NASA’s Lunar Surface Innovation Initiative – Regolith Processing for a Sustainable Presence on the Moon
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- Bjarke Ingels Group - ICON/MMPACT Lunar Architectural Design Concepts
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- Peter Collins - Penn State Cements and Geopolymers
Agenda

- Space Technology Mission Directorate: Technology Drives Exploration
  - Lunar Surface Innovation Initiative (LSII)
    - In Situ Resource Utilization (ISRU)
    - Excavation, Construction, and Outfitting (ECO)
  - Advanced Manufacturing
    - In Space Manufacturing (ISM) – Portfolio and Challenges
- Opportunities for Materials Science for Lunar Surface Systems
- Questions
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

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
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

**Challenges and Capability Gaps**
- Excavation and transfer of regolith
- Processes for extraction of basic products:
  - Consumables – water, oxygen, and volatiles capture
  - Feedstock materials – metals, alloys and binder constituents
- Scale of production (10’s to 100’s mT)
- Long duration, autonomous operation and failure recovery
- System reliability and maintenance
- Storage of consumables

**Excavation & Regolith Processing for O₂ & Metal Production**

**Consumable Storage & Delivery**

**Consumable Users**
- Rovers & EVA Suits
- Habitats & Life Support
- Landers
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

Lunar Surface Innovation Initiative
- 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

Nuclear Technologies and Advanced Propulsion
- Landing Heavy Payloads
- Landing for Science Exploration
- New Discovery Vehicle Technology

Cryogenic Fluid Management
- Precision Landing

Satellite Servicing and Assembly
NextGen Avionics and Communications
Small Spacecraft Technologies
Advanced Manufacturing

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Building a Sustainable Presence on the Moon

• What infrastructure are we going to need?

- launch/landing pads
- roads
- power plants
- habitats, refineries, green houses
- blast shields
Excavation for ISRU and Construction:
*Finding, Excavating and Transporting the Resources*

**Resource Prospecting – Looking for Resources**
- Volatiles Investigating Polar Exploration Rover (VIPER) ~2024 mission
- Lunar Reconnaissance Orbiter (LRO)

**Excavation & Processing for Aggregates and Binders**
- RASSOR Excavator ~2026 mission

**Challenges and Capability Gaps**
- Reduced gravity and low reaction forces
- Abrasive materials lead to significant component wear
- Site prep: inspection and sensors
- Health monitoring and repair strategies
- Autonomy
- Scale up
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
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
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
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.

"Houston, we have a solution."

ISS is the testbed for ISM.

ISM capabilities demonstrated on ISS are applicable to Gateway and the lunar surface.
Lunar regolith must be used for multiple applications (consumables, manufacturing, infrastructure construction) to enable a sustainable human presence and future lunar economy.
Lunar Regolith Processing – LSII Capability Gaps and Challenges

Consumables and Feedstock Production
- Excavation and transfer of regolith
- Processes for extraction of basic products:
  - Consumables – water, oxygen, and volatiles capture
  - Feedstock materials – metals, alloys and binder constituents
- Scale-up of production (10’s to 100’s mT)
- Long duration, autonomous operation and failure recovery
- System reliability and maintenance
- Storage of consumables

Excavation
- Reduced gravity and low reaction forces
- Abrasive materials lead to significant component wear
- Site prep: inspection and sensors
- Health monitoring and repair strategies
- Autonomy
- Scale up

Construction
- Regolith excavation, beneficiation, transfer, conveyance, quality assurance
- Interface with excavators and other support systems
- Deposition processes and associated materials for horizontal and vertical construction
- Printer mobility system for large-scale construction
- Increased autonomy of operations
- Long-duration operation of mechanisms under extreme lunar environmental conditions and dormancy
- Reliability and Maintainability of systems
- Scale-up of construction activities
- Structural Health Monitoring and Repair
- Inspection and Certification of as-built structure (V & V)
- Interdependencies on other infrastructure capabilities
- Material and construction requirements and standards

Common Infrastructure Capability Needs
- Power
- Communications Systems
- Navigation Systems
- Lander Off-Loading
- Dust Mitigation
- High Quality Highlands Simulant
BACK-UP
Potential Opportunities for Materials Science/Biological and Physical Sciences to Support Lunar Construction, Manufacturing, and Outfitting

• Beneficiation Processes for Icy Regolith/Regolith/Process Byproducts
  • Products/Outcomes:
    • Consumables: Water, oxygen, other volatiles
    • Feedstock for manufacturing (tools, spares, furnishings, printed electronics etc)
    • Binder constituents for construction (calcium, sulfur, aluminum, magnesium, silicates)
    • Studies of solidification and resulting microstructure of cementitious materials
  • Candidate Processes
    • Carbothermal Reduction
    • Ionic Liquid Extraction
    • Molten Oxide Electrolysis

• Physics of Regolith Beneficiation – Development of new methods for:
  • Fluid handling
  • Liquification of gases
  • Transport of solids

• ICME for Lunar Materials
  • Accelerate Development of Lunar Processes and Materials for Construction, Manufacturing and Outfitting
  • Solidification and Microstructure Studies for Feedstock Materials
Development and Testing of Capabilities for On-Demand Spare Component Manufacturing

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.

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

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.
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.

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

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

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

(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.
NASA Lunar Surface Innovation Initiative (LSII)

Space Technology for 2024 and Beyond

- High Performance Spaceflight Computing
- Precision Landing
- Solar Electric Propulsion
- Cryofluid Management
- Lunar Dust Mitigation
- Surface Excavation/Construction
- Extreme Environments
- Extreme Access
- Lunar Surface Power
- In Situ Resource Utilization
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

<table>
<thead>
<tr>
<th>Lightweight Composites Spacecraft</th>
<th>United States Manufacturing Public/Private Partnerships</th>
<th>In-Space Spares and Repairs</th>
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<tbody>
<tr>
<td>• &gt; 30% More Payload, Equipment and Experiments</td>
<td>• Manufacturing technology has a multiplier effect to competitiveness and expands the industrial base</td>
<td>• &gt; 50% mass reduction, &gt; 99% 3D printer readiness with sustainable supply chain, multiple materials</td>
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<tr>
<th>3D Printing Affordable Rocket Engines</th>
<th>Industries of the Future Powered by Digital Twins and Artificial Intelligence</th>
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<tbody>
<tr>
<td>• &gt; 30% Cost reduction, three months instead of five years, Parts &gt;1,100 to &lt;10</td>
<td>• More intelligent and more accurate predictions and capabilities, &gt; 50% % of physical resources replaced with virtual</td>
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<th>Factories in Space and Space Infrastructure</th>
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<tr>
<td>• Creating economic opportunities - increased launches, spacecraft, products</td>
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All activities depicted not currently funded or approved. Depicts “notional future” to guide technology vision.
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
- Development of photonic sintering process
- nScrypt 3D Multi-Material Printer
- Dimatix inkjet thin film printer
- Printed cortisol (stress) sensor. Image from California Institute of Technology.
- Diagram of AstroSense next-generation flexible, wireless, multi-sensor printed device for crew health monitoring. Image from Nextflex.
- 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.
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

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<tr>
<th>Gravity Level</th>
<th>Porosity (%)</th>
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<tbody>
<tr>
<td>10^-4</td>
<td>17.7</td>
</tr>
<tr>
<td>0.17</td>
<td>16.6</td>
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<tr>
<td>0.38</td>
<td>13.1</td>
</tr>
<tr>
<td>0.70</td>
<td>12.7</td>
</tr>
<tr>
<td>1</td>
<td>8.2</td>
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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