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

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Presentation to ESA Workshop: Towards the Use of Lunar Resources
July 3, 2018
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

Site Preparation & Infrastructure Emplacement

Habitats
- Power
- Propulsion
- Life Support & EVA
- Depots

Product Storage & Utilization

Comm & Autonomy
ISRU Changes How We Can Explore Space

**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

**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

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

**Space Resource Utilization**
- Develops alternative & renewable energy technologies
- New additive construction
- CO₂ remediation
- Green metal production

**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**
- 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%

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

2FeTiO₃ + 2H₂ → 2H₂O + 2Fe + 2TiO₂

Desolve/Digest Reactor

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

Methane Reduction Furnace

2FeTiO₃ + 2H₂ + 2CH₄ → 2CO + 4H₂ + 2MgO + Si

Methane Reduction (Carbothermal) Process

2H₂O → 2H₂ + O₂

Molten Electrolysis Reactor

2SiO₂ + 2MgO + SiO₂ → 2SiO + O₂

Molten Electrolysis

Pyrolysis Reactor/Condenser

2SiO₂ + 2FeO → 2SiO + O₂

Thermal Volatile Extraction

Hydrogen Reduction of Ilmenite/glass Process

Sulfuric Acid Reduction Process

Methane Reduction (Carbothermal) Process

Molten Electrolysis

Vapor Pyrolysis Process
## Global Assessment of Lunar Volatiles

### Apollo Samples
- **Instrument**: Apollo samples, Neutron Spectrometer

### Moon Mineralogical Mapper (M³)
- **Core Derived Water**: Apollo samples
- **Water/Hydroxyl**: M3/DIVINER

### Lunar Prospector Lunar Recon Orbiter (LRO)
- **Polar Volatiles**: LCROSS
- **Polar Ice**: Mini SAR/RF

### Lunar Crater Observation & Sensing Sat. (LCROSS)
- **Instrument**: Lunar Crater Observation & Sensing Sat. (LCROSS)

### Clementine Chandrayaan LRO Mini SAR/RF
- **Instrument**: Clementine Chandrayaan LRO Mini SAR/RF

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<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>Core Derived Water</th>
<th>Water/Hydroxyl</th>
<th>Polar Volatiles</th>
<th>Polar Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Instrument</strong></td>
<td>Apollo samples</td>
<td>Apollo samples</td>
<td>M3/DIVINER</td>
<td>LCROSS</td>
</tr>
<tr>
<td><strong>Concentration</strong></td>
<td>Hydrogen (50 to 150 ppm) Carbon (100 to 150 ppm) Helium (3 to 50 ppm)</td>
<td>0.1 to 0.3 wt % water in Apatite</td>
<td>0.1 to 1% water; 1-2% frost in shadowed craters</td>
<td><strong>3 to 10% Water</strong> equivalent Solar wind &amp; cometary volatiles (CO, H₂, NH₃, organics)</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Regolith everywhere</td>
<td>Regolith; Apatite</td>
<td>Upper latitudes</td>
<td>Poles</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Sunlit</td>
<td>Sunlit</td>
<td>Low sun angle Permanent shadow &lt;100 K</td>
<td>Low or no sunlight; Temperatures sustained at &lt;100 K</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>Top several meters; Gardened</td>
<td>Top 10's of meters</td>
<td>Top mm's of regolith</td>
<td>Below 10 to 20 cm of desiccated layer</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

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)
- **Water Electrolysis Module**
- **Regolith hopper/auger lift system (2)**
- **Regolith reactor exhaust** - 660 kg O₂ per year

- **Rotating H₂ Reduction Reactor - 17 kg/batch**
- **O₂ Cryo Tank**
- **Hydrogen Storage**
- **PILOT** - 250 kg O₂ per year

- **Bucket Drum Excavator (IR&D)**
- **Dump Chute**

### 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 Case (current strands in red)**
- **Phase Boundary (1900K)**
- **Cathode (FeO) → 2e⁻ + Fe₂O₃**
- **Anode (Fe) → 2e⁻ + Fe₂O₃**

- **Power Source**
- **Temp (K)**
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

Science Involvement

Infrastrcture Emplacement

Bucketdrum Excavator Rover
Center Scoop Excavator Rover

Crushing/Sizing/Beneficiation

Spent Material Removal

Hardware & Operation Integration at 2010 Analog Field Test

Resource Assessment (Prospecting)

LO$_2$/CH$_4$ Storage & Throat

Solar Concentrator

Electrical Power

Processing

NI$_2$ Hydride Storage

NI$_2$ (g)

NI$_2$ (liquid)

H$_2$ O$_2$ (g)

Waste Water Electrolysis & GO$_2$ Storage

Carbon Mathematical Reduction Reactor

Product Storage & Utilization

N$_2$ Product Delivery & Oxidizer

Panasonic Regolith Transfer

Lunar Polar Volatile & Mineral Prospecting at 2012 Analog Field Test

Science Involvement

Bucketdrum Center Scoop Excavator Rover

Propulsion/Storage

Gas Turbine

Fuel Cell

Solar Power

Site Preparation & Infrastructure Emplacement

Electrical Power

Pending Delivery & Storage

N$_2$ Product Storage & Utilization

Manned/Unmanned

Remote Sensing

Magnetic Susceptibility Camera, and Analyzer

Mechanical Sample Manipulator and Handling System (MSMH)

Volatiles Analysis using Pressure and Mass Spectroscopy

MCM

Juno II Rover with actuators for Wire, Switch, GPS, and Magnetic Sensing

Lighting System (LPS)

Mission Control, Navigation, and Display (NCD"

Magnetic Susceptibility Analyzer

Spectral 

500 kHz

Near Infrared Spectrometer

Magnetic Sample Sensing & Handling (MSSH)

Neutron Spectrometer

N$_2$ O$_2$ (g)

3D O$_2$ Blinds on Rover

Resistive Sintering on Rover

3-D Table

Sinter Pad

Oceanography Pad

Exchange & Rock-Handling

Power

Electrolysis Module

PILOT System

Combined Sample Metering & Crusher Unit

Water Electrolysis Module

Tabletop Electrolysis Unit
# 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>
</tr>
<tr>
<td>H\textsubscript{2} Reduction of Regolith</td>
<td>2-3</td>
<td>5</td>
<td>2-3</td>
</tr>
<tr>
<td>CH\textsubscript{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>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regolith Transfer &amp; Handling</td>
<td></td>
<td></td>
<td></td>
</tr>
<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>
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<tr>
<td>Oxygen Extraction From Regolith</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H\textsubscript{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\textsubscript{4} Reduction of Regolith Reactor</td>
<td>3</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>CH\textsubscript{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>
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<tr>
<td>Water/Fuel from Trash Processing</td>
<td></td>
<td></td>
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<td>Trash Processing Reactor</td>
<td>2</td>
<td>2-3</td>
<td>0-1</td>
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<td>In-Situ Energy Generation, Storage, and Transfer</td>
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<td>Solar Thermal Energy for Regolith Reduction</td>
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<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

Government Interest & Legislation

US Space Law & Directives
- US Space Resource Act
- Luxembourg Space Law

Public Law 114-90
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.

Presidential Documents
Space Directive 1
Reinvigorating America's Human Space Exploration Program

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

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

Satellite Servicing
- Use lunar derived propellants

ULA Cislunar 1000 Vision
- Polyorbital Launch to CisLunar
- Dragon Thaw
- Crew & Cargo
- Lunar Manned Operations
- Interplanetary Transport
- Asteroid microlander

ULS Space Directive-1 of December 11, 2017
Reinventing America's Human Space Exploration Program

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>Water (Hydrogen)</th>
<th>Oxygen</th>
<th>Carbon (Gases)</th>
<th>Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar wind hydrogen with Oxygen</td>
<td>Carbon Dioxide in the atmosphere (~96%)</td>
<td>Solar Wind from Sun (~50 ppm)</td>
<td>Minerals in Lunar Regolith</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Asteroids</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhydrated Sulfates</td>
<td>Subsurface Regolith on C-type Carbonaceous Chondrites</td>
</tr>
<tr>
<td>Subsurface Icy Soils in Mid-latitudes to Poles</td>
<td>Minerals in Regolith on S-type Ordinary and Enstatite Chondrites</td>
</tr>
<tr>
<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>Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite</td>
<td>Iron/Ti: Ilmenite, Silicon: Silica, Phylosilicates, Aluminum: Laterites, Aluminosilicates, Plagioclase, Magnesium: Mg-sulfates, Carbonates, &amp; Smectites, Mg-rich Olivine</td>
</tr>
<tr>
<td>Silicon: Silica, Phylosilicates</td>
<td>Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids</td>
</tr>
<tr>
<td>Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites</td>
<td>In situ fabrication of parts</td>
</tr>
<tr>
<td>Fuel Production for Propulsion and Power</td>
<td>Electrical power generation and transmission</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

Perform Mining Ops
- 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
- Evaluate Processing Options
- 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
- Select Mining Site
- Environmental Analysis
- Electronic Modeling & Simulation
- Develop Power Sources
- Infrastructure Analysis
- Design Transportation and Comm.
- Contingency Planning
- Infrastructure Development/Setup
- 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

Resource Prospecting/Proof-of-Concept Demos

- 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

Engineering Validation & Pilot Operations

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

- Mars Surface Pathfinder
- Lunar short stay

Utilize/Full Implementation Human

- 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

---

<table>
<thead>
<tr>
<th>A Kilogram of Mass Delivered Here…</th>
<th>...Adds This Much Initial Architecture Mass in LEO</th>
<th>...Adds This Much To the Launch Pad Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kg propellant on Mars</td>
<td></td>
<td>20.4 kg</td>
</tr>
<tr>
<td>2.9 kg prior to Mars EDL</td>
<td>4.3 kg</td>
<td>87.7 kg</td>
</tr>
<tr>
<td>226 kg on Earth</td>
<td>7.5 kg</td>
<td>153 kg</td>
</tr>
<tr>
<td>11.3 kg in LEO</td>
<td>9.0 kg</td>
<td>183.6 kg</td>
</tr>
<tr>
<td>1.9 kg used for EDL</td>
<td>12.0 kg</td>
<td>244.8 kg</td>
</tr>
<tr>
<td>8.4 kg used for TMI propulsion</td>
<td>14.7 kg</td>
<td>300 kg</td>
</tr>
<tr>
<td>226 kg on Earth</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
    - \( \text{O}_2 \) only provides up to 80% of propellant mass
    - \( \text{O}_2/\text{fuel} \) – 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

**ISRU for Lunar Ascent/Descent & Global Surface Exploration**

- Produce O₂ & Fuel

**ISRU For Lunar Ascent Only**

- Propellant for Ascent Only; Descent Propellant from Earth or Orbital Depot

- Requires reusable single stage lunar lander w/ substantial payload capability

- **Approach considered for Constellation & most Lunar architecture studies since it supports two stage non-reusable lander concepts from start**

- **Requires reusable single stage lunar lander**
  - **Does not require orbital depot for ascent/descent if both O₂ & fuel can be produced on the surface**

- **Cryos vs Water**

---

The greater the Delta-V of maneuvers performed by ISRU-derived propellants, the greater the benefit
<table>
<thead>
<tr>
<th>ISRU Impact on Exploration System Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without ISRU</strong></td>
</tr>
<tr>
<td><strong>Propulsion</strong></td>
</tr>
<tr>
<td>Propellant selection based on development cost and performance</td>
</tr>
<tr>
<td>Propulsion cycle (pressure vs pump) based on development cost and performance</td>
</tr>
<tr>
<td>Non-reusable or limited reusability with Earth supplied propellants and depots</td>
</tr>
<tr>
<td><strong>Life Support</strong></td>
</tr>
<tr>
<td>Air and Water recycling technologies and systems based on maximizing closure of oxygen and water loops</td>
</tr>
<tr>
<td>Trash/waste processing aimed at maximizing water extraction and minimizing oxygen usage</td>
</tr>
<tr>
<td><strong>Habitat</strong></td>
</tr>
<tr>
<td>Radiation and micrometeoroid shields based on Earth supplied materials. Storm closets to minimize mass impact</td>
</tr>
<tr>
<td>Fully constructed on Earth. Hard shell or inflatble</td>
</tr>
<tr>
<td>Self-contained thermal management</td>
</tr>
<tr>
<td><strong>Mobility</strong></td>
</tr>
<tr>
<td>Mobility primarily based on science and human activities</td>
</tr>
<tr>
<td>Full situational awareness and flexible navigation system</td>
</tr>
<tr>
<td><strong>Power</strong></td>
</tr>
<tr>
<td>Self-contained units. Solar array and batteries</td>
</tr>
<tr>
<td>Fuel cell reactant based on regeneration technique alone</td>
</tr>
<tr>
<td>Increase in power generation is a function of delivery from Earth</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
- O₂, H₂, and CH₄ Storage and Transfer

ISRU Resources & Processing

- Resource & Site Characterization
- Regolith/Soil Excavation & Sorting
- Water/Volatile Transport
- Regolith/Soil Transport
- Regolith Crushing & Processing
- Regolith for O₂ & Metals
- Water/Volatiles from Soil/Regolith
- CO₂ from Mars Atmosphere
- CO₂ & Trash/Waste
- CH₄, O₂, H₂O, H₂O, CO₂ from Soil/Regolith
- Regolith, Metals, & Plastics
- Metals & Plastics

Modular Power Systems

- Solar & Nuclear
- Regenerative Fuel Cell
- Surface Hopper
- Lander/Ascent

Life Support & EVA

- Pressurized Rover
- Habitats

In-Space Construction

- Civil Engineering, Shielding, & Construction

In-Space Manufacturing

- Parts, Repair, & Assembly

ISRU Integrated with Exploration Elements (Mission Consumables)
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 O₂ from Regolith**
- ROxygen H₂ Reduction
- Water Electrolysis
- Cratos Excavator

**Process Control & Science**
- PILOT H₂ Reduction
- Water Electrolysis
- Bucketdrum Excavator
- 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**
Resource Assessment (Prospecting)

- RESOLVE
- XRD/XRF
- Mossbaeur
- Mole
- Mole

Science Involvement

Habitats

Power

Propulsion

Life Support & EVA

Depots

Product Storage & Utilization

Mining

Bucketdrum Excavator Rover

Center Scoop Excavator Rover

Combined Sample Metering & Crusher Unit

Crushing/Sizing/Beneficiation

Processing

Water Electrolysis Module

ROxygen Reactor

PILOT System

Infrastrucutre Emplacement

Spent Material Removal

0
2nd ISRU Analog Field Test: 2010 (1 of 3)

NASA Hardware List & Team Members

<table>
<thead>
<tr>
<th>Site &amp; Resource Exploration</th>
<th>Participant/Hardware Supplier</th>
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</thead>
<tbody>
<tr>
<td>RESOLVE Drill</td>
<td>NASA/NORCAT</td>
</tr>
<tr>
<td>Combined Moessbauer/XRF</td>
<td>JSC KA/University of Mainz (Germany) &amp; DLR</td>
</tr>
<tr>
<td>MMAMA/FSAT Instruments</td>
<td>Honeybee Robotics</td>
</tr>
<tr>
<td>– Cone Penetrometers (Dynamic, Percussive, &amp; Manual)</td>
<td>Honeybee Robotics</td>
</tr>
<tr>
<td>– Heat Flow Probe</td>
<td>Arizona State Univ.</td>
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<tr>
<td>– Multispectral Microscopic Imager (MMI)</td>
<td>Arizona State Univ.</td>
</tr>
<tr>
<td>– X-Ray Diffraction</td>
<td>LaRC, APL/Univ of Wash.</td>
</tr>
<tr>
<td>– Borehole XRF</td>
<td>GSFC</td>
</tr>
<tr>
<td>– VAPoR Mass Spectrometer</td>
<td>KSC, JSC, GRC, ASRC</td>
</tr>
<tr>
<td>– RESOLVE Chemical Plant – Gas Chromatograph</td>
<td>ARC, UC Davis, &amp; McMaster Univ</td>
</tr>
<tr>
<td>– Data Integration</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th>Site Preparation &amp; Excavation</th>
<th></th>
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<tbody>
<tr>
<td>Solar Concentrator &amp; fiber optics with sun tracking system</td>
<td>PSI (SBIR Phase III)</td>
</tr>
<tr>
<td>Resistive heater surface sintering</td>
<td>KSC</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Oxygen Extraction from Regolith</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Carbothermal reduction module with regolith feed system</td>
<td>Orbitec</td>
</tr>
<tr>
<td>ROxygen Gen 1 water electrolysis module</td>
<td>JSC</td>
</tr>
<tr>
<td>Pneumatic regolith lift device</td>
<td>KSC/ASRC &amp; Honeybee</td>
</tr>
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</table>

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<th>Energy</th>
<th></th>
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<tr>
<td>Solar Concentrator &amp; fiber optics with sun tracking system</td>
<td>PSI (SBIR Phase III)</td>
</tr>
<tr>
<td>Sunlight flux/intensity measurement instrument</td>
<td>PSI</td>
</tr>
<tr>
<td>Power conditioning for fuel cell power system</td>
<td>NORCAT &amp; JSC</td>
</tr>
</tbody>
</table>

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

8 System Modules – 7 Instruments
6 NASA Centers, 6 Small Businesses, 5 Universities
(42 people plus visitors)
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/H$_2$ 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)
3rd ISRU Analog Field Test:
Lunar Polar Prospecting Mission Simulation

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

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