semiconductor, Inc.

Made In Space

Provided by Jennifer Edmunson

www.nasa.gov/spacetech

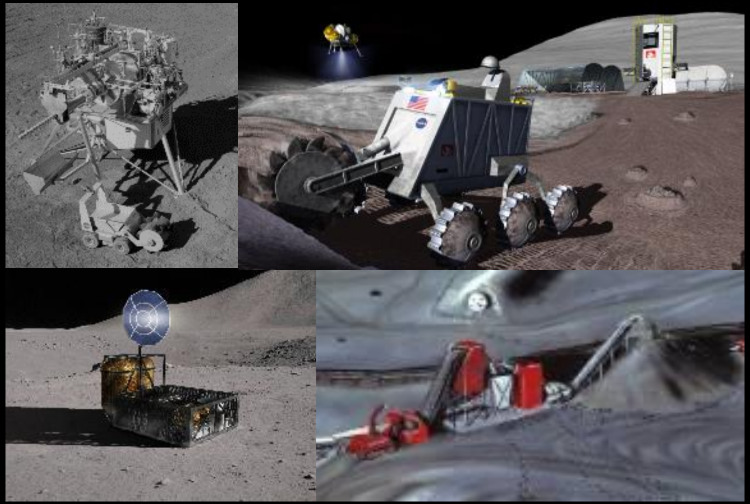
BACK-UP

Consumables and Feedstock Production: *Living off the Land*

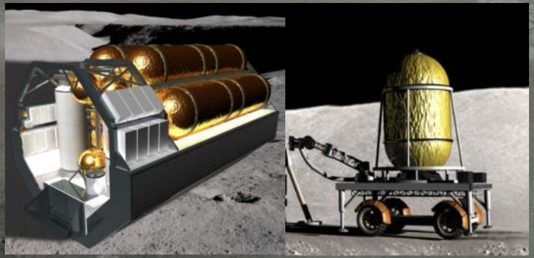
Products

- Oxygen
- Water and other volatiles
- Consumables for in-space and surface transportation and crop growth
- Feedstock materials for manufacturing, e.g. metals and silicates
- Feedstock constituent materials for construction
- Production of commodities for future lunar economy

Excavation & Regolith Processing for O_2 & Metal Production



Consumable Storage & Delivery



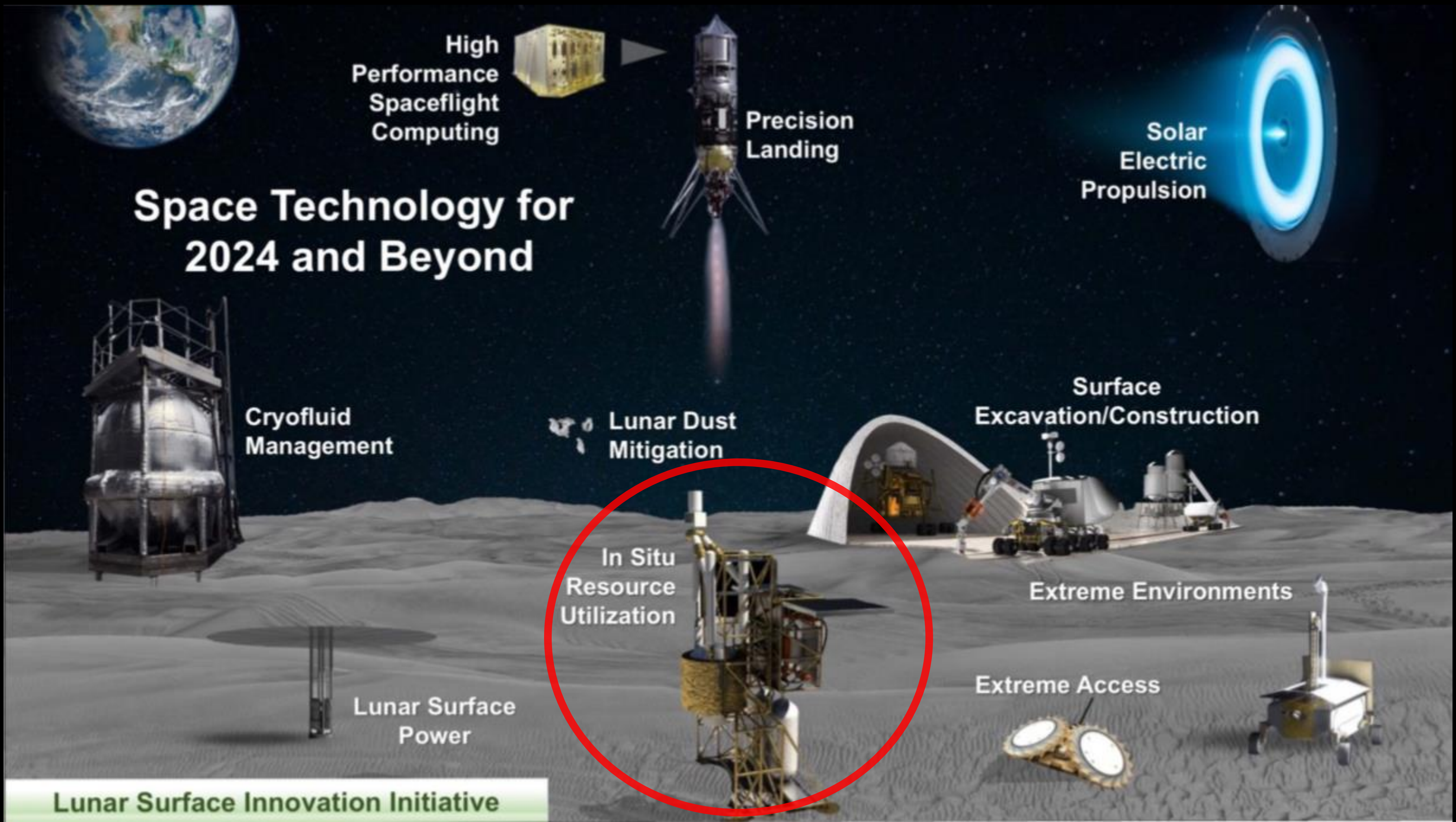
Consumable Users

Rovers & EVA Suits

Habitats & Life Support

Landers

NASA Lunar Surface Innovation Initiative (LSII)



EXPLORE – ADVANCED MANUFACTURING: Develop technologies supporting emerging space industries including In Space/Surface Manufacturing

Across the Space Technology portfolio spanning the range of technology readiness levels and supporting many other Primary Capabilities

Lightweight Composites Spacecraft

- > 30% More Payload, Equipment and Experiments

United States Manufacturing Public/Private Partnerships

- Manufacturing technology has a multiplier effect to competitiveness and expands the industrial base

In-Space Spares and Repairs

- **> 50% mass reduction, > 99% 3D printer readiness with sustainable supply chain, multiple materials**

3D Printing Affordable Rocket Engines

- > 30% Cost reduction, three months instead of five years, Parts >1,100 to <10

Industries of the Future Powered by Digital Twins and Artificial Intelligence

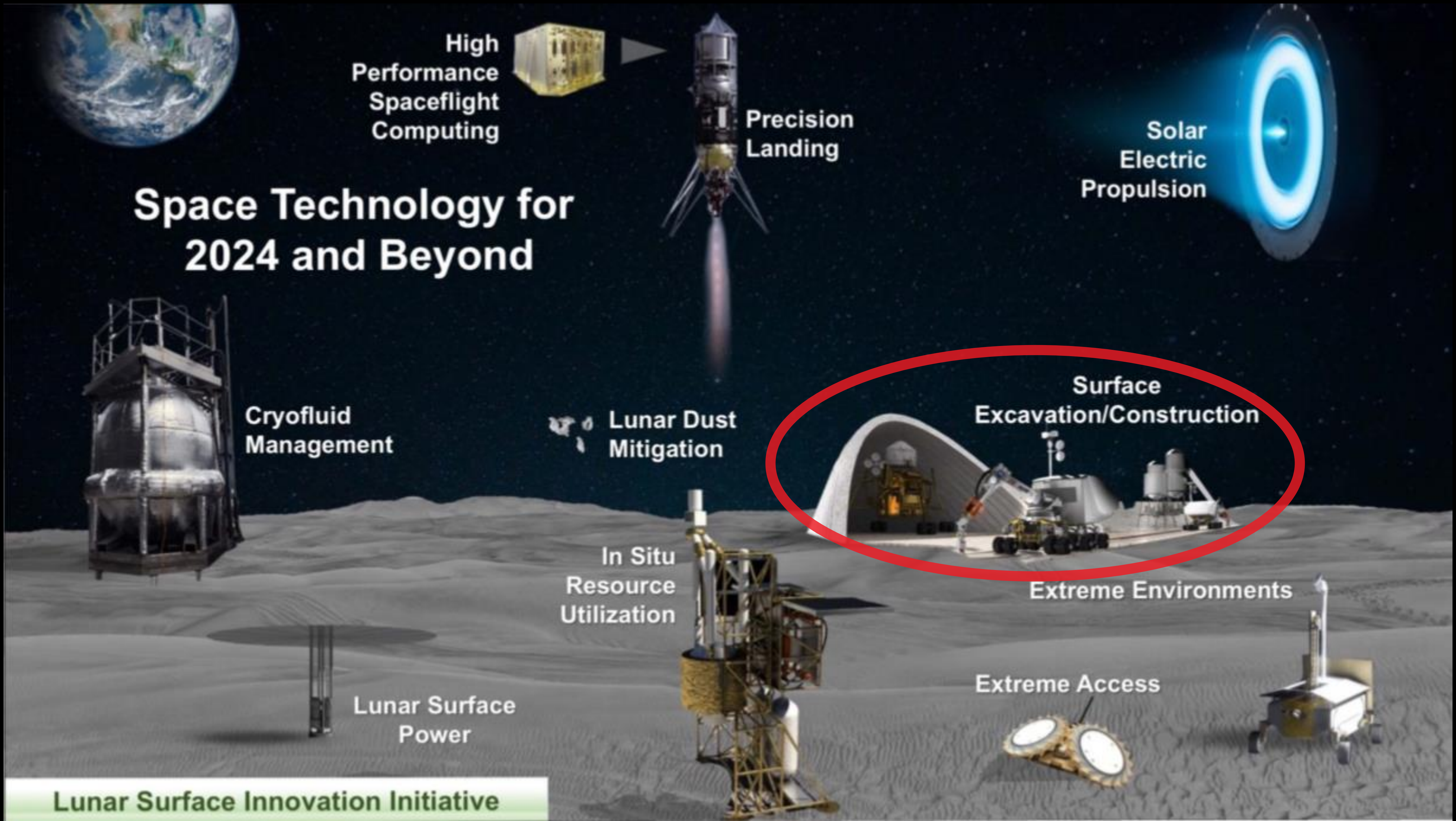
- More intelligent and more accurate predictions and capabilities, > 50% % of physical resources replaced with virtual

Factories in Space and Space Infrastructure

- Creating economic opportunities - increased launches, spacecraft, products

All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.

NASA Lunar Surface Innovation Initiative (LSII)

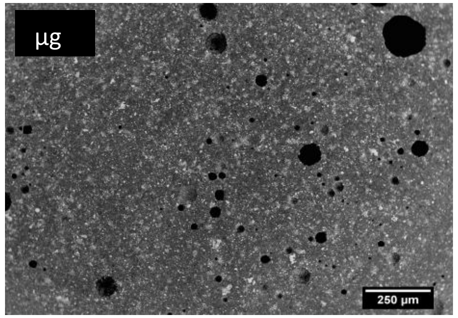


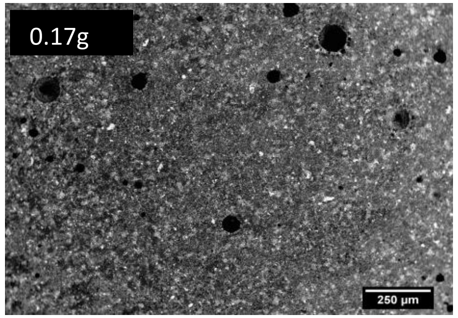
Penn State Microgravity investigations of cements and geopolymers for lunar infrastructure

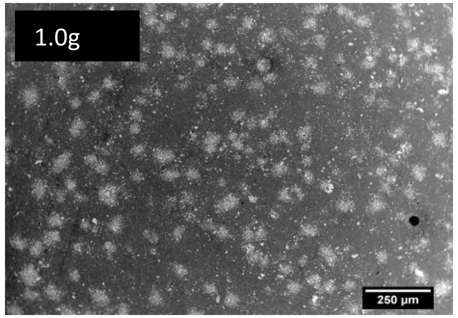
Microgravity Investigation of Cement Solidification (MICS) was a first step towards producing durable lunar infrastructure

ISS experiments were conducted at 0, 0.17, 0.38, and 0.7 G

- Influence on strength - As the gravity level decreased the amount of trapped air and porosity in the samples increased
- Furthermore, crystals tend to grow larger and more uniform in microgravity
- The results also showed that cement solidification at Lunar gravity is more similar to microgravity than to Earth gravity

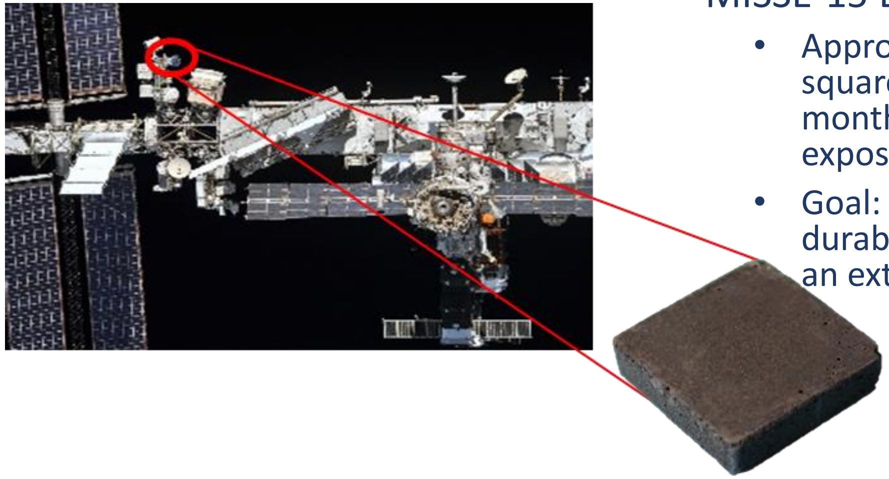






Gravity Level	Porosity (%)
10^{-6}	17.7
0.17	16.6
0.38	13.1
0.70	12.7
1	8.2

Assessment of LEO variables on an in-situ geopolymer lunar concrete



- MISSE-15 Experiment
  - Approach: Multiple 1-inch square samples with 6-month zenith orientation exposure
  - Goal: Understanding the durability of the samples in an extreme environment

- Microgravity Solidification Experiment
  - Approach: Similar experimental setup as the Microgravity Investigation of Cement Solidification (MICS) project
  - Goal: Understanding how the reduction in gravity influences the solidification

PennState

Images courtesy of Dr. Aleksandra Radlinska and Peter Collins