National Aeronautics and Space Administration

Lunar Research for Advanced Manufacturing

R. G. Clinton, Jr., PI, Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT)
Physical Sciences Lunar Surface Science Workshop
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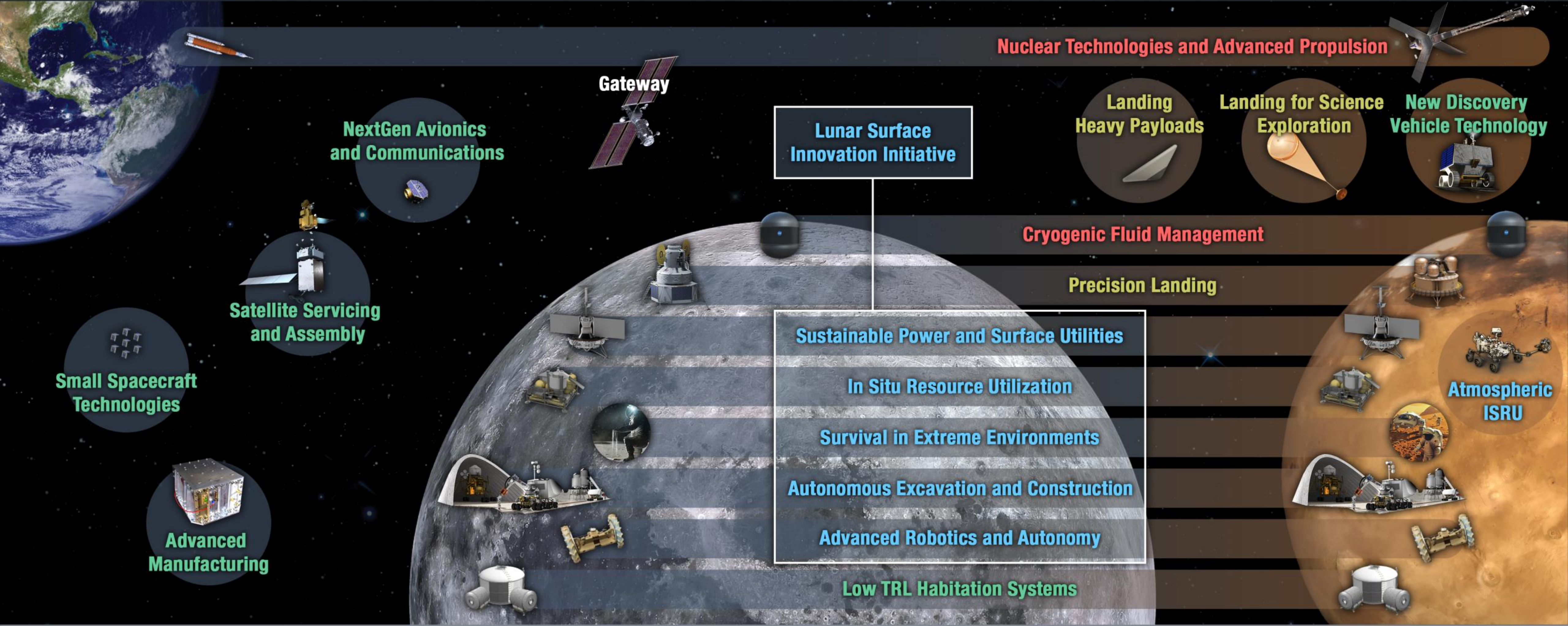
Agenda

- Space Technology Mission Directorate: Technology Drives Exploration
  - Advanced Manufacturing
    - In Space Manufacturing (ISM) – Portfolio and Challenges
  - Lunar Surface Innovation Initiative (LSII)
    - Excavation, Construction, and Outfitting (ECO)
    - Penn State University experiments with Geopolymers and Cement in Microgravity
    - In Situ Resource Utilization (ISRU)
- Questions

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

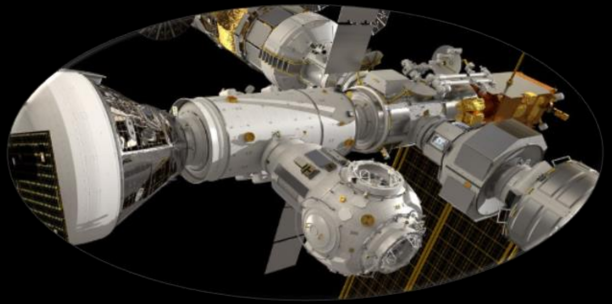


2020 GO | LAND | LIVE | EXPLORE 203X

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

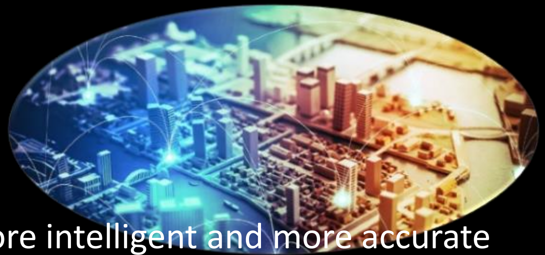
IN-SPACE SPARES AND REPAIRS

- **> 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.

In-Space Manufacturing Project Portfolio

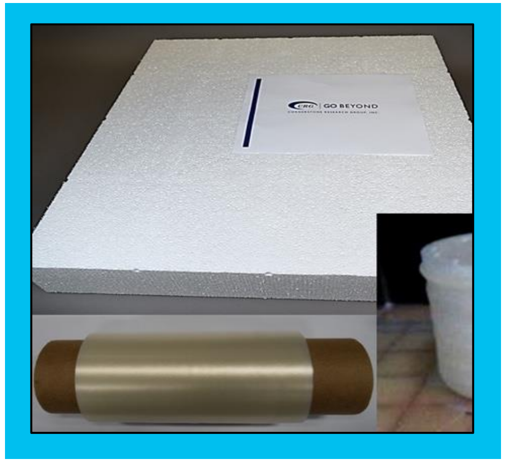
Objective: provide a solution towards sustainable, flexible missions through development of on-demand fabrication, replacement, and recycling capabilities

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

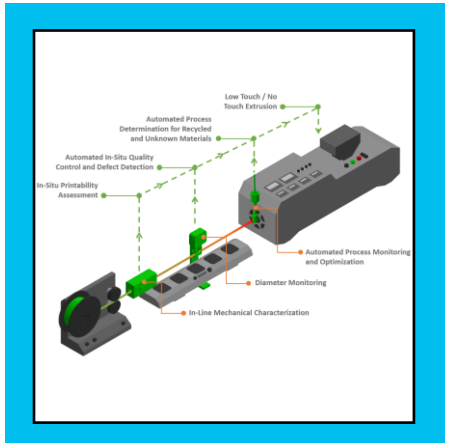
One of the pre-eminent ISM challenges is verification of parts produced on-orbit or on the lunar surface.

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



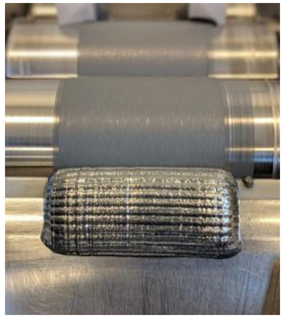
(LEFT) Thermally reversible packaging materials (which can also be used for 3D printing) and (RIGHT) in-process monitoring system for polymer filament production from Cornerstone Research Group (CRG). Images from CRG.

<u>Potential Areas for Future Exploration</u>

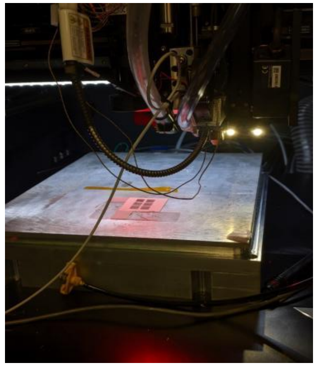
- Metals Recycling
- Sterilization and Sanitization Technologies
- Increased feedstock strength
- Validation and characterization of recycled feedstock
- In Situ Resource Extraction
- Cleaning Technologies (esp. food packaging)
- Disassembly of multi material products

On-Demand Manufacturing of Electronics (ODME)

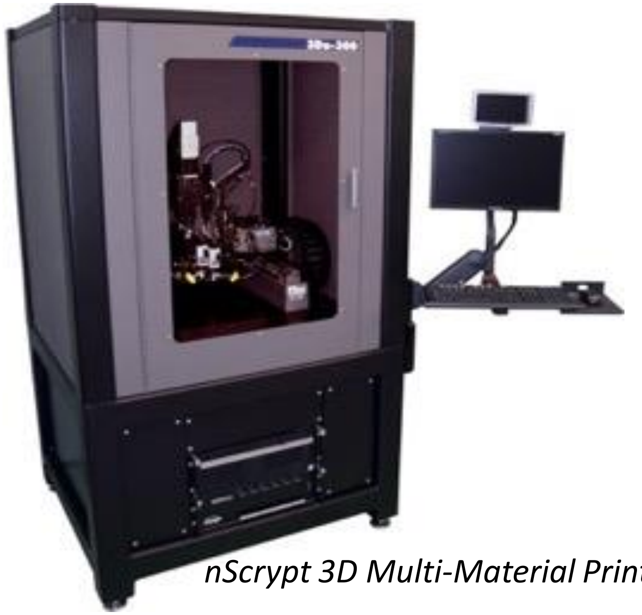
ODME is developing printed electronics, sensors, and power devices for initial testing and demonstration on ISS. In parallel, deposition processes used with printed electronics (direct write and plasma spray) are being matured for future flight demos.



Development of electronic inks



Development of laser sintering process



nScrypt 3D Multi-Material Printer

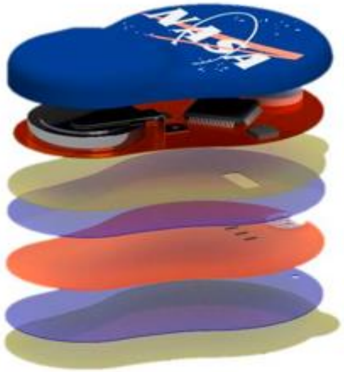
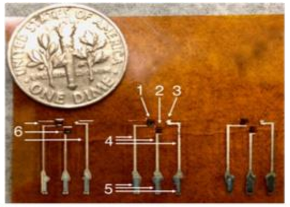


Diagram of AstroSense next-generation flexible, wireless, multi-sensor printed device for crew health monitoring. Image from Nextflex.

Development of photonic sintering process

Dimatix inkjet thin film printer

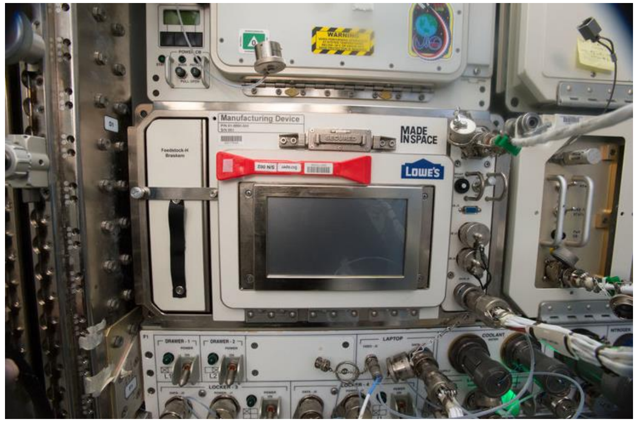


Printed cortisol (stress) sensor. Image from California Institute of Technology.

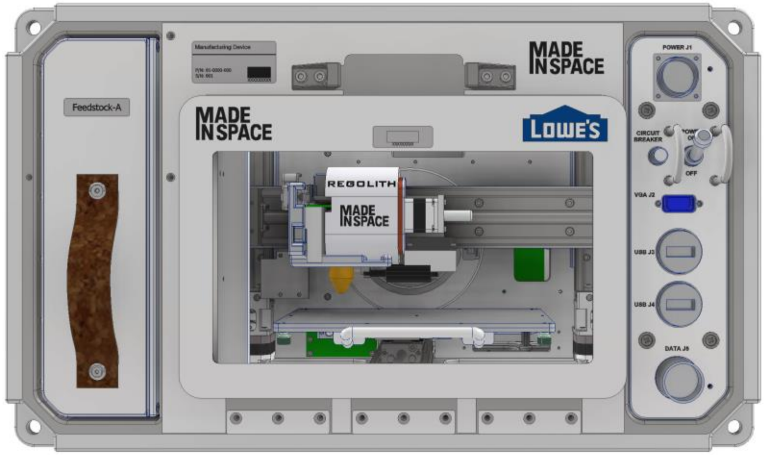
1st Generation Personal CO_2 Monitor

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).

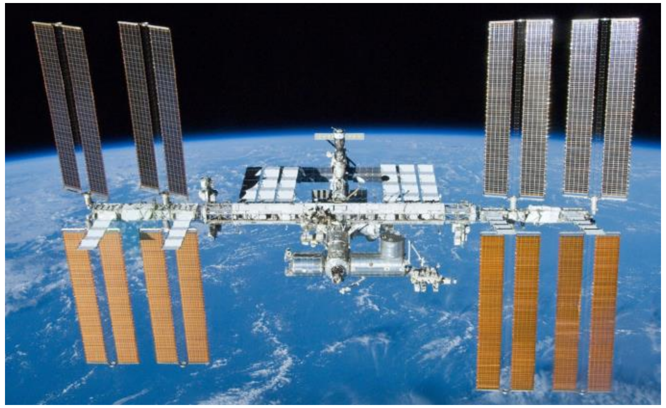


In this effort, a previously flown version of AMF will be modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.

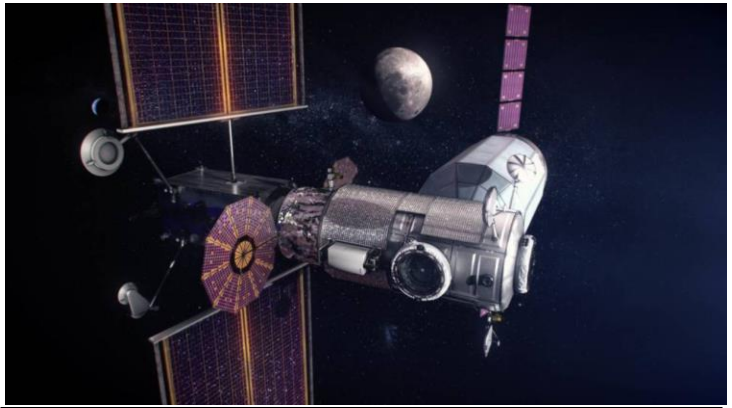
Printing (top) and testing (bottom) of a compression cylinder with a regolith simulant/polymer feedstock.

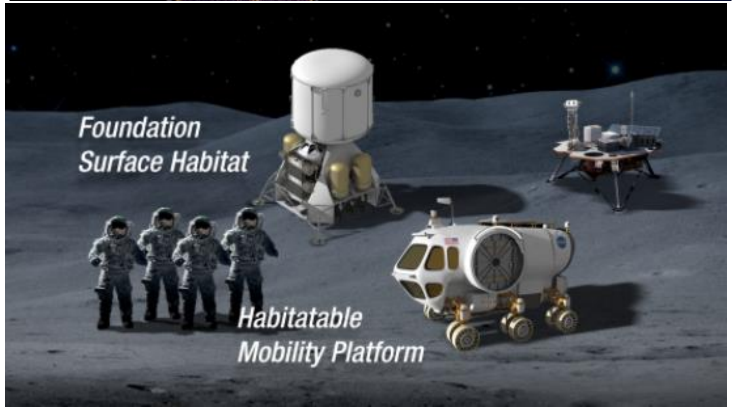
The Vision of Space Sustainability

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.

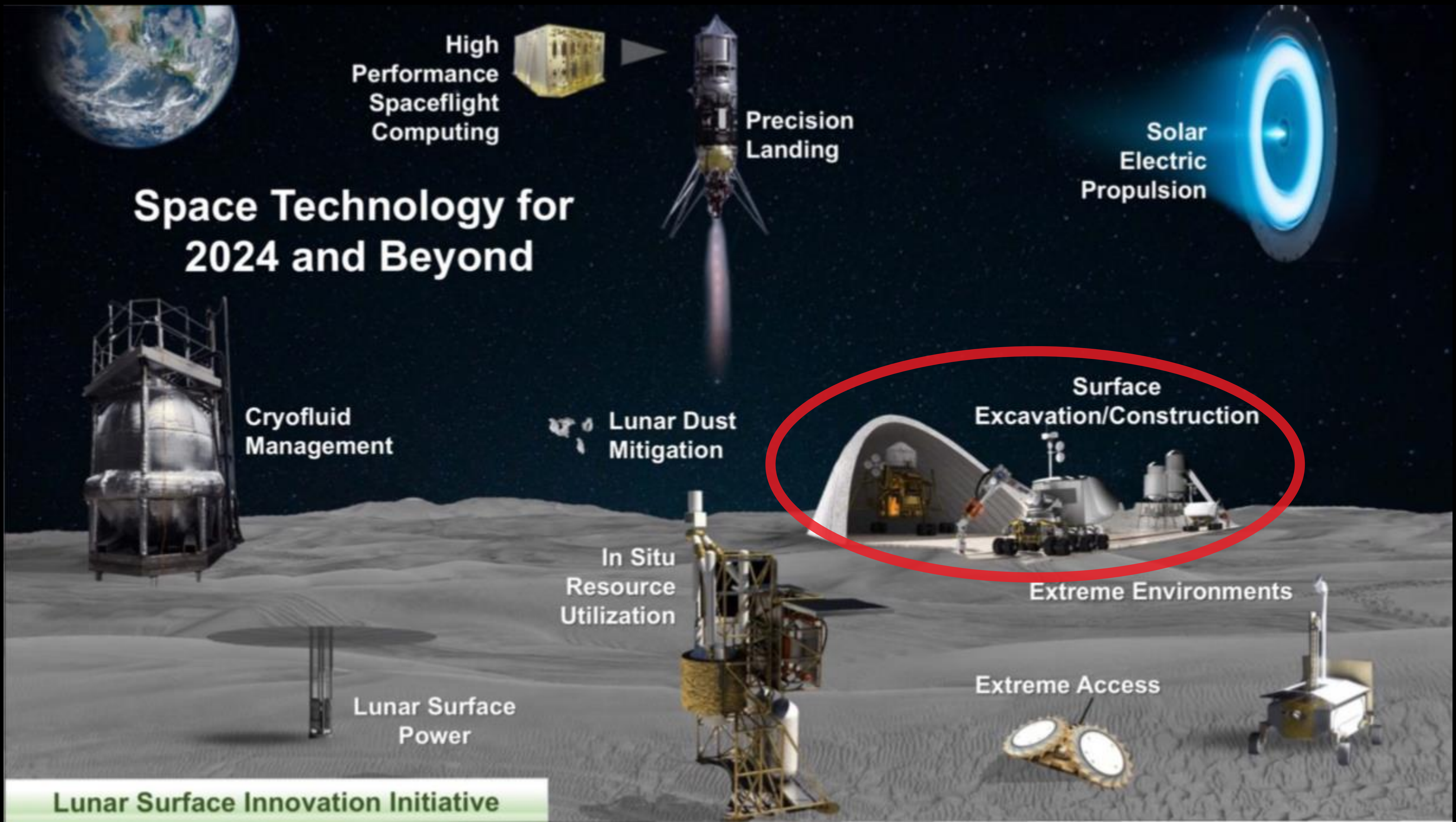




ISM capabilities demonstrated on ISS are applicable to Gateway and the lunar surface.

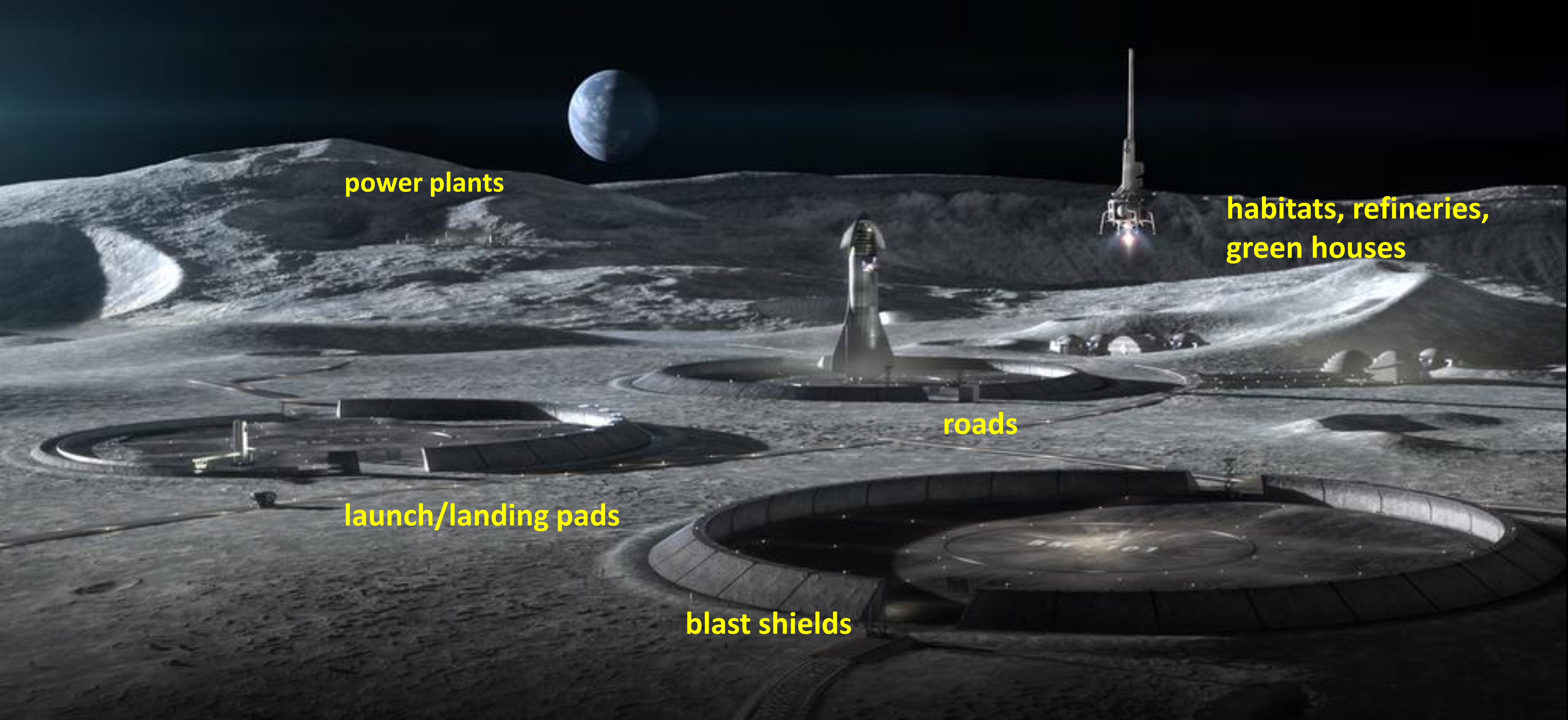
"Houston, we have a solution."

NASA Lunar Surface Innovation Initiative (LSII)



Building a Sustainable Presence on the Moon

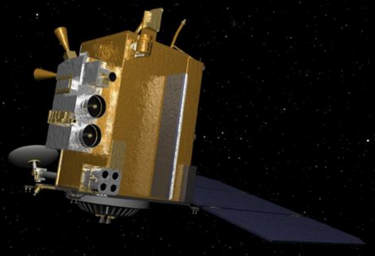
- What infrastructure are we going to need?

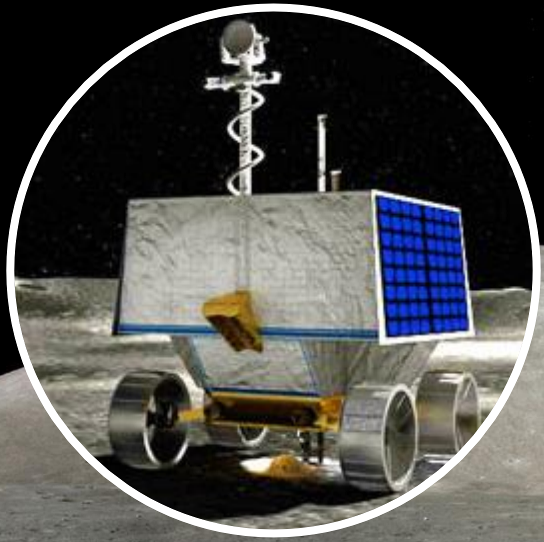


In-Situ Construction: *Finding and Excavating the Resources*

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

Unique Challenges

- Reduced gravity and low reaction forces
- Abrasive materials lead to significant component wear
- Health monitoring and repair strategies
- Autonomy

Autonomous Construction for the Lunar Outpost

Regolith-based Materials and Processes:

- Cementitious
- Geopolymers
- Thermosetting materials, including melting
- Laser sintered
- Microwave sintered

High Level Capability Gaps and Challenges

- Regolith excavation, beneficiation, transfer, and conveyance
- Deposition processes and associated materials
- Increased autonomy of operations
- Long-duration operation of mechanisms and parts under lunar environmental conditions (Reliability and Maintainability)
- Scale of construction activities
- Structural Health Monitoring and Repair
- Inspection and Certification of as-built structure
- Interdependencies on other infrastructure capabilities
- Material and construction requirements and standards

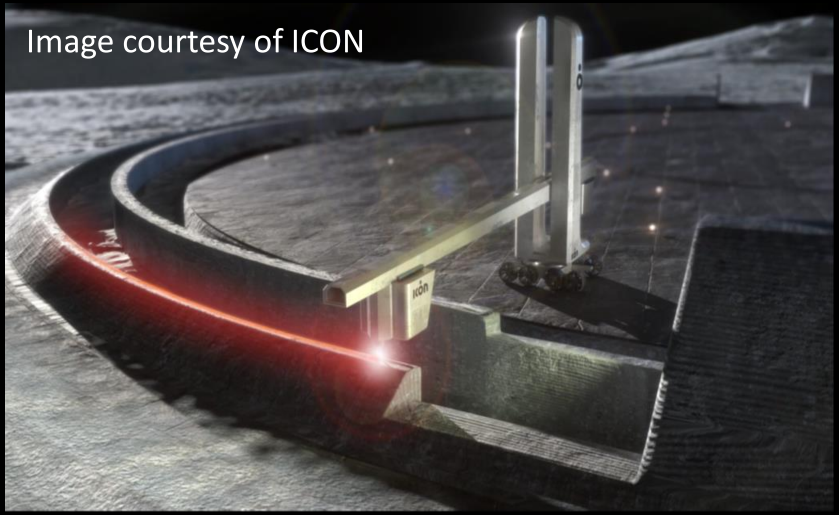


Image courtesy of ICON

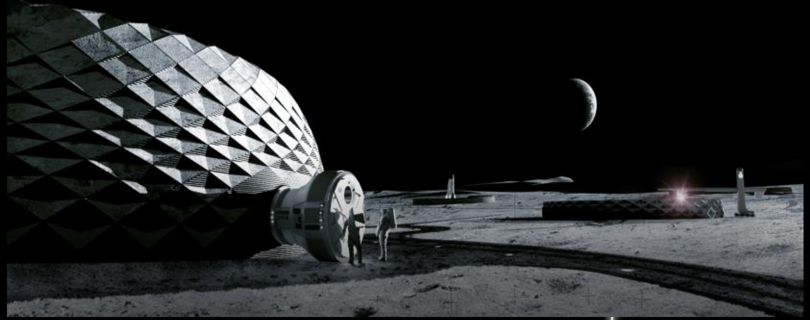


Image courtesy of Bjarke Ingels Group

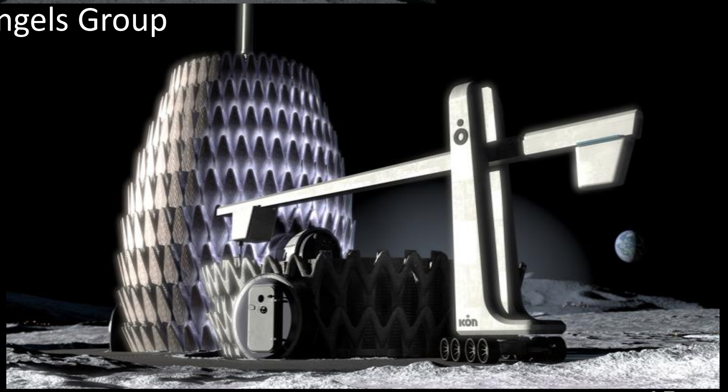
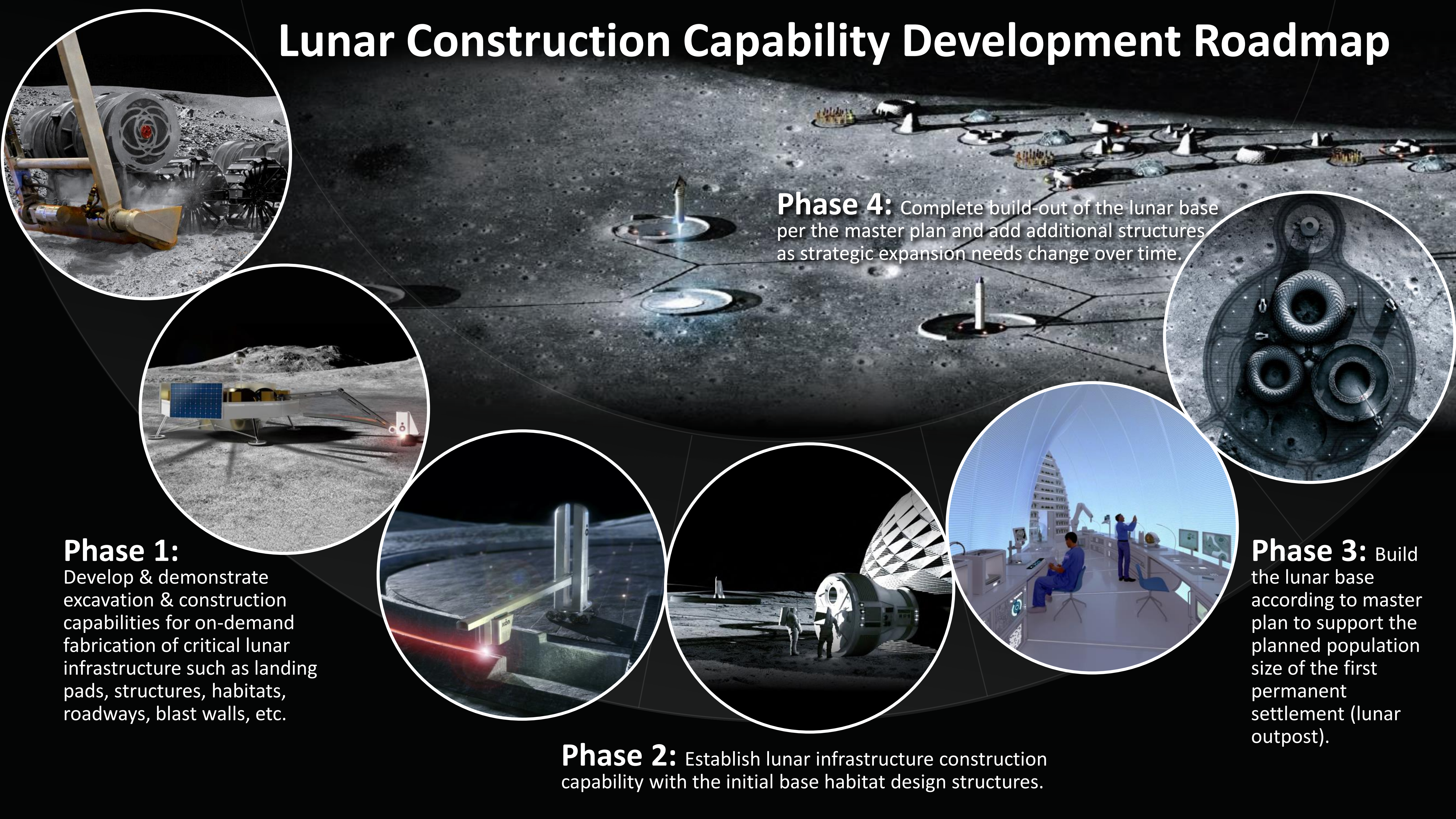
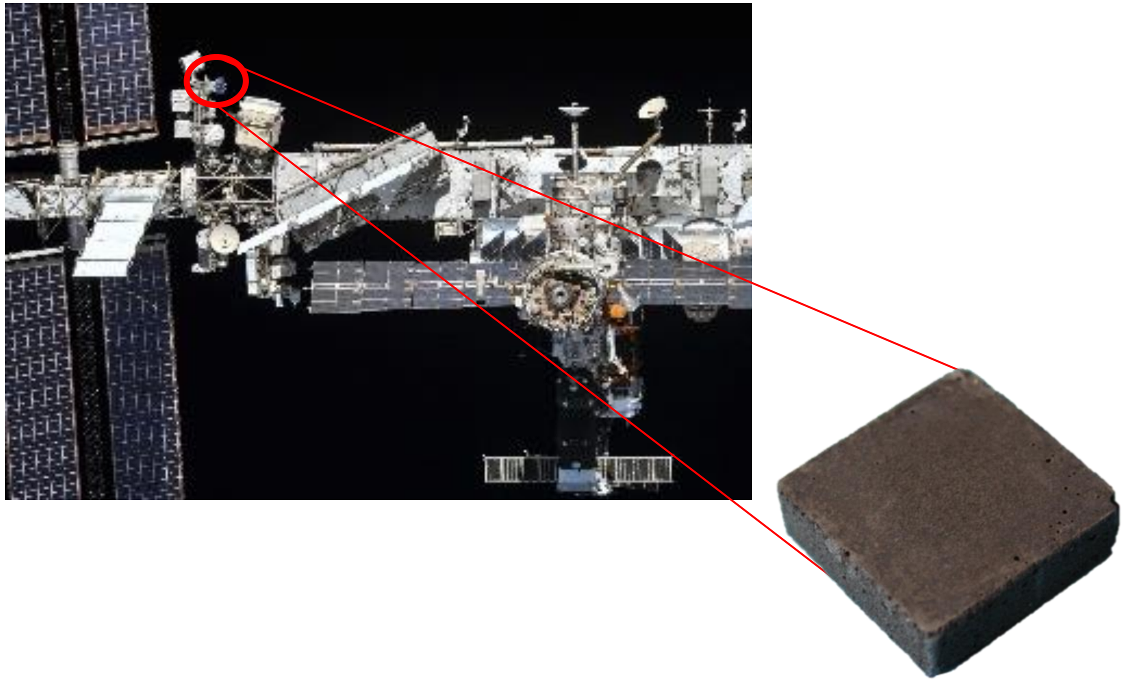


Image courtesy of SEArch+


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.

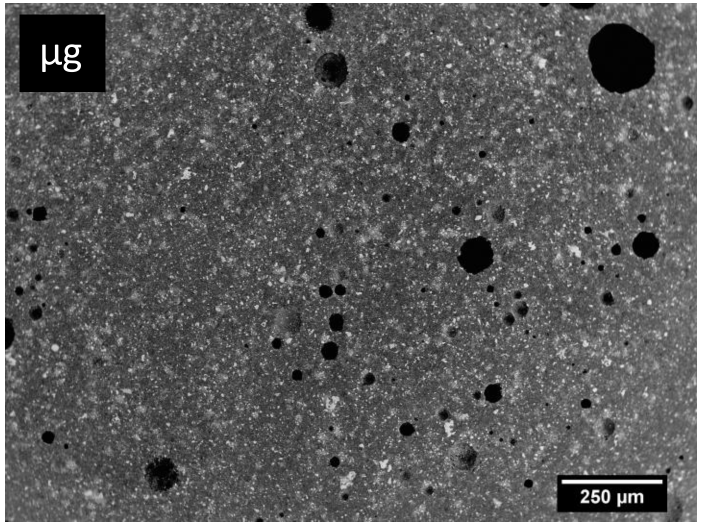
Assessment of LEO variables on an in-situ geopolymer lunar concrete

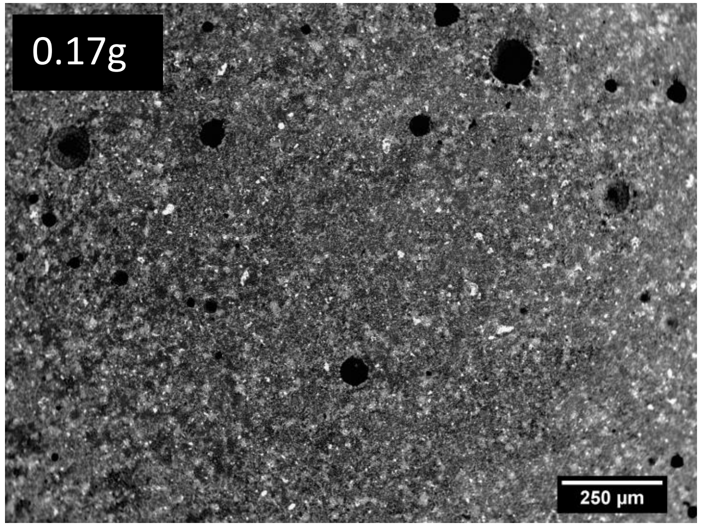


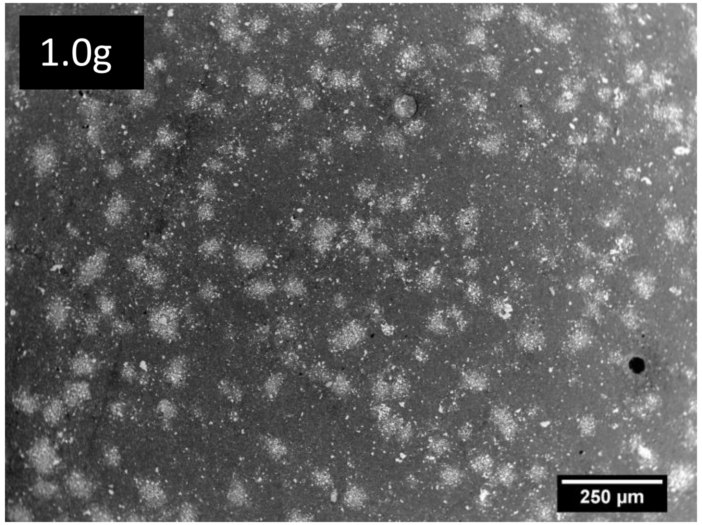
- MISSE-15 Experiment
  - Approach: Multiple 1-inch square samples with 6-month zenith orientation exposure
  - Goal: Understanding the durability of the samples in an extreme environment
- Microgravity Solidification Experiment
  - Approach: Similar experimental setup as the Microgravity Investigation of Cement Solidification (MICS) project
  - Goal: Understanding how the reduction in gravity influences the solidification

Images courtesy of Dr. Aleksandra Radlinska and Peter Collins

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







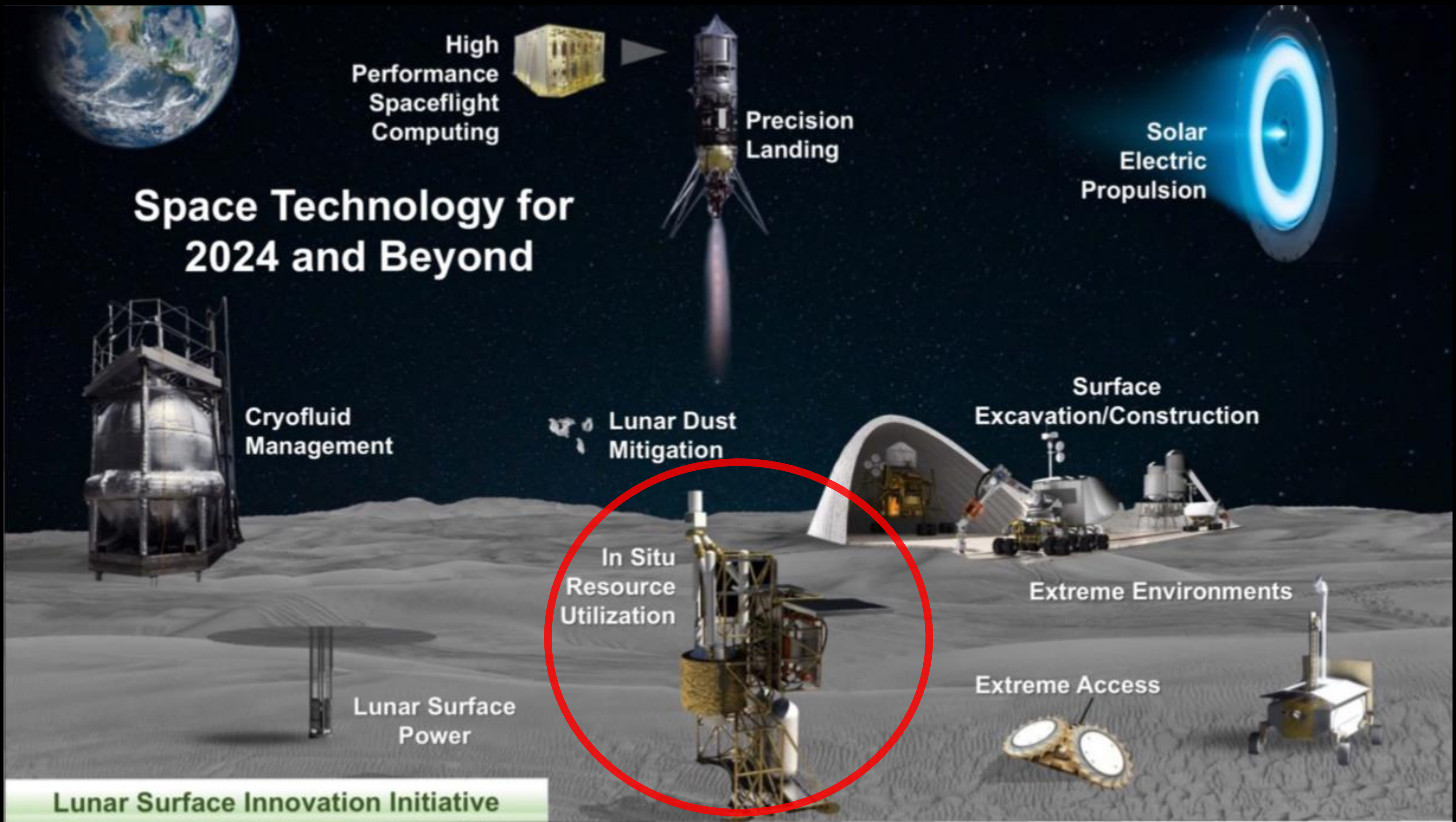
Gravity Level	Porosity (%)
10^{-6}	17.7
0.17	16.6
0.38	13.1
0.70	12.7
1	8.2

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

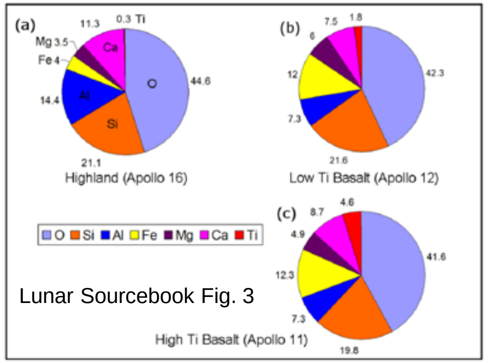
- Influence on strength - As the gravity level decreased the amount of trapped air and porosity in the samples increased
- Furthermore, crystals tend to grow larger and more uniform in microgravity
- The results also showed that cement solidification at Lunar gravity is more similar to microgravity than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

Images courtesy of Dr. Aleksandra Radlinska and Peter Collins

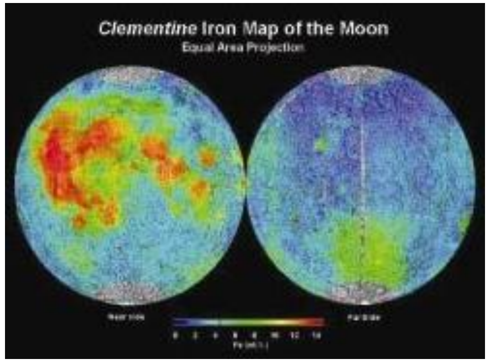
NASA Lunar Surface Innovation Initiative (LSII)



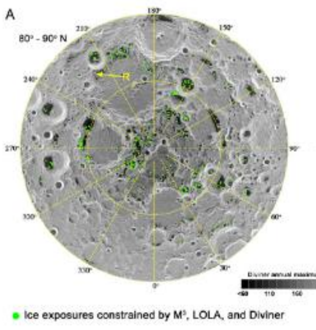
Lunar Resources: Regolith, Solar Wind Volatiles, Polar Water/Volatiles



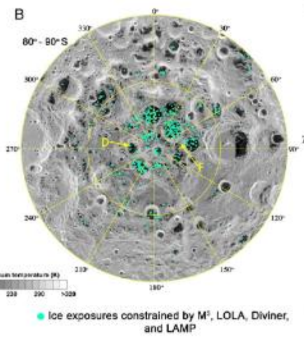
Lunar Sourcebook Fig. 3



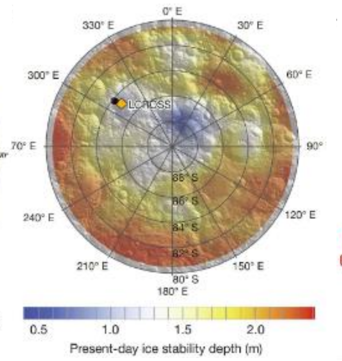
North Pole



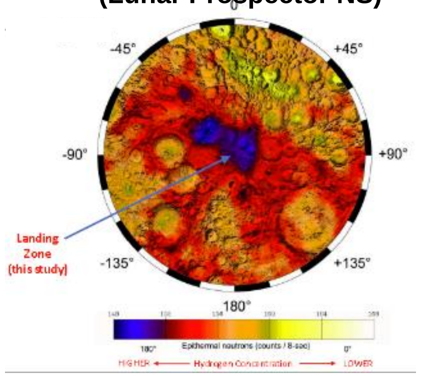
South Pole



Ice Stability Temperatures



Evidence of Hydrogen (Lunar Prospector NS)



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
- Green and blue dots show positive results for surface water ice and temperatures <110 K using orbital data.
- 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	

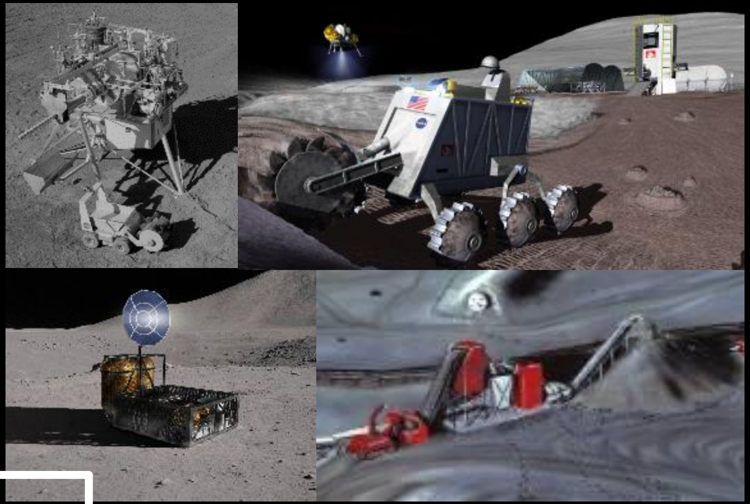
Consumables and Feedstock Production: *Living off the Land*

Lunar Regolith = Resource

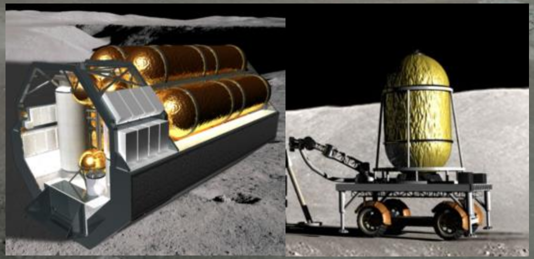
Products
- Oxygen
- Water and other volatiles
- Rocket propellants
- Feedstock materials for manufacturing, e.g. metals and silicates
- Feedstock constituent materials for construction
- Production of commodities for future lunar economy

Challenges
- Excavation and transfer of regolith
- Processes for extraction of basic products – consumables and feedstock constituent materials
- Scale of production
- Long duration, autonomous operation and failure recovery
- System reliability and maintenance
- Storage of consumables

Excavation & Regolith Processing for O_2 & Metal Production



Consumable Storage & Delivery



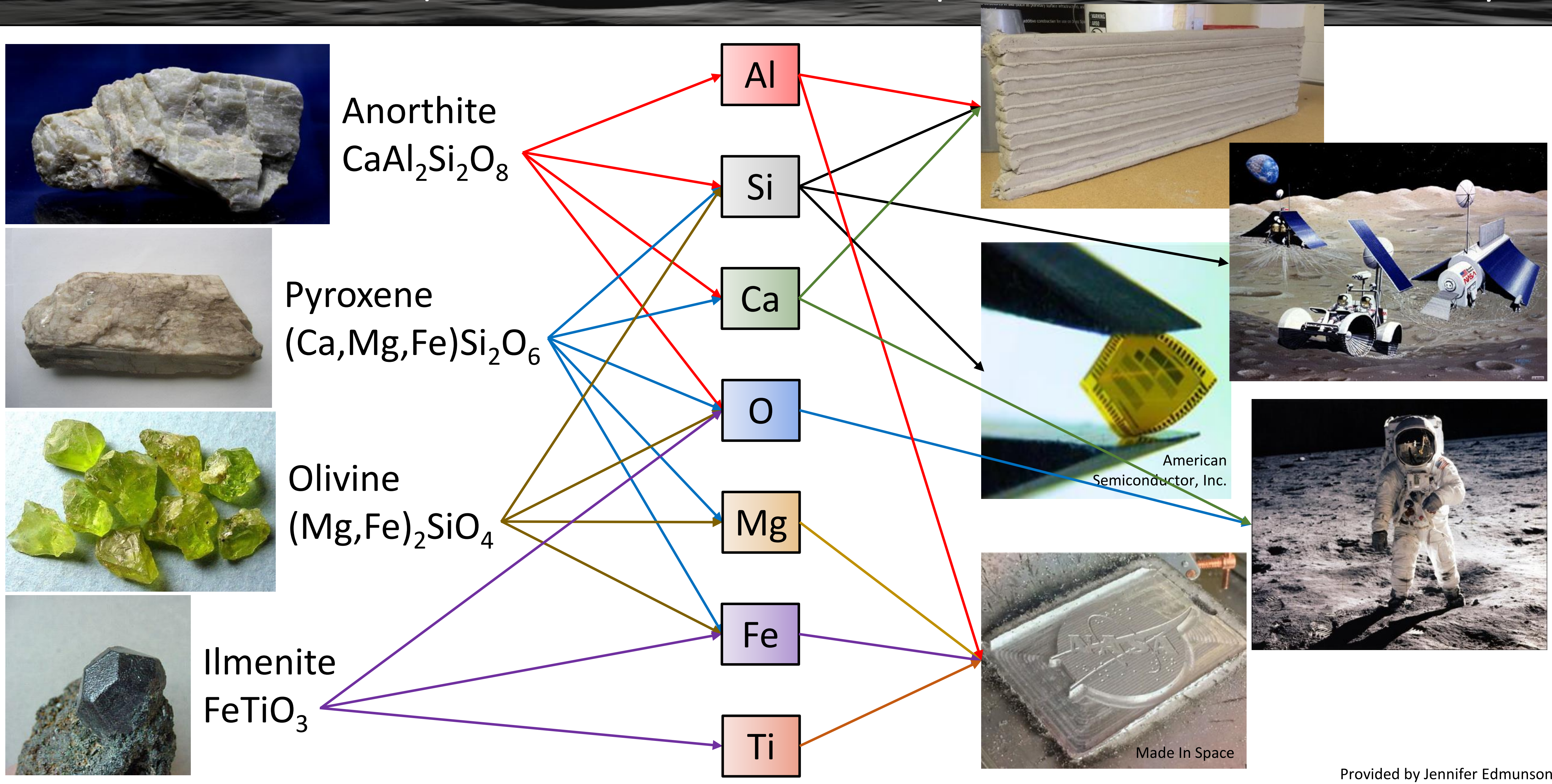
Consumable Users

Rovers & EVA Suits

Habitats & Life Support

Landers

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



Provided by Jennifer Edmunson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