Overview of Past Lunar \textit{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
- Propulsion
- Power
- Life Support & EVA
- Depots

Processing
- Crushing/Sizing/Beneficiation
- Product Storage & Utilization
- Waste
- Remediation
- Spent Material Removal

Comm & Autonomy
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

Solves Terrestrial Challenges & Enables Space Commercialization

- 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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Reduces dependence on Earth
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 \( (O_2) \) and water \( (H_2O) \)
  - Produce/regenerate Fuel Cell Reactants (in conjunction with Power)
  - Gases for science and cleaning
  - **Propellant production**: \( O_2 \) and fuel \( (H_2 \text{ and/or CH}_4) \) 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
- **Extraction & Regolith Processing for O₂ 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

- **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%

Fluidized Bed Reactor

\[
2\text{FeTiO}_3 + 2\text{H}_2 \xrightarrow{900°C} \text{2H}_2\text{O} + \text{2Fe} + \text{2TiO}_2 \\
\text{O}_2 + \text{2H}_2 \xrightarrow{25°C} \text{2H}_2\text{O}
\]

Desolve/Digest Reactor

\[
2\text{FeTiO}_3 + \text{2H}_2\text{SO}_4 \rightarrow \text{2H}_2\text{O} + \text{2FeSO}_4 + \text{2TiO}_2 \\
\text{O}_2 + \text{2Fe} + \text{2H}_2\text{SO}_4 \rightarrow \text{2H}_2\text{O} + \text{2FeSO}_4
\]

Methane Reduction Furnace

\[
2\text{FeTiO}_3 \rightarrow \text{2TiO}_2 + \text{2Fe} \\
\text{Fe}_2\text{SiO}_3 \rightarrow \text{FeO} + \text{Si} \\
\text{Mg}_2\text{SiO}_4 + 2\text{CH}_4 \xrightarrow{1625°C} 2\text{CO} + 4\text{H}_2 + 2\text{MgO} + \text{Si} \\
\text{MgSiO}_3 \rightarrow \text{MgO} + \text{Si} \\
\text{CaSiO}_3 \rightarrow \text{CaO} + \text{Si} \\
\text{2H}_2\text{O} + \text{2CH}_4 \xrightarrow{250°C} 2\text{CO} + 6\text{H}_2 \\
\text{2H}_2\text{O} \xrightarrow{25°C} \text{2H}_2 + \text{O}_2
\]

Molten Electrolysis Reactor

\[
2\text{SiO}_2 \rightarrow 2\text{SiO} + \text{O}_2 \\
2\text{FeTiO}_3 \rightarrow 2\text{Fe} + 2\text{TiO}_2 + \text{O}_2 \\
2\text{FeO} \rightarrow 2\text{Fe} + \text{O}_2
\]

Pyrolysis Reactor/Condenser

\[
2\text{SiO}_2 \xrightarrow{>2000°C} 2\text{SiO} + \text{O}_2 \\
2\text{FeTiO}_3 \xrightarrow{>2000°C} 2\text{Fe} + 2\text{TiO}_2 + \text{O}_2 \\
2\text{FeO} \xrightarrow{>2000°C} 2\text{Fe} + \text{O}_2 \\
2\text{Al}_2\text{O}_3 \xrightarrow{>2000°C} 4\text{AlO} + \text{O}_2 \\
2\text{Al}_2\text{O}_3 \xrightarrow{>2000°C} 2\text{AlO} + 2\text{Al} + \text{O}_2 \\
2\text{MgO} \xrightarrow{>2000°C} 2\text{Mg} + \text{O}_2 \\
2\text{CaO} \xrightarrow{>2000°C} 2\text{Ca} + \text{O}_2 \\
2\text{CaAl}_2\text{Si}_2\text{O}_8 \xrightarrow{2500°C} 2\text{Ca} + 4\text{AlO} + 4\text{SiO} + 4\text{O}_2 \\
2\text{CaAl}_2\text{Si}_2\text{O}_8 \xrightarrow{2500°C} 2\text{Ca} + 2\text{AlO} + 2\text{Al} + 4\text{SiO} + 5\text{O}_2
\]

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
![Apollo Samples Image]

<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)</td>
<td>Regolith everywhere</td>
<td>Sunlit</td>
<td>Top several meters; Gardened</td>
</tr>
<tr>
<td>Neutron Spectrometer</td>
<td>Carbon (100 to 150 ppm)</td>
<td>Regolith; Apatite</td>
<td>Sunlit</td>
<td>Top 10's of meters</td>
</tr>
<tr>
<td></td>
<td>Helium (3 to 50 ppm)</td>
<td>Upper latitudes</td>
<td>Low sun angle</td>
<td>Top mm's of regolith</td>
</tr>
</tbody>
</table>

### Instrument
- Apollo samples Neutron Spectrometer
- M3/DIVINER
- LCROSS
- Mini SAR/RF

### Core Derived Water
- 0.1 to 0.3 wt % water in Apatite
- 0 to 50 ppm water in volcanic glass

### Water/Hydroxyl
- 0.1 to 1% water;
- 1-2% frost in shadowed craters

### Polar Volatiles
- 3 to 10% Water equivalent Solar wind & cometary volatiles (CO, H2, NH3, organics)

### Polar Ice
- Ice layers
- Poles
- Poles; Permanent shadowed craters
- <100 K, no sunlight

### Locations
- Regolith everywhere
- Upper latitudes

### Environments
- Sunlit
- Low sun angle
- Permanent shadow <100 K
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

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

- Two Fluidized H₂ Reduction Reactors - 10 kg/batch each (>900 °C)
- Regolith hopper/auger lift system (2)
- Regolith reactor exhaust
- 660 kg O₂ per year

**PILOT**

- Hydrogen Storage
- O₂ Cryo Tank
- Hydrogen Storage Reactor - 17 kg/batch
- Rotating H₂ Reduction Reactor - 17 kg/batch

**HYDROGEN STORAGE**

**Regolith reactor exhaust**

**PILOT**

- Lift System and Auger Loading
- Bucket Drum Excavator (IR&D)

**Carbothermal Reduction of Regolith**

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

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

**Molten Electrolysis of Regolith**

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

- Molten Regolith Core (current strandline in red)
- Anode (Fe³⁺) → 3e⁻ → Fe
- Cathode (O²⁻) + 2e⁻ → O₂

**O₂ Cryo Tank**

250 kg O₂ per year

**O₂ Cryo Tank**

660 kg O₂ per year

125 to 250 kg O₂ per year
ISRU Development: System Testing and Integration Through Analog Field Tests

Hardware & Operation Integration at 2008 Analog Field Test

Hardware & Operation Integration at 2010 Analog Field Test

Lunar Polar Volatile & Mineral Prospecting at 2012 Analog Field Test
### 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>H$_2$ Reduction of Regolith</td>
<td>2-3</td>
<td>5</td>
<td>2-3</td>
</tr>
<tr>
<td>CH$_4$ 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>
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<tr>
<td>Regolith Transfer &amp; Handling</td>
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<tr>
<td>Regolith Transport Into/Out of Reactor</td>
<td>2</td>
<td>5</td>
<td>3</td>
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<tr>
<td>Beneficiation of Lunar Regolith</td>
<td>2-3</td>
<td>2-3</td>
<td>0-1</td>
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<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>
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<tr>
<td>H$_2$ 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>CH$_4$ Reduction of Regolith Reactor</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>CH$_4$ 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>
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<td>Trash Processing Reactor</td>
<td>2</td>
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<td>In-Situ Energy Generation, Storage, and Transfer</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Solar Thermal Energy for Regolith Reduction</td>
<td>2</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

- **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 InfracRed 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

Government Interest & Legislation
US Space Law & Directives

Luxembourg Space Law

US Commercial Space Launch Competitiveness Act

US Space Resource Act

Presidential Documents
Space Directive 1

NASA NextSTEP Broad Agency Announcements
Crew habitats
FabLab
Power & Propulsion Studies

ULA Cislunar 1000 Vision

Satellite Servicing

Use lunar derived propellants

Commercial Cargo & Crew

SpaceX
ATK
Cygnus

SpaceX
Dragon2
Boeing
CST-100

SNC
Dream Chaser

ULTRA C Wol

Use lunar derived propellants

Use lunar derived propellants
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>Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhydrated Sulfates</td>
<td>Subsurface Regolith on C-type Carbonaceous Chondrites</td>
</tr>
<tr>
<td>Solar wind hydrogen with Oxygen</td>
<td>Subsurface Icy Soils in Mid-latitudes to Poles</td>
<td></td>
<td>▪ Drinking, radiation shielding, plant growth, cleaning &amp; washing</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>Minerals in Regolith on S-type Ordinary and Enstatite Chondrites</td>
</tr>
<tr>
<td>▪ CO, CO₂, and HC’s in PSR</td>
<td>Carbon Dioxide in the atmosphere (~96%)</td>
<td>Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites</td>
<td></td>
</tr>
<tr>
<td>Solar Wind from Sun (~50 ppm)</td>
<td></td>
<td></td>
<td>▪ Fuel Production for Propulsion and Power</td>
</tr>
<tr>
<td><strong>Carbon (Gases)</strong></td>
<td>Minerals in Lunar Regolith</td>
<td>Minerals in Mars Soils/Rocks</td>
<td>▪ <em>In situ</em> fabrication of parts</td>
</tr>
<tr>
<td>▪ Iron/Ti: Ilmenite</td>
<td>▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite</td>
<td>▪ Silicon: Silica, Phyllosilicates</td>
<td>▪ Electrical power generation and transmission</td>
</tr>
<tr>
<td>▪ Silicon: Pyroxene, Olivine, Anorthite</td>
<td>▪ Silicon: Silica, Phyllosilicates</td>
<td>▪ Aluminum: Laterites, Aluminosilicates, Plagioclase</td>
<td></td>
</tr>
<tr>
<td>▪ Magnesium: Mg-rich Silicates</td>
<td>▪ Magnesium: Mg-sulfates, Carbonates, &amp; Smectites, Mg-rich Olivine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>▪ Al: Anorthitic Plagioclase</td>
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## Metals

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<td>▪ Iron/Ti: Ilmenite</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>▪ Silicon: Pyroxene, Olivine, Anorthite</td>
<td>▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite</td>
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<td>▪ Magnesium: Mg-rich Silicates</td>
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<td>▪ Aluminum: Laterites, Aluminosilicates, Plagioclase</td>
<td></td>
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</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

**Establish Site & Operations**
- Mining Technology Readiness
- Site-Mine Planning
- Site-Mine Development

**Perform Mining Ops**
- Site-Mine Operations & Maintenance
- Processing
- Product and Application

- Determine Resource Utilization End Goals
- Initial Feasibility Study
- Multi-Site Evaluation
- Initial Cost Analysis
- Weigh Alternatives
- **Go/No-Go Decision**
- Plan Program and Approach

- Global Resource Evaluation
- Site Selection
- Site Imaging/Characterization
- Resource Identification and Verification
- Estimate Reserve Size
- Test/Sample Resource Quality
- Understand Geotechnical Properties of Minerals
- Resource Analysis for Other Potential Uses/Users
- Assess Return On Investment
- Demonstrate ‘Scalable’ Hardware
- Demonstrate Operations for All Processes from Extraction to Product Storage
- Evaluate Processing Options
- Select Mining Site
- Environmental Analysis
- Electronic Modeling & Simulation
- Develop Power Sources
- Infrastructure Analysis
- Design Transportation and Comm.
- Contingency Planning
- Infrastructure Development/Set up
- Site Preparation, Landing, and Roads
- Construct Infrastructure and Processing Facilities
- Excavation
- Resource Extraction
- Manage Operations
- Remediate Site as Needed
- Sort and Refine Resources
- Process Resources Into Feedstocks
- Resource Transfer
- Recycle or Repurpose Wastes or Byproducts for Useful Purposes
- Export Resources from Site
- Convert Resource to Finished Product
- Deliver to End Users

**Pilot Operation – Not Human Mission Critical**

**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?

**Full Operation - Human Mission Critical**

**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

<table>
<thead>
<tr>
<th>Resource Prospecting/Proof-of-Concept Demos</th>
<th>Engineering Validation &amp; Pilot Operations</th>
<th>Utilize/Full Implementation Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Supplied</td>
<td></td>
<td>Mission Criticality</td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>0%</td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

**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

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

- Mars mission
  - Oxygen (O$_2$) only 75% of ascent propellant mass: 20 to 23 mT
  - O$_2$/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 O$_2$/CH$_4$ 1000+ kg of propellant

A Kilogram of Mass Delivered Here...

<table>
<thead>
<tr>
<th>Mass Source</th>
<th>LEO to LEO</th>
<th>LEO to Lunar Orbit</th>
<th>LEO to Lunar Surface</th>
<th>LEO to Lunar Orbit to Earth Surface</th>
<th>Lunar Surface to Earth Surface</th>
<th>LEO to Lunar Surface to Lunar Orbit</th>
<th>LEO to Lunar Surface to Earth Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Architecture Mass in LEO</td>
<td>-</td>
<td>4.3 kg</td>
<td>7.5 kg</td>
<td>9.0 kg</td>
<td>12.0 kg</td>
<td>14.7 kg</td>
<td>19.4 kg</td>
</tr>
<tr>
<td>Launch Pad Mass</td>
<td>20.4 kg</td>
<td>87.7 kg</td>
<td>153 kg</td>
<td>183.6 kg</td>
<td>244.8 kg</td>
<td>300 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 O₂/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 O₂ & Fuel
- Requires reusable single stage lunar lander
- Does not require orbital depot for ascent/descent if both O₂ & 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 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 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
- \( \text{O}_2, \text{H}_2, \text{and CH}_4 \) Storage and Transfer

ISRU Resources & Processing
- Resource & Site Characterization
- Regolith/Soil Excavation & Sorting
- Regolith/Soil Transport
- Water/Volatile Extraction
- Regolith Crushing & Processing
- Regolith for \( \text{O}_2 & \text{Metals} \)
- \( \text{H}_2\text{O}, \text{CO}_2 \) from Soil/Regolith
- \( \text{CO}_2 \) from Mars Atmosphere
- Regolith, Metals, & Plastics
- Metals & Plastics
- \( \text{CH}_4, \text{O}_2, \text{H}_2\text{O} \)

Modular Power Systems
- Solar & Nuclear
- Regenerative Fuel Cell

Life Support & EVA
- Pressurized Rover
- Habitats
- Used Descent Stage
- Propellant Depot
- Lander/Ascent

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

In-Space Manufacturing
- Parts, Repair, & Assembly

Storage

Support Functions
- Power Generation & Storage
- \( \text{O}_2, \text{H}_2, \text{and CH}_4 \) Storage and Transfer
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

In-Situ Energy
- Extract Oxygen and/or Metals
- Collect & Separate Oxygen/Metals

In-Situ Manufacturing
- Produce Feedstock for Manufacturing
- Produce Resources

Consumable Production
- Produced Feedstock
- Resource Preparation
- Solid Resource Preparation
- Extract Water/Volatiles
- Collect & Separate Water/Volatiles

Primary Process
- Collect & Separate Products
- Oxygen Water Fuels Life Support Gases

Secondary Process
- Extract Oxygen and/or Metals
- Collect & Separate Oxygen/Metals
- Produce O2, Fuel, and/or water

Resource Acquisition
- Resource Acquisition
- Transfer
- Resource Preparation
- Gas Resource Preparation
- Hard Mat/Trash
- Granular Mat
- Arm/Gas
- Trash/Granular

Consumeable Production
- Consumable Production
- Produce Feedstock for Construction
- Concrete 3-D Construction Material
- Shielding Material

Manufacturing
- Energy Manufacturing
- Concrete
- Metals
- Plastic
- Ceramics
- 3-D Construction Material
- Plastic Precursors

Site Selection
- Site Selection
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)
1st ISRU Analog Field Test: 2008 (1 of 2)

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**
1st ISRU Analog Field Test: 2008 (2 of 2)

Resource Assessment (Prospecting)

Science Involvement

Bucketdrum Excavator Rover

Center Scoop Excavator Rover

Mining

Combined Sample Metering & Crusher Unit

Crushing/Sizing/Beneficiation

Water Electrolysis Module
ROxygen Reactor
PILOT System

Processing

Spent Material Removal

Infrastructure Emplacement

Habitats
Power
Propulsion
Life Support & EVA
Depots

Product Storage & Utilization

Science Involvement

RESOLVE
XRD/XRF
Mossbaeur
Mole
Mole
Site & Resource Exploration
- RESOLVE Drill
- Combined Moessbauer/XRF
- MMAMA/FSAT Instruments
  - Cone Penetrometers (Dynamic, Percussive, & Manual)
  - Heat Flow Probe
  - Multispectral Microscopic Imager (MMI)
  - X-Ray Diffraction
  - Borehole XRF
  - VAPoR Mass Spectrometer
  - RESOLVE Chemical Plant – Gas Chromatograph
  - Data Integration

Site Preparation & Excavation
- Solar Concentrator & fiber optics with sun tracking system
- Resistive heater surface sintering

Oxygen Extraction from Regolith
- Carbothermal reduction module with regolith feed system
- ROxygen Gen 1 water electrolysis module
- Pneumatic regolith lift device

Energy
- Solar Concentrator & fiber optics with sun tracking system
- Sunlight flux/intensity measurement instrument
- Power conditioning for fuel cell power system

Product Storage and Utilization
- Liquid oxygen/methane tank and cryocooler cart
- Hydrogen hydride tanks
- \(O_2/CH_4\) thruster hot-fire into tephra

Participant/Hardware Supplier
- NASA/NORCAT
- JSC KA/University of Mainz (Germany) & DLR
- Honeybee Robotics
- Arizona State Univ.
- LaRC, APL/Univ of Wash.
- GSFC
- KSC, JSC, GRC, ASRC
- ARC, UC Davis, & McMaster Univ
- PSI (SBIR Phase III)
- KSC
- Orbitec
- JSC
- KSC/ASRC & Honeybee
- PSI
- NORCAT & JSC
- JSC
- JSC and CSA
- JSC and WASK

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
- 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)
2nd ISRU Analog Field Test: 2010 (3 of 3)

Resource Assessment (Prospecting)

GPR
Geo Tech
MML/Terr
Mossbauer
RESOLV
VAPoR
Mole

Science Involvement

Load-Haul-Dump Rover

Propulsion/Storage

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

Solar Concentrator

Fuel Cell
H₂ Hydride Storage

Power

Solar Power

H₂ Oxidation

H₂O

Processing

O₂

H₂

Water Electrolysis & GO₂ Storage

Carbothermal Reduction Reactor

Water

5-25 psig
200 g/day

Hydrogen

5-150 psig
3 g/hr

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

Site Preparation & Infrastructure Emplacement

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

Load-Haul-Dump Rover

Site Preparation & Infrastructure Emplacement

Sintered Pad
X-Y-Z Table
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Site Preparation & Infrastructure Emplacement

Sintered Pad
X-Y-Z Table
Resistive Sintering on Rover
3 DoF Blade on Rover
3rd ISRU Analog Field Test: Lunar Polar Prospecting Mission Simulation

- Rover Communications (CSA)
- Total Station-Relative Navigation (CSA)
- Situational Awareness Camera (NASA)
- Communications (NASA)
- Lander (NASA)
- Destination Drill System (CSA)
- Rover Communications (CSA)
- Navigation & Situational Awareness Cameras & Lights (CSA)
- Solar Array (NASA)
- Artemis Jr. Rover (CSA)
- LAVA Gas Chromatograph/Mass Spectrometer (NASA)
- Neutron Spectrometer (NASA)
- Near Infrared Spectrometer (NASA)
- OVEN Sample Heating Unit (NASA)
- Avionics & Software (CSA & NASA)
- Mission Control, Timeline, Traverse & Data Display Software (NASA)

*Note: CSA stands for Canadian Space Agency, NASA stands for National Aeronautics and Space Administration.*
3rd ISRU Analog Field Test:
Lunar Polar Prospecting Mission Simulation

Juno II Rover with actuators for Mossbauer, GPR, and Magnetic Susceptibility Probe (CSA)

Mechanized Sample Processing and Handling System (MeSH)

Volatile Analysis by Pyrolysis (VAPoR)