NASA Lunar ISRU Strategy

Presented at the
What Next for Space Resource Utilization? Workshop
Luxembourg

Oct. 10, 2019
Artemis Phase 1: To the Lunar Surface by 2024

Artemis 1: First human spacecraft to the Moon in the 21st century

Artemis 2: First humans to the Moon in the 21st century

First high power Solar Electric Propulsion (SEP) system

First Pressurized Crew Module delivered to Gateway

Artemis 3: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services
- CLPS delivered science and technology payloads

Early South Pole Crater Rim Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles

Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions

LUNAR SOUTH POLE TARGET SITE

2019 2024
Lunar Science by 2024

**Polar Landers and Rovers**
- First direct measurement of polar volatiles, improving understanding of lateral and vertical distribution, physical state, and chemical composition
- Provide geology of the South-Pole Aitken basin, largest impact in the solar system

**Non-Polar Landers and Rovers**
- Explore scientifically valuable terrains not investigated by Apollo, including landing at a lunar swirl and making first surface magnetic measurement
- Using PI-led instruments to generate Discovery-class science, like establishing a geophysical network and visiting a lunar volcanic region to understand volcanic evolution

**Orbital Data**
- Deploy multiple CubeSats with Artemis 1
- Potential to acquire new scientifically valuable datasets through CubeSats delivered by CLPS providers or comm/relay spacecraft
- Global mineral mapping, including resource identification, global elemental maps, and improved volatile mapping

**In-Situ Resource Initial Research**
- Answering questions on composition and ability to use lunar ice for sustainment and fuel
Artemis Phase 2: Building Capabilities for Mars Missions

- **Artemis 4**: Reusable human lander elements refueled
- **Artemis 5**: Lunar surface asset deployment for longer surface expeditions
- **Artemis 6**: CLPS opportunities
- **Artemis 7**: Artemis Support Mission

**SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION**

2025

**INTERNATIONAL PARTNERSHIP OPPORTUNITIES**

**MULTIPLE SCIENCE AND CARGO PAYLOADS**

**TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS**

2029
NASA Lunar ISRU Purpose

Lunar ISRU To Sustain and Grow Human Lunar Surface Exploration

- Lunar Resource Characterization for Science and Prospecting
  - Provide ground-truth on physical, mineral, and volatile characteristics – provide geological context;
  - Test technologies to reduce risk for future extraction/mining
- Mission Consumable Production (O₂, H₂O, Fuel):
- Learn to Use Lunar Resources and ISRU for Sustained Operations
  - \textit{In situ} manufacturing and construction feedstock and applications

Lunar ISRU To Reduce the Risk and Prepare for Human Mars Exploration

- Develop and demonstrate technologies and systems applicable to Mars
- Use Moon for operational experience and mission validation for Mars; Mission critical application
  - Regolith/soil excavation, transport, and processing to extract, collect, and clean water
  - Pre-deploy, remote activation and operation, autonomy, propellant transfer, landing with empty tanks
- Enable New Mission Capabilities with ISRU
  - Refuelable hoppers, enhanced shielding, common mission fluids and depots

Lunar ISRU To Enable Economic Expansion into Space

- Lunar Polar Water/Volatiles is Game Changing/Enabling
- Promote Commercial Operations/Business Opportunities
- Support/promote establishment of reusable/commercial transportation
Lunar Surface ISRU Capabilities

Resource Prospecting – Looking for Water

Mining Polar Water & Volatiles

Landing Pads, Berms, Roads, and Structure Construction

Excavation & Regolith Processing for O₂ & Metal Production

Refueling and Reusing Landers & Rovers
Lunar Resources
Regolith, Solar Wind Volatiles, Polar Water/Volatiles

Lunar Regolith
- >40% Oxygen by mass; numerous metals (Si, Fe, Al, Ti)
- 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

<table>
<thead>
<tr>
<th>Volatiles</th>
<th>Concentration ppm (µg/g)</th>
<th>Average mass per m³ of regolith (g)</th>
</tr>
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<tbody>
<tr>
<td>H</td>
<td>46 ± 16</td>
<td>76</td>
</tr>
<tr>
<td>D²He</td>
<td>0.0042 ± 0.0034</td>
<td>0.007</td>
</tr>
<tr>
<td>D³He</td>
<td>14.0 ± 11.3</td>
<td>23</td>
</tr>
<tr>
<td>C</td>
<td>124 ± 45</td>
<td>206</td>
</tr>
<tr>
<td>N</td>
<td>81 ± 37</td>
<td>135</td>
</tr>
<tr>
<td>F</td>
<td>70 ± 47</td>
<td>116</td>
</tr>
<tr>
<td>Cl</td>
<td>30 ± 20</td>
<td>50</td>
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</tbody>
</table>

Polar Water/Volatiles
- LCROSS Impact estimated 5.5 wt% water in plume
  - Solar wind & cometary volatiles (H₂, NH₃, C₂H₄, CO₂, CH₃OH, CH₄): 0.1 to 1.5 wt%
- Green and blue dots show positive results for surface water ice using M³ and LOLA data for the North pole, and M³, LOLA, and LAMP data for the South pole.
- Data points also have maximum annual temperatures of <110 K from Diviner data.
- Spectral modeling shows that some ice-bearing pixels may contain ~30 wt% ice (mixed with dry regolith)
- Ice detections in the south are clustered near the craters Haworth, Shoemaker, Sverdrup, and Shackleton, while those in the north are more isolated.
Lunar ISRU Mission Consumables: Oxygen from Regolith vs Polar Water

**Oxygen from Regolith**
- Lunar regolith is >40% oxygen (O₂) by mass
- Can be incorporated into the architecture from the start with low-moderate risk
- Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)
- Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions

**Water (and Volatiles) from Polar Regolith**
- Form, concentration, and distribution of Water in shadowed regions/craters is not known
- Cannot be incorporated into the architecture from the start with low to moderate risk
- Provides 100% of chemical propulsion propellant mass
- Polar water is “Game Changing” and enables long-term sustainability
  - Strongly influences design and reuse of cargo and human landers and transportation elements
  - Strongly influences location for sustained surface operations

**Current Plan:** Develop and fly demonstrations for both lunar ISRU consumable approaches
- Develop oxygen extraction to meet near term sustainability objectives
- Utilize orbital missions and early lunar surface missions to understand and characterize polar environments, regolith, and water resources to address risks and technology needs
Current NASA ISRU-Related Instruments & Orbital Missions

**Lunar Reconnaissance Orbiter (LRO) – 2009 to Today**
- Lyman-Alpha Mapping Project (LAMP) – UV;
- Lunar Exploration Neutron Detector (LEND) - Neutron;
- Diviner Lunar Radiometer Experiment (DLRE) – IR;
- Cosmic Ray Telescope for the Effects of Radiation (CRaTER) – Radiation;
- Lunar Orbiter Laser Altimeter (LOLA)
- Lunar Reconnaissance Orbiter Camera (LROC) – Sun/Imaging;
- Mini-RF Radar

**Korea Pathfinder Lunar Orbiter (KPLO) – 12/2020**
- ShadowCam  Map reflectance within permanently shadowed craters

**Science/Prospecting Cubesats (SLS Artemis-1 2020)**
- Lunar Flashlight: Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Broadband InfraRed Compact High Resolution Explorer Spectrometer
- LunaH-MAP: Two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire/LunIR: Spectroscopy and thermography for surface characterization
- NEA Scout: Multispectral camera for NEA morphology, regolith properties, spectral class

**Lunar Trailblazer (SIMPLEX) – TBD**
- Miniaturized imaging spectrometer and multispectral thermal imager
Current NASA ISRU-Related Instruments & Surface Missions

Commercial Lunar Payload Services (CLPS)
- Astrobotic: 14 payloads; Lacus Mortis site – 7/21
- Intuitive Machines: 5 payloads; Oceanus Procellarum – 7/21
- Orbit Beyond: 4 payloads; Mare Imbrium – 9/2020

Instruments for CLPS
- 13 NASA internal science & technology payloads:
- 12 external science & technology payloads:
  - Regolith collection: PlanetVac and Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith (SAMPLR)
  - Lunar Compact InfraRed Imaging System (L-CIRiS)

Dev. And Advancement of Lunar Instruments (DALI) – TBD
- 10 teams funded to mature CLPS instruments:
  - Beneficial for ISRU prospecting: Submillimeter Solar Observation Lunar Volatiles Experiment (SSOLVE); Characterization of Regolith and Trace Economic Resources (CRATER)- laser MS; Bulk Elemental Composition Analyzer (BECA) – Pulsed neutrons; eXTraterrestrial Regolith Analyzer for Lunar Soil – XRD/XRF; Ultra-Compact Imaging Spectrometer – shortwave IR; Electrostatic Dust Analyzer (EDA)

Volatiles Investigation Polar Exploration Rover
- Prospecting rover to fly to south polar region on late 2022

Polar Resource Ice-Mining Experiment-1 (PRIME-1) – TBD
- FY19 Drill down-select with mass spectrometer
Backup/Optional
Integration of ISRU with Exploration Elements
(Mission Consumables)

**ISRU Functions & Elements**
- Resource Prospecting/Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide Processing
- Water Processing
- Manufacturing
- Civil Engineering & Construction

**Support Functions & Elements**
- Power Generation & Storage
- O₂, H₂, and CH₄ Storage and Transfer
- Regolith, Metals, & Plastics
- In Situ Construction
- In Space Manufacturing
- ISRU Resources & Processing
  - Resource & Site Characterization
  - Regolith/Soil Excavation & Sorting
  - Water/Volatile Transport
  - Regolith/Soil Transport
  - Regolith Crushing & Processing
  - Water/Volatile Extraction
  - Regolith for O₂ & Metals
  - CO₂ from Mars Atmosphere
  - H₂O, CO₂ from Soil/Regolith
  - CO₂ & Trash/Waste

**Life Support & EVA**
- Pressurized Rover
- Habitations
- Used Descent Stage
- Propellant Depot

**Power Systems**
- Solar Electric/Thermal
- Regenerative Fuel Cell
- Nuclear
- Lander/Ascent
- Surface Hopper
- Parts, Repair, & Assembly
- Civil Engineering, Shielding, & Construction
- In Space Manufacturing
- Storage
- Lander/Ascent
ISRU Capability & Gap Assessment
Lunar Polar Water/Volatile Mining

**Current State of Development:** Proof of Concept Development
- At least 8 concepts are currently being explored including:
  - Excavation w/ Auger dryer
  - Heated coring auger
  - Microwave heating
  - Heated Dome
- 3 Architectural Approaches:
  - Excavate in PSR and remove to sunlit region for processing
  - Excavate/process in PSR and move water to sunlit region for processing
    - On multiple mobile platforms
    - Multiple excavators deliver to centralized processor
  - In situ (underground) process and move water to sunlit region

**Gap**
- Continue development of multiple options to advance to TRL 6 until polar data is available
- Long-duration testing (100’s of days)
- Increase autonomy and maintainability
- Lunar environmental testing
Current State of Development: Engineering Breadboards – TRL 3 to 5
- Over 20 processes have been identified to extract oxygen from regolith
  - Components required range from TRL 3 to TRL 9
  - Typically, as processing temps increase, O₂ yield increases, and technical and engineering challenges increase
- Constellation Program focused on three processes
  1. Hydrogen (H₂) reduction
  2. Carbothermal (CH₄) reduction
  3. Molten regolith electrolysis
- Two processes (#1 & 2) developed to TRL 4-5 at human mission relevant scale and tested at analog site for days at sub-pilot scale
- Examining lower TRL concepts as well

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<tr>
<th>Resource Knowledge</th>
<th>O₂ Extraction</th>
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<tr>
<td></td>
<td>H₂ Reduction</td>
</tr>
<tr>
<td>Site Specificity</td>
<td>Moderate to High (Ilminite &amp; Pyroclastic Glasses Preferred)</td>
</tr>
<tr>
<td>Temperature to Extract</td>
<td>Moderate (900 C)</td>
</tr>
<tr>
<td>Energy per Kilogram</td>
<td>High</td>
</tr>
<tr>
<td>Extraction Efficiency wt%*</td>
<td>1 to 5</td>
</tr>
<tr>
<td>TRL</td>
<td>4-5</td>
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*kg O₂/kg bulk regolith
ISRU Capability
Lunar Regolith Excavation, Transfer, and Preparation

- Built and tested multiple excavation approaches for granular regolith: scoops, percussive blades, bucket ladders, bucket wheels, bucket drums (NASA, SBIRs, Challenges)
- Built and tested auger and ripper for hard materials (SBIRs)
- Built and tested multiple transfer approaches: lift buckets, vertical augers, horizontal augers, pneumatic
- Examined and lab tested size sorting and mineral separation approaches
- Built and tested multiple small excavation vehicles (NASA, SBIRs, Challenges)
**ISRU Capability**

**Civil Engineering and In Situ Construction**

- **Current State of Development:** Proof of Concept/Eng. Breadboards – TRL 3 to 5

### Areas Clearing/Berm Building
- Moses Lake, 2007

### Landing Pad Construction:
- NASA, PISCES, Honeybee Robotics
- **Grading & Leveling Blade**
- **Compactor Roller**
- **Paver Deployment**
- **Completed Landing Pad**

Images Courtesy Rodrigo Romo, Pacific Int’l Space Center for Exploration Systems (PISCES)

### NASA Centennial Challenge:
- **3D Printed Habitat** ($2.5 Million Prize)

- **Phase 1:** Concepts
- **Phase 2:** 1.5 m Printed Dome
- **Phase 3:** Structure Fabrication – April 2019

### Synthetic Biology
- **CO₂ Based Manufacturing**
- **BioMaterials**
- **Center for Utilization of Biological Engineering in Space (CUBES)**

### Additive Construction with Mobile Emplacement (ACME)
- 2D and 3D printing on a large (structure) scale using in-situ resources as construction materials

### Automated Construction for Expeditionary Structures (ACES) - NASA with U.S. Army Corps of Engineers
- 3D print large structures to support deployment in remote areas

### Sintering
- **Solar Concentrator**
- **Radiative heating**

### Landing Pad Construction:
- CSA, Neptec, ODG, NORCAT
- Autonomous area clearing, leveling, and berm building
Lunar Mobility Strategy

• Primary drivers include science and human exploration objectives and soonest landing; target is late 2022 in the South Pole region

• Primary objectives:
  - Ground truth of volatiles (horizontal and vertical distribution, composition, and form)
  - Long duration operation (months)

• Parallel Rover Development Paths
  • NASA in-house development (VIPER)
  • Study task order to existing CLPS providers
  • RFI to industry to determine potential commercial sources and availability
  • Investigate international contribution (e.g., ESA, CSA)
• Commercial Lunar Payload Services (CLPS)
  ➢ Two deliveries per year
  ➢ Drive to enable community-driven science

• Instrument Development and Delivery
  ➢ Instruments for CLPS
  ➢ Maturation of instrument concepts (DALI)

• VIPER Polar Rover
  ➢ NASA-built rover to the lunar surface in late CY2022
    ☑ Delivery by CLPS provider via on-ramp for enhanced capability

• Follow on missions (commercial rovers) approximately every 24 months

• Long Duration Rover Investments

• Lunar Reconnaissance Orbiter Mission Operations

• Lunar SmallSats
  ➢ SIMPLEX
  ➢ CubeSats/SmallSats delivered into lunar orbit by CLPS

• Apollo Next Generation Sample Analysis (ANGSA)
ISRU Development and Implementation Challenges Must Be Addressed

<table>
<thead>
<tr>
<th>Space Resource Challenges</th>
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| **R1** What resources exist at the site of exploration that can be used?  
  Form, amount, distribution, contaminants, terrain |
| **R2** What are the uncertainties associated with these resources?  
  Forward contamination/sterilization, operating in a special region, creating a special region |
| **R3** How to address planetary protection requirements?  
  Forward contamination/sterilization, operating in a special region, creating a special region |

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| **T1** Is it technically and economically feasible to collect, extract, and process the resource?  
  Energy, Life, Performance |
| **T2** How to achieve high reliability and minimal maintenance requirements?  
  Thermal cycles, mechanisms/pumps, sensors/calibration, wear |

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<th>ISRU Operation Challenges</th>
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| **O1** How to operate in extreme environments?  
  Temperature, pressure/vacuum, dust, radiation, grounding |
| **O2** How to operate in low gravity or micro-gravity environments?  
  Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation |
| **O3** How to achieve long duration, autonomous operation and failure recovery?  
  No crew, non-continuous monitoring, time delay |
| **O4** How to survive and operate after long duration dormancy or repeated start/stop cycles with lunar sun/shadow cycles?  
  'Stall' water, lubricants, thermal cycles |

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<th>ISRU Integration Challenges</th>
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<td><strong>I1</strong> How are other systems designed to incorporate ISRU products?</td>
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<tr>
<td><strong>I2</strong> How to optimize at the architectural level rather than the system level?</td>
</tr>
<tr>
<td><strong>I3</strong> How to manage the physical interfaces and interactions between ISRU and other systems?</td>
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Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.