Overview of Past Lunar *In Situ* Resource Utilization (ISRU) Development by NASA

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What is *In Situ* Resource Utilization (ISRU)?

ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration.

**Resources**
- Traditional: *Water*, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, sunlight, etc.
- Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.

**Resource Assessment (Prospecting)**
- Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment.

**Resource Acquisition**
- Atmosphere constituent collection, and material/volatile collection via drilling, excavation, transfer, and/or manipulation before Processing.

**Resource Processing/Consumable Production**
- Conversion of acquired resources into products with immediate use or as feedstock for construction & manufacturing.
  - Propellants, life support gases, fuel cell reactants, etc.

**In Situ Manufacturing**
- Production of replacement parts, machines, and integrated systems from feedstock derived from one or more processed resources.

**In Situ Construction**
- Civil engineering, infrastructure emplacement and structure construction using materials produced from *in situ* resources.
  - Radiation shields, landing pads, roads, berms, habitats, etc.

**In Situ Energy**
- Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials.
  - Solar arrays, thermal storage and energy, chemical batteries, etc.

- ‘ISRU’ is a capability involving multiple elements to achieve final products.
- ‘ISRU’ does not exist on its own. Must connect and tie to users/customers of ISRU products.
Space ‘Mining’ Cycle: Prospect to Product

Resource Assessment (Prospecting)
- Global Resource Identification
- Local Resource Exploration/Planning

Mining
- Site Preparation & Infrastructure Emplacement
- Maintenance & Repair
- Crushing/Sizing/Beneficiation

Processing
- Spent Material Removal
- Waste

Product Storage & Utilization
- Habitations
- Power
- Propulsion
- Life Support & EVA
- Depots

Comm & Autonomy

Remediation
ISRU Changes How We Can Explore Space

**Mass Reduction**
- >7.5 kg mass savings in Low Earth Orbit for every 1 kg produced on the Moon or Mars
- Chemical propellant is the largest fraction of spacecraft mass

**Risk Reduction & Flexibility**
- Number of launches & mission operations reduced
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- Radiation & landing/ascent plume shielding
- Reduces dependence on Earth

**Cost Reduction**
- Allows reuse of transportation systems
- Reduces number and size of Earth launch vehicles

**Expands Human Presence**
- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

**Space Resource Utilization**
- Develops alternative & renewable energy technologies
- New additive construction
- CO₂ remediation
- Green metal production
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

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ISRU for Lunar Missions

- **Lunar Resource Prospecting & Mine Planning**
  - Terrain and surface feature mapping
  - Surface/subsurface mineral and glass concentration & distribution mapping
  - Solar wind & polar volatile concentration & distribution mapping

- **Mission Consumable Production**
  - Complete Life Support/Extra Vehicular Activity closure for Oxygen (O₂) and water (H₂O)
  - Produce/regenerate Fuel Cell Reactants (in conjunction with Power)
  - Gases for science and cleaning
  - **Propellant production**: O₂ and fuel (H₂ and/or CH₄) for robotic and human vehicles

- **Site Preparation and Outpost Deployment/Emplacement**
  - Site surveying and terrain mapping
  - Crew radiation protection (In-situ water production or bulk regolith)
  - Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
  - Area and road clearing to minimize risk of payload delivery and emplacement

- **Outpost Growth and Self-Sufficiency**
  - Fabrication of structures that utilize in-situ materials (with Habitats)
  - Production of feedstock for fabrication and repair (with Sustainability)
  - Solar array, concentrator, and/or rectenna fabrication (with Power)
  - Thermal energy storage & use from processed regolith (with Power)
Lunar ISRU Mission Capability Concepts

- **Resource Prospecting** – Looking for Polar Ice
- **Excavation & Regolith Processing** for $O_2$ Production
- **Carbothermal Processing** with Altair Lander Assets
- **Thermal Energy Storage Construction**
- **Landing Pads, Berm, and Road Construction**
- **Consumable Depots for Crew & Power**
Use the Moon as a Precursor to Mars

- **Identify and characterize available resources (especially polar region) that:**
  - Strongly influence mission phases, locations, and designs to achieve maximum benefit of ISRU
  - Is synergistic with Science and space commercialization objectives
  - Is synergistic with surface water characterization on Mars

- **Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human Mars missions**
  - Excavation and material handling & transport
  - Volatile/hydrogen/water extraction
  - Thermal/chemical processing subsystems for oxygen and fuel production
  - Cryogenic fluid storage & transfer
  - Trash/Waste Processing in conjunction with Life Support
  - Metal extraction and fabrication of spare parts

- **Use Moon for operational experience and mission validation for Mars**
  - Pre-deployment & remote activation and operation of ISRU assets without crew
  - Making and transferring mission consumables (propellants, life support, power, etc.)
  - Landing crew with pre-positioned return vehicle or ‘empty’ tanks
  - ‘Short’ (<90 days) and ‘Long’ (300 to 500 days) Mars surface stay dress rehearsals

- **Develop and evolve surface exploration assets linked to ISRU capabilities that enable new exploration capabilities**
  - Human and robotic hoppers for long-range surface mobility and global science access; power-rich distributed systems; enhanced radiation shielding, etc.
  - Repair, fabrication, and assembly techniques to mitigate mission risk and logistics mass.
Lunar 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%

Volatile (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%

Fluidized Bed Reactor

2FeTiO₃ + 2H₂ → 900°C → 2H₂O + 2Fe + 2TiO₂

O₂ + 2H₂ → 25°C → 2H₂O

Desolve/Digest Reactor

2FeTiO₃ + 2H₂SO₄ → 2H₂O + 2FeSO₄ + 2TiO₂

O₂ + 2Fe + 2H₂SO₄ → 2H₂O + 2FeSO₄

Methane Reduction Furnace

2FeTiO₃ + Fe₂SiO₄ → 2FeO + 2Si
FeSiO₃ + Mg₂SiO₄ + 2CH₄ → 1625°C → 2CO + 4H₂ + 2MgO + 2Si
MgSiO₃ → 250°C → 2CO + 6H₂
CaSiO₃ → 250°C → 2H₂O + 2H₂

Methane Reformer

Molten Electrolysis Reactor

2SiO₂ → 2SiO + O₂
2FeTiO₃ → 2FeO + 2TiO₂ + O₂
2FeO → 2Fe + O₂

Pyrolysis Reactor/Condenser

2SiO₂ → >2000°C → 2SiO + O₂
2FeTiO₃ → >2000°C → 2Fe + 2TiO₂ + O₂
2FeO → >2000°C → 2Fe + O₂
2Al₂O₃ → >2000°C → 4AlO + O₂
2Al₂O₃ → >2000°C → 2AlO + 2Al + O₂
2MgO → >2000°C → 2Mg + O₂
2CaO → >2000°C → 2Ca + O₂
2CaAl₂Si₂O₈ → >2000°C → 2Ca + 4AlO + 4SiO + 4O₂
2CaAl₂Si₂O₈ → >2000°C → 2Ca + 2AlO + 2Al + 4SiO + 5O₂

Hydrogen Reduction of Ilmenite/glass Process

Sulfuric Acid Reduction Process

Methane Reduction (Carbothermal) Process

Molten Electrolysis

Vapor Pyrolysis Process

Thermal Volatile Extraction
# Global Assessment of Lunar Volatiles

## Apollo Samples

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Concentration</th>
<th>Location</th>
<th>Environment</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo samples</td>
<td>Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)</td>
<td>Regolith everywhere</td>
<td>Sunlit</td>
<td>Top several meters; Gardened</td>
</tr>
<tr>
<td>Neutron Spectrometer</td>
<td>0.1 to 0.3 wt % water in Apatite 0 to 50 ppm water in volcanic glass</td>
<td>Regolith; Apatite</td>
<td>Low sun angle Permanent shadow &lt;100 K</td>
<td>Top 10's of meters</td>
</tr>
</tbody>
</table>

## Core Derived Water

<table>
<thead>
<tr>
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</table>

## Water/Hydroxyl

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<tr>
<th>Instrument</th>
<th>Concentration</th>
<th>Location</th>
<th>Environment</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3/DIVINER</td>
<td>0.1 to 1% water; 1-2% frost in shadowed craters</td>
<td>Upper latitudes</td>
<td>Low or no sunlight; Temperatures sustained at &lt;100 K</td>
<td>Top mm's of regolith</td>
</tr>
</tbody>
</table>

## Polar Volatiles

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Concentration</th>
<th>Location</th>
<th>Environment</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCROSS</td>
<td>3 to 10% Water equivalent Solar wind &amp; cometary volatiles (CO, H2, NH3, organics)</td>
<td>Poles</td>
<td>&lt;100 K, no sunlight</td>
<td>Below 10 to 20 cm of desiccated layer</td>
</tr>
</tbody>
</table>

## Polar Ice

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Concentration</th>
<th>Location</th>
<th>Environment</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mini SAR/RF</td>
<td></td>
<td>Poles</td>
<td>&lt;100 K, no sunlight</td>
<td>Top 2 meters</td>
</tr>
</tbody>
</table>
Development of Lunar ISRU Technologies & Systems

- **Resource Characterization & Mapping**
  - Lunar polar ice/volatile characterization
    - RESOLVE/Resource Prospector

- **Mission Consumable Production**
  - Oxygen Extraction from Regolith
    - Hydrogen Reduction
    - Carbothermal Reduction
    - Molten Oxide Electrolysis
    - Ionic Liquids
  - Oxygen and Fuel from Mars Atmosphere
    - Carbon Dioxide Capture
    - Mars Soil Drying
  - Water and Fuel from Trash
    - Steam Reforming
    - Combustion/Pyrolysis
  - Water Processing
    - Water Electrolysis
    - Water Cleanup

- **In-Situ Energy Generation, Storage & Transfer**
  - Solar Concentrators
  - Heat Pipes

- **Civil Engineering & Surface Construction**
  - Lunar Regolith Excavation
  - Lunar Regolith and Mars Soil Transfer
  - Lunar Regolith Size Sorting & Beneficiation
  - Lunar Regolith Simulant Production
  - Surface Preparation
NASA ISRU Soil/Water Extraction and Trash Processing Technology Development

Soil Acquisition and Excavation
- Sample drills and augers (JPL, ARC, SBIRs)
- Scoops and buckets (GRC, KSC, JPL, Univ., SBIRs)
- Auger and pneumatic transfer (KSC, GRC, SBIRs)

Water Extraction from Soils
- Closed soil reactors: fluidized & auger (JSC, SBIRs)
- Microwave soil processing (MSFC, JPL, SBIR)
- Open soil processing reactors (GRC)
- Downhole soil processing (MSFC, SBIRs)
- Capture for lunar/Mars soil processing (NASA, SBIRs)
- Water cleanup for lunar/Mars soil processing (KSC, JSC, SBIRs)

Trash/Waste Processing into Gases/Water
- Combustion, Pyrolysis, Oxidation/Steam Reforming (GRC, KSC, SBIRs)
Lunar Processing – Oxygen & Metal Extraction

Hydrogen Reduction of Regolith

- Two Fluidized H₂ Reduction Reactors - 10 kg/batch each (>900 °C)
- Water Electrolysis Module
- Regolith reactor exhaust - 660 kg O₂ per year

1. Heat Regolith to >900°C
2. React with Hydrogen to Make Water
3. Crack Water to Make O₂

Carbothermal Reduction of Regolith

- Solar Concentrator & Fiber-optic Cables
- Regolith Reduction Chamber
- Pneumatic Lift System and Auger Loading

1. Melt Regolith to >1600°C
2. React with Methane to produce CO and H₂
3. Convert CO and H₂ to Methane & Water
4. Crack Water to Make O₂

Molten Electrolysis of Regolith

- Solar Concentrator
- Molten Regolith Cell

1. Melt Regolith to >1600°C
2. Apply Voltage to Electrodes To Release Oxygen

PILOT

- 250 kg O₂ per year
- Lift System and Auger Loading
- Bucket Drum Excavator (IR&D)

Regolith hopper/auger lift system (2)
ISRU Development: System Testing and Integration Through Analog Field Tests

Hardware & Operation Integration at 2008 Analog Field Test

Resource Assessment (Prospecting)
- Habitats
- Power
- Propulsion
- Life Support & EVA
- Depots
- Product Storage & Utilization

Infrastructure Emplacement
- Water Electrolysis Module
- ROxygen Reactor
- PILOT System
- Combined Sample Metering & Crusher Unit
- Crushing/Sizing/Beneficiation
- Mining
- Science Involvement

Propulsion/Storage
- LOx/CH4 Storage & Thruster
- Fuel Cell
- H2 Hydride Storage
- Combined Sample Metering & Crusher Unit
- Crushing/Sizing/Beneficiation
- Spent Material Removal

Product Storage & Utilization
- Payload
- Propulsion/Storage
- Site Preparation & Infrastructure Emplacement
- Power
- Processing

Lunar Polar Volatile & Mineral Prospecting at 2012 Analog Field Test

Habitats
- Power
- Propulsion
- Life Support & EVA
- Depots
- Product Storage & Utilization

Science Involvement
- Science Involvement

Propulsion/Storage
- CH3(K-bottle)
- Solar Concentrator
- Water Electrolysis & O2 Storage
- Propulsion/Storage
- Processing
- Product Storage & Utilization

Nasa

Power
- Electrical Power
- Mechanical Power
- Propulsion/Storage
- Processing
- Product Storage & Utilization
## Lunar ISRU TRL Advancement

### Significant advancement from 2006 to 2010

<table>
<thead>
<tr>
<th>TRL increase in ETDP</th>
<th>At Start</th>
<th>At End</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Level</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar Volatile Characterization (RESOLVE)</td>
<td>1</td>
<td>5</td>
<td>4</td>
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<tr>
<td>H₂ Reduction of Regolith</td>
<td>2-3</td>
<td>5</td>
<td>2-3</td>
</tr>
<tr>
<td>CH₄ Reduction of Regolith</td>
<td>2-3</td>
<td>5</td>
<td>2-3</td>
</tr>
<tr>
<td>Molten Oxide Reduction of Regolith</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Trash Processing for Water/Methane Production</td>
<td>2</td>
<td>2-3</td>
<td>0-1</td>
</tr>
<tr>
<td><strong>Subsystem Level</strong></td>
<td></td>
<td></td>
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<tr>
<td>Regolith Transfer &amp; Handling</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Regolith Transport Into/Out of Reactor</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Beneficiation of Lunar Regolith</td>
<td>2-3</td>
<td>2-3</td>
<td>0-1</td>
</tr>
<tr>
<td>Size Sorting of Lunar Regolith</td>
<td>2-3</td>
<td>2-3</td>
<td>0-1</td>
</tr>
<tr>
<td>Oxygen Extraction From Regolith</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ Reduction of Regolith Reactor</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Gas/Water Separation &amp; Cleanup</td>
<td>2</td>
<td>4-5</td>
<td>2-3</td>
</tr>
<tr>
<td>CH₄ Reduction of Regolith Reactor</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>CH₄ Reduction Methanation Reactor</td>
<td>3-4</td>
<td>4-5</td>
<td>1-2</td>
</tr>
<tr>
<td>MOE of Regolith Anode/Cathode</td>
<td>1-2</td>
<td>3-4</td>
<td>2-3</td>
</tr>
<tr>
<td>MOE of Regolith Molten Mat'l Removal</td>
<td>1-2</td>
<td>3</td>
<td>1-2</td>
</tr>
<tr>
<td>MOE Cell and Valving</td>
<td>2-3</td>
<td>3</td>
<td>0-1</td>
</tr>
<tr>
<td>Water/Fuel from Trash Processing</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Trash Processing Reactor</td>
<td>2</td>
<td>2-3</td>
<td>0-1</td>
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<tr>
<td>In-Situ Energy Generation, Storage, and Transfer</td>
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<td></td>
<td></td>
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<td>Solar Thermal Energy for Regolith Reduction</td>
<td>2</td>
<td>5</td>
<td>3</td>
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**Advanced since 2010**
Lunar ISRU-Related Missions

Science/Prospecting Cubesats (SLS EM-1 2018)
- 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

Korea Pathfinder Lunar Orbiter (KPLO) - 2020
- ShadowCam: Map reflectance within permanently shadowed craters

Commercial Lunar Payload Services (CLPS)
- Request for Proposals for 50, 200, and 500 kg class payload missions

Dev. & Advancement of Lunar Instrumentation (DALI)
- Request for Proposals for science instruments & ISRU experiments
Space Commercialization & Mining
Promote Terrestrial Involvement in Space & ISRU: Spin In-Spin Out

Private Industry
Resource Prospecting
Deep Space Industries
Planetary Resources

Commercial Cargo & Crew
SpaceX
ATK Cybern
SpaceX Dragon2
Boeing CST-100
SNC Dream Chaser

ULA Cislunar 1000 Vision

Government Interest & Legislation
US Space Law & Directives
Luxembourg Space Law

US Space Resource Act

Public Law 114-90
114th Congress

An Act

To facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions, and for other purposes.

US Commercial Space Launch Competitiveness Act

Presidential Documents
Space Policy Directive-1 of December 11, 2017
Reinvigorating America's Human Space Exploration Program

NASA NextSTEP Broad Agency Announcements
Crew habitats

Satellite Servicing

FabLab

Power & Propulsion Studies

ISRU

Use lunar derived propellants
Final Comment

It’s not about being able to do ISRU.
It’s not about having the most efficient ISRU system.

It is about achieving the benefits of ISRU for a reasonable cost, mass, and risk.
Thank You

Questions?
## Main Natural Space Resources of Interest for Human Exploration

<table>
<thead>
<tr>
<th><strong>Moon</strong></th>
<th><strong>Mars</strong></th>
<th><strong>Asteroids</strong></th>
<th><strong>Uses</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water (Hydrogen)</strong></td>
<td>Icy Regolith in Permanently Shadowed Regions (PSR)</td>
<td>Water (Hydrogen)</td>
<td>- Drinking, radiation shielding, plant growth, cleaning &amp; washing</td>
</tr>
<tr>
<td></td>
<td>Solar wind hydrogen with Oxygen</td>
<td>- Making Oxygen and Hydrogen</td>
<td></td>
</tr>
<tr>
<td><strong>Oxygen</strong></td>
<td>Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite</td>
<td>Carbon Dioxide in the atmosphere (~96%)</td>
<td>- Breathing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Oxidizer for Propulsion and Power</td>
</tr>
<tr>
<td><strong>Carbon (Gases)</strong></td>
<td>Carbon Dioxide in the atmosphere (~96%)</td>
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<td>- Fuel Production for Propulsion and Power</td>
</tr>
<tr>
<td></td>
<td>CO, CO₂, and HC’s in PSR</td>
<td>Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites</td>
<td>- Plastic and Petrochemical Production</td>
</tr>
<tr>
<td></td>
<td>Solar Wind from Sun (~50 ppm)</td>
<td></td>
<td>- In situ fabrication of parts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Electrical power generation and transmission</td>
</tr>
<tr>
<td><strong>Metals</strong></td>
<td>Minerals in Lunar Regolith</td>
<td>Minerals in Mars Soils/Rocks</td>
<td>Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids</td>
</tr>
<tr>
<td></td>
<td>- Iron/Ti: Ilmenite</td>
<td>- Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Silicon: Pyroxene, Olivine, Anorthite</td>
<td>- Silicon: Silica, Phyllosilicates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Magnesium: Mg-rich Silicates</td>
<td>- Aluminum: Laterites, Aluminosilicates, Plagioclase</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Al: Anorthitic Plagioclase</td>
<td>- Magnesium: Mg-sulfates, Carbonates, &amp; Smectites, Mg-rich Olivine</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** Rare Earth Elements (REE) and Platinum Group Metals (PGM) are not driving Resources of interest for Human Exploration.
ISRU Implementation Life Cycle

Identify Resource & Products

- Resource Definition
- Prospecting
- Resource Analysis
- Mining Technology Readiness

Establish Site & Operations

- Site-Mine Planning
- Site-Mine Development
- Site-Mine Operations & Maintenance

PerformMiningOps

- Processing
- Product and Application

- Decision: Are Resources, Site, & Technology Viable for Exploitation?
- Milestone: Is Site & Infrastructure Ready for Initial Mining?
- Decision: Is Initial Mining and Product Viable for Mission Critical Use?
- Decision: Are Resources, Site, & Technology Viable for Full Mining?
- Milestone: Is Site & Infrastructure Ready for Full Mining?
Phased Approach to ISRU Architecture Incorporation

Current approach is to utilize phased approach to incorporate ISRU with minimum risk to mission success

Purpose
- Characterize local material/resources; evaluate terrain, geology, lighting, etc.
- Demonstrate critical technologies, functions, and operations
- Verify critical engineering design factors & environmental impacts
- Address unknowns or Earth based testing limitations (simulants, micro/low-g, contaminants, etc.)

ExoMars
- Resource Prospector
- Mars 2020
- Lunar Cubesats

Purpose
- Enhance or extend capabilities/reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verify use of ISRU products

Mars Surface Pathfinder
- Lunar short stay

Purpose
- Enhance or enable new mission capabilities
- Reduce mission risk
- Increase payload & science capabilities

Mars DRA 5.0
- Evolvable Mars Campaign
- Lunar Outpost
Leverage (Gear) Ratios using ISRU

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

- **Mars mission**
  - Oxygen \(\text{O}_2\) only 75% of ascent propellant mass: 20 to 23 mT
  - \(\text{O}_2/\text{Methane (CH}_4\) 100% of ascent propellant mass: 25.7 to 29.6 mT
  - Regeneration of rover fuel cell reactant mass

- **Phobos mission**
  - Trash to \(\text{O}_2/\text{CH}_4\) 1000+ kg of propellant

Potential 334.5 mT launch mass saved in LEO = 3 to 5 SLS launches avoided per Mars Ascent

### Table: Mass Delivered and Mass Added

<table>
<thead>
<tr>
<th>Stage</th>
<th>Initial Architecture Mass in LEO</th>
<th>Launch Pad Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground to LEO</td>
<td>-</td>
<td>20.4 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit (1→2)</td>
<td>4.3 kg</td>
<td>87.7 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface (1→3; e.g., Descent Stage)</td>
<td>7.5 kg</td>
<td>153 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit to Earth Surface (1→4→5; e.g., Orion Crew Module)</td>
<td>9.0 kg</td>
<td>183.6 kg</td>
</tr>
<tr>
<td>Lunar Surface to Earth Surface (3→5; e.g., Lunar Sample)</td>
<td>12.0 kg</td>
<td>244.8 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface to Lunar Orbit (1→3→4; e.g., Ascent Stage)</td>
<td>14.7 kg</td>
<td>300 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface to Earth Surface (1→3→4→5; e.g., Crew)</td>
<td>19.4 kg</td>
<td>395.8 kg</td>
</tr>
</tbody>
</table>

Estimates based on Aerocapture at Mars
ISRU Influence on Mission Architectures

ISRU has greatest influence at the site of the resource/production

- **Transportation** *(propellant is the largest ‘payload’ mass from Earth)*
  - Crew ascent from Moon/Mars surface
    - $O_2$ only provides up to 80% of propellant mass
    - $O_2$/fuel – full asset reuse and surface hopping
  - Crew/Cargo ascent and descent from Moon/Mars surface – reusable
  - Supply orbital depots for in-space transportation
    - Cis-lunar (L1 to GEO or LEO)
    - Trans-Mars

- **Power** *(mission capabilities are defined by available power)*
  - Nighttime power storage/generation
    - Fuel cell reactants – increase amount and regeneration
    - Thermal storage
  - Mobile power – fuel cell reactants
  - Power generation: in situ solar arrays, ‘geo’thermal energy

- **Infrastructure and Growth**
  - Landing pads and roads to minimize wear and damage
  - Structures and habitats

- **Crew Safety**
  - Radiation protection
  - Logistics shortfalls (life support consumables, spare parts)
Benefit of ISRU Derived Propellants is a Function of Lander Design, Use, & Rendezvous/Depot Orbit

**ISRU for Lunar Ascent/Descent & Other Destination Use**
- Deliver O$_2$/Fuel or Water to Depots for usage elsewhere
  - Return to Earth (cis-lunar)
  - Delivery to LEO
  - NEO’s and Mars
- Requires reusable single stage lunar lander w/ substantial payload capability
- Cryos vs Water

**ISRU for Lunar Ascent/Descent & Global Surface Exploration**
- Produce O$_2$ & Fuel
- Requires reusable single stage lunar lander
- Does not require orbital depot for ascent/descent if both O$_2$ & fuel can be produced on the surface

**ISRU For Lunar Ascent Only**
- Propellant for Ascent Only; Descent Propellant from Earth or Orbital Depot
- Approach considered for Constellation & most Lunar architecture studies since it supports two stage non-reusable lander concepts from start

The greater the Delta-V of maneuvers performed by ISRU-derived derived propellants, the greater the benefit
## ISRU Impact on Exploration System Requirements

<table>
<thead>
<tr>
<th></th>
<th>Without ISRU</th>
<th>With ISRU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Propulsion</strong></td>
<td>Propellant selection based on development cost and performance</td>
<td>Propellant selection based on ISRU products from available resources</td>
</tr>
<tr>
<td></td>
<td>Propulsion cycle (pressure vs pump) based on development cost and performance</td>
<td>Production cycle based on influence of ISRU on Delta-V and reusability</td>
</tr>
<tr>
<td></td>
<td>Non-reusable or limited reusability with Earth supplied propellants and depots</td>
<td>Reusability with single stage landers possible</td>
</tr>
<tr>
<td><strong>Life Support</strong></td>
<td>Air and Water recycling technologies and systems based on maximizing closure of oxygen and water loops</td>
<td>ISRU products can reduce the level of closure required, thereby reducing development cost and system complexity</td>
</tr>
<tr>
<td></td>
<td>Trash/waste processing aimed at maximizing water extraction and minimizing oxygen usage</td>
<td>Trash/waste transferred to ISRU to maximize fuel production and minimize residuals. Trash processing hardware can be minimized to some level of drying</td>
</tr>
<tr>
<td><strong>Habitat</strong></td>
<td>Radiation and micrometeoroid shields based on Earth supplied materials. Storm closets to minimize mass impact</td>
<td>Regolith (piling or habitat burial) or in-situ water for greater radiation protection possible. This can change habitat layout and eliminate need for storm closets</td>
</tr>
<tr>
<td></td>
<td>Fully constructed on Earth. Hard shell or inflatable</td>
<td>In-situ shelters construction possible. Consumables for inflation</td>
</tr>
<tr>
<td></td>
<td>Self-contained thermal management</td>
<td>Use of thermal energy sharing with ISRU or creation of in-situ thermal storage for heat removal or usage</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
<td>Mobility primarily based on science and human activities</td>
<td>Mobility based on high torque/low speed excavation and civil engineering needs</td>
</tr>
<tr>
<td></td>
<td>Full situational awareness and flexible navigation system</td>
<td>Simplified situational awareness and navigation required for ISRU applications</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>Self-contained units. Solar array and batteries</td>
<td>Distributed power generation and storage, esp. fuel cell reactant storage and regeneration</td>
</tr>
<tr>
<td></td>
<td>Fuel cell reactant based on regeneration technique alone</td>
<td>Fuel cell reactant based on in-situ resources available</td>
</tr>
<tr>
<td></td>
<td>Increase in power generation is a function of delivery from Earth</td>
<td>In-situ growth of power thru fuel cell consumable, in-situ thermal, and in-situ manufacturing</td>
</tr>
</tbody>
</table>
ISRU Integrated 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/Water Processing
- Manufacturing
- Civil Engineering & Construction

**Support Functions & Elements**
- Power Generation & Storage
- $O_2$, $H_2$, and $CH_4$ Storage and Transfer

**In-Space Construction**
- Civil Engineering, Shielding, & Construction

**In-Space Manufacturing**
- Parts, Repair, & Assembly

**ISRU Resources & Processing**
- Resource & Site Characterization
- Regolith/Soil Excavation & Sorting
- Regolith/Soil Transport
- Water/Volatile Extraction
- Regolith Crushing & Processing
- Regolith for $O_2$ & Metals

**Life Support & EVA**
- Pressurized Rover
- Habitations

**Habitats**
- Regenerative Fuel Cell

**Modular Power Systems**
- Solar & Nuclear

**Lander/Ascent**
- Used Descent Stage
- Propellant Depot
- Storage

**Surface Hopper**
- Lander/Ascent
ISRU Capability-Function Flow Chart

Survey/Prospect
- Global Resource Assessment
- Site Imaging/Characterization
- Locate Sample/Mining Locations
- Select Mining Site/Anchor to Surface
- Physical/Mineral/Volatile Assessment
- Resource Analysis & Mapping

In-Situ Construction
- Produce Feedstock for Construction
- Resource Acquisition/Transfer
- Resource Assessment

In-Situ Energy
- Solid Resource Preparation
- Gas Resource Preparation
- Extract Oxygen and/or Metals
- Extract Water/Volatiles

In-Situ Manufacturing
- Produce Feedstock for Manufacturing
- Collect & Separate Oxygen/Metals
- Collect & Separate Water/Volatiles
- Collect & Separate Products

Primary Process
- Produce O₂, Fuel, and/or water
- Collect & Separate Products

Secondary Process
- Collect Processed Matt
- Collect Precursors

Consumable Production
- Extract Oxygen and/or Metals
- Collect & Separate Oxygen/Metals
- Collect & Separate Water/Volatiles
- Collect & Separate Products

In-Situ Construction
- Produce Feedstock for Construction
- Resource Acquisition/Transfer

Global Resource Assessment
- Concrete 3-D Construction Material
- Shielding Material

Consumable Production
- Concrete 3-D Construction Material
- Shielding Material

Primary Process
- Produce O₂, Fuel, and/or water
- Collect & Separate Products

Secondary Process
- Collect Processed Matt
- Collect Precursors

In-Situ Construction
- Produce Feedstock for Construction
- Resource Acquisition/Transfer

Primary Process
- Produce O₂, Fuel, and/or water
- Collect & Separate Products

Secondary Process
- Collect Processed Matt
- Collect Precursors
Mission Consumables: Regolith vs Polar Water/Volatiles

- **Oxygen from Regolith**
  - Can be incorporated into the architecture from the start with low-moderate risk
    - Resource characteristics and parameters are reasonably well known
    - Multiple approaches for extraction possible; 2 demonstrated to TRL 4-5 for short periods of time
  - Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)
  - Experience from regolith excavation, beneficiation, and transfer applicable to In Situ Manufacturing and Construction and Mars hydrated soil extraction

- **Water and Volatiles from Polar Regolith**
  - Cannot be incorporated into the architecture from the start with low-moderate risk
    - Resource characteristics and parameters are not well known
  - Polar Water/Volatiles is “Game Changing” and Enables Long-term sustainability
    - Availability of water for propellants can strongly influence propulsion system design (propellant selection and reusability) and transportation architecture (depots, hoppers, lander reuse, etc.)
    - Provides 100% of chemical propulsion propellant mass
    - Reuse of cargo and human landers and transportation elements can reduce long-term mission costs and enable new mission concepts
    - Provides significantly more options for radiation protection, food production, etc. over what is available from lunar regolith

NASA should pursue both Development and Insertion of Oxygen from Regolith with Prospecting and Evaluation of Polar Ice/Volatiles for Long Term Sustainability
Why Perform Analog Field Testing for Science, Exploration & ISRU?

Key Programmatic Analogue Field Test Purpose
- Expand NASA and CSA partnership; Include other International Partners in analogues
- Expand integration of Science & Engineering for exploration, particularly with ISRU
- Link separate technology and system development activities
- Develop and enhance remote operations and mission concepts; introduce new technologies
- Evaluate parallel paths and competing concepts
- Be synergistic with other analogue test activities (past and future)
- Public Outreach, Education, and “Participatory Exploration”

Key Technical Analogue Field Test Purpose
- Stress hardware under realistic environmental and mission operation conditions to improve path to flight
- Improve remote operations & control of hardware for surface exploration and science
- Promote the testing of multiple surface and transportation systems to better understand integration and operation benefits and issues
- Promote use of common software, interfaces, & standards for control and operation (ISECG)
- Focus on interfaces, standards, and requirements (ISECG)
- Focus on modularity and ‘plug n play’ integration (ISECG)

Intrinsic Benefits of Field/Analog Testing
- Develop Scientists, Engineers, and Project Managers for future flight activities
- Develop International Partnerships
- Develop Teams and Trust Early
- Develop Data Exchange & Interactions with International Partners (ITAR)
Lunar Prospecting

- Scarab Rover
- RESOLVE
- TriDAR Vision System
- Tweels

Outpost-Scale $O_2$ from Regolith

- ROxygen $H_2$ Reduction
- Water Electrolysis
- Cratos Excavator

- PILOT $H_2$ Reduction
- Water Electrolysis
- Bucketdrum Excavator

Process Control & Science

- Moessbauer
- Mini Chemin XRD/XRF

**Canadian Space Agency**

- TriDAR imager, Satellite communications, remote operation of Drill and TriDAR navigation, and on-site personnel and payload mobility
- NORCAT, Xiphos, Argo, Virgin Technologies, EVC, Ontario Drive Gear, University of Toronto

**German Space Agency (DLR)**

- Instrumented “Mole” & Sample Capture Mole

**Carnegie Mellon University**

- SCARAB Rover

**JPL Partnership with Michelin on ‘Tweels’ testing**
<table>
<thead>
<tr>
<th>Site &amp; Resource Exploration</th>
<th>Participant/Hardware Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>RESOLVE Drill</td>
<td>NASA/NORCAT</td>
</tr>
<tr>
<td>Combined Moessbauer/XRF</td>
<td>JSC KA/University of</td>
</tr>
<tr>
<td></td>
<td>Mainz (Germany) &amp; DLR</td>
</tr>
<tr>
<td>MMAMA/FSAT Instruments</td>
<td>Honeybee Robotics</td>
</tr>
<tr>
<td>- Cone Penetrometers</td>
<td>Honeybee Robotics</td>
</tr>
<tr>
<td>(Dynamic, Percussive, &amp;</td>
<td>Arizona State Univ.</td>
</tr>
<tr>
<td>- Heat Flow Probe</td>
<td>LaRC, APL/Univ of Wash.</td>
</tr>
<tr>
<td>- Multispectral Microscopic</td>
<td>GSFC</td>
</tr>
<tr>
<td>Imager (MMI)</td>
<td>KSC, JSC, GRC, ASRC</td>
</tr>
<tr>
<td>- X-Ray Diffraction</td>
<td>ARC, UC Davis, &amp; McMaster</td>
</tr>
<tr>
<td>- Borehole XRF</td>
<td>Univ</td>
</tr>
<tr>
<td>- VAPoR Mass Spectrometer</td>
<td></td>
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<tr>
<td>- RESOLVE Chemical Plant</td>
<td></td>
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<tr>
<td>– Gas Chromatograph</td>
<td></td>
</tr>
<tr>
<td>- Data Integration</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Site Preparation &amp; Excavation</th>
<th>Participant/Hardware Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Concentrator &amp; fiber</td>
<td>PSI (SBIR Phase III)</td>
</tr>
<tr>
<td>optics with sun tracking</td>
<td>KSC</td>
</tr>
<tr>
<td>system</td>
<td></td>
</tr>
<tr>
<td>Resistive heater surface</td>
<td></td>
</tr>
<tr>
<td>sintering</td>
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</table>

<table>
<thead>
<tr>
<th>Oxygen Extraction from Regolith</th>
<th>Participant/Hardware Supplier</th>
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</thead>
<tbody>
<tr>
<td>Carbothermal reduction module</td>
<td>Orbitec</td>
</tr>
<tr>
<td>with regolith feed system</td>
<td>JSC</td>
</tr>
<tr>
<td>ROxygen Gen 1 water electrolysis</td>
<td>KSC/ASRC &amp; Honeybee</td>
</tr>
<tr>
<td>module</td>
<td></td>
</tr>
<tr>
<td>Pneumatic regolith lift device</td>
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<table>
<thead>
<tr>
<th>Energy</th>
<th>Participant/Hardware Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Concentrator &amp; fiber</td>
<td>PSI (SBIR Phase III)</td>
</tr>
<tr>
<td>optics with sun tracking system</td>
<td>KSC</td>
</tr>
<tr>
<td>Sunlight flux/intensity</td>
<td>PSI</td>
</tr>
<tr>
<td>measurement instrument</td>
<td>NORCAT &amp; JSC</td>
</tr>
<tr>
<td>Power conditioning for fuel</td>
<td></td>
</tr>
<tr>
<td>cell power system</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product Storage and Utilization</th>
<th>Participant/Hardware Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid oxygen/methane tank</td>
<td>JSC</td>
</tr>
<tr>
<td>and cryocooler cart</td>
<td>JSC and CSA</td>
</tr>
<tr>
<td>Hydrogen hydride tanks</td>
<td>JSC and WASK</td>
</tr>
<tr>
<td>O₂/CH₄ thruster hot-fire into</td>
<td></td>
</tr>
<tr>
<td>tephra</td>
<td></td>
</tr>
</tbody>
</table>

8 System Modules – 7 Instruments
6 NASA Centers, 6 Small Businesses, 5 Universities
(42 people plus visitors)
2nd ISRU Analog Field Test: 2010 (2 of 3)

CSA Hardware/Software List

Site & Resource Exploration
- TriDAR vision system (Triangulating LIDAR)
- ERT (Extended Range TriDAR, also called DTO)
- HPC (data compression software) (Hybrid Processing Card)
- Ground Penetrating Radar (3)
- 3D Data Fusion (3D subsurface visualization software)
- EXPLORE (ISRU site selection filter and algorithm software)
- Geotechnical Measurement Equipment (Cone Penetrometer/Shear Vane)

Participant/Hardware Supplier
- Neptec
- Neptec
- Xiphos
- Noggin
- Xiphos
- NORCAT
- NORCAT

Site Preparation & Excavation
- ISRU MAT/ANT Rovers (6) (Multi Agent Teaming/Artificial Neural Tissue)
- Articulated joint (coupling of 2 rovers to accommodate heavy payloads)
- Plow Attachments (3)
- Excavation Attachments: Long (1) & Short (1)
- Autonomous Regolith Delivery system (1)
- Solar Sintering XYZ Table Rastering Device (1)

Participant/Hardware Supplier
- NORCAT/ODG/Univ of Toronto
- NORCAT/ODG
- NORCAT/EVC
- NORCAT/EVC
- NORCAT/Neptec
- NORCAT

Product and Utilization
- Mining vehicle Fuel Cell/H₂ Hydride Tank (1 at 10 KW)

Participant/Hardware Supplier
- NRCan (Natural Resources Canada)

Infrastructure
- Satellite Communications to CSA HQ (Mainland) VoIP service
- Secure telemetry links to other agencies from CSA
- On-Site Wireless Communications
- Multi media studio
- ExDOC Control Center at CSA HQ (Exploration Development Ops Centre)
- Large Rover (Argo Avenger)
- Lunar Link Emulator (LLE)
- Base Camp (mining camp structures), personnel tracking system
- Food Preparation

Participant/Hardware Supplier
- CSA/CRC (Communications Research Center)
- CSA/CRC
- Virgin Tech
- CSA/CRC
- CSA
- CSA/Ontario Drive (ODG)
- Xiphos
- CSA/NRCan
- YUM Culinary/Cambrian College

12 System Modules & Attachments; Infrastructure
3 Government Agencies, 8 Small Businesses, 2 Universities
(46 people plus visitors)
Resource Assessment (Prospecting)

GPR
Geo Tech
Mossbau
RESOLVE
VAPoR
Mole

Science Involvement

Load-Haul-Dump Rover

Propulsion/Storage

CH₄ (K-bottle)
LO₂/CH₄ Storage & Thruster Firing

Solar Concentrator

Solar Power

Fuel Cell
H₂ Hydride Storage

Power

H₂, O₂ (Air)

H₂, H₂O

Product Storage & Utilization

Site Preparation & Infrastructure Emplacement

Thruster Firing

Sintered Pad
X-Y-Z Table
Resistive Sintering on Rover
3 DoF Blade on Rover

Electrical Power

O₂

Processing

Water 5-25 psig 200 g/day

Water Electrolysis & GO₂ Storage

Carbothermal Reduction Reactor

O₂

H₂

Hydrogen 80-250 psig 320 g/hr

Hydrogen 5-150 psig; 17 g/hr

Excavation & Back-blading

Tephra Delivery & Removal

Pneumatic Regolith Transfer

Load-Haul-Dump Rover

Hydrogen 5-150 psig; 17 g/hr
3rd ISRU Analog Field Test: Lunar Polar Prospecting Mission Simulation

- Solar Array (NASA)
- LAVA Gas Chromatograph/Mass Spectrometer (NASA)
- OVEN Sample Heating Unit (NASA)
- Neutron Spectrometer (NASA)
- Near Infrared Spectrometer (NASA)
- Avionics & Software (CSA & NASA)
- Mission Control, Timeline, Traverse & Data Display Software (NASA)
- DESTIN Drill System (CSA)
- Artemis Jr. Rover (CSA)
- Rover Communications (CSA)
- Total Station-Relative Navigation (CSA)
- Situation Awareness Camera & Lights (CSA)
- Lander (NASA)
- Communications (NASA)
- Situation Awareness Camera (NASA)
3rd ISRU Analog Field Test: Lunar Polar Prospecting Mission Simulation

- Panoramic Video Camera
- 400 MHz Ground Penetrating Radar (GPR)
- GPS/Mössbauer/X-Ray Spectrometer Avionics Box
- Magnetic Susceptibility Sensor on Actuator
- 3-axis accelerometer
- Panoramic Video Camera Controller Box
- Rover video camera transmitter
- Mechanized Sample Processing and Handling System (MeSH)
- Volatile Analysis by Pyrolysis Regolith (VAPoR)
- Juno II Rover with actuators for Mössbauer, GPR, and Magnetic Susceptibility Probe (CSA)