In-Situ Resource Utilization (ISRU)

Living off the Land
on the Moon and Mars

ACS National Meeting & Exposition
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April 1, 2019
**What is In Situ Resource Utilization (ISRU)?**

*Living Off the Land:*

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

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<th>Resource Examples</th>
<th>Product Examples</th>
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<td>Water</td>
<td>Propellant</td>
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<tr>
<td>Oxygen</td>
<td>Life Support Consumables</td>
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<tr>
<td>Hydrogen</td>
<td>Feed stock for:</td>
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<tr>
<td>Carbon</td>
<td>• Additive manufacturing</td>
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<tr>
<td>Metals</td>
<td>• Construction</td>
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<tr>
<td>Silicon</td>
<td>• Agriculture substrate and/or fertilizer</td>
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<tr>
<td>Nitrogen</td>
<td></td>
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<tr>
<td>Regolith/Rock</td>
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<td>Discarded materials</td>
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- ‘ISRU’ is a capability involving multiple elements to achieve final products (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
- ‘ISRU’ does not exist on its own. By definition it must connect and tie to users/customers of ISRU products and services.
**In Situ Resource Utilization (ISRU) encompasses:**

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

2. **Resource Acquisition**
   - Drilling, excavation, transfer, and preparation/beneficiation before processing.

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

4. **In Situ Manufacturing**
   - Production of feedstock potentially derived from one or more processed resources for use in manufacturing of replacement parts, complex products, machines, and integrated systems.

5. **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.

6. **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: Make It vs Bring It!

*It Changes How We Explore Space*

**Increases Mission Performance**
- Launch mass savings/Lander size reduction (>7.5 kg saving per 1 kg produced on Moon/Mars surface)
- Longer stays, increased EVA, or increased number of crew over baseline with ISRU consumables
- Increased payload-to-orbit or delta-V for faster rendezvous with fueling of ascent vehicle
- Increased and more efficient surface nighttime and mobile fuel cell power architecture with ISRU

**Increases Sustainability and Decreases Life Cycle Costs**
- Potential reuse of landers with in-situ propellants can provide significant cost savings
- Enables in-situ growth capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

**Reduces Mission and Crew Risk**
- Minimizes/eliminates life support consumable delivery from Earth – Eliminates cargo delivery failure issues & functional backup to life support system
- Increases crew radiation protection over Earth delivered options – *In-situ* water, plastic, and/or regolith
- Can minimize impact of shortfalls in other system performance – Launch vehicles, landers, & life support
- Minimizes/eliminates ascent propellant boiloff leakage issues – *In-situ* refueling
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction
- Decreased logistics and spares brought from Earth – *In situ* manufacturing

**Increases Science**
- Greater surface location and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU excavation and trenching capabilities
- Increased science payload per mission by reducing launch payload mass/consumables

*ISRU Must Be Considered from the Start or Benefits & Cost Reductions are Minimized*
Primary Resources of Interest for Human Exploration

**Moon**
- **Water (Hydrogen):** Icy Regolith in Permanently Shadowed Regions (PSR), Solar wind hydrogen with Oxygen
- **Oxygen:** Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite
- **Carbon (Gases):** CO, CO₂, and HC’s in PSR, Solar Wind from Sun (~50 ppm)
- **Metals:** Iron/Ti: Ilmenite, Silicon: Pyroxene, Olivine, Anorthite, Magnesium: Mg-rich Silicates, Al: Anorthitic Plagioclase

**Mars**
- **Water (Hydrogen):** Hydrated Soils/Minerals: Gypsum, Jarosite, Phyllosilicates, Polyhydrated Sulfates
- **Oxygen:** Carbon Dioxide in the atmosphere (~96%)
- **Carbon (Gases):** Carbon Dioxide in the atmosphere (~96%)
- **Metals:** Minerals in Mars Soils/Rocks: Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smeectite, Silicon: Silica, Phyllosilicates, Aluminum: Laterites, Aluminosilicates, Plagioclase, Magnesium: Mg-sulfates, Carbonates, Smeectites, Mg-rich Olivine

**Asteroids**
- **Water (Hydrogen):** Subsurface Regolith on C-type Carbonaceous Chondrites
- **Oxygen:** Minerals in Regolith on S-type Ordinary and Enstatite Chondrites
- **Carbon (Gases):** Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites
- **Metals:** Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids

**Uses**
- Drinking, radiation shielding, plant growth, cleaning & washing
- Making Oxygen and Hydrogen
- Breathing
- Oxidizer for Propulsion and Power
- Fuel Production for Propulsion and Power
- Plastic and Petrochemical Production
- In situ fabrication of parts
- Electrical power generation and transmission

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

- **Oxygen from Regolith**: Oxygen is bound to minerals within the regolith: Iron and Silica oxides. Can be obtained from surface and Mare regolith. Easy access, readily available, but relatively low yield. High energy processes required to process material. Reacted byproduct has high potential as construction feedstock. Sample return from Apollo provides solid chemical characterization. Oxygen alone provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth).

- **Water from Polar Regolith**: Ice has been identified at the permanently shadowed regions at the Lunar poles. Regolith is ~5 wt% according to LCROSS data. Recent data from Moon Mineralogy Mapper (M(3)) indicates up to 30 wt% in some craters. Distribution and characteristics of ice is not well known without ground-truth. Water would provide: Both fuel and oxidizer for propulsion (Hydrogen/Methane + Oxygen). Options for radiation protection, food production, etc. over what is available from lunar regolith.
Lunar Polar Water

- Accessing ice requires accessing permanently shadowed craters
  - Maximum annual temperature < 110 K
  - Crater slope and lack of sunlight for solar power

- Depth distribution of Ice TBD
  - Surface processing possible for frost
  - Subsurface methods may be required

Fig. 4. Distribution of water-ice-bearing pixels (green and cyan dots) overlain on the Diviner annual maximum temperature for the (A) northern- and (B) southern polar regions. Ice detection results are further filtered by maximum temperature (<110 K), LOLA albedo (>0.35) (12), and LAMP off and on band ratio (>1.2, only applicable in the south) (13). Each dot represents an M (3) pixel, ~280 m × 280 m.
Lunar Oxygen Extraction

**Hydrogen Reduction of Regolith**

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

**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

**Molten Electrolysis of Regolith**

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

- **Consumable production**
  - Chemical propellants for robotic and human vehicles
  - Life support (O_2 and H_2O)
  - Fuel Cell reactants

- **Site preparation/Civil engineering**
  - Radiation protection (H_2O and/or Regolith)
  - Landing pads, berms for plume mitigation
  - Road clearing for payload emplacement

- **Mars Forward**
  - Demonstrate compatible technologies like
    - Excavation, material handling, thermal processing, cryogenic fluid storage and transfer, etc.
    - Autonomous operations: e.g. Land empty ascent vehicle and produce propellant prior to human presence
    - Link to Gateway mission concepts provide for Gateway/lunar sorties or Mars transit
MARS ISRU
Atmosphere Processing

- **Atmosphere**
  - Pressure: 6 to 10 torr (~0.08 to 0.1 psi)
  - >95% Carbon Dioxide
  - Temperature: +35 C to -125 C

- **Everywhere on Mars; Lower altitude the better**
- Chemical processing similar to life support and regenerative power

- **Mars Garden Variety Soil**
  - Low water concentration 1-3%
  - At surface
  - Granular; Easy to excavate
  - 300 to 400 C heating for water removal
  - Excavate and transfer to centralized soil processing plant
  - Most places on Mars: 0 to +50 Deg. latitude

- **Gypsum or Sulfates**
  - Hydrated minerals 5-10%
  - At Surface
  - Harder material: rock excavation and crushing may be required
  - 150 to 250 C heating for water removal
  - Localized concentration in equatorial and mid latitudes

- **Subsurface Ice**
  - 90%+ concentration
  - Subsurface glacier or crater: 1 to 3 m from surface
  - Hard material
  - 100 to 150 C heating for water removal
  - Downhole or on-rover processing for water removal
  - Highly selective landing site for near surface ice or exposed crater; >40 to +55 Deg. latitude

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**Increasing Complexity, Difficulty, and Site Specificity**
• The circles represent terrain features consistent with terrestrial glacial feature.
• The Diamonds are recently discovered ice scarps (‘roadcuts’ showing exposed ice).
Propellant Production on Mars

**Oxygen**
- **Resource:** Atmospheric CO<sub>2</sub>
- **Reaction:**
  - Solid Oxide Electrolysis
  - Reverse Water Gas Shift
- **Accounts for 75% of propellant mass**
  - Mixture ratio: 3.5:1

**Methane**
- **Resource:** Atmospheric CO<sub>2</sub> + Water
- **Reaction:**
  - Water Electrolysis + Sabatier
- **Closes loop:** All propellants for ascent + excess oxygen
  - Sabatier produces at a 4:1 ratio

\[
2 \text{H}_2\text{O} + \text{CO}_2 \rightarrow 2 \text{O}_2 + \text{CH}_4
\]

**Solid Oxide CO<sub>2</sub> Electrolysis (SOE)**

\[
2 \text{CO}_2 \xrightarrow{800-1000 \degree C} 2 \text{CO} + \text{O}_2 \quad \text{[Ni catalyst]}
\]

**Reverse Water Gas Shift (RWGS)**

\[
\text{CO}_2 + \text{H}_2 \xleftrightarrow{400-650 \degree C} \text{CO} + \text{H}_2\text{O} \quad \text{[Fe catalyst]}
\]
Oxygen production from atmosphere integrated system (solid oxide electrolysis option)
Oxygen and methane production from atmosphere and soil water integrated system

4.1 Atmosphere Carbon Dioxide (CO₂) Collection Subsystem

Dust Filtration / Mitigation → Atmosphere Blower → CO₂ Separation, Collection, and Pressurization → N₂, Ar, trace gases vented

4.3 Methane Fuel Production Subsystem

Sabatier Reactor → H₂, CH₄ → H₂O / gas separator (condenser) → H₂O separator → CH₄ Dryer

4.7 & 4.8 Excavation and Soil Processing Subsystems

Soil Excavation for Water → Soil Hoppers / Transfer → Soil Dryer → H₂O Collection, Clean-up, and Storage

4.9 Product Storage and Distribution Subsystem

CH₄ Transfer → CH₄ Storage → CH₄ Liquefaction & Maintenance

O₂ Transfer → O₂ Storage → O₂ Liquefaction & Maintenance

4.4 Water Electrolysis Subsystem

Water Electrolysis → H₂ Dryer
### Examples of Technologies

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Components</th>
<th>Heritage</th>
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<tr>
<td><strong>Excavation</strong></td>
<td>RASSOR 2.0 excavator – Bucket drum rover</td>
<td>KSC prototype hardware, laboratory tests in regolith simulants</td>
</tr>
<tr>
<td><strong>Regolith Processing</strong></td>
<td>Auger Conveyor Dryer – heated auger with gas loop for continuous regolith processing</td>
<td>JSC design concept – numerical sizing model, conceptual CAD</td>
</tr>
<tr>
<td></td>
<td>Vapor cleanup – Membrane separator</td>
<td>COTS</td>
</tr>
<tr>
<td></td>
<td>Water collection – Cold trap</td>
<td>JSC design concept – numerical sizing model</td>
</tr>
<tr>
<td><strong>CO₂ Acquisition</strong></td>
<td>Cryofreezer</td>
<td>COTS – flight heritage KSC cold head conceptual design numerical sizing</td>
</tr>
<tr>
<td>Sabatier</td>
<td>Microchannel Sabatier</td>
<td>Solicited: Battelle PNNL</td>
</tr>
<tr>
<td></td>
<td>Regenerative Gas dryer, desiccant</td>
<td>JSC development hardware</td>
</tr>
<tr>
<td></td>
<td>CH₄/H₂ separator</td>
<td>Solicited: Hamilton Sunstrand</td>
</tr>
<tr>
<td>Propellant Production</td>
<td>PEM electrolysis stack, Cathode feed</td>
<td>Giner Inc.</td>
</tr>
<tr>
<td></td>
<td>Deionizer</td>
<td>COTS</td>
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<tr>
<td></td>
<td>Inlet pump, micropump</td>
<td>COTS</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>Regenerative Gas dryer, desiccant</td>
<td>JSC development hardware</td>
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<tr>
<td></td>
<td>Cryocooler</td>
<td>COTS</td>
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<tr>
<td>Liquefaction</td>
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Soil Processing Technologies for Hydrated Surface material

Examples of technologies to process granular surface material for resource extraction.

- Designed for Mars surface material: low yield hydrates (1.5% to 10% water)
- In-house efforts

Auger Dryer: JSC

Microwave: JPL

Open "Air": GRC
NASA ISRU system study example: Evolvable Mars Campaign

- **Evolvable Mars Campaign**
  - Pre-deployed Mars ascent vehicle (MAV)
  - 4 crew members
  - Propellants: Oxygen & Methane

- **Production rate based on a mission timeline of 480 days (16 months)**
  - ISRU system arrives one launch opportunity ahead of humans
  - MAV must be fully fueled before human departure from earth

- **Assumptions:**
  - Water from low yield hydrated surface material
  - Regolith transferred to fixed processing site
  - Liquefaction in MAV tanks
  - Modular systems: 3 operating at 40% each
  - Estimates do NOT include:
    - Power source
    - Radiators

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Total mass needed</th>
<th>Rate at 480 days continuous operation</th>
</tr>
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<tbody>
<tr>
<td>CH₄</td>
<td>6978 kg</td>
<td>0.61 kg/hr</td>
</tr>
<tr>
<td>H₂O</td>
<td>15701 kg (785,050 kg 2% soil)</td>
<td>1.36 kg/hr (68.2 kg/hr soil@2%)</td>
</tr>
<tr>
<td>CO₂</td>
<td>19190 kg</td>
<td>1.67 kg/hr</td>
</tr>
<tr>
<td>Results in:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>27912 kg total (22728 kg propellant, 5184 kg leftover)</td>
<td>2.43 kg/hr</td>
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www.nasa.gov
Notional Packaging: Full ISRU System

Approach: Production requirement met by 3 independent ISRU systems including:

| 3 Propellant production (atmosphere processing/water electrolysis) modules | 3 mobile RASSOR excavators | 3 regolith processing (water production) modules |

*Liquefaction takes place in the MAV/Lander tanks

*Working with MAV team for current packaging
Overall Mass comparison

- Mass reductions are compared to total ascent propellants only
- Mass savings in LEO is about 10kg per ever 1 kg of propellant produced
  - LEO Mass savings on the order of 300 mT with full ISRU system
  - Reduces cost and eliminates several heavy lift launch vehicles
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 only
- Methane + Oxygen

75% of ascent propellant mass; 20 to 23 mT
100% of ascent propellant mass: 25.7 to 29.6 mT

Regeneration of rover fuel cell reactant mass

A Kilogram of Mass Delivered Here...

<table>
<thead>
<tr>
<th></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>Ground to LEO</td>
<td>-</td>
<td>20.4 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit</td>
<td>4.3 kg</td>
<td>87.7 kg</td>
</tr>
<tr>
<td>(r₁→r₂)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO to Lunar Surface</td>
<td>7.5 kg</td>
<td>153 kg</td>
</tr>
<tr>
<td>(r₁→r₃; e.g., Descent Stage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO to Lunar Orbit to Earth Surface</td>
<td>9.0 kg</td>
<td>183.6 kg</td>
</tr>
<tr>
<td>(r₁→r₄→r₅; e.g., Orion Crew Module)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar Surface to Earth Surface</td>
<td>12.0 kg</td>
<td>244.8 kg</td>
</tr>
<tr>
<td>(r₃→r₅; e.g., Lunar Sample)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEO to Lunar Surface to Lunar Orbit</td>
<td>14.7 kg</td>
<td>300 kg</td>
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</table>
HIGHLIGHT AN ISRU TECHNOLOGY – SOLID OXIDE ELECTROLYSIS OF CO$_2$
Solid oxide electrolysis of carbon dioxide

Brief description:
$\text{CO}_2$ disassociates into $\text{CO}$ and oxygen ions ($\text{O}^{2-}$) on cathode,

$$\text{CO}_2 + 2\text{e}^- \rightarrow \text{CO} + \text{O}^{2-}$$

$\text{O}^{2-}$ ions transport across YSZ membrane and recombine to form $\text{O}_2$ on anode:

$$\text{O}^{2-} \rightarrow \frac{1}{2}\text{O}_2 + 2\text{e}^-$$

Materials/catalysts (typical):
Cathode: Ni-YSZ (Nickel-Yttria-doped Zirconia cermet), Ni-doped ceria (Ni with samaria or gadolinia doped ceria cermet)

Anode: LSCF (lanthanum strontium cobalt ferrite), LSM (lanthanum strontium manganite), $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$

Electrolyte: YSZ (yttria stabilized zirconia), ScSZ (scandia stabilized zirconia)

Interconnect: Chromium/iron/yttrium alloy

Some Advantages:
• Solid state electrochemical process (no moving parts).
• Produces pure dry oxygen (important for liquefaction).
• Does not require hydrogen (or water source).
MOXIE (Mars Oxygen ISRU Experiment): Mars 2020

- In-Situ Demonstration of Mars ISRU technology
- Solid Oxide Electrolysis
  - Electrochemical conversion of atmospheric CO₂ to O₂
  - Approximately 1% scale: 12 g/hr (versus human mission scale)
- Lead by MIT. SOXE by Ceramatec, Inc. (now OxEon LLC)

MOXIE Assembly, 15 kg, ~11.5" X 10.25" X 12"

SOXE stack before assembling in insulated box
CO₂ Solid Oxide Electrolysis Technology Challenges

• Energy intensive process (ΔH_r = +293.0 kJ/mol compared to ΔH_r = +285.9 kJ/mol for H₂O)
• High temperature operation (800-900 C)
• Thermal cycling
  – CTE mis-match, thermal gradients due to poor thermal conductivity of ceramic layers.
  – Effects CONOPS (i.e. start-up time).
• Performance degradation
  – CO₂ reduction cathode degrades at high rate in dry CO₂ (redox stability, Ni coarsening, gas contaminants).
  – Anode (delamination of electrode layer under high current density, high ionic O²⁻ flux).
  – Carbon deposition (coking) at high CO/CO₂ gas ratios. (Limits CO₂ utilization/conversion).
• Structural integrity
  – Structural materials are brittle (ceramics).
  – Require metal-to-ceramic interfaces.
• Sealing
  – Sealing for long-term high temperature operation. Limited work in other technologies above 700 deg C.
  – Thermal cycling adds additional challenges, again due to CTE mis-match between sealing materials and sealing interfaces.
  – Tubular SOFC/SOE designs more tolerant [but not as mass or volumetrically compact as planar.]
• Packaging
  – High temperature thermal insulation, electrical heaters, gas connections, etc.

MOXIE development has solved thermal cycling, structural, and sealing issues for their specific design and requirements.
Brief description of CO$_2$ reduction electrochemistry

A qualitative illustration of (a) electronic-only conducting and (b) mixed-conducting porous electrode design. In (a), the three phase boundary (TPB) area is confined to the limited area where the electronic-only conducting electrode meets the ionic-conducting electrolyte. In (b), the TPB area is enhanced due to the mixed ionic-electronic conducting properties of the electrode; the reaction can occur over a larger extent of the internal surface area of the porous electrode, away from the electrode/electrolyte interface. The variation in shade of red color illustrates this variation in the CO$_2$ reduction reaction rate through the thickness of the electrode.

**Triple-Phase Boundary (TPB)**

Electron conducting phase

Gas phase

Ionic conducting phase

CO$_2$ reduction: CO$_2$ + 2e$^- \leftrightarrow$ CO + O$_2^-$
MOXIE team did extensive work characterizing this effect for their system.
Summary

• ISRU advantages include:
  – Enabling missions and architectures that were not possible otherwise
  – Significantly reducing mission cost and risk
  – Extending mission duration, reducing earth reliance
  – Can be leveraged at multiple destinations at a variety of scales (e.g. human, robotic sample return, robotic science exploration)

• ISRU primary challenges include:
  – Highly multi-disciplinary (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.)
  – Infrastructure: Long term operation that requires understanding and management of component life-cycles.
  – Requires autonomous operations on a level not yet achieved (mining/excavating, system operation, etc)

• ISRU technology challenges:
  – The technical development challenges for multiple technologies
  – CO$_2$ solid oxide electrolysis technology issues were highlighted here.
Acknowledgements

• NASA’s Advanced Exploration Systems (AES) and Space Technology Mission Directorate (STMD) fund the ISRU Project.

• A thanks to Gerald Voecks (NASA JPL) for providing MOXIE experiment images and data.
BACKUP
CURRENT NASA ISRU ACTIVITIES
NASA ISRU Project

**Scope:** Develop and demonstrate, in ground demonstrations, the component, subsystem, and system technology to enable production of mission consumables from regolith and atmospheric resources at a variety of destinations

- **Initial focus**
  - Critical technology gap closure
  - Component development in relevant environment (TRL 5)

- **Interim goals**
  - ISRU subsystems tests in relevant environment (Subsystem TRL 6)

- **End goals**
  - End-to-end ISRU system tests in relevant environment (System TRL 6)
  - Integrated ISRU-Exploration elements demonstration in relevant environment

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**Overall Project Goals**

*System-level TRL 6 to support future flight demonstration missions*

*Provide Exploration Architecture Teams with validated, high-fidelity answers for mass, power, and volume of ISRU Systems*
Assumptions

- **Production Rate driver:** 6978 kg of Methane needed + 0.5% margin
  - Methane is the driver since excess oxygen will be produced using Sabatier process

- **Time of ISRU production:** 480 day operation, 24hr/day

- **Soil Water resource (baseline):** **Water from surface regolith = hydrates**
  - Ubiquitous (location independent)
  - Available in surface material (subsurface excavation not required)
  - Lower resource yield is more of a worse case for water extraction system

- **Processing:** Regolith is transported and delivered to a centralized processing plant that is co-located with the Lander/MAV

- **Liquefication:** Takes place in the MAV tanks. ISRU system only includes mass/power for crycoolers needed to liquefy. MAV responsible for tanks and zero boil-off systems

- **Power Source:** Not part of ISRU system. Assumes a fission reactor will be needed for human presence, ISRU will use reactor when humans are not present. (TBD - as power needs are identified)

- **Radiators:** Not part of ISRU system. ISRU will be packed on lander.
**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%

**Lunar Volatiles** *(Controlled Water Vapor)*

- 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%

**New: Ionic Liquids**

**Fluidized Bed Reactor**

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

O₂ + 2H₂ → 25°C 2H₂O

**Molten Electrolysis Reactor**

2FeTiO₃ → 2FeO + TiO₂

2FeO + O₂ → 2Fe + O₂

2Fe + 2TiO₂ → 2FeTiO₃

2H₂O + 2MgO + 2H₂ → 2MgO + 2H₂ + O₂

**Pyrolysis Reactor/Condenser**

2SiO₂ → 2SiO + O₂

2FeTiO₃ → 2Fe + 2TiO₂ + O₂

2FeO → 2Fe + O₂

2CaO → 2CaO + O₂

2Ca₂Al₂Si₂O₈ → 2Ca + 4AlO + 4SiO + 4O₂

2CaAl₂Si₂O₈ → 2Ca + 2AlO + 2Al + 4SiO + 5O₂

**Desolve/Digest Reactor**

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

O₂ + 2Fe + 2H₂SO₄ → 2H₂O + 2FeSO₄

MₙOₙ + 2m[H⁺] → mH₂O + nM⁺⁺

**Methane Reduction Furnace**

2FeTiO₃ + 2CO + 4H₂ → 1625°C 2Fe + 2TiO₂ + 2H₂O

2FeO + Si → Fe + Si

MgO + Si → MgSiO + Si

CaSiO₃ → CaO + Si

**Methane Reforming**

2H₂ + CO → 250°C 2H₂O + 2CO + 2H₂

2H₂O → 25°C 2H₂ + O₂

**Methane Reduction (Carbothermal) Process**

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

2FeO + H₂O → 2Fe + O₂ + 2H₂

2SiO₂ + H₂O → 2SiO + O₂ + H₂O

**Vapor Pyrolysis Process**

2SiO₂ → 2SiO + O₂

2FeO → 2Fe + O₂

2CaO → 2CaO + O₂

2Ca₂Al₂Si₂O₈ → 2Ca + 4AlO + 4SiO + 4O₂

2CaAl₂Si₂O₈ → 2Ca + 2AlO + 2Al + 4SiO + 5O₂

**Hydrogen Reduction of Ilmenite/glass Process**

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

O₂ + 2H₂ → 25°C 2H₂O

**Sulfuric Acid Reduction**

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

O₂ + 2Fe + 2H₂SO₄ → 2H₂O + 2FeSO₄

MₙOₙ + 2m[H⁺] → mH₂O + nM⁺⁺

**Molten Electrolysis**

2FeTiO₃ + 2H₂O + 2MgO + 2H₂ → 2MgSiO₄ + 2Fe + TiO₂ + 2H₂O

2FeO + Si → Fe + Si

MgO + Si → MgSiO + Si

CaSiO₃ → CaO + Si

**Water Electrolysis**

2H₂O → 25°C 2H₂ + O₂

**Thermal Volatile Extraction**

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

2FeO + H₂O → 2Fe + O₂ + 2H₂
Together, the 10 awarded proposals represent an excellent portfolio meeting important ISRU Project objectives for significant technical advancement and effective public-private partnerships, while filling critical gaps for both Moon and Mars destinations.

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<td>Production of O2 &amp; Fuels from In-Situ Resources on Mars</td>
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Some Backup information

- Analog for Mars hydrated soil used in some of NASA’s ground testing: Borax or sodium tetraborate pentahydrate, \( \text{Na}_2\text{B}_4\text{O}_7 \cdot 5\text{H}_2\text{O} \)

- Boiling points for propellants being considered for production via ISRU processes:
  - Hydrogen (\( \text{H}_2 \))  BP: -253 °C (20 K)
  - Oxygen (\( \text{O}_2 \))  BP: -183 °C (90 K)
  - Methane (\( \text{CH}_4 \))  BP: -161.5 °C (111.5 K)

- Apollo Lunar Module (LM)
  - Launch mass: 33,500 pounds (15,200 kg)
  - Dry mass: 9,430 pounds (4,280 kg)
Resource Prospector (RP)

• Resource Characterization (Prospecting): Lunar Polar Water
  1. Locate surface and near-subsurface volatiles,
  2. Excavate and analyze samples of the volatile-bearing regolith
  3. Demonstrate the form, extractability and usefulness of the materials

• Rover based instrument suite including
  – Neutron Spectrometer and Near Infrared Spectrometer: surface water signatures
  – 1m sampling drill: Subsurface water distribution
  – Oven with Gas chromatograph/Mass Spectrometer: sample characterization

• Targeting South Pole
• 6-14 day mission
• Class D, Category 3

Status
• RP was canceled in May 2018 due to agency reorganization.
• Instrument development will continue separately
• Discussions for incorporation onto upcoming commercial lander opportunities (NASA CLPS program)
Subsurface Ice Mining: Rodwell

- Rodwells are in use terrestrially (Antarctic field stations) for water generation from subsurface ice sheets.
- CRREL (Cold Regions Research and Engineering Laboratory) has generated a numeric model for Rodwell design. This model has been leveraged to develop an ISRU Mars Rodwell system to:
  - Estimate mass & power for Mars relevant hardware
  - Examine Concept of Operations of Rodwell for various operating conditions (production rates, location, etc)
  - Initial trade study results to be published at AIAA Space 2018.

Phase 1: Drill through overburden into top of ice.
Phase 2: Melt into ice. Begin forming water pool.
Phase 3: Steady state operation.
# Shared Requirements and Hardware With In Situ Resource Utilization

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