National Aeronautics and
Space Administration

Don’t Take It – Make It on the Moon: Manufacturing, Construction, and Outfitting on the Lunar Surface

Additive World: Excellence in Space Seminar

Bristol, The United Kingdom, April 20, 2022

R. G. Clinton, Jr., PhD

Contributors

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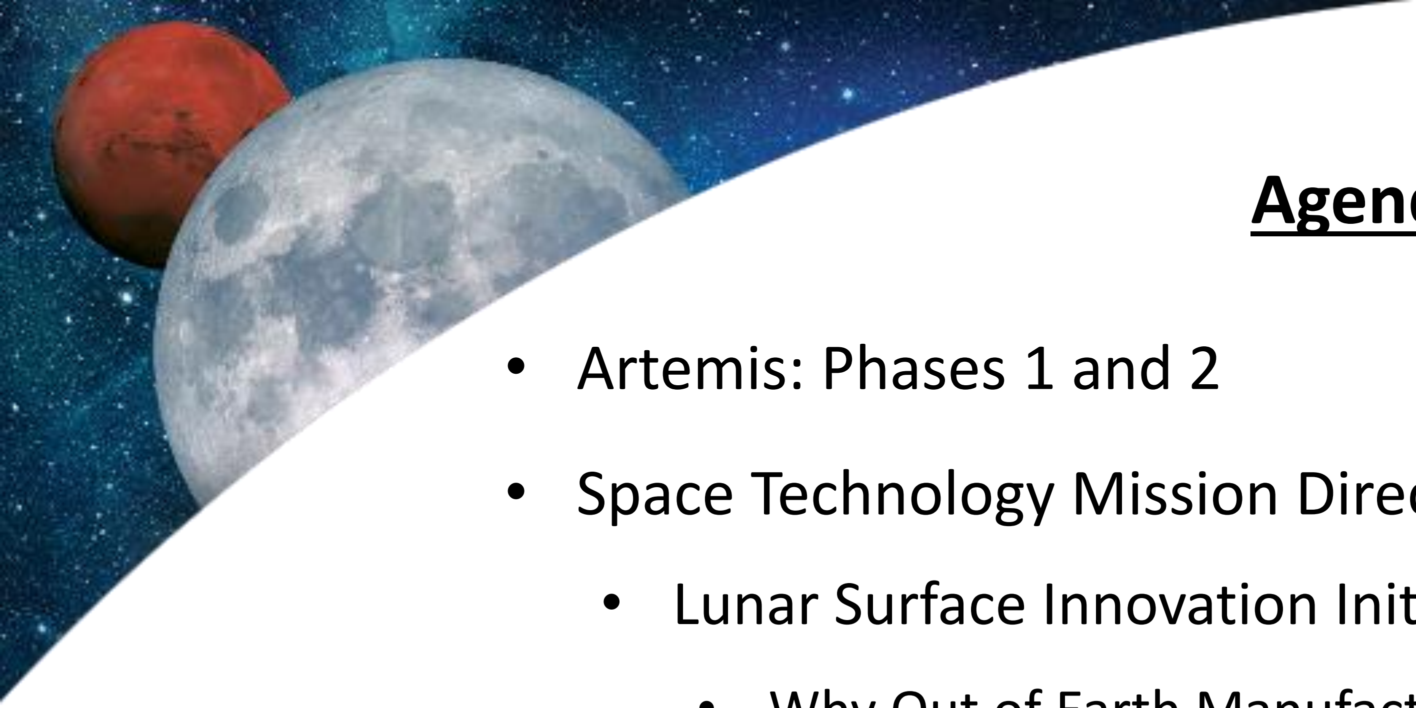
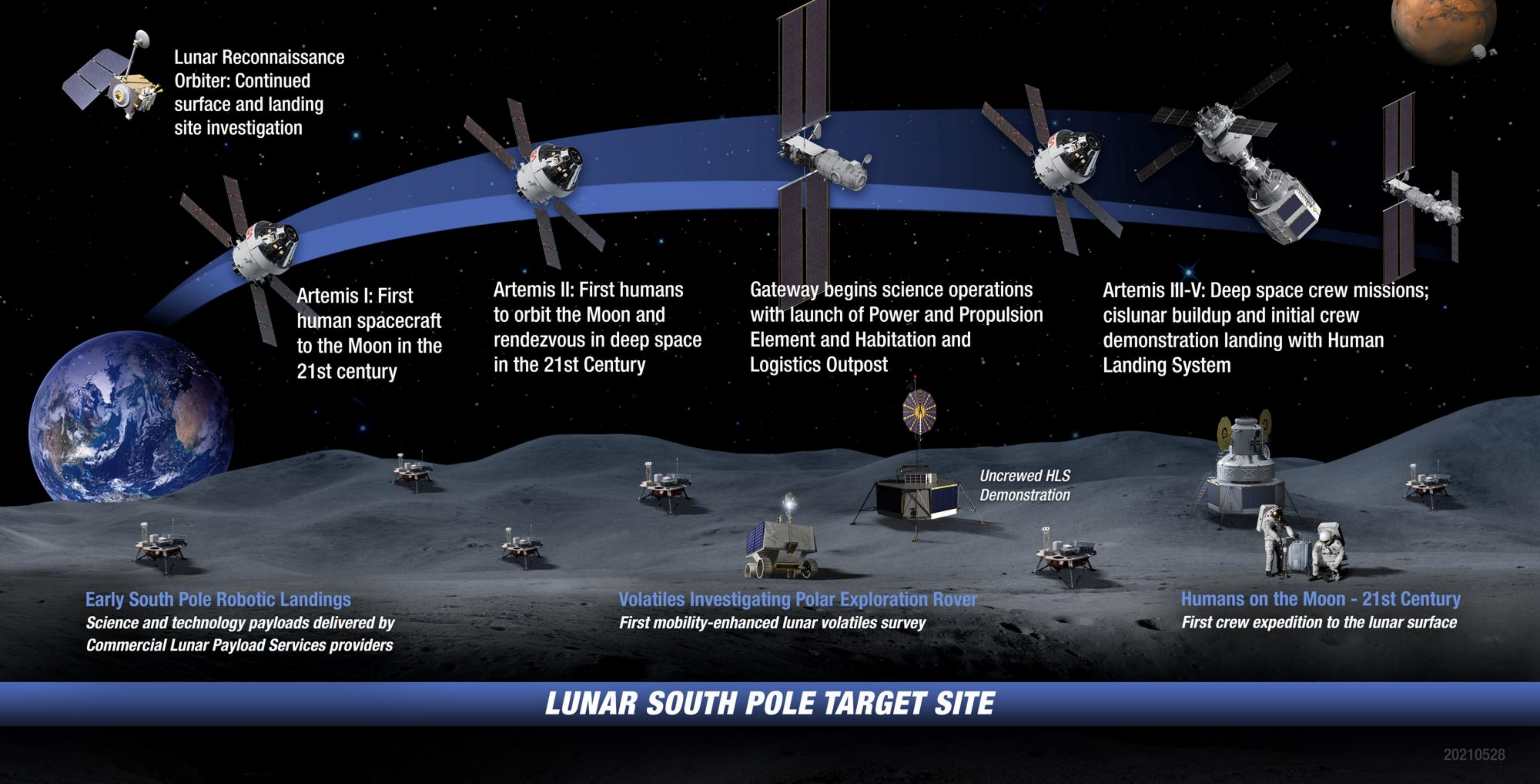
- Jason Ballard – CEO ICON Technologies
- Evan Jensen – ICON PM MMPACT
- SEArch+ - ICON/MMPACT Lunar Architectural Design Concepts
- Bjarke Ingels Group - ICON/MMPACT Lunar Architectural Design Concepts
- Dr. Aleksandra Radlinska – Penn State Cements and Geopolymers
- Peter Collins - Penn State Cements and Geopolymers



Agenda

- Artemis: Phases 1 and 2
- Space Technology Mission Directorate: Technology Drives Exploration
  - Lunar Surface Innovation Initiative (LSII)
    - Why Out of Earth Manufacturing and Construction
    - Excavation, Construction, and Outfitting (ECO)
  - 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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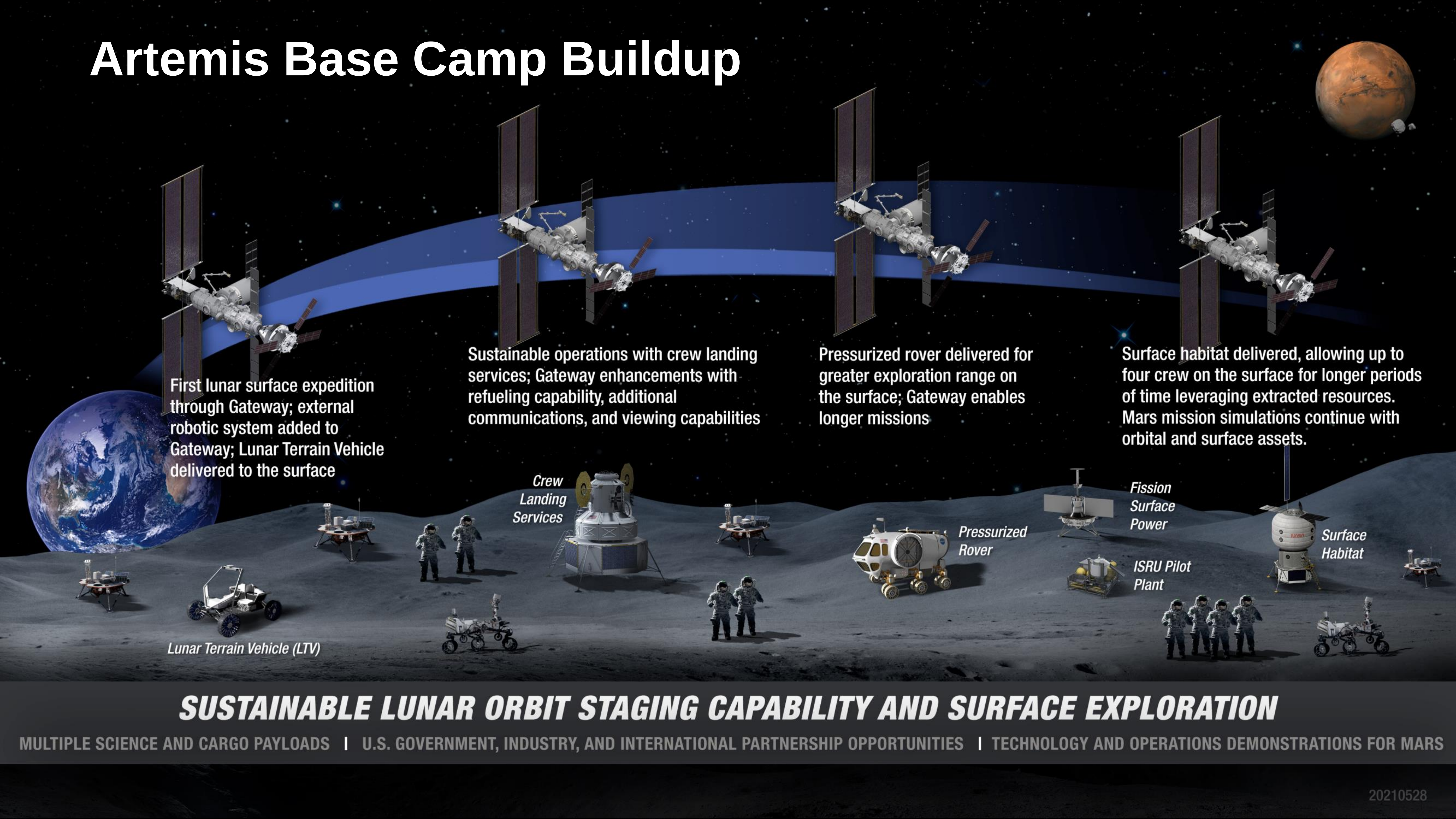
Artemis Base Camp Buildup



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

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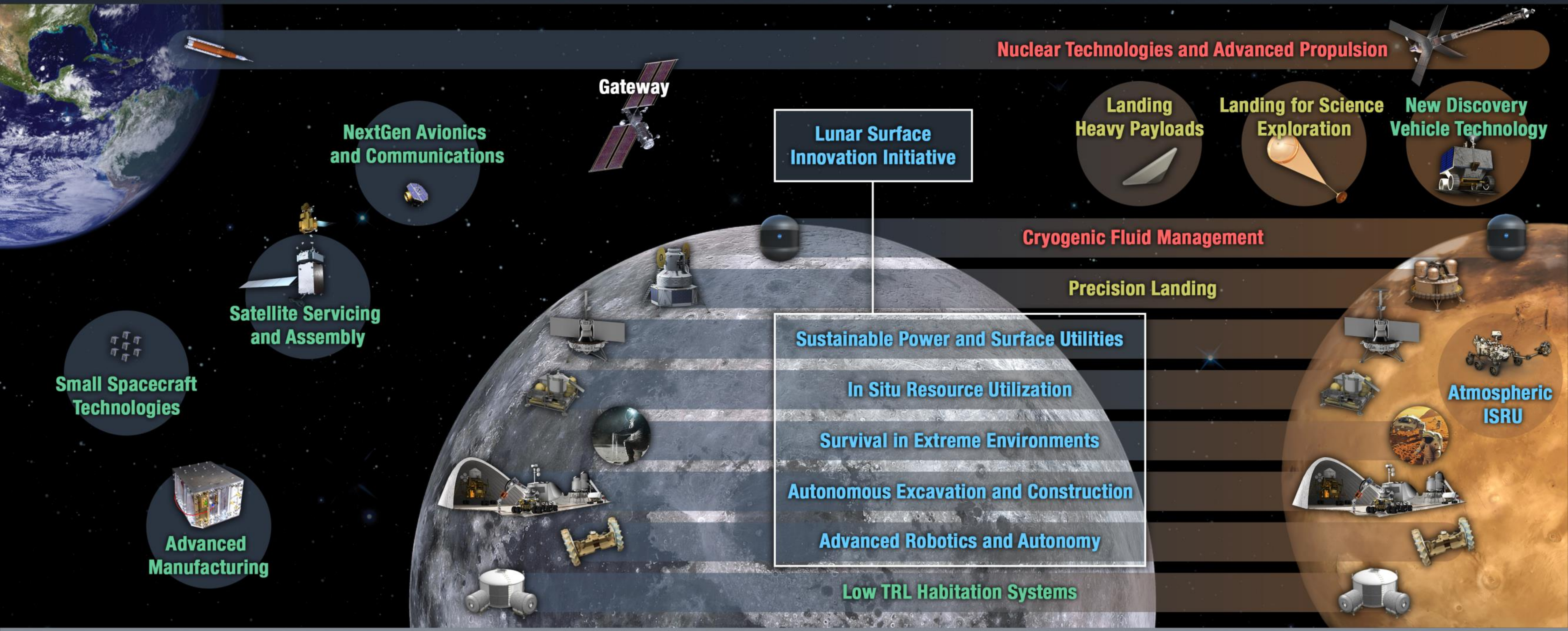
TECHNOLOGY DRIVES EXPLORATION

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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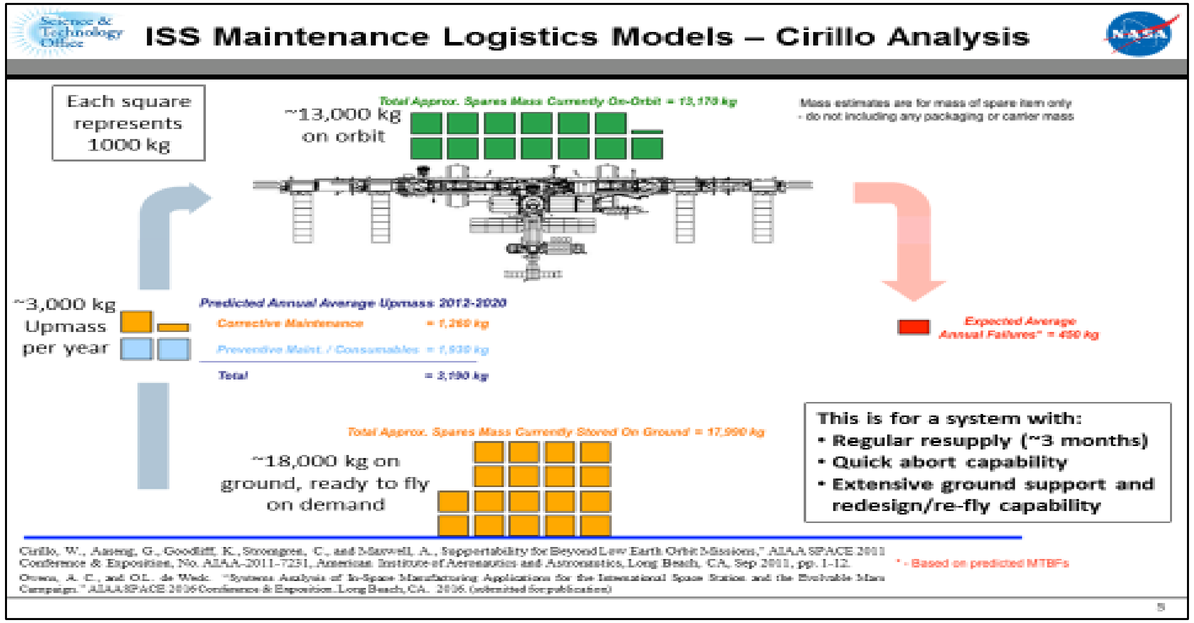
The Case for In Space Manufacturing: WHY



ISS Maintenance Logistics Models – Cirillo Analysis

Each square represents 1000 kg

~13,000 kg on orbit

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass

~3,000 kg Upmass per year

Predicted Annual Average Upmass 2012-2020

Corrective Maintenance	= 1,260 kg
Preventive Maint. / Consumables	= 1,930 kg
Total	= 3,190 kg

Expected Average Annual Failures* = 450 kg

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

This is for a system with:
- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., "Supportability for Beyond Low Earth Orbit Missions," AIAA SPACE 2011 Conference & Exposition, No. AIAA-2011-7231, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sep 2011, pp. 1-12.

Owens, A. C., and O.L. de Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign." AIAA SPACE 2016 Conference & Exposition, Long Beach, CA. 2016. (submitted for publication)

* - Based on predicted MTBFs

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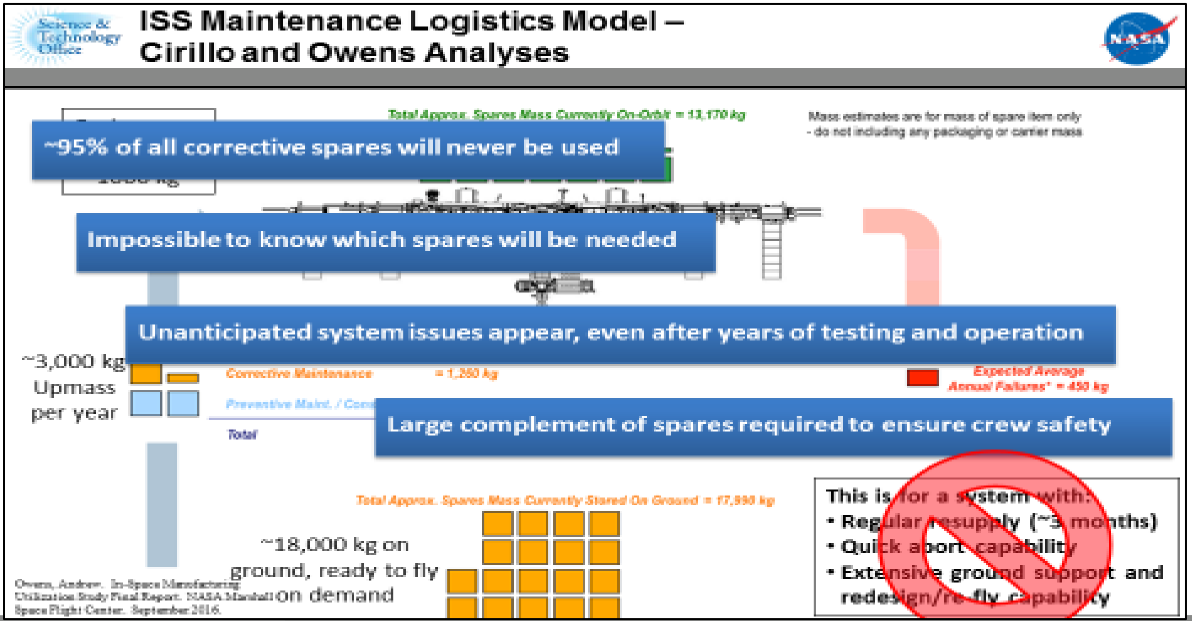


ISS Maintenance Logistics Model – Cirillo and Owens Analyses

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass

~95% of all corrective spares will never be used

Impossible to know which spares will be needed

Unanticipated system issues appear, even after years of testing and operation

~3,000 kg Upmass per year

Corrective Maintenance = 1,260 kg

Preventive Maint. / Cons

Total

Expected Average Annual Failures* = 450 kg

Large complement of spares required to ensure crew safety

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

This is for a system with:
- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Owens, Andrew. In-Space Manufacturing Utilization Study Final Report. NASA Marshall Space Flight Center. September 2016.

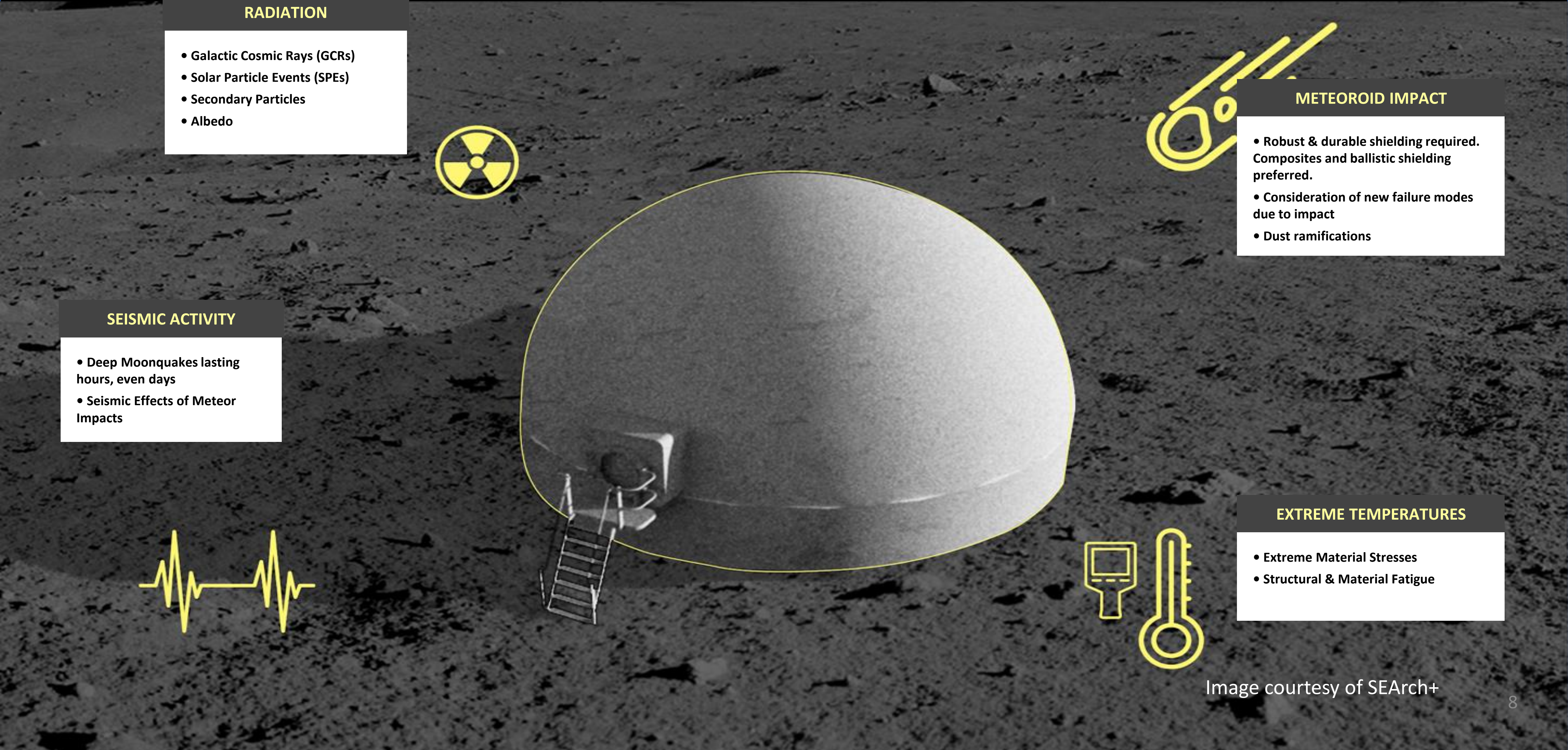
Current maintenance logistics strategy ***will not be effective*** for deep space exploration missions

Benefits from Incorporation of ISM

ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability

PROTECTION - The Case for Lunar Surface Construction: 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

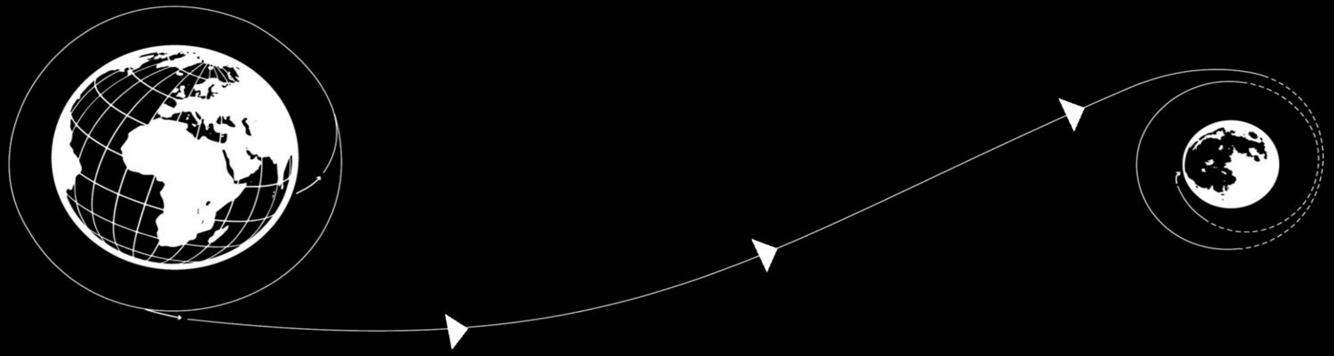
- Extreme Material Stresses
- Structural & Material Fatigue

Image courtesy of SEArch+

COST - The Case for Lunar Surface Construction

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

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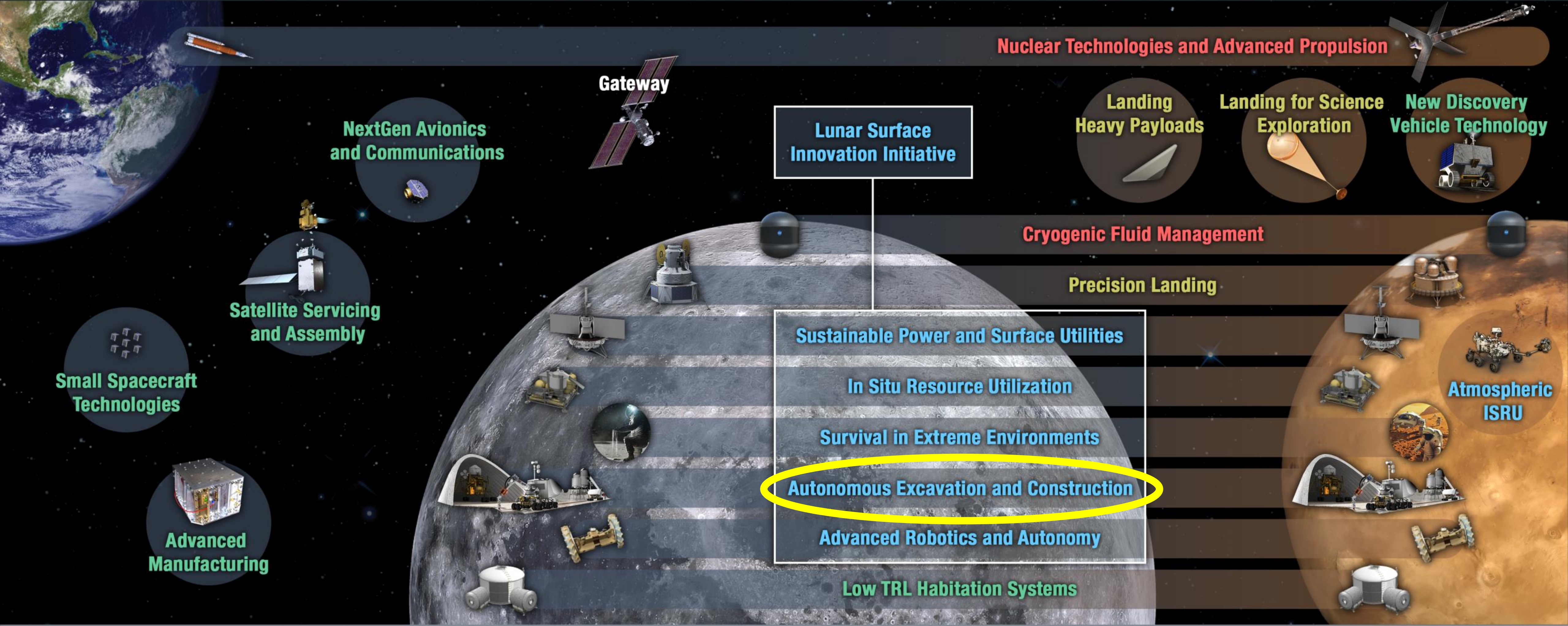

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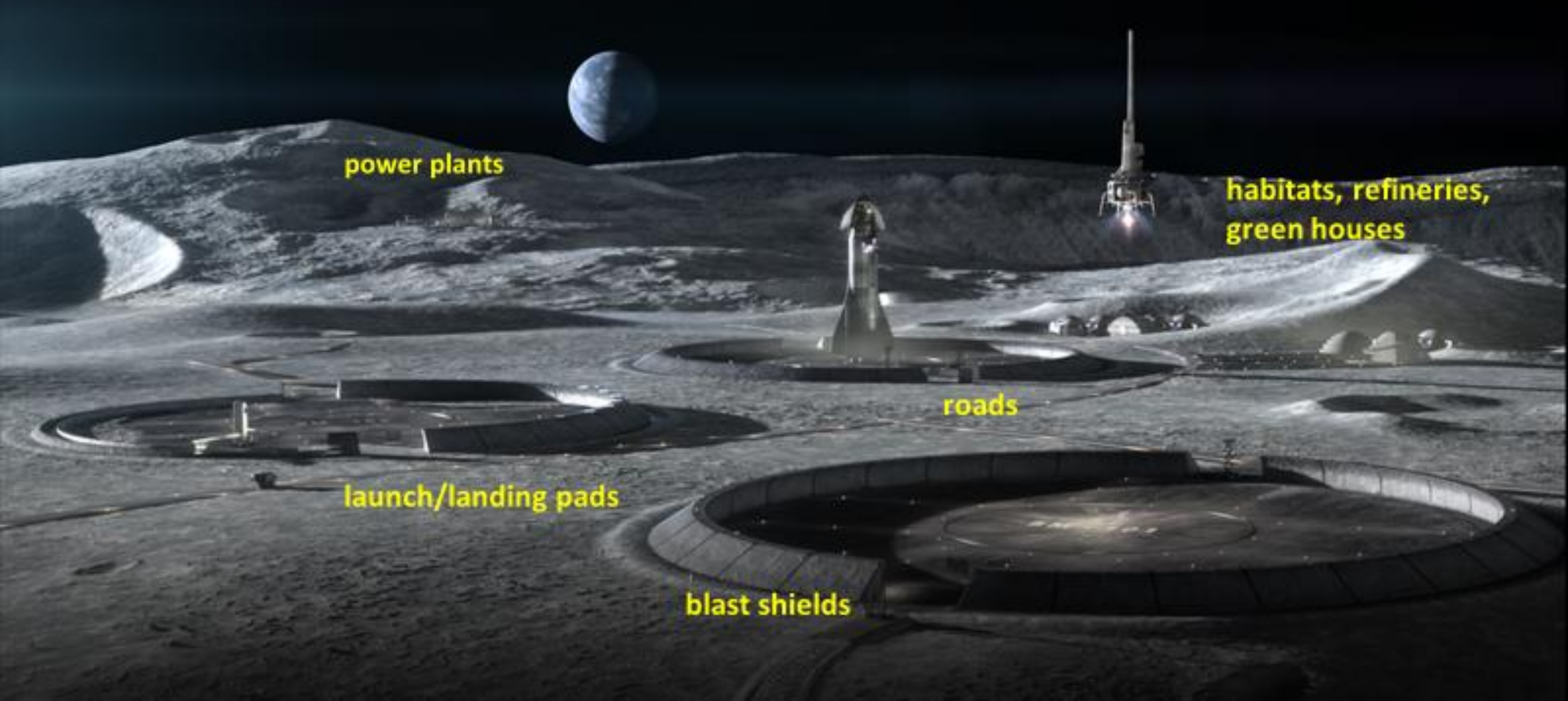
Building a Sustainable Presence on the Moon

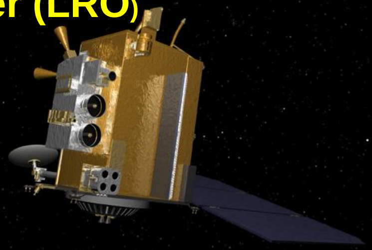
- What infrastructure are we going to need?



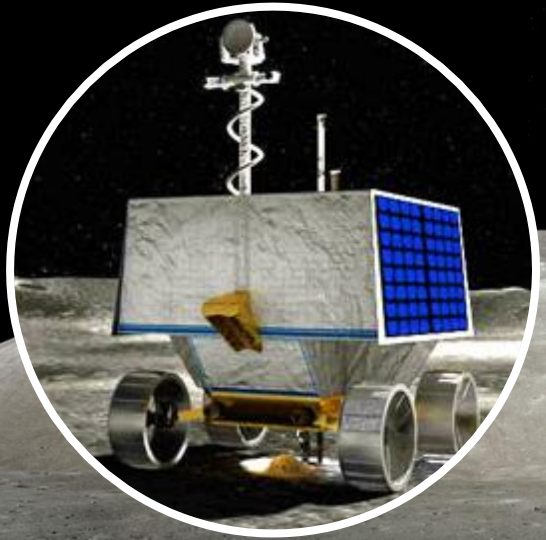
Excavation for ISRU and Construction:

Finding, Excavating and Transporting the Resources

Resource Prospecting – Looking for Resources



Lunar Reconnaissance Orbiter (LRO)

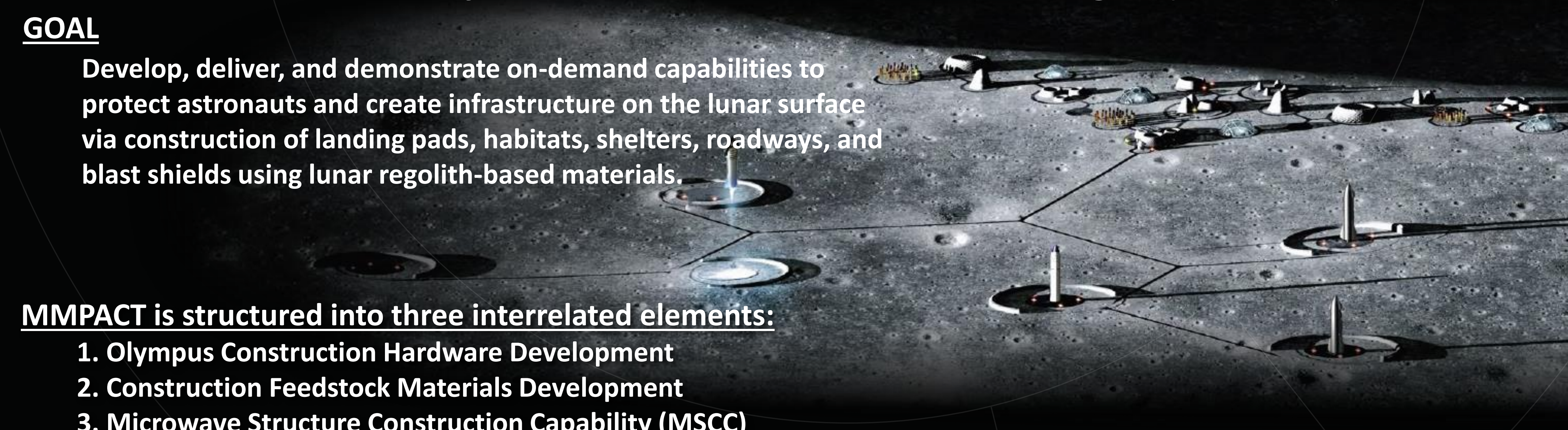


Volatiles Investigating Polar Exploration Rover (VIPER) ~2024 mission

Excavation & Processing for Aggregates and Binders

RASSOR Excavator Candidate for mid-to-late decade 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 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

MMPACT – Current Partners

NASA Centers
- MSFC
- LaRC
- KSC
- JPL

OGA Leveraging

Potential:
- Innovation Unit US Air Force (AF)

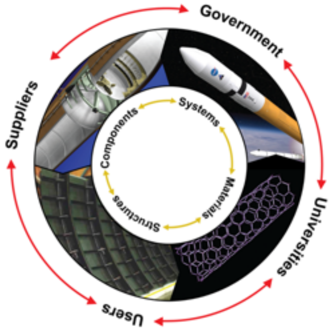
Contributing:
- AF Civil Engineering Center
- AF Special Operations Command
- Defense Innovation Unit
- Texas Air National Guard
- USAF

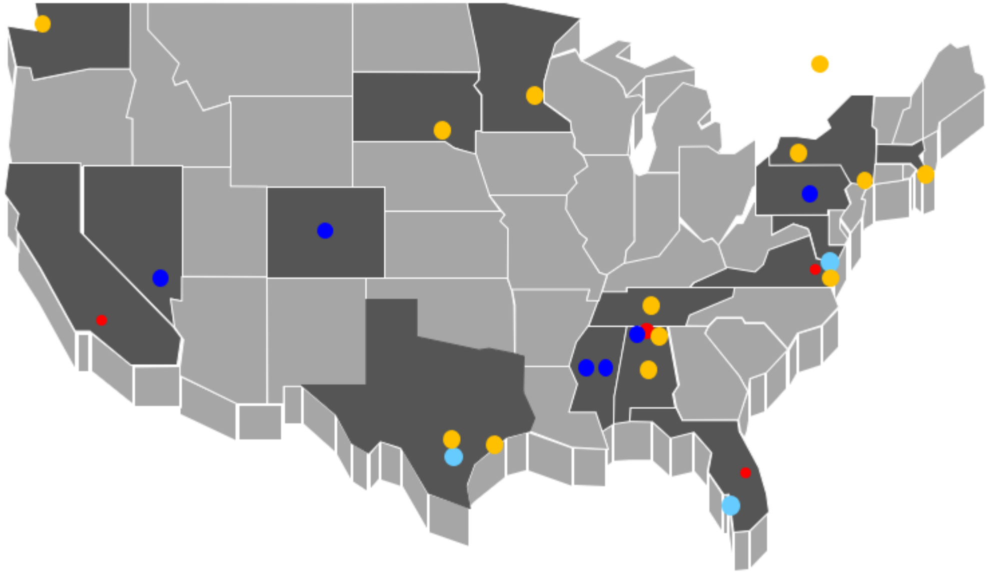
Public/Private Partnerships
- Dr. Holly Shulman
- ICON Build
- Radiance Technologies
- RW Bruce Associates, LLC
- Blue Origin
- Jacobs Space Exploration Group
- JP Gerling
- Logical Innovations
- Microwave Properties North
- MTS Systems Corp.
- Southeastern Universities Research Association
- Southern 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 for the Lunar Outpost

Regolith-based Materials and Processes:

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

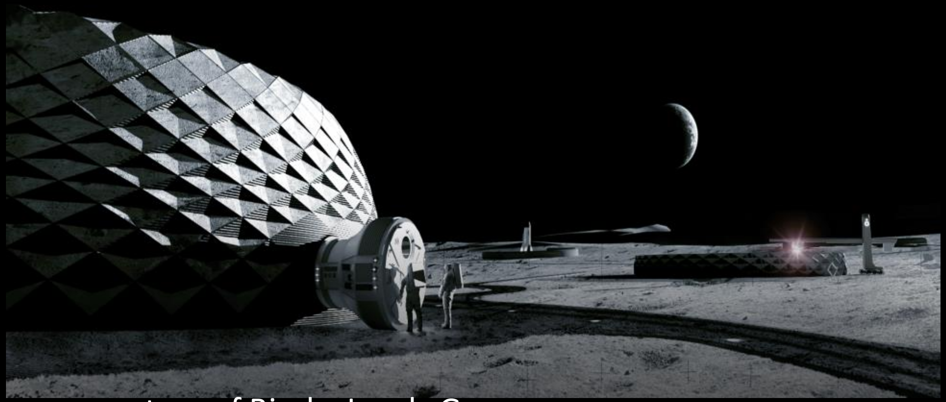


Image courtesy of Bjarke Ingels Group

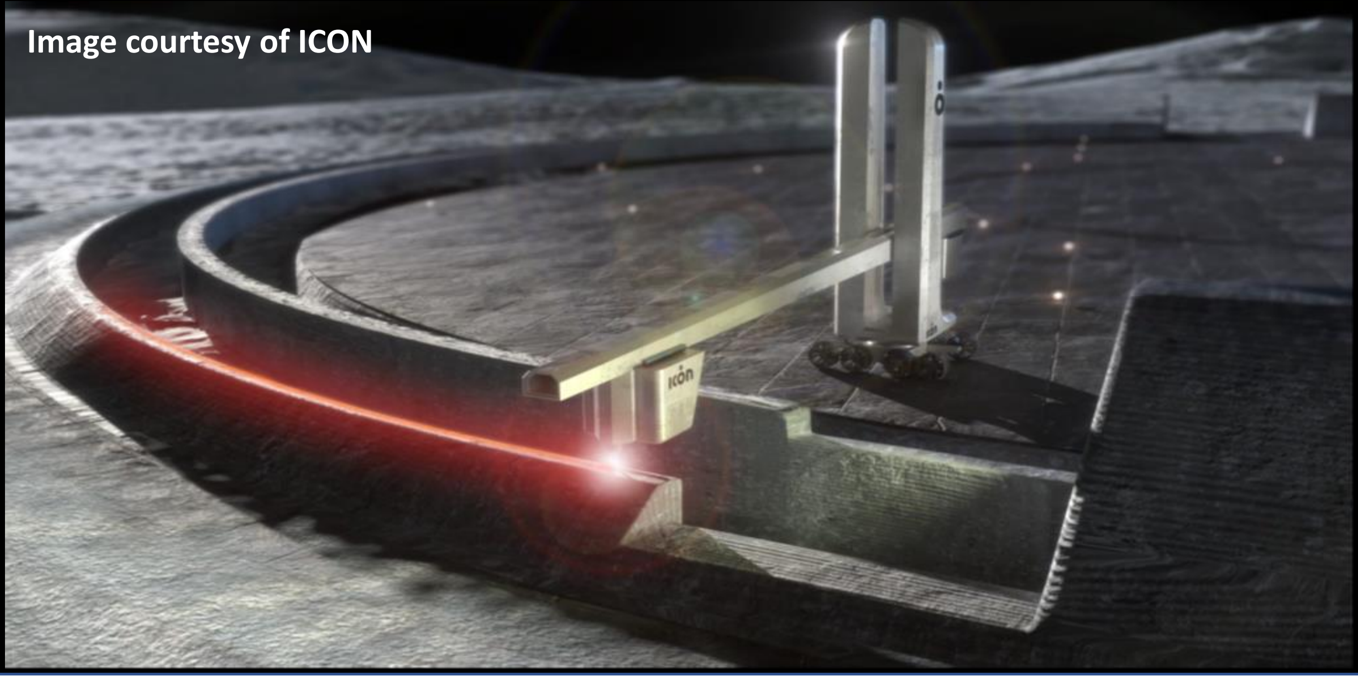


Image courtesy of ICON

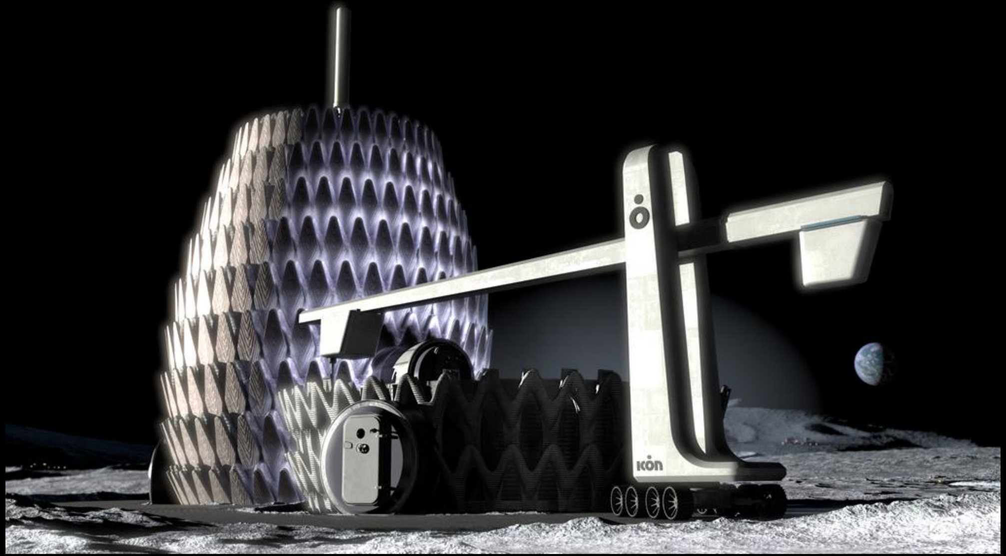
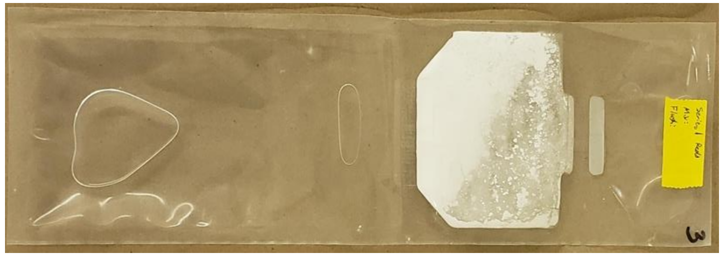
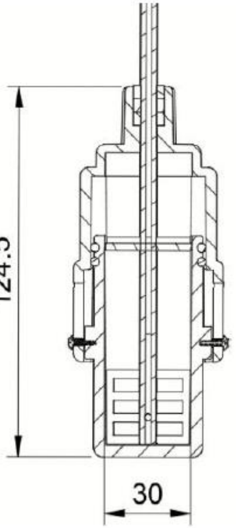


Image courtesy of SEArch+

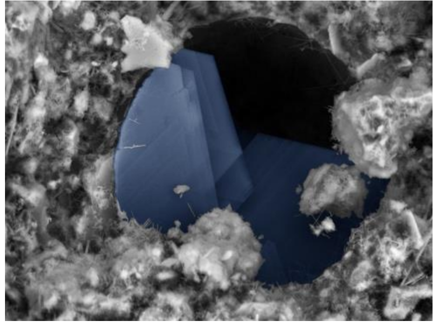
MICS and MASON teams have been collaborating on extraterrestrial concrete since 2020 to advance in-situ resource utilization and develop lunar and Martian binders





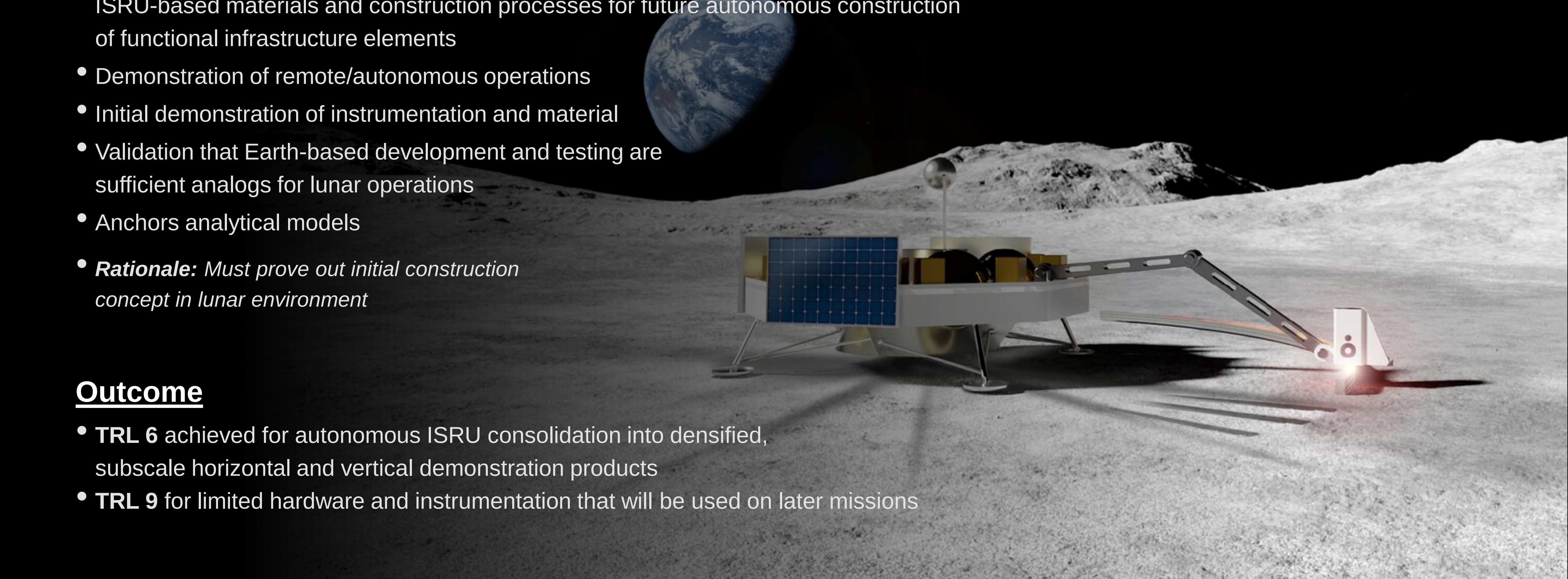
MICS *(Microgravity of Cement Solidification):*
Radlińska, Collins, Grugel, Littles, Edmunson, Fiske

MASON *(Material science on Solidification of cONcrete):*
Sperl, Schnellenbach-Held, Rattenbacher, Tell, Müller, Welsch



- Regularly scheduled scientific workshop featuring the group and external speakers
- Collaboration on hardware development and experimental planning
- Scientific discussions and planned joint publications
- Awaiting official collaboration document signed by NASA and ESA
- Pictures showing German astronauts performing experiments (MICS: Alexander Gerst, MASON: Matthias Maurer)

Initial Candidate Construction Technology Demonstration Mission



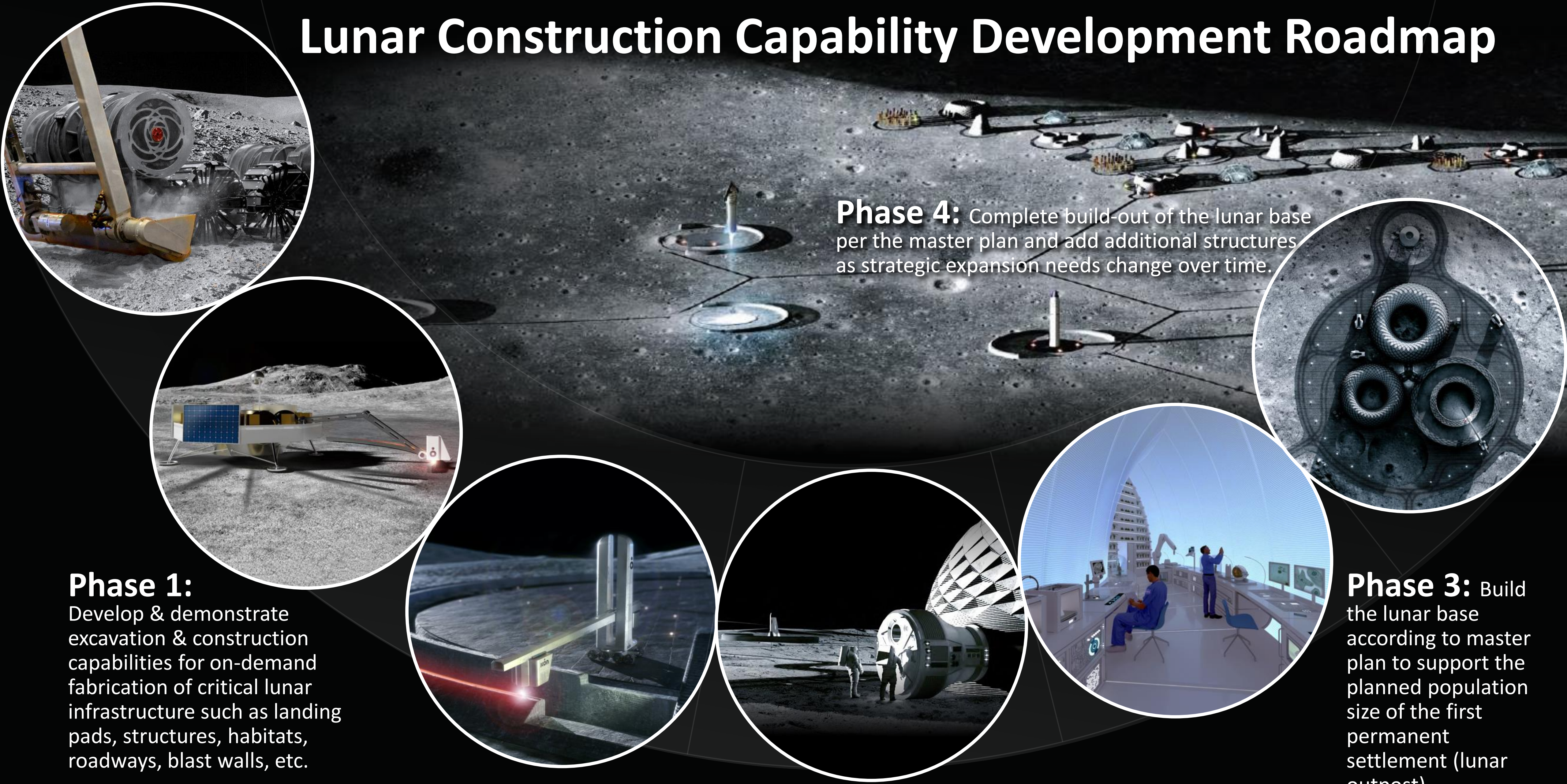
Construction Roadmap

- 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.

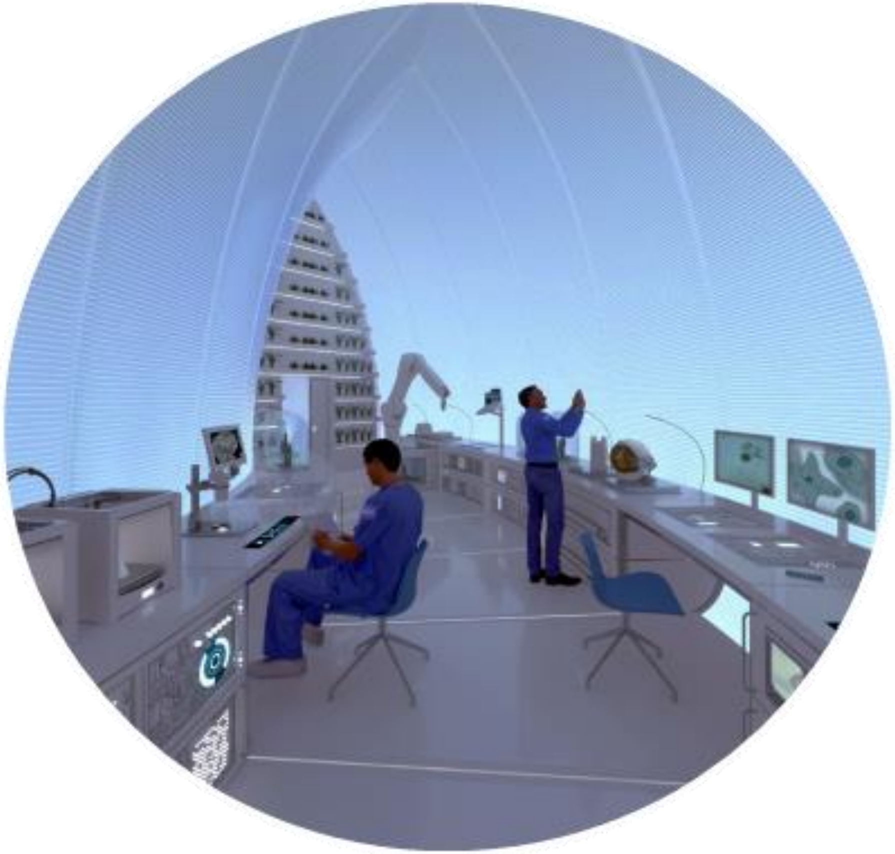
Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.

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



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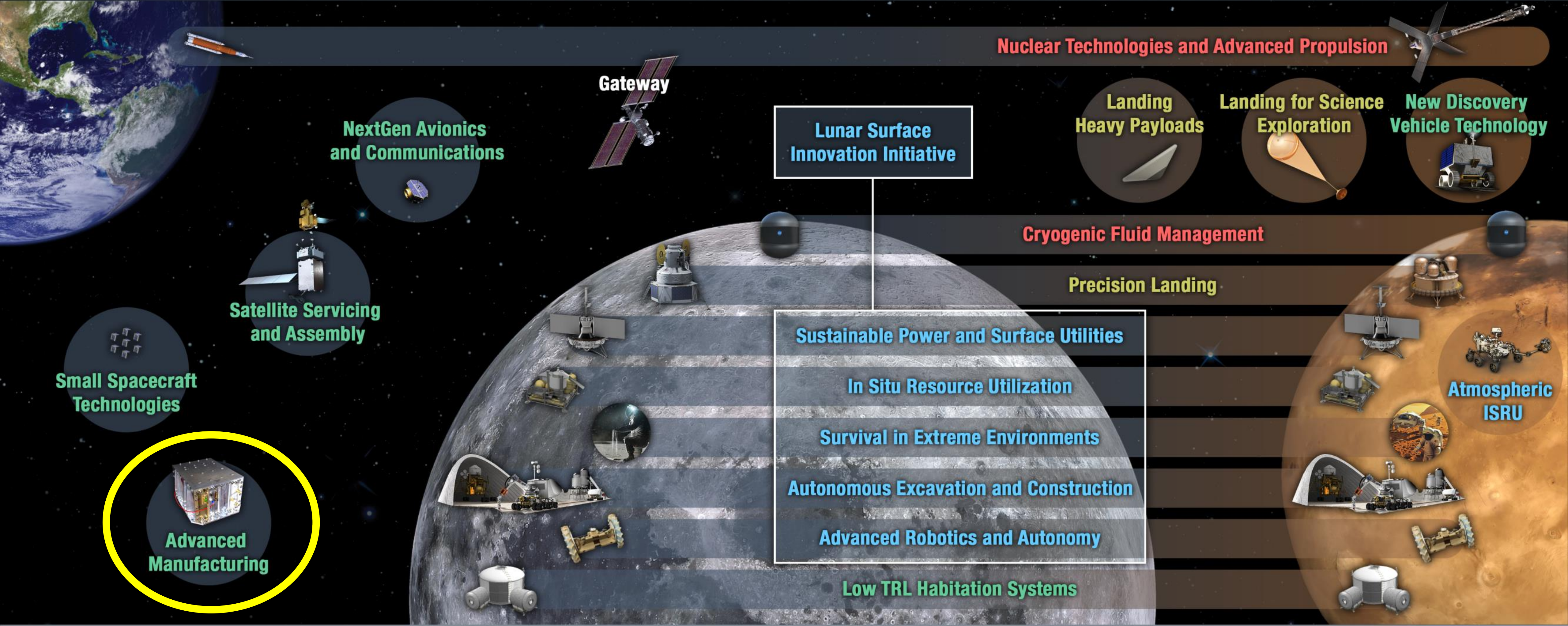

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In-Space Manufacturing Project Portfolio

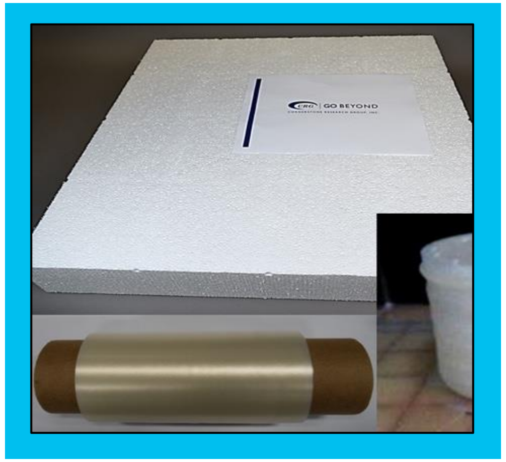
Objective: provide a solution towards sustainable, flexible missions through development of on-demand fabrication, replacement, and recycling capabilities

On Demand Metals Manufacturing

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

Image Courtesy of Made In Space (Redwire)

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. (Redwire)

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

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
- 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

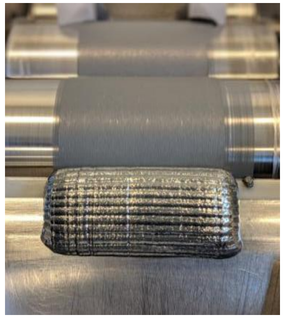
(LEFT) Thermally reversible packaging materials (which can also be used for 3D printing) and (RIGHT) in-process monitoring system for polymer filament production from Cornerstone Research Group (CRG). Images from CRG.

Potential Areas for Future Exploration

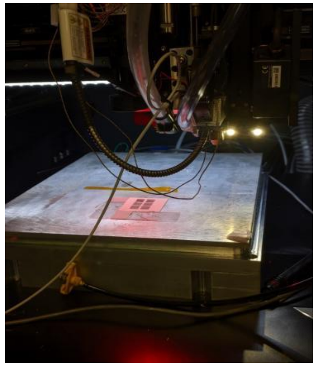
- Metals Recycling
- Sterilization and Sanitization Technologies
- Increased feedstock strength
- Validation and characterization of recycled feedstock
- In Situ Resource Extraction
- Disassembly of multi material products

On-Demand Manufacturing of Electronics (ODME)

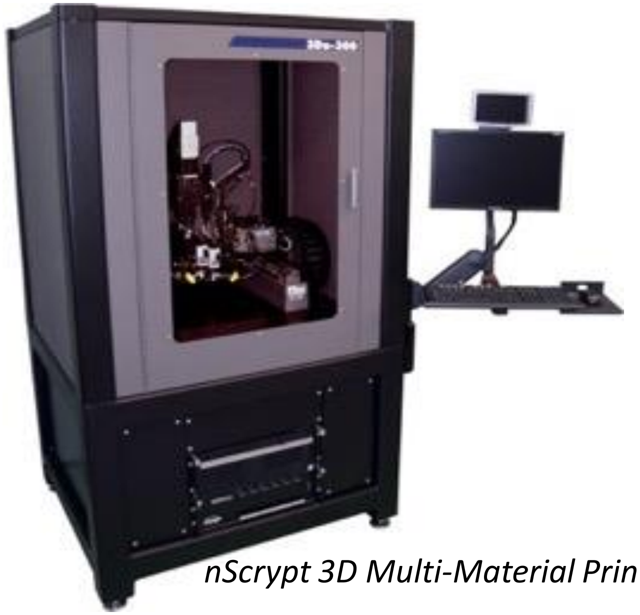
ODME is developing printed electronics, sensors, and power devices for initial testing and demonstration on ISS. In parallel, deposition processes used with printed electronics (direct write and plasma spray) are being matured for future flight demos.



Development of electronic inks



Development of laser sintering process

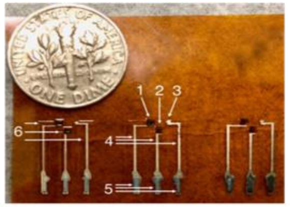


nScrypt 3D Multi-Material Printer

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

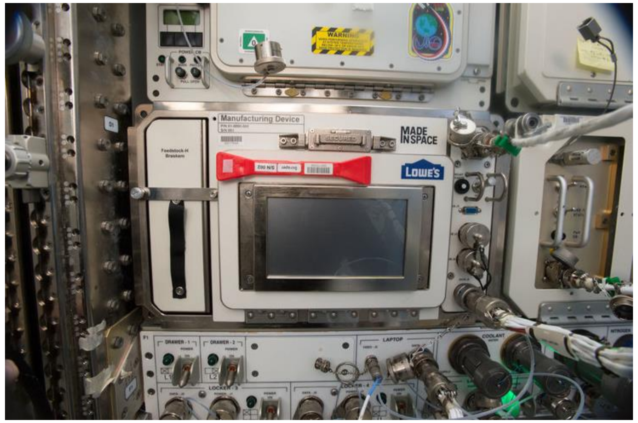


Printed cortisol (stress) sensor. Image from California Institute of Technology.

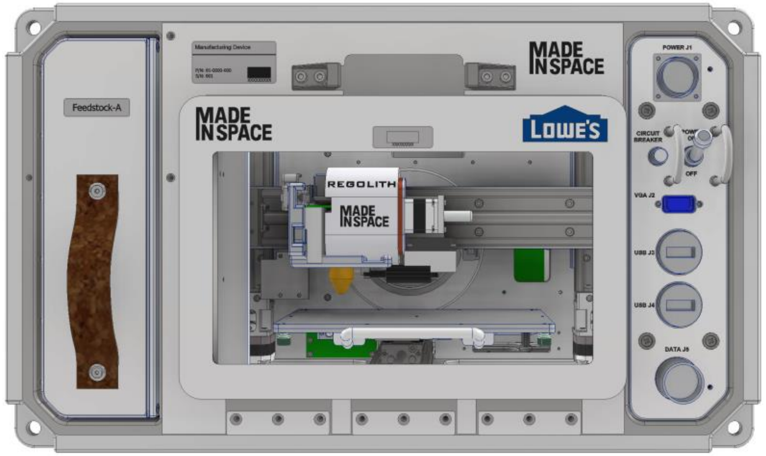
1st Generation Personal CO_2 Monitor

3D Printing and In Situ Resource Utilization (ISRU): Redwire Regolith Print (RRP)

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



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



A previously flown version of AMF was modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.

- Launched 8/10/21
- Prints experienced off-nominal operations on ISS.
- RRP returned to Earth

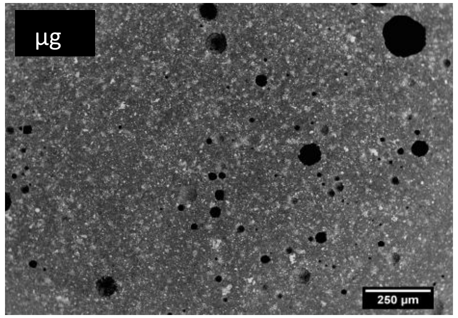
Printing (top) and testing (bottom) of a compression cylinder with a regolith simulant/polymer feedstock.

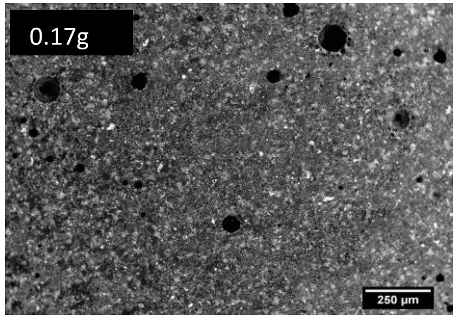
Penn State Microgravity investigations of cements and geopolymers for lunar infrastructure

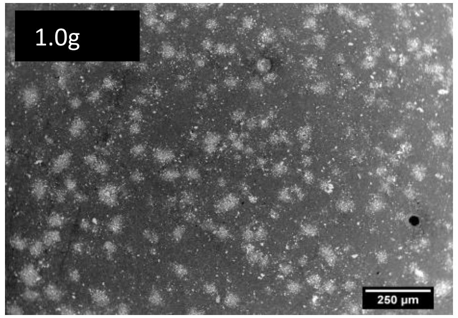
Microgravity Investigation of Cement Solidification (MICS) was a first step towards producing durable lunar infrastructure

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

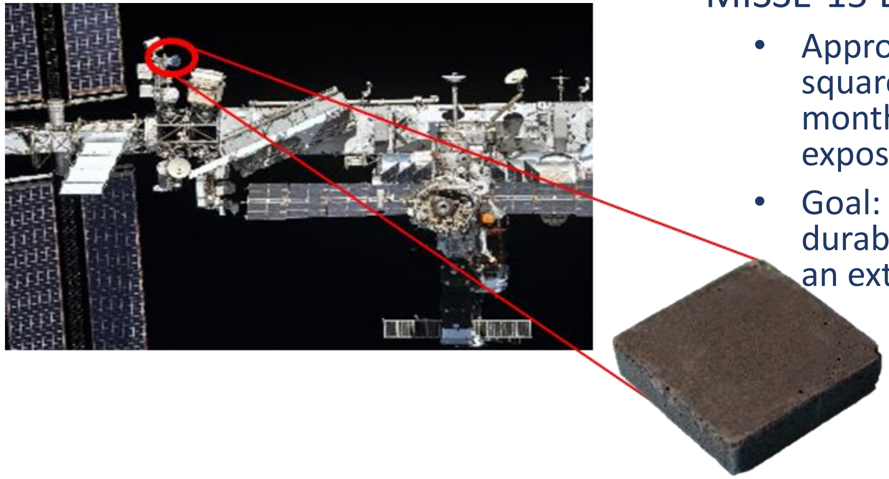






Gravity Level	Porosity (%)
10^{-6}	17.7
0.17	16.6
0.38	13.1
0.70	12.7
1	8.2

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

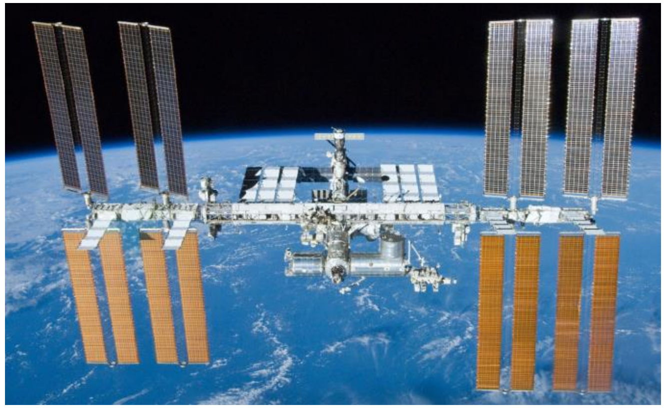
- Microgravity Solidification Experiment
  - Approach: Similar experimental setup as the Microgravity Investigation of Cement Solidification (MICS) project
  - Goal: Understanding how the reduction in gravity influences the solidification

PennState

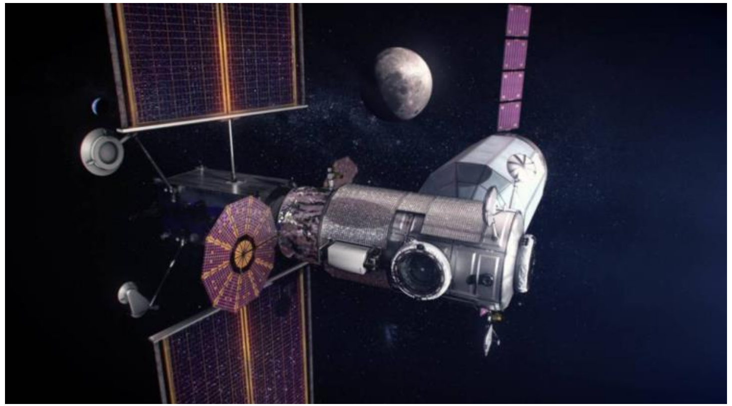
Images courtesy of Dr. Aleksandra Radlinska and Peter Collins

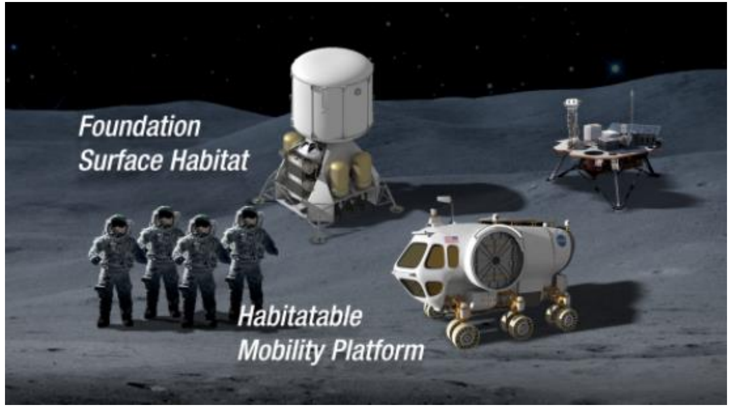
The Vision of Space Sustainability

Manufacturing in space is a destination-agnostic capability with clear mission benefits beyond low earth orbit. Cargo resupply opportunities are limited or nonexistent. These technologies are key enablers for sustainable space exploration.



DEMONSTRATE: *ISS is the testbed for ISM.*





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

INSTITUTIONALIZE: *"Houston, we have a solution."*

www.nasa.gov/spacetech

BACK-UP

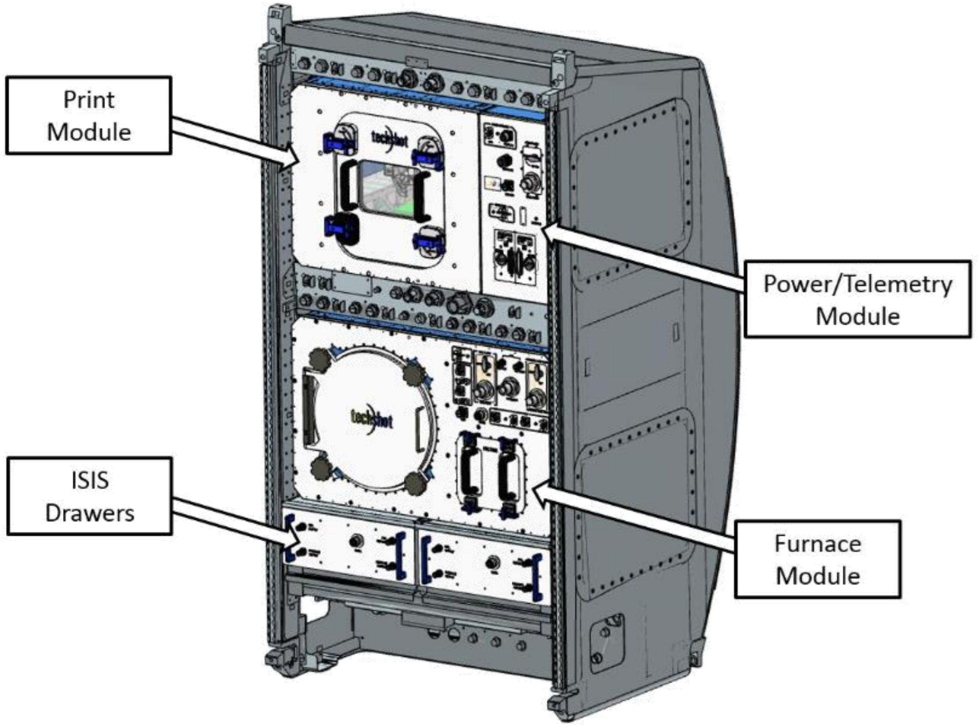
In Space Manufacturing: ODMM

Techshot Fabrication Laboratory (FabLab):

Goal: The Techshot FabLab aims at maturing a bound metal deposition system capable of producing Ti64 components in space providing a pioneering approach to enable sustainable and affordable exploration operations and logistics.

Background:

- Bound metal deposition technology
  - A paste or filament is used to print a “green” part
  - Astronaut transfers “green” part to furnace chamber. Furnace combines a low temp thermal debind to remove binder and a high temperature sinter procedure to consolidate material
  - Finishing milling completes high precision features
- Started under AES with a NextSTEP BAA
  - Result: ground-based prototype manufacturing facility that printed, debound, and sintered Ti64 parts from a paste feedstock.



In Space Manufacturing: ODMM

Vulcan from Redwire:

Goal: The Vulcan System aims at maturing a Wire+Arc Additive Manufacturing (WAAM) system capable of producing aluminum components in space providing a pioneering approach to enable sustainable and affordable exploration operations and logistics.

Background:

- WAAM Technology
  - Creates near-net-shape part using a MIG type process
  - Final geometry machined from the primitive.
  - Reduced argon flow minimizes consumables

- Started under the SBIR project and completed a Phase I, II, and II-E.
  - Result: ground-based prototype of critical systems and demonstration of manufacturing using Al4043 welding wire.

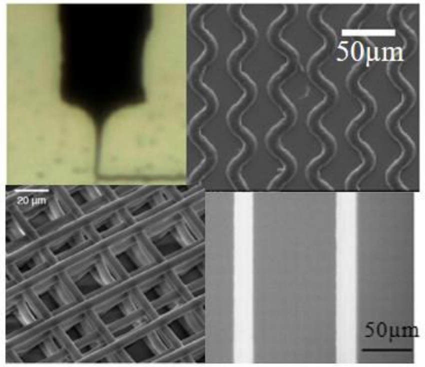
Vulcan prototype system. Image credit: Redwire

EDU Vacuum Chamber. Image credit: Redwire

In Space Manufacturing: ODME

Development of Thin Film Deposition Capability in Microgravity

- Objective: Evaluate alternate thin film deposition systems for use in microgravity.
- Threshold: 300 microns resolution (minimum printable feature size)
- Goal: 100 micron or better resolution.
- Current State-of-the-Art (SOA) of printed resolution of electronic materials is between 30 and 50 microns for analogous ground-based processes.



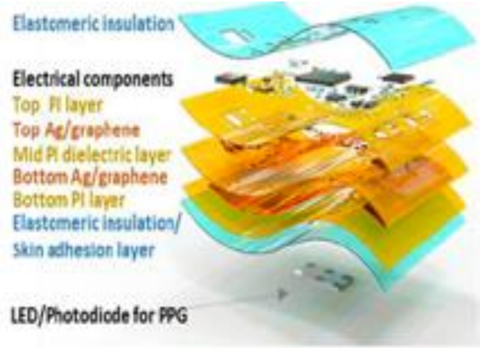
Electrohydrodynamic inkjet deposition for microgravity

Development of Multilayer Technology for Microgravity

- Objective: Develop materials, processes, and hardware necessary for the stacking of circuitry layers of printed electronics.
- Threshold: fabricate single layer printed “board” in microgravity
- Goal: fabricate multi-layered electronic devices in microgravity

Development of Validation and Verification In-Situ Capability for Flight Demo

- Objective: Develop test procedures, software, and hardware to test function and operation of the ODME printed flight demo on ISS.
- Two-year project to develop and evaluate optimum methods, hardware, and integration to the 3D printer operation, in order to effectively validate the operation of flexible hybrid electronics sensors and devices.

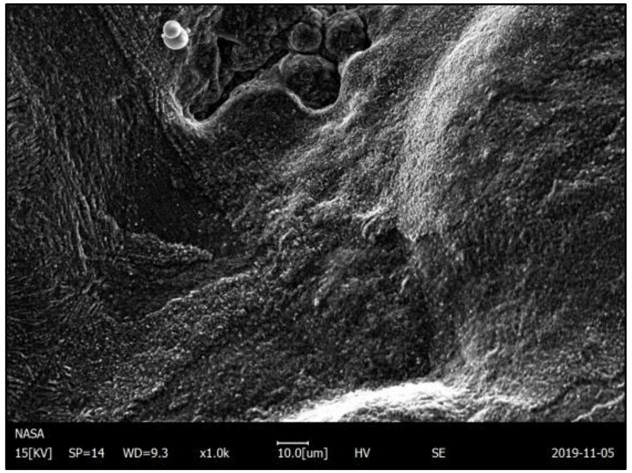


Multilayer thin film printed device

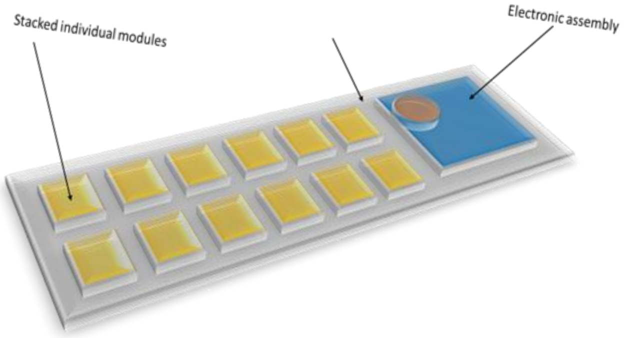
In Space Manufacturing: ODME

Sensor & process/materials development development at MSFC

- Development of post-processing processes.
  - Evaluating laser sintering, photonic sintering, and UV curing.
- Development of materials and processes for printing of electronics and sensors
- Testing and verification of sensors, printed devices from collaboration partners.
- Materials development and printing support to our various collaboration partners.
- Leading center for the development of printed power generation and energy storage technologies.
- MSFC ODME provides the planning and project direction for other NASA ODME groups and collaboration partners



Laser sintered Ti64



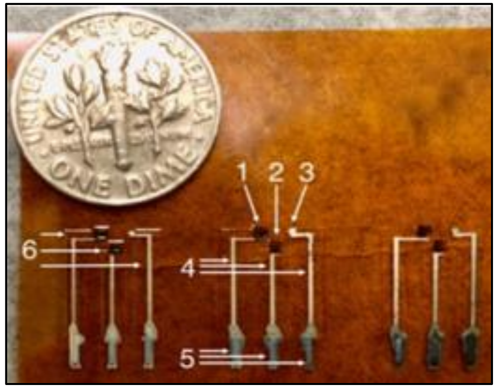
Flexible, printed thermoelectric for power generation

nScrypt Multimaterial 3D printer

In Space Manufacturing: ODME

Sensor development at Ames Research Center

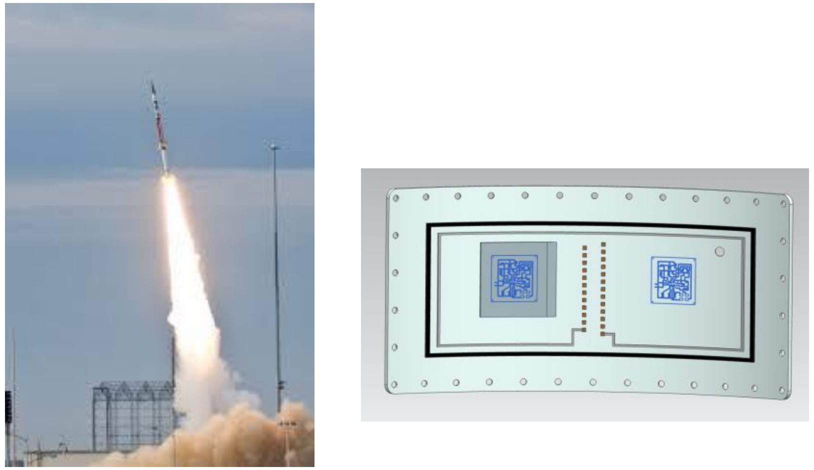
- Two groups at ARC working ODME project:
  - Biosensor development for printed cortisol and other wearable biosensors
  - The other group develops the technology for environmental sensors as well as supporting the development of energy and power applications.



Printed cortisol sensor

ODME development at Goddard Space Flight Center

- GSFC ODME group is leading the Sounding Rocket test flight development effort
- Their ODME and Power groups are evaluating flexible batteries for the wearable sensor devices



Sounding Rocket test flight

In Space Manufacturing: RnR

Goal: Develop and demonstrate recyclable packaging materials and recycling technology in a microgravity environment.

Why? The current logistics model is unsustainable for long duration space missions. Recycling and reuse has the potential to reduce mass, increase mission flexibility, provide a path towards sustainable on demand manufacturing.

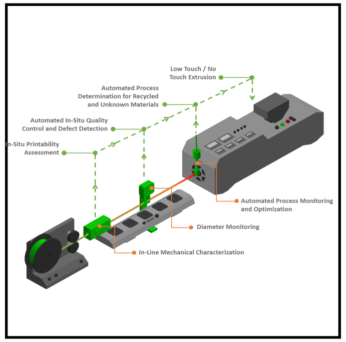
Technology Product Capability

- Developing and demonstrating recycling and in-situ resource manufacturing technologies for NASA Exploration Missions. This includes testing & advancing the desired technologies, as well as establishing the required skills & processes for the processes that will enable the technologies to become institutionalized.

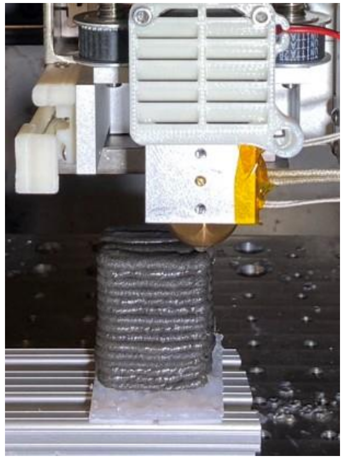
Technical Capabilities

- Development of Recyclable Packaging Materials and Processes
- Development of In-Process Monitoring technologies for filament feedstock production
- Demonstration of regolith/polymer blend printing on orbit
- Demonstration of a closed-loop recycling ecosystem of flexible thermoplastic polyurethane material

Recyclable Packaging Materials Image Courtesy **of Cornerstone Research Gr**oup



In Process Monitoring Suite Image Courtesy of Cornerstone Research Group



Regolith Polymer Printing Image Courtesy of Redwire

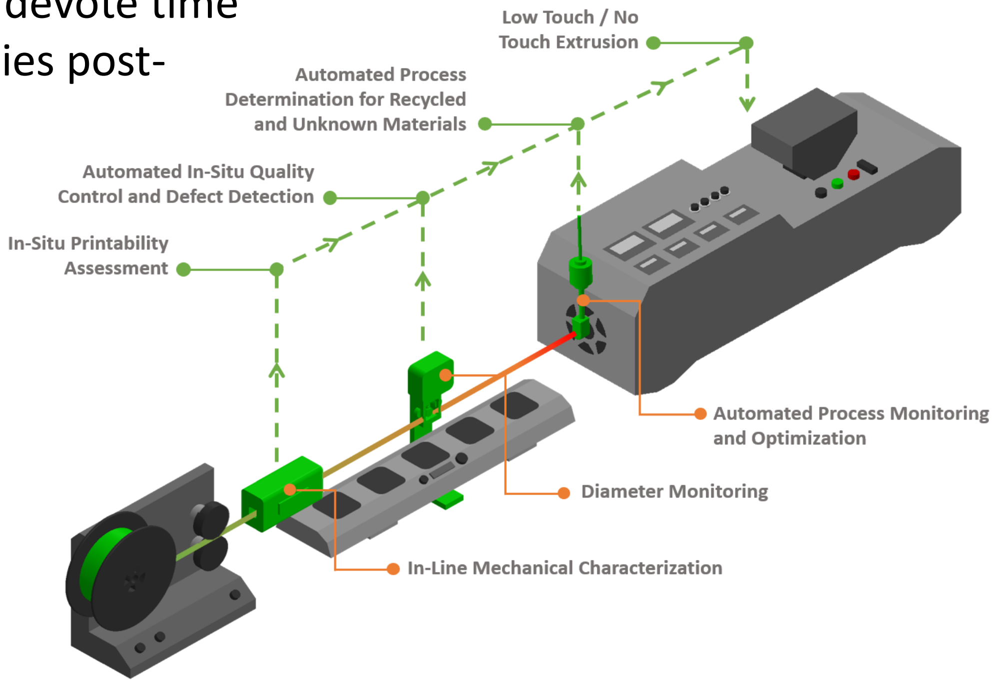
In Space Manufacturing: RnR

Goal: Develop a suite of tools that can feed data back to control an extruder leading to filament production with a consistent diameter within a tight threshold.

Why: Astronauts challenged with critical mission success will be unable to devote time to ensure high-quality filament. Additionally, inconsistent filament properties post-recycling can lead to poor filament diameter control.

In Process Monitoring

- Wound down a two-year effort with Cornerstone Research Group (CRG) to develop an in-process monitoring system for polymer filament production. (Completed August 2021)
- Demonstrated successful closed loop feedback control of the polymer extrusion process.
- Integrated diameter measurement capabilities with extrusion controller.
- Accurate and precise measurements of filament over extended periods were achieved.
- 2.5 lbs. of RVT and 0.8 lbs. of polycarbonate filament were produced.



In Process Monitoring Suite Image Courtesy of Cornerstone Research Group

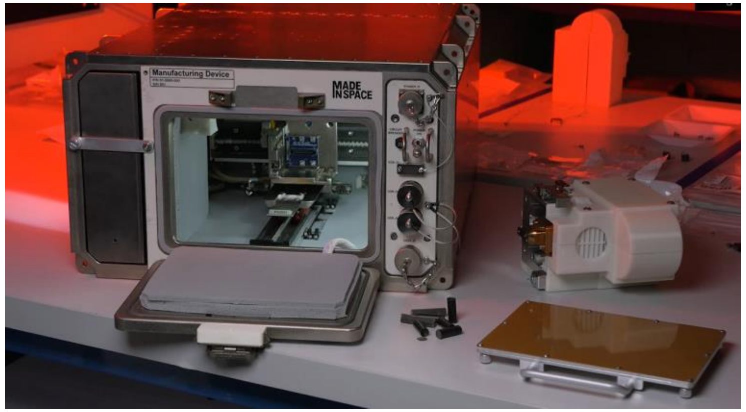
In Space Manufacturing: RnR

Goal: Demonstrate polymer/regolith simulant blend printing on station.

Why: As people move beyond low-Earth orbit to other celestial bodies the need for in-situ resource utilization for the fabrication of habitats will be necessary.

Redwire Regolith Print (RRP):

- Developed concept of operations, systems requirements, specimen matrix for flight and ground-based printing for technology demonstration mission, assembly of new print heads and print beds for the additive manufacturing facility (AMF), and development of linear low-density polyethylene/regolith simulant blend.
- Launched 8/10/2021
- Anomalies seen on orbit.



The Redwire Regolith Print facility suite, consisting of Redwire's Additive Manufacturing Facility, and the print heads, plates and lunar regolith simulant feedstock that will be launching to the International Space Station.
Image Credit: Redwire Space, Inc

3D Printing of regolith-based feedstock material.
Image credit: Made in Space.

In Space Manufacturing: Summary

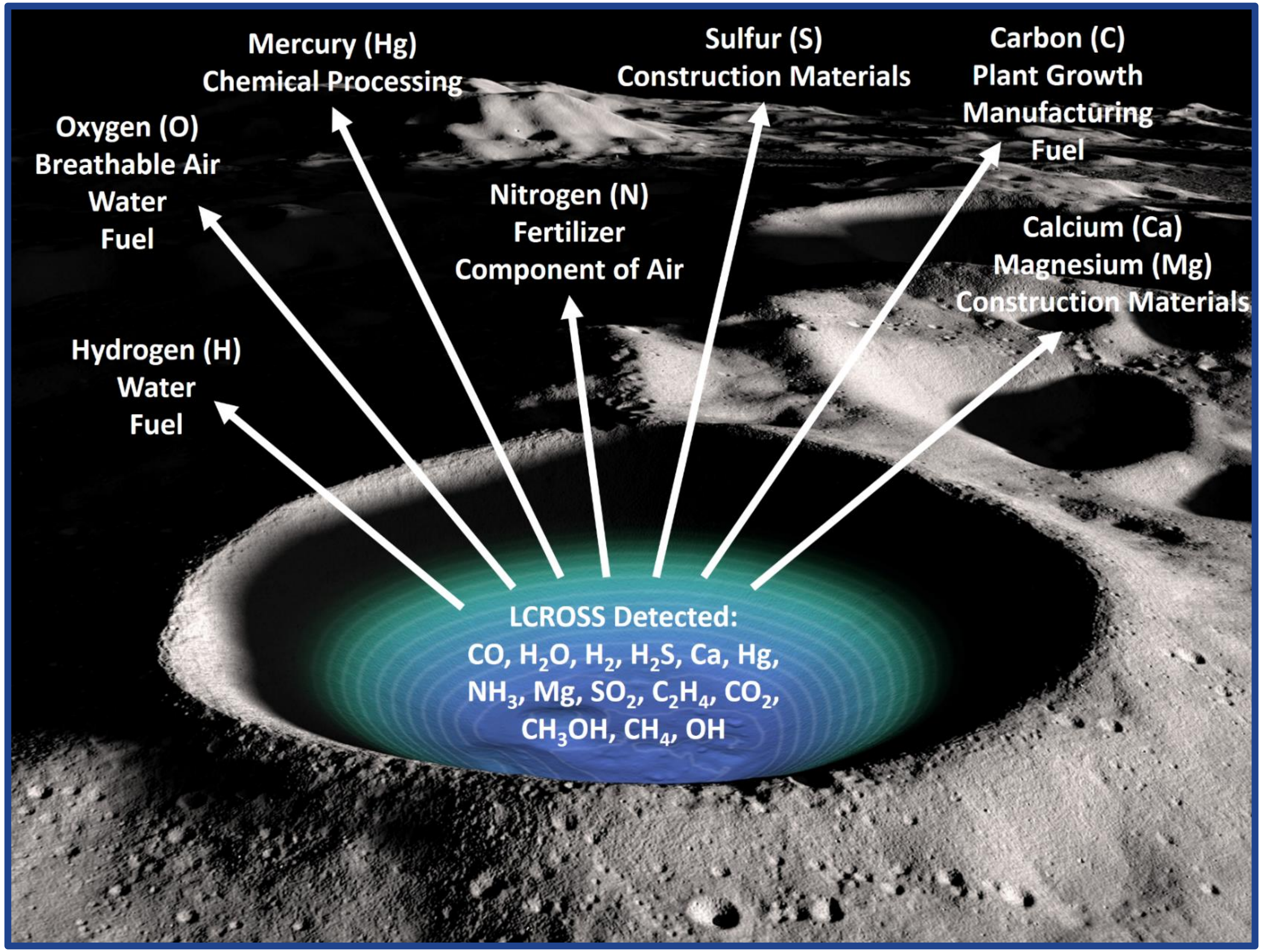
The technologies developed by ISM are just the beginning.

Support technologies need to be developed:

1. Geometric Inspection
2. Volumetric Inspection
3. Mechanical Characterization
4. Cleaning Procedures
5. Post Processing Techniques
6. Standards for In Space Manufacturing (or implementation of existing standards)

Leveraging Lunar Resources

Lunar CRater Observation and Sensing Satellite (2009)



Mercury (Hg)
Chemical Processing

Sulfur (S)
Construction Materials

Carbon (C)
Plant Growth
Manufacturing
Fuel

Oxygen (O)
Breathable Air
Water
Fuel

Nitrogen (N)
Fertilizer
Component of Air

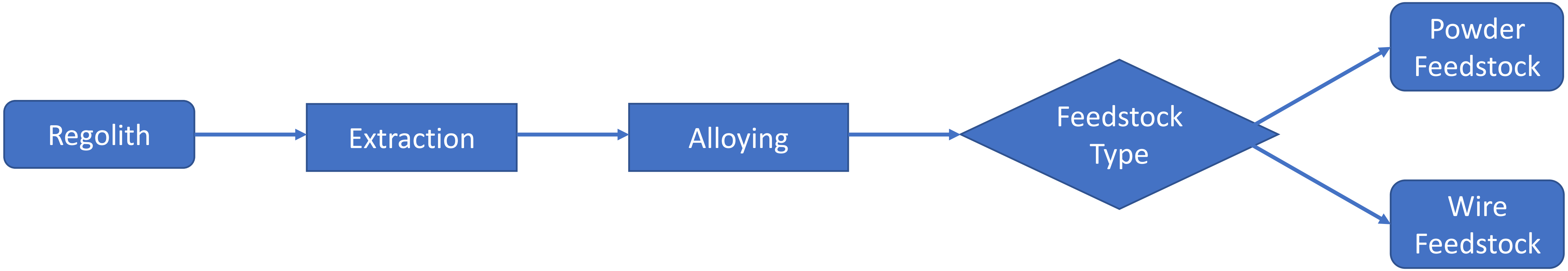
Calcium (Ca)
Magnesium (Mg)
Construction Materials

Hydrogen (H)
Water
Fuel

LCROSS Detected:
CO, H_2O, H_2, H_2S, Ca, Hg, NH_3, Mg, SO_2, C_2H_4, CO_2, CH_3OH, CH_4, OH

ISRU/ECO - Technology Gaps

- Extraction of elements/compounds from regolith on an industrial scale
- Conversion of extracted elements/compounds into manufacturing or construction precursors (e.g., metal alloys, cement components)
- Production of usable manufacturing or construction feedstock (e.g., creating metal microspheres for powder bed fusion, metal wire for free form fabrication, or combining cement components into cement)



ISRU – In-Situ Resource Utilization. ECO – Excavation, Construction, and Outfitting.

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