NASA IN-SITU RESOURCE UTILIZATION PROJECT—AND SEAL CHALLENGES

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NASA In-Situ Resource Utilization Project
– and Seals Challenges

Kurt Sacksteder and Diane Linne
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New Space Exploration Vision

• On January 14, 2004, the President announced a new vision for NASA
  – Implement a *sustained and affordable* human and robotic program to explore the solar system and beyond;
  – Extend *human presence* across the solar system, starting with a human return to the Moon in preparation for human exploration of Mars and other destinations;
  – Develop the *innovative technologies*, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
  – Promote *international and commercial participation* in exploration to further U.S. scientific, security, and economic interests.

“Making use of the Moon’s abundant resources…”
What Are Space Resources?

- **Traditional material resources including:**
  - Water from the soil or atmosphere
  - Atmospheric gases (CO₂, O₂, N₂, etc.)
  - Volatile species from the solar wind or comets (H₂, He, H₂O, CH₄, etc.)
  - Minerals/metals (Fe, Ti, Ni, Si, etc.)

- **Energy**
  - (Near) Continuous sunlight for electrical/thermal power and stable thermal control
  - (Near) Continuous Darkness for cryogenic fluid storage, scientific instruments and stable thermal control

- **Environment**
  - Vacuum/Dryness
  - Micro/Partial Gravity
  - High Thermal Gradients

- **Location**
  - Stable Locations for Earth/Sun/deep-space observations, mission staging
  - Isolation from Earth’s electromagnetic noise, storage of duplicate vital information
  - Isolation for Earth to conduct hazardous testing (nuclear, biological, etc.) and extraterrestrial sample curation & analysis, etc.

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In-Situ Resource Utilization exploits these resources, creating products & services that significantly reduce the mass, cost, & risk of extended-duration space exploration
**Space Resource Utilization for Exploration**

**Mission Consumable Production**
- Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles
- Fuel cell reagents for mobile (rovers, EVA) & stationary backup power
- Life support consumables (oxygen, water, buffer gases)
  - Gases for science equipment and drilling
  - Bio-support products (soil, fertilizers, etc.)
  - Feedstock for in-situ manufacturing & surface construction

**Surface Construction**
- Radiation shielding for habitat & nuclear reactors from in-situ resources or products (Berms, bricks, plates, water, hydrocarbons, etc.)
- Landing pad clearance, site preparation, roads, etc.
  - Shielding from micro-meteoroid and landing/ascent plume debris
  - Habitat and equipment protection

**Manufacturing w/ Space Resources**
- Spare parts manufacturing
  - Locally integrated systems & components (especially for increasing resource processing capabilities)
  - High-mass, simple items (chairs, tables, replaceable structure panels, wall units, wires, extruded pipes/structural members, etc.)

**Space Utilities & Power**
- Storage & distribution of mission consumables
- Thermal energy storage & use
- Solar energy (PV, concentrators, rectennas)
- Chemical energy (fuel cells, combustion, catalytic reactors, etc.)
ISRU Enables Affordable, Sustainable & Flexible Exploration

**Mass Reduction**
- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit

**Cost Reduction**
- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost

**Risk Reduction & Flexibility**
- Fewer Earth launches & reduced mission operations
- Reduced dependence on Earth
- Common hardware & mission consumables
- In-situ fabrication of spare parts for sustainable self-sufficiency
- Dissimilar redundancy
- Radiation & Plume Shielding

**Expands Human Presence**
- Increase surface mobility and extend missions
- Habitat & infrastructure construction
- Consumables for propellant, life support, power, etc.
- Substitute infrastructure cargo for Earth-source propellant & consumables

**Enables Space Commercialization**
- Material handling and processing technologies
- Infrastructure for space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Lunar Surface
Propellant from the Moon Could Revolutionize Space Transportation

Apollo missions utilized Earth-supplied propellant (Saturn V liftoff mass = 2,962 tons)

Refueling at L1 and on Moon reduces launch to 73% of Apollo mass (2,160 tons)

Refueling at Low Earth Orbit, L1 and on Moon reduces launch to 12% of Apollo mass (355 tons)

Lunar lander refueled on the Moon's surface reduces launch to 34% of Apollo mass (1,004 tons)

Add a reusable lunar lander reduces launch to 268 tons

Add a reusable upper stage & lander reduces launch to 119 tons

Note: Apollo stage height is scaled by estimated mass reduction due to ISRU refueling.
Timeline for ISRU Capability Implementation

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>2005</td>
<td>Early Robotic Exploration</td>
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<tr>
<td>2006</td>
<td>1st Robotic Landers</td>
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<td>2007</td>
<td>2nd Robotic Landers</td>
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<td>2008</td>
<td>Lunar Reconn Orbiter</td>
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<td>2009</td>
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<td>2010</td>
<td>Mars Sample Return</td>
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<td>2011</td>
<td>ISRU Robotic Hopper</td>
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<td>2012</td>
<td>ISRU Science Hopper</td>
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<td>2013</td>
<td>ISRU Science Hopper Capability</td>
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<tr>
<td>2014</td>
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<td>2015</td>
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<tr>
<td>2016</td>
<td>Mars Subscale Human Propellant Production &amp; Storage Capability</td>
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<td>2018</td>
<td>Mars Deep Drilling Capability</td>
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<tr>
<td>2019</td>
<td>Propellant Production &amp; Delivery for Surface Access &amp; Cislunar Transportation</td>
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<tr>
<td>2020</td>
<td>Mars Atmosphere Propellant Production &amp; Storage Demonstrated</td>
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<td>Subscale Mars Regolith Excavation &amp; H2O Extraction</td>
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In-Situ Resource Utilization must earn acceptance for mission critical roles in crewed missions through convincing demonstrations early in the Exploration timeline.
Lunar ISRU Implementation Approach

**Lunar Mission Assumptions with ISRU** (Lunar Exploration Analysis Group-LEAG)
- Robotic precursors identify resources and validate critical processes
- Early human missions (4 to 14 days) gain system & operational experience until a candidate long-term site is selected
  - Pre-deployed ISRU/mission assets before human missions
- Develop infrastructure at one base for Mars mission ‘dress rehearsals’ (90 day & 500 day) and sustained human presence in space
  - Traverse or hop to other locations for short term science mission objectives

**Initial Capabilities**
- Surface regolith excavation and manipulation
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H₂, CO, N₂, H₂O)
- Oxygen (O₂) production from regolith processing
- Production/regeneration of fuel cell reagents
- Cryogenic storage & transfer

**Mid-Term ISRU Capabilities**
- In-situ fabrication and repair
- Space Power
- Thermal energy storage & use

**Long-Term Lunar Capabilities**
- In-situ manufacturing of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- Life Support System – bio support (soil, fertilizers, etc.)
- Helium-3 isotope (³He) mining
ISRU Technical-to-Mission Capability Roadmap

**In-Situ Resource Determination & Engineering Data**
- Prospecting Flight Experiments

**Volatile Source Gases for Power, Propulsion, & Life Support**

**Regolith & Atmosphere Source Gases for Power, Propulsion & Life Support**
- Lunar Polar Water Explorer
- Lunar Volatile Extraction
  - \( H_2, H_2O, He \) & \( He^3 \)
- Mars Polar Water Extraction Demo

**Resource Excavation & Separation**
- Regolith Excavation and Handling
- Regolith Beneficiation
- Thermal/Microwave Volatiles Extraction
- \( H_2O \) Separation
- \( CO_2 \) & \( N_2 \) Separation

**Resource Processing**
- Reduction of Metals & Silicon for Oxygen and Solid Fuel
- \( H_2O \) Separation for Oxygen and Fuel
- \( CO_2 \) Separation for Oxygen and Fuel

**Consumable Storage & Distribution**
- Liquefaction and Pressurization
- Storage and Distribution Logistics

**In-Situ Manufacturing**
- Metallic parts
- Polymer parts
- Solar cell production

**In-Situ Construction**
- Habitats
- Spaceport
- Surface Transportation

**Solid Resource Utilization, Improved Logistics & Infrastructure Growth**
- Lunar O\textsubscript{2} Pilot Plant
- Mars O\textsubscript{2} & Fuel Production Demo
- Micro-Gravity Manufacturing Demo on ISS
- Lunar Construction Demo
- ISRU-based Infrastructure

**Mission Capabilities**
- Lunar Fuel Production
- Lunar O\textsubscript{2} Production
- Mars O\textsubscript{2} & Fuel Production
- Solar Cell & Spare Parts Manufacturing Demo

**Prospects**
- Lunar Volatile Extraction (\( H_2, H_2O, He \) & \( He^3 \))
- Mars Polar Water Extraction Demo
- Lunar O\textsubscript{2} Pilot Plant
- Mars O\textsubscript{2} & Fuel Production Demo
- Micro-Gravity Manufacturing Demo on ISS
- Lunar Construction Demo
- ISRU-based Infrastructure

**ISRU Technical Capabilities**

**ISRU Mission Capabilities**
ISRU Resources & Products of Interest

LUNAR RESOURCES

MARE REGOLITH

Ilmenite - 15%
FeO·TiO₂ 98.5%

Pyroxene - 50%
CaO·SiO₂ 36.7%
MgO·SiO₂ 29.2%
FeO·SiO₂ 17.6%
Al₂O₃·SiO₂ 9.6%
TiO₂·SiO₂ 6.9%

Olivine - 15%
2MgO·SiO₂ 56.6%
2FeO·SiO₂ 42.7%

Anorthite - 20%
CaO·Al₂O₃·SiO₂ 97.7%

VOLATILES (Solar Wind & Polar Ice/H₂)

Hydrogen (H₂) 50 - 150 ppm
Helium (He) 3 - 50 ppm
Helium-3 (³He) 10⁻² ppm
Carbon (C) 100 - 150 ppm
Polar Water (H₂O)/H₂ 1 - 10%

Thermal Volatile Extraction

Hydrogen Reduction of Ilmenite/glass

Sulfuric Acid Reduction

Methane Reduction (Carbothermal)

Molten Electrolysis

Vapor Pyrolysis

Fluidized Bed Reactor

2FeTiO₃ + 2H₂ 900°C 2H₂O + 2Fe + 2TiO₂
Water electrolysis
O₂ + 2H₂ 2H₂O

Desolve/Digest Reactor

2FeTiO₃ + 2H₂SO₄ 2H₂O + 2FeSO₄ + 2TiO₂
Electrolysis bed
O₂ + 2Fe + 2H₂SO₄ 2H₂O + 2FeSO₄

Methane Reduction Furnace

Pyrolysis Reactor/Condenser

2SiO₂ 2SiO + O₂
2FeTiO₃ 2FeO + 2TiO₂ + O₂
2FeO 2FeO + O₂
2Al₂O₃ 4AlO + O₂
2CaAl₂SiO₆ 2CaO + 4AlO + 2SiO + O₂
2MgO 2MgO + O₂
2CaO 2CaO + O₂
2CaAl₂SiO₆ 2Ca + 2AlO + 2SiO + O₂
5O₂, 2Al, 2Ca

Pyrolysis Reactor/Condenser

2SiO₂ 2SiO + O₂
2FeTiO₃ 2FeO + 2TiO₂ + O₂
2FeO 2FeO + O₂
2Al₂O₃ 4AlO + O₂
2CaAl₂SiO₆ 2CaO + 4AlO + 2SiO + O₂
2MgO 2MgO + O₂
2CaO 2CaO + O₂
2CaAl₂SiO₆ 2Ca + 2AlO + 2SiO + O₂
5O₂, 2Al, 2Ca

Vapor Pyrolysis

Molten Electrolysis Reactor

2FeTiO₃ 2FeO + 2TiO₂ + O₂
2FeO 2FeO + O₂
2Al₂O₃ 4AlO + O₂
2CaAl₂SiO₆ 2CaO + 4AlO + 2SiO + O₂
2MgO 2MgO + O₂
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2CaAl₂SiO₆ 2Ca + 2AlO + 2SiO + O₂
5O₂, 2Al, 2Ca

Methane Reduction (Carbothermal)

Molten Electrolysis Reactor

2FeTiO₃ 2FeO + 2TiO₂ + O₂
2FeO 2FeO + O₂
2Al₂O₃ 4AlO + O₂
2CaAl₂SiO₆ 2CaO + 4AlO + 2SiO + O₂
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2CaO 2CaO + O₂
2CaAl₂SiO₆ 2Ca + 2AlO + 2SiO + O₂
5O₂, 2Al, 2Ca

Methane Reduction (Carbothermal)
Challenging Seals Requirements for ISRU

The Moon is a Harsh Environment

- Temperatures from 40K (-230°C) to 450K (150°C)
- High Vacuum, 10^-10 mm Hg
- Dust: abrasive, static cling, etc.
- Partial gravity

Initial ISRU Capabilities

- Surface regolith excavation and manipulation – mechanism bearings and regolith abrasion
  - Excavation for volatile extraction and regolith processing
  - Berms and shielding for radiation and plume protection
  - Site/landing pad preparation and road/dust mitigation
- Extraction & recovery of useful volatiles from surface resources (H₂, CO, N₂, H₂O) – encapsulate regolith during excavation and heating
- Oxygen (O₂) production from regolith processing – high temperature reactors and reagent recovery systems
- Production/regeneration of fuel cell reagents – fuel transfer operations
- Cryogenic storage & transfer – valves and other plumbing issues