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
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

Reusable human lander elements refueled

Artemis Support Mission
Lunar surface asset deployment for longer surface expeditions

CLPS opportunities

SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS

INTERNATIONAL PARTNERSHIP OPPORTUNITES

TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

2025

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
    - *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
Space Technology for 2024 and Beyond

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

Mining Polar Water & Volatiles
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

<table>
<thead>
<tr>
<th>Volatile</th>
<th>Concentration ppm (μg/g)</th>
<th>Average mass per m² of regolith (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>46 ± 16</td>
<td>76</td>
</tr>
<tr>
<td>H₂</td>
<td>0.0042 ± 0.0034</td>
<td>0.007</td>
</tr>
<tr>
<td>He</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>CI</td>
<td>30 ± 20</td>
<td>50</td>
</tr>
</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
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

ISRU Resources & Processing
- Water/Volatile Extraction
- Regolith/Soil Excavation & Sorting
- Regolith/Soil Transport
- Regolith Crushing & Processing
- Regolith for O₂ & Metals
- CO₂ from Mars Atmosphere
- H₂O, CO₂ from Soil/Regolith
- CH₂O, O₂, H₂, CH₄
- Water/Volatiles
- O₂
- Metals & Plastics
- Life Support & EVA

Power Systems
- Solar Electric/Thermal
- Regenerative Fuel Cell
- Nuclear

In Situ Construction
- Civil Engineering, Shielding, & Construction

In Space Manufacturing
- Parts, Repair, & Assembly

Lander/Ascent
- Propellant Depot
- Habitat

Storage
- Regolith for O₂ & Metals
- CO₂ & Trash/Waste

Used Descent Stage
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

<table>
<thead>
<tr>
<th>Resource Knowledge</th>
<th>O₂ Extraction</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>H₂ Reduction</td>
</tr>
<tr>
<td>Site Specificity</td>
<td></td>
</tr>
<tr>
<td>Moderate to High</td>
<td>Good - Orbital High Resolution &amp; Apollo Samples</td>
</tr>
<tr>
<td>Temperature to Extract</td>
<td>High (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>
</tr>
</tbody>
</table>

*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)

- CRATOS - 2008
- Centaur Excavator - 2010

Volume equivalent to 1 Metric Ton of lunar regolith

8 cm (3.15 in) deep; 60% year; 1600 kg/m³

10 wt%  14 wt%  20 wt%

1 wt% = ~ 2 Football Fields

TOUCHDOWN

0.85 m

Volume equivalent to 1 Metric Ton of lunar regolith
**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)

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

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

**Phase 2: Structural Member Competition**

**Phase 3: Structure Fabrication – April 2019**

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

**Sintering**
- Solar Concentrator
- Radiative heating

**Automated Construction for Expeditionary Structures (ACES) - NASA with U.S. Army Corps of Engineers**
- 3D print large structures to support deployment in remote areas
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)
Lunar Discovery and Exploration Program (LDEP)

• 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

**Space Resource Challenges**

R1 What resources exist at the site of exploration that can be used?
R2 What are the uncertainties associated with these resources?
   Form, amount, distribution, contaminants, terrain
R3 How to address planetary protection requirements?
   Forward contamination/sterilization, operating in a special region, creating a special region

**ISRU Operation Challenges**

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

**ISRU Technical Challenges**

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

**ISRU Integration Challenges**

I1 How are other systems designed to incorporate ISRU products?
I2 How to optimize at the architectural level rather than the system level?
I3 How to manage the physical interfaces and interactions between ISRU and other systems?

Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.