Mars ISRU: State-of-the-Art and System Level Considerations

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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.

<table>
<thead>
<tr>
<th>Resource Assessment (Prospecting)</th>
<th>Resource Processing/Consumable Production</th>
<th>In Situ Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of physical, mineral/chemical, and volatile/water resources, terrain, geology, and environment</td>
<td>Processing resources into products with immediate use or as feedstock for construction and/or manufacturing - Propellants, life support gases, fuel cell reactants, etc.</td>
<td>Production of replacement parts, complex products, machines, and integrated systems from feedstock derived from one or more processed resources</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource Acquisition</th>
<th>In Situ Construction</th>
<th>In Situ Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Involves extraction, excavation, transfer, and preparation before processing</td>
<td>Civil engineering, infrastructure emplacement and structure construction using materials produced from in situ resources - Radiation shields, landing pads, roads, berms, habitats, etc.</td>
<td>Generation and storage of electrical, thermal, and chemical energy with in situ derived materials - Solar arrays, thermal wadis, chemical batteries, etc.</td>
</tr>
</tbody>
</table>

- ‘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.

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Space ‘Mining’ Cycle: Prospect to Product

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

Communication & Autonomy

Mining

Site Preparation & Infrastructure Emplacement

Processing
- Crushing/Sizing/Beneficiation
- Waste

Maintenance & Repair

Product Storage & Utilization
- Spent Material Removal

Power
- Depots
- Life Support & EVA
- Propulsion
## Mars Resources

### Atmosphere
- Pressure: 6 to 10 torr (~0.08 to 0.1 psi);
- Temperature: +35 °C to -125 °C

<table>
<thead>
<tr>
<th>Gas</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>95.32%</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>2.7 %</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>1.6%</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>0.13%</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>0.08%</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>&lt;0.03%</td>
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### Soil/Minerals

<table>
<thead>
<tr>
<th>Resource</th>
<th>Potential Mineral Source</th>
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</thead>
</table>
| Water, Hydration/ Hydroxyl | Gypsum – (CaSO₄·2H₂O)  
Jarosite – (KFe³⁺₃(OH)₆(SO₄)₂)  
Opal & hydrated silica  
Phyllosilicates  
Other hydrated minerals (TBR) |
| Water, Ice        | Icy soils  
Glacial deposits                                                                                 |
| Iron*             | Hematite  
Magnetite  
Laterites                                                                                     |
| Aluminum*         | Laterites  
Alumino-silicates  
Plagioclase  
Scapolite                                                                   |
| Magnesium*        | Mg-sulfates                                                                                     |
| Silicon           | Pure amorphous silica  
Hydrated silica  
Phyllosilicates                                                        |
| Titanium*         | Ilmenite                                                                                       |

Mid- and high-latitude shallow ice is thought to be dominated by hydrated minerals. New craters confirm shallow, nearly pure ice. Newly formed craters exposing water ice (red) are a subset of all new craters (yellow). Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)
Mars ISRU Depends on Resource of Interest

Atmospheric Resource Processing

- **Strengths**
  - Atmospheric resources are globally obtainable (no landing site limitations)
  - Production of $O_2$ only from carbon dioxide ($CO_2$) makes >75% of ascent propellant mass
  - Significant research and testing performed on several methods of atmospheric collection, separation, and processing into oxygen and fuel; including life support development

- **Weaknesses**
  - Production of methane delivery of hydrogen ($H_2$) from Earth which is volume inefficient or water from the Mars soil (below)
  - Mars optimized ISRU processing does not currently use baseline ECLSS technologies

Mars Soil Water Resource Processing (ties to Lunar Ice & Regolith)

- **Strengths**
  - Surface material characteristics studied from Mars robotic landers and rovers
  - Water (in the form of hydrated minerals) identified globally near the surface
  - Lunar regolith excavation and thermal processing techniques can be utilized for Mars
  - Low concentrations of water in surface hydrated mineral soil (3%) still provides tremendous mass benefits with minimal planetary protection issues

- **Weaknesses**
  - Risk associated with the complexity of the required surface infrastructure needs must be evaluated. Significant autonomous operations required.
  - Local/site dependency on water resource concentration and form
  - Release of contaminants with water
  - Concerns from planetary protection and search for life with water extraction at higher concentrations

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ISRU Consumables Production Decision Tree

Resource Type

Earth Delivered Consumables

Resource Separation & Preparation

Solid Processing

Resource of Interest

Gas/Liquid Processing

ISRU Products

ISRU Secondary Products

Oxygen (O₂)

HC Fuel (CH₄)

H₂ Fuel

Buffer & Science Gases

Manufacturing Feedstock

Water

Ammonia

Alcohol

Plastic

Fertilizer

From (H₂, N₂)

(CO, CO₂, H₂, O₂, &/or CH₄)

ISRU

Mars Atmosphere

Hydrogen (H₂)

Methane (CH₄)

Discarded Materials

Mineral Resources

Excavation, Crushing, Beneficiation

Gas Collection & Separation

Mars Atm. Processing for O₂

Carbon Dioxide (CO₂)

Nitrogen (N₂)

Argon (Ar)

Carbon Gases (CO/CO₂)

Hydrocarbons (HCs)

Ammonia (NH₃)

Oxygen (O₂)

Metals

Silicon

CO₂ Reduction

CO₂ Conversion

Water

O₂ Conversion

Chemical Conversion

CC NEO or Trash Processing for H₂ & CO₂ to Fuel

Soil Heating, Oxidation, & Steam Reforming

Soil Heating, Oxidation, & Steam Reforming

Soil Heating, Oxidation, & Steam Reforming

Soil Heating, Oxidation, & Steam Reforming

Solid Reduction
### Space Resource Challenges
- What resources exist at the site of exploration that can be used?
- What are the uncertainties associated with these resources?
- How to address planetary protection requirements?

### ISRU Technical Challenges
- Is it technically feasible to collect, extract, and process the resource?
- How to achieve long duration, autonomous operation and failure recovery?
- How to achieve high reliability and minimal maintenance requirements?

### ISRU Operation Challenges
- How to operate in extreme environments, including temperature, pressure, dust, and radiation?
- How to operate in low gravity or micro-gravity environments?

### ISRU Integration Challenges
- How are other systems designed to incorporate ISRU products?
- How to optimize at the architectural level rather than the system level?
- How to manage the physical interfaces and interactions between ISRU and other systems?

Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.
The Chemistry of Mars ISRU

Oxygen (O₂) Production Only

- **Reverse Water Gas Shift (RWGS)**
  \[ \text{CO}_2 + \text{H}_2 \xleftrightarrow{400 - 650 \degree C} \text{CO} + \text{H}_2\text{O} \]
  \[ \text{[催化剂]} \]
  \[ \rightarrow \text{H}_2\text{O} \]

Oxygen (O₂) & Methane (CH₄) Production

- **Bosch**
  \[ \text{CO}_2 + 2 \text{H}_2 \xrightarrow{450 - 600 \degree C} \text{C} + 2 \text{H}_2\text{O} \]
  \[ \text{[Ni, Ru, Fe, or Co catalyst]} \]
  \[ \rightarrow \text{H}_2\text{O} \]

- **Sabatier Catalytic Reactor (SR)**
  \[ \text{CO}_2 + 4 \text{H}_2 \xrightarrow{200 - 300 \degree C} \text{CH}_4 + 2 \text{H}_2\text{O} \]
  \[ \text{[Ru catalyst]} \]
  \[ \rightarrow \text{H}_2\text{O, CH}_4 \]

Other Hydrocarbon Fuel Production

- **Methane Reformer**
  \[ \text{CO} + 3 \text{H}_2 \xrightarrow{250 \degree C} \text{CH}_4 + \text{H}_2\text{O} \]
  \[ \text{[Ni catalyst]} \]
  \[ \rightarrow \text{H}_2\text{O, CH}_4 \]

- **Co-Production/Electrolysis**
  \[ \text{CO}_2 + 2 \text{H}_2\text{O} \rightarrow \text{CH}_4 + 2 \text{O}_2 \]
  \[ \text{[Anode/Cathode]} \]
  \[ \rightarrow \text{O}_2, \text{CH}_4 \]

Oxygen (O₂) &/or Hydrogen (H₂) Production

- **Fischer-Tropsch (FT)**
  \[ n \text{CO} + (2n+1) \text{H}_2 \xrightarrow{>150 \degree C} \text{C}_n\text{H}_{2n+2} + n \text{H}_2\text{O} \]
  \[ \text{[catalyst]} \]
  \[ \rightarrow \text{H}_2\text{O, C}_n\text{H}_{2n+2} \]

- **Methanol**
  \[ \text{CO} + 2 \text{H}_2 \xrightarrow{250 \degree C} 50 - 100 \text{atm} \text{CH}_3\text{OH} \]
  \[ \text{[ZnO catalyst]} \]
  \[ \rightarrow \text{H}_2\text{O, CH}_3\text{OH} \]

- **Water Electrolysis (WE)**
  \[ 2 \text{H}_2\text{O} \rightarrow 2 \text{H}_2 + \text{O}_2 \]
  \[ \rightarrow \text{O}_2, 2 \text{H}_2 \]

- **Steam Reforming**
  \[ \text{H}_2\text{O} + \text{CH}_4 \rightarrow 3 \text{H}_2 + \text{CO} \]
  \[ \rightarrow 3 \text{H}_2 \]

- **Dry Reforming**
  \[ \text{CO}_2 + \text{CH}_4 \rightarrow 2 \text{H}_2 + 2 \text{CO} \]
  \[ \rightarrow 2 \text{H}_2 \]
**Four Options for Mars ISRU Ascent Propellant Production:**

1. Make oxygen ($O_2$) from Mars atmosphere carbon dioxide ($CO_2$); Bring fuel from Earth
2. Make $O_2$ and fuel/CH$_4$ from Mars atmosphere $CO_2$ and hydrogen ($H_2$) from Earth
3. Make $O_2$ and fuel/CH$_4$ from Mars atmosphere $CO_2$ and water ($H_2O$) from Mars soil
4. Make $O_2$ and $H_2$ from $H_2O$ in Mars soil

<table>
<thead>
<tr>
<th>ISRU Resource Processing Options</th>
<th>ISRU Products</th>
<th>Mars Resource(s)</th>
<th>Earth Supplied</th>
<th>Process Subsystems/Options</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>CO$_2$ Collection &amp; Conditioning</td>
</tr>
<tr>
<td></td>
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<td>Solid Oxide CO$_2$ Electrolysis</td>
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<td></td>
<td>Reverse Water Gas Shift (RWGS)</td>
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<td></td>
<td>Sabatier Bosch</td>
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<td>Liquid Water Electrolysis</td>
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<td></td>
<td></td>
<td>Solid Oxide H$_2O$ Electrolysis</td>
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<td></td>
<td></td>
<td></td>
<td>Ionic Liquid Electrolysis</td>
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<td></td>
<td>Soil Processing</td>
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<td></td>
<td></td>
<td>Soil Excavation &amp; Delivery</td>
</tr>
</tbody>
</table>

- **Enabling Atmosphere Processing**
  - $O_2$, $CO_2$, $CH_4$ (~6600 kg)
  - $H_2$* (~2000 kg)

- **Enabling Soil Processing**
  - $O_2$, $CH_4$, $H_2O$, $H_2O$
  - $CH_4$ **(~6600 kg)**

- **Enabling Soil & Atmosphere Processing**
  - $O_2$, $CH_4$, $H_2O$, $CO_2$ & $H_2O$

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*H$_2$ for water and methane production

**Assumes methane fuel vs hydrogen fuel for propulsion

1, 2, & 3 Were Evaluated in Mars DRA 5.0
Mars Human Exploration DRA 5.0
ISRU vs Non-ISRU Ascent Results

- **Lowest Power/Volume:** Process atmospheric CO$_2$ into O$_2$; Bring methane (CH$_4$) from Earth
- **Lowest Mass:** Process atmospheric CO$_2$ with Soil processing for H$_2$O into O$_2$ and CH$_4$
- **Study Results**
  - Atmosphere processing into O$_2$ baselined: **Lowest Risk**
  - Continue evaluation of water on Mars and soil processing to reduce risk

### DAV Mass (no ISRU)

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascent Stg 2</td>
<td>18,540 kg</td>
</tr>
<tr>
<td>Ascent Stg 1</td>
<td>27,902 kg</td>
</tr>
<tr>
<td>Minimal Habitat†</td>
<td>5687 kg</td>
</tr>
<tr>
<td>Descent stage*</td>
<td>27,300 kg</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>79,428 kg</td>
</tr>
</tbody>
</table>

* Wet mass; does not include EDL System
† Packaging not currently considered

### DAV Mass (w/O2 ISRU)

<table>
<thead>
<tr>
<th></th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascent Stg 2</td>
<td>9,330 kg</td>
</tr>
<tr>
<td>Ascent Stg 1</td>
<td>12,156 kg</td>
</tr>
<tr>
<td>ISRU and Power†</td>
<td>11280 kg</td>
</tr>
<tr>
<td>Descent stage*</td>
<td>21,297 kg</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>54,062 kg</td>
</tr>
</tbody>
</table>

>25 MT savings (>30%)
## ISRU system Mass Comparison

The ISRU system leverages the power and radiator systems that are pre-positioned by the lander for human systems. So these are not explicitly part of the ISRU system.

<table>
<thead>
<tr>
<th>Case</th>
<th>Hardware Mass, mt</th>
<th>Total Mass, mt (ISRU Hardware + Propellant from Earth)</th>
<th>Ratio: Propellant produced per kg of landed mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1.6</td>
<td>1.6</td>
<td>22.1</td>
</tr>
<tr>
<td>ISRU for LO₂ &amp; LCH₄: Sulfates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 2</td>
<td>1.7</td>
<td>1.7</td>
<td>20.5</td>
</tr>
<tr>
<td>ISRU for LO₂ &amp; LCH₄: Regolith</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3</td>
<td>1.0</td>
<td>8.0 (1 mt hardware + 7 mt Methane)</td>
<td>3.1</td>
</tr>
<tr>
<td>ISRU for LO₂ only (no water)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 4</td>
<td>NA</td>
<td>31.6 (24 mt Oxygen + 7 mt Methane)</td>
<td>NA</td>
</tr>
<tr>
<td>Propellant only (no ISRU)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Landed Mass Comparison**

![Bar chart showing landed mass comparison for different cases of ISRU system.]  

- **LOX & LCH₄ Baseline**
- **LOX only**
- **No ISRU (propellant only)**

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How Propellant Production Enables Future Moon & Mars Missions

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

**Mars mission**
- Oxygen only
- Methane + Oxygen

75% of ascent propellant mass: ~ 23 mT
100% of ascent propellant mass: ~ 30 mT

Regeneration of rover fuel cell reactant mass

Potential 340 mT launch mass saved in LEO = 3 to 5 SLS launches avoided per Mars Ascent

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<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>Ground to LEO</td>
<td>-</td>
<td>20.4 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit (r₁→r₂)</td>
<td>4.3 kg</td>
<td>87.7 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface (r₁→r₃, e.g., Descent Stage)</td>
<td>7.5 kg</td>
<td>153 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit to Earth Surface (r₁→r₄→r₅, e.g., Orion Crew Module)</td>
<td>9.0 kg</td>
<td>183.6 kg</td>
</tr>
<tr>
<td>Lunar Surface to Earth Surface (r₃→r₅, e.g., Lunar Sample)</td>
<td>12.0 kg</td>
<td>244.8 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface to Lunar Orbit (r₁→r₃→r₄, e.g., Ascent Stage)</td>
<td>14.7 kg</td>
<td>300 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface to Earth Surface (r₁→r₃→r₅, e.g., Crew)</td>
<td>19.4 kg</td>
<td>395.8 kg</td>
</tr>
</tbody>
</table>

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Why Methane Fuel?

- Simplicity of ISRU Processing
  - Single step process for methane.
    - Two or more steps for most other hydrocarbon fuels
  - High processes conversion:
    - >99% methane product from CO₂ in single pass (recycle H₂)
    - Other fuels (such as Fischer Tropsch) have wide band of hydrocarbons produced; must separate and recycle (increase complexity), or accept (decrease in engine performance)

- Higher propulsion efficiency
  - Pros: Higher Isp than most other hydrocarbons
    - High ox/fuel (O/F) mixture ratio. (Max. benefit for O₂ only ISRU)
    - Clean burning; no coking
  - Cons: Methane is lower density than other hydrocarbons
    - High H-to-C ratio (Min. benefit for Earth provided H₂ ISRU options)

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</thead>
<tbody>
<tr>
<td>Isp</td>
<td>328</td>
<td>365</td>
<td>362</td>
<td>357</td>
<td>335</td>
<td>340</td>
<td>364</td>
<td>352</td>
<td>441</td>
<td>454</td>
</tr>
<tr>
<td>MR</td>
<td>1.9</td>
<td>1.0</td>
<td>3.5</td>
<td>3.25</td>
<td>1.5</td>
<td>2</td>
<td>2.75</td>
<td>3.0</td>
<td>5.25</td>
<td>6.0</td>
</tr>
<tr>
<td>Fuel Density (kg/m³)</td>
<td>880</td>
<td>1020</td>
<td>422</td>
<td>500-580</td>
<td>792</td>
<td>789</td>
<td>568</td>
<td>810</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td>Fuel B.P (K)</td>
<td>360</td>
<td>387</td>
<td>111.7</td>
<td>230.9</td>
<td>337.8</td>
<td>351.5</td>
<td>169.5</td>
<td></td>
<td>20.3</td>
<td>20.3</td>
</tr>
</tbody>
</table>

Based on Chamber Pressure (Pc) = 500 psi; Area Ratio (AR)=150:1; Efficiency = 93%

- Higher compatibility with liquid oxygen
  - Same technology, insulation, cryocoolers, and tanks used for CH₄ as with LO₂
  - Thermal compatibility of lines and engine/thruster thermal management

Overall, choice of methane fuel is an overall balance of performance, storage, compatibility, and production
ISRU Fuel and Oxygen Production End-to-End Integrated System (PEM Based)

Each Function influences the design & operation of connecting boxes

You can’t optimize a single functional box; You need to optimize the system
Past/Recent Mars ISRU Technology Development

**CO₂ Collection & Separation**
- Mars dust filtration – filter, electrostatic, cyclone (GRC, KSC, JPL, SBIR)
- Mars atmosphere adsorption pump - Day/Night (LMA, JPL, ARC, JSC)
- Microchannel rapid-cycle adsorption pump (PNNL, SBIR)
- Mars atmosphere solidification (CO₂ freezing) pump (LM, SBIR, KSC)
- Mars atmosphere compressor (MOXIE/SBIR)
- Ionic liquids adsorption/electrochemistry (MSFC, SBIRs)

**CO₂ Processing**
- Solid Oxide CO₂ Electrolysis (NASA, Universities, Industry, SBIRs)
- Low pressure CO₂ Glow/Plasma Dissociation (Universities)
- Reverse Water Gas Shift (KSC, PNNL, SBIRs)
- Sabatier reactors (NASA, Industry, SBIRs)
- Bosch/Boudouard reactors – MSFC, KSC, Industry, Univ., SBIRs
- Methane reformer (JPL, SBIRs)
- Hydrocarbon fuel reactors - methanol, toluene, ethylene, etc. (SBIRs)
- Microchannel chemical reactors/heat exchangers (PNNL, SBIRs)
- ElectrolysisCo-Production O₂/Fuel – PEM and Ionic Liquids (MSFC/KSC, SBIRs)

**Water Processing**
- Water electrolysis/decomposition (NASA, Industry, SBIRs)
- PEM-High and Low Pressure & Solid Oxide (NASA, Industry, SBIRs)
- Water separation/collection – membrane & cooling (NASA, Industry)
Past/Recent Mars ISRU 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)

Soil Processing
- $\text{H}_2$ Reduction of regolith reactors (NASA, LMA)
- Microwave soil processing (MSFC, JPL, SBIR)
- Open and closed Mars soil processing reactors (JSC, GRC, SBIRs)
- 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)
Past/Recent Mars ISRU System Development

Mars Atmosphere Processing

- **1st Gen Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing in late ‘90s/early 00’s (NASA, Lockheed Martin)**
- **1st Generation Reverse Water Gas Shift with and w/o Fuel production (NASA, Pioneer Astronautics)**

- **2nd Gen MARCO POLO atmosphere processing (JSC, KSC)**

**Atm Processing Module**
- 0.088 kg/hr CO₂
- 0.033 kg/hr CH₄
- 0.071 kg/hr H₂O

**Water Processing Module**
- 0.52 kg/hr H₂O
- 0.46 kg/hr O₂
- 0.058 kg/hr H₂

Sabatier/Water Electrolysis w/ CO₂ Absorption (LMA & JSC) [Tested under simulate Mars surface conditions]

Combined Sabatier/ RWGS/Water Electrolysis (Pioneer Ast.)

CO₂ Electrolysis (GRC) [Tested under conference conditions]

Reverse Water Gas Shift/ Water Electrolysis (KSC & Pioneer Astrobotics)
Past/Recent Mars ISRU System Development

Lunar/Mars Soil Processing

- 1st Gen H$_2$ Reduction from Regolith Systems (NASA, LMA)
  - ROxygen H$_2$ Reduction
  - Water Electrolysis
  - Cratos Excavator

- 2nd Gen MARCO POLO soil processing system (JSC, KSC)
  - Soil Processing Module
    - 10kg per batch; 5 kg/hr
    - 0.15 kg/hr H$_2$O
    - (3% water by mass)
Current ISRU Missions

Mars 2020 ISRU Demo
- Make O2 from Atm. CO2: \(~0.01\) kg/hr O2; <600 W-hrs; >10 sols of operation
- Scroll Compressor and Solid Oxide Electrolysis technologies
- Payload on Mars 2020 rover

Resource Prospector – RESOLVE Payload
- Measure H2O: Neutron spec, IR spec., GC/MS
- Measure volatiles – H2, CO, CO2, NH3, CH4, H2S: GC/MS
- Possible mission in 2020

Orbiters/Cubesats
- Lunar Flashlight: Use laser and spectrometer to look into shadowed craters for volatiles
- Lunar Ice Cube: Broadband InfraRed Compact High Resolution Explorer Spectrometer (BIRCHES) instrument
- Skyfire: Spectroscopy and thermography for surface characterization
- Mars 2022 Orbiter: Radar for ground ice and spectrometers for hydrated minerals
Mars ISRU Propellant Production

**Needs**

- **Propellant production for human mission ascent (Mars DRA 5.0)**
  - For O₂ only: 2.2 to 3.5 kg/hr O₂; 480 days or 300 days
  - For O₂/CH₄:
    - 0.55 to 0.88 kg/hr CH₄
    - 1.2 to 2.0 kg/hr H₂O; (41 to 66 kg/hr soil @ 3% H₂O by mass)

- **Propellant production for Mars Sample Return**
  - 0.35 to 0.5 kg/hr O₂; 420 to 500 days (multiple studies)
  - 0.75 to 1.5 kg/hr O₂; 35 or 137 days (Mars Collaborative Study 4-2012)

- **Propellant production for Mars ISRU Demo**
  - 0.02 kg/hr O₂; 50 operations (Mars 2020 AO requirement)
  - 0.00004 kg/hr O₂; 10 operations (MIP demo on Mars 2001 Surveyor)

**Demonstrated**

- **Mars ISRU Testbeds (late '90s early '00s):**
  - LMA/JSC Sabatier/Water Electrolysis: 0.02 kg/hr O₂; 0.01 kg/hr CH₄
  - KSC RWGS/Water Electrolysis: 0.087 kg/hr O₂
  - Pioneer Astronautics (SWE & RWGS): 0.02 kg/hr O₂; 0.01 kg/hr CH₄
    (IMISPPS): 0.031 kg/hr O₂, 0.0088 kg/hr CH₄

- **Atmosphere Processing: MARCO POLO (Individual subsystems)**
  - CO₂ Collection: 0.088 kg/hr CO₂
  - CO₂ Processing: 0.066 kg/hr of O₂; 0.033 kg/hr of CH₄; 0.071 kg/hr of H₂O
  - Water Processing: 0.52 kg/hr H₂O; 0.46 kg/hr O₂

- **Soil Processing:**
  - Lunar H₂ Reduction - ROxygen Reactor: 5 to 10 kg/hr soil:
  - Lunar H₂ Reduction - PILOT Reactor: 4.5 to 6 kg/hr soil:
  - Mars Soil Auger - MISME: 0.18 to 0.2 kg/hr soil
  - Mars Soil Reactor-Pioneer Ast. Hot CO₂ 4 kg/hr soil per batch

Large Gap between Needs and Demonstrated
ISRU Strongly Influences Element Designs and Architecture Choices

**Construction & Manufacturing**
- Hydrocarbons for plastics
- Materials for concrete & metal structures
- Gas for pneumatic systems
- Explosives

**Environmental Control & Life Support System (ECLSS)**
- O₂, H₂O and N₂/Ar for Habitat & EVA suits
- CO₂ for dust cleaning
- Water and carbon waste from ECLSS
- Defines level of closed-loop ECLSS required

**ECLSS technology common with ISRU**
- Thermal Energy
- Resource instruments
- Gases for science instruments and cleaning

**In-Situ Resource Utilization (ISRU)**
- Lander/Ascent Propulsion
- Propellant (O₂ or O₂/fuel)
- Purge gas/tank pressurant
- Residual Propellants

**Fuel cell reagents (O₂ and fuel)**
- Water from fuel cell
- Water for science activities
- Extra Vehicular Activity (EVA)

**Surface Mobility**
- Defines resource excavation & transportation capabilities

**Surface & Fuel Cell Power Generation**
- Defines surface power needs and fuel cell reagents

**Science Activities**
- Defines propellant options & propulsion capabilities
- Defines propellant excavation & transportation capabilities

**Lander/Ascent Propulsion**
- Fuel cell, water processing, & CFM technologies common with ISRU

**Construction & Manufacturing**
- Residual Propellants
- CFM technology common with ISRU
- In-Situ Resource Utilization (ISRU)
Integrated Fluids & Commodities For Exploration Systems

Goal is to ‘Close the Loops’ Across Multiple Systems

- Identify where common fluids, pressures, quality, and standards are possible
  - Enables common storage, distribution, and interfaces
- Identify where common processes and technologies are possible
  - Enables common hardware for flexibility and reduced DDT&E
  - Enables modularization of non-unique hardware for multiple systems

In-Situ Resource Utilization (ISRU)

Atmosphere
- Soil/Regolith
- Trash/Waste
- Power

Power

Water Electrolysis & Clean Water Storage

Gas & Cryo Storage

Life Support/EVA

Propulsion

- Atmosphere
- Soil/Regolith
- Trash/Waste
- Power

- Electrical Power
- CO₂
- H₂O

- In-Situ Resource Utilization (ISRU)
  - H₂O
  - H₂
  - CH₄
  - O₂

- Solar/Thermal Energy

- Trash/Waste
- Electrical Power
  - H₂O
  - CH₄

- Life Support/EVA
  - H₂
  - O₂

- Propulsion
  - H₂O
  - CH₄

- Gas & Cryo Storage
  - O₂
  - H₂
Integrated ISRU, Power, Life Support, and Propulsion Systems

Mission Scenarios

1. Utilize residual propellant in descent tanks to operate SOFC
2. Make and store propellants for Mars ascent vehicle -- Continuous up to 480 days
3. Transfer LO₂ and CH₄ to crewed pressurized rover/spacecraft
4. Examine integration of life support with ISRU and/or propellant/fuel cells consumables

It is important that technologies and processes selected and element operations be considered at the architecture level vs optimized for each element.
Backup
ISRU Integrated with Exploration Elements (Mission Consumables)

ISRU Functions/Elements
- Resource Prospecting
- Excavation
- Regolith Transport
- Regolith Processing

Support Functions/Elements
- Power Generation & Storage
- O₂, H₂, and CH₄ Storage and Transfer

Shared Hardware to Reduce Mass & Cost
- Solar arrays/nuclear reactor
- Water Electrolysis
- Cryogenic Storage
- Mobility

ISRU Resources & Processing

Modular Power Systems
- Solar & Nuclear

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

In-Space Manufacturing
- Parts, Repair, & Assembly

Life Support & EVA
- Pressurized Rover
- Regenerative Fuel Cell
- Used Descent Stage

Consumable Storage
- Propellant Depot
- Lander/Ascent

ISRU Functions/Elements
- Resource & Site Characterization
- Regolith/Soil Excavation & Sorting
- Regolith Transport
- Regolith Crushing & Processing
- Water/Volatile Extraction
- Regolith for O₂ & Metals
- H₂O, CO₂ from Soil/Regolith
- CO₂ from Mars Atmosphere

Support Functions/Elements
- Power Generation & Storage
- O₂, H₂, and CH₄ Storage and Transfer

Shared Hardware to Reduce Mass & Cost
- Solar arrays/nuclear reactor
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- Propellant Depot
- Lander/Ascent

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- Resource Prospecting
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Life Support & EVA
- Pressurized Rover
- Regenerative Fuel Cell
- Used Descent Stage

Consumable Storage
- Propellant Depot
- Lander/Ascent
ISRU Examples and Analogies

- Excavation rates required for lunar 10 MT O\textsubscript{2}/yr production range based on extraction efficiency of process selected and location
  - H\textsubscript{2} reduction at poles (~1% efficiency): 150 kg/hr
  - CH\textsubscript{4} reduction (~14% efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr

- Excavation rates required for 14.2 MT H\textsubscript{2}O/mission production range based on water content
  - Hydrated soil (3%): 41 kg/hr
  - Icy soil (30%): 4 kg/hr

- Cratos & LMA rovers: 10 to 20 kg/bucket at field test in Hawaii

- Robotic excavation competitions:
  - 2009: 437 kg in 30 min.; remote operation
  - 2015: 118 kg in 20 min; autonomous operation

- Soil Processing
  - ROxygen: 5-10 kg/hr
  - PILOT: 4.5-6 kg/hr
  - Pioneer SBIR: 4 kg/hr
  - MISME: 0.2 kg/hr

10 MT of lunar oxygen per year requires excavation of a Soccer field to a depth of 0.6 to 8 cm! (14% to 1% efficiencies)

14.2 MT of Mars water per mission requires excavation of a Football field to a depth of 1.1 to 9.6 cm! (30% to 3% water by mass)
<table>
<thead>
<tr>
<th>Resource</th>
<th>Potential Mineral Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jarosite – (KFe(^{3+})(OH)(_6)(SO(_4))(_2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Opal &amp; hydrated silica</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phyllosilicates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other hydrated minerals (TBR)</td>
<td></td>
</tr>
<tr>
<td>Water, Ice</td>
<td>Icy soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glacial deposits</td>
<td></td>
</tr>
<tr>
<td>Iron*</td>
<td>Hematite</td>
<td>Ming et al. (2006), Geochemical and mineralogical indicators for Aqueous processes in Columbia Hills of Gusev Crater, Mars” JGR 111, E02S12</td>
</tr>
<tr>
<td></td>
<td>Magnetite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Laterites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jarosite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Triolite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ilmenite</td>
<td></td>
</tr>
<tr>
<td>Aluminum*</td>
<td>Laterites</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminosilicates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plagioclase</td>
<td></td>
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<tr>
<td></td>
<td>Scapolite</td>
<td></td>
</tr>
<tr>
<td>Magnesium*</td>
<td>Mg-sulfates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrated silica</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phyllosilicates</td>
<td></td>
</tr>
<tr>
<td>Titanium*</td>
<td>Ilmenite</td>
<td></td>
</tr>
</tbody>
</table>
New Craters Confirm Shallow, Nearly Pure Ice

- Newly formed craters exposing water ice (red) are a subset of all new craters (yellow).
  Background color is TES dust index. (Adapted from Byrne et al. (2011) Science)

Mid- and high-latitude shallow ice
Thought to be dominated by hydrated minerals

Mid-Latitude Ice-Rich Mantles
### Summary of What we Know About Water in “Hydrated Mineral Deposits”

<table>
<thead>
<tr>
<th>Type of Deposit</th>
<th>General Description</th>
<th>How it has been Modeled Spectrally</th>
<th>Possible water content</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose regolith</td>
<td>Powdered rock, salts, amorphous materials</td>
<td>Mix of plagioclase, olivine, pyroxene, npFeOx</td>
<td>4(2-5)% from spectral modeling and direct measurement</td>
<td>Easy to harvest; perchlorate salts may be common</td>
</tr>
<tr>
<td>Layered phyllosilicate</td>
<td>Stratified deposits rich in smectite</td>
<td>Mix of up to 50% smectite clays with primary igneous minerals (ol, px. Plag)</td>
<td>9-10% based on spectral modeling and assumed low hydration state of clays</td>
<td>Indurated and competent; more erodible than basalt</td>
</tr>
<tr>
<td>Crustal phyllosilicate</td>
<td>Smectite clays in basaltic groundmass</td>
<td>Mix of 5-10% smectite with weakly altered basalt</td>
<td>3-5% based on spectral modeling, examination by Opportunity</td>
<td>Fractured bedrock</td>
</tr>
<tr>
<td>Sulfate-bearing layered deposits</td>
<td>Dust + sand with variable content and type of sulfate cement</td>
<td>Mix of sulfate and hematite with Mix of plagioclase, olivine, pyroxene, npFeOx</td>
<td>6-14% from direct measurement of elemental abundances, hydration state from spectral models</td>
<td>Competent but easily erodible by wind; leaves little debris so must be fine-grained</td>
</tr>
<tr>
<td>Carbonate-bearing deposits</td>
<td>Olivine partly altered to carbonate</td>
<td>Mixture of olivine basalt and carbonate</td>
<td>7% based on spectral models</td>
<td>Probably very indurated bedrock</td>
</tr>
<tr>
<td>Hydrate silica-bearing deposits</td>
<td>Silica with range of hydration mixed w/ basalt</td>
<td>(Assumed: cement in basaltic sediment)</td>
<td>(5% based on assumed composition, could be up to )</td>
<td>Induration and purity probably highly variable</td>
</tr>
</tbody>
</table>
Water/Volatiles Released from Mars Soil
(SAM instrument: Rocknest sample)

Region 1: <300 C
- 40-50% of the water released
- Minimal release of HCl or H$_2$S

Region 2: <450 C
- >80% of the water released
- CO$_2$ and O$_2$ released from decomposition of perchlorates
- Some release of HCl or H$_2$S but before significant amounts are release

Predicted Volatile Release Based on Lab Experiments

CO$_2$ released by
1. Absorbed atmosphere <200C
2. Oxidation of organic material >200 C
3. Thermal decomposition of carbonates >450 C

O$_2$ released by
1. Dehydroxylation of clays <350 C
2. Decomposition of non-metal and metal oxides >500 C

CH$_3$Cl and CH$_2$Cl$_2$ released by
1. Decomposition of Mg(ClO$_4$)$_2$ perchlorate >200C
Need for Early ISRU Demonstration (2020)

- Resource uncertainty and environmental impact on ISRU processes are the greatest risks for ISRU implementation:
  - Water (hydration and ice) resources have significant interest for science, search for life, and ISRU.
  - Dust content, concentration, size/shape distribution at surface are extremely important for long-term operation
    - Joint Science/Exploration mission examining soil/water, dust, atmosphere, and impact on critical ISRU systems provide synergistic goals/objectives

- To Minimize Risk, sequential development and demonstration approach recommended where lessons-learned flow into next effort before PDR/CDR

> Need to start now for human mission to Mars by end of 2030’s
# ISRU Processes Affected by Mars Environment & Resource Characteristics

<table>
<thead>
<tr>
<th>Mission Environment</th>
<th>ISRU Process</th>
<th>Potential Impacts/Effects</th>
</tr>
</thead>
</table>
| Surface regolith properties (fines & bulk) | Excavation and Material Transfer | Could reduce efficiency of regolith excavation and material transfer due to:  
  * Adhesion of particles/grains  
  * Compactness  
  * Water/ice content |
| Soil Processing unit Inlet/Outlet | | Could cause sealing problems for multiple cycle processing |
| Water Filtration & Cleanup | | Fines in soil could reduce performance of water cleanup and processing |
| Dust property uncertainties  
  * Particle size/shape distribution  
  * Local dust amount  
  * Dust particle deposition rate  
  * Dust mineral composition | Filter Design | Could reduce CO₂ acquisition due to:  
  * Improper micron size level required to filter dust  
  * Change in flow rate/Delta P across filter  
  * Improper dust holding capacity or regeneration capability |
| Chemical Reactors | | Could cause reduced performance or failure due to dust poisoning catalysts and electro-chemical/thermal reactors |
| Radiators & Thermal Control | | Could cause insufficient heat rejection or increased thermal power demand at night due to:  
  * Change in surface emissivity  
  * Change in heat transfer coefficient |
| Solar Power | | Could cause insufficient power or oversized array to handle degradation over time  
  * Dust coating and abrasion could reduce cell efficiency  
  * Deployment and sun tracking mechanism binding from dust |
| Mobility/Excavation | | Could cause reduced performance or failure due to dust intrusion into rotating mechanisms |
| Control Electronics | | Could cause arching, grounding, and electrostatic discharge |
| Solar/thermal conditions based on:  
  * Landing site elevation  
  * Landing latitude  
  * Day/night cycles | Solar Power | Could cause insufficient power or oversized array to handle degradation over time  
  * Temperature cycles and UV radiation degraded cells  
  * Structure and deployment mechanisms need to withstand dust/wind loads |
| Radiators & Thermal Control | | Radiator/thermal control system must be sized to surface and sky temperatures, and solar flux/angle on incidence |
| Atmospheric conditions based on:  
  * Landing site elevation  
  * Annual pressure/temperature cycle  
  * Day/night cycles  
  * Atmospheric constituents & concentration | Atmosphere Collection | Adsorption beds, pumps, and separation units must be sized to CO₂ partial pressure |
| Control Electronics | | Low pressure atmosphere could cause arching, grounding, and electrostatic discharge for high voltage applications |
| Chemical Reactors | | Atmospheric constituents/impurities could reduce performance or failure due to poisoning catalysts and electro-chemical/thermal reactors |
Space Resource Challenges

- **What resources exist that can be used?**
  - Oxygen and metals from regolith/soils
  - Water/Ice
  - Atmospheres & volatiles
  - Thermal environments
  - Sunlight
  - Shielding: Lava tubes, regolith, water, hills/craters

- **What are the Uncertainties associated with the Resources?**
  - Polar volatiles:
    - *Where is it*, What is there, how is it distributed, terrain and environment, contaminants?
  - Mars water/ice in soil
    - What form is the water (ice, mineral-bound), how is it distributed, terrain and environment, contaminants?
  - Near Earth Objects/Asteroids/Mars Moons
    - What is there, how is it distributed, environment, contaminants
    - Ability to revisit NEO of interest (time between missions)
    - What techniques are required for micro-g mining and material processing?
ISRU Technical Challenges

- **Is it Technically feasible to collect, extract, and process the Resource?**
  - Energy: Amount and type (especially for polar resources in shadowed regions)
  - Life, maintenance, performance
  - Amount of new technology required

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery
  - No crew for maintenance; Non-continuous monitoring from Earth

- **High reliability and minimum (zero) maintenance**
  - No (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Develop highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Develop highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)

- **Operation in severe environments**
  - Efficient excavation of resources in dusty/abrasive environments
  - Methods to mitigate dust/filtration for Mars atmospheric processing
  - Micro-g environment for asteroids and Phobos/Deimos

- **Integration and Operation with other Exploration Systems**
  - Exploration systems must be designed to utilize ISRU provided products; may cause selection of different technologies/approaches
Mars ISRU Challenges

- **Resource Unknowns**
  - **Atmosphere resource unknowns:** i) size distribution, number of particles, and dust type near surface
  - **Water resource unknowns:** No single form of water resource
    - **Hydrated mineral/soil unknowns:** i) Water content in soil as a function of location, depth, and soil type; ii) hydrated mineral/soil physical characteristics for excavation and transfer; iii) contaminants released during evolution and collection of water from hydrated minerals/soil
    - **Subsurface ice unknowns:** i) Ice content in soil as a function of location, depth, and soil type; ii) soil/ice physical characteristics for drilling and transfer; iii) contaminants released during evolution and collection of water from icy soils

- **Long-duration, autonomous operation**
  - Autonomous control & failure recovery
  - No crew for maintenance; Non-continuous monitoring from Earth

- **High reliability and minimum (zero) maintenance**
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  - Micro-g environment for Phobos/Deimos
Core ISRU Technologies Are Applicable To Both Moon and Mars

Lunar & Mars ISRU Share Many Common Technologies & Modules

**Lunar ISRU**
- Site preparation
- Oxygen extraction
- Water & volatile extraction
- Pneumatic excavation
- Methane regeneration for carbothermal reduction
- Crew waste/trash processing
- Water electrolysis
- All processing systems
- All oxygen storage and transfer systems

**Core Technologies**
- Soil excavation and transfer
- Water extraction from soil/solid material
- Water Distillation/Cleanup
- CO₂ & N₂ Acquisition & Separation
- Sabatier Reactor
- Methane Reforming
- RWGS Reactor
- CO₂ Electrolysis
- H₂O Separators
- H₂O Electrolysis
- H₂O Storage
- Heat Exchangers
- Liquid Vaporizers
- O₂ & Fuel Storage (0-g & reduced-g)
- O₂ Feed & Transfer Lines
- O₂/Fuel Couplings

**Mars ISRU**
- Water extraction from soil
- Mars atmosphere resource collection and conditioning
- Fuel production
- Oxygen production
- Water electrolysis
- All processing systems
- All oxygen storage and transfer systems
  (Note: Mars atmosphere does not allow for MLI usage)
ISRU Shares Common Technologies with Other Mission Elements

**ISRU Maximizes Benefits, Flexibility, & Affordability**

- Modular hardware & common mission fluids reduced logistics, increases reliability & flexibility, and reduces development and mission costs

**Core Technologies**

**In-Situ Production Of Consumables for Propulsion, Power, & ECLSS**

- Soil Excavation and Transfer
- Water extraction from Soil/Solid Material
- Water Distillation/Cleaning
- CO₂ & N₂ Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- CO₂ Electrolysis
- Methane Reforming
- H₂O Separators
- H₂O Electrolysis
- Fuel Cells
- H₂O Storage
- Heat Exchangers
- Liquid Vaporizers
- O₂ & Fuel Storage (0-g & reduced-g)
- O₂ Feed & Transfer Lines
- O₂/Fuel Couplings
- O₂/Fuel Igniters & Thrusters

**Fuel Cell Power for Spacecraft, Rovers & EVA**

**Life Support Systems for Habitats & EVA**

- Habitat, EVA, and radiation shielding

**Water – Gaseous H₂/O₂ Based Propulsion**

- Station keeping, depots, integrated power

**Non-Toxic O₂-Based Propulsion**

- Launch vehicle & human/robotic landers

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov
## Difference between Mars ISRU & Life Support

<table>
<thead>
<tr>
<th>ISRU</th>
<th>Life Support</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resource Feedstock</strong></td>
<td></td>
</tr>
<tr>
<td>Potentially unlimited (except for Trash)</td>
<td>Controlled feedstock as function of number of crew</td>
</tr>
<tr>
<td>&lt;100% collection efficiency acceptable</td>
<td>Maximize collection efficiency</td>
</tr>
<tr>
<td>Feedstock input ratios function of resource availability</td>
<td>Feedstock input rations function of crew waste products</td>
</tr>
<tr>
<td><strong>Processing Systems</strong></td>
<td></td>
</tr>
<tr>
<td>External to habitable volumes</td>
<td>Internal to habitable volumes</td>
</tr>
<tr>
<td>Pressures and temperatures are a function of optimizing chemical reaction and system mass/power</td>
<td>Pressures based on cabin pressure; temperatures minimized for thermal control and touch</td>
</tr>
<tr>
<td>Carbon dioxide/Carbon monoxide (CO₂/CO) processing reactors run hydrogen rich with H₂ recycling to maximize CO₂/CO conversion</td>
<td>CO₂ processing reactors run hydrogen poor to mitigate H₂ leakage concerns</td>
</tr>
<tr>
<td>Production and venting of CO allowed</td>
<td>Production of CO avoided due to toxicity risk</td>
</tr>
<tr>
<td><strong>System Design</strong></td>
<td></td>
</tr>
<tr>
<td>CO₂ Acquisition, CO₂ Processing, &amp; H₂O Processing highly integrated (esp. thermally)</td>
<td>Subsystems for ISS were designed and built separately</td>
</tr>
<tr>
<td>Subsystems designed to operate all at the same time. Separate subsystem operation or batch process a function of available power or CO₂ collection approach.</td>
<td>Subsystems for ISS operate at same or different times</td>
</tr>
<tr>
<td>Small amount of leakage acceptable</td>
<td>Leakage not acceptable because of habitable volume concerns</td>
</tr>
<tr>
<td><strong>Oxygen Storage</strong></td>
<td></td>
</tr>
<tr>
<td>Storage pressure optimized for system performance and liquefaction energy</td>
<td>Storage pressure for EVA portable life support system recharge</td>
</tr>
<tr>
<td>Oxygen purity based on end user (propulsion, fuel cell, or life support)</td>
<td>Oxygen purity based on crew</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td></td>
</tr>
<tr>
<td>Operate continuously while power is available (sunlight or nuclear); minimize start-up/shutdown operations</td>
<td>Operate on as needed basis. Continuous if possible</td>
</tr>
<tr>
<td>ISRU systems must be designed for minimum/no mainanance since operations often occur before crew arrives</td>
<td>Crew mainanace acceptable</td>
</tr>
</tbody>
</table>
ISRU Influences other Exploration Systems

- **Integration and Operation with other Exploration Systems is critical**
  - Early integrated ground development activities required to foster interaction

<table>
<thead>
<tr>
<th>System Maturation Teams</th>
<th>Required From</th>
<th>Delivered To</th>
<th>Shared Areas of Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA</td>
<td>Maintance and repair</td>
<td>Consumables (quality, type, amount)</td>
<td>CO₂ and water management</td>
</tr>
<tr>
<td>Human Robotic Mission Ops</td>
<td>Mobility, Manipulation</td>
<td>Requirements for mobility &amp; manipulation</td>
<td>End effectors for civil engineering</td>
</tr>
<tr>
<td>Crew Health &amp; Protection</td>
<td>Requirements for radiation shielding</td>
<td>Approaches for radiation shielding</td>
<td>Radiation material effectiveness testing</td>
</tr>
<tr>
<td>Autonomous Mission Ops</td>
<td>Autonomy, failure tolerance</td>
<td>Requirements</td>
<td>System and analog testing; precursors</td>
</tr>
<tr>
<td>Communication &amp; Navigation</td>
<td>Comm and nav.</td>
<td>Requirements</td>
<td>Comm time delay operations</td>
</tr>
<tr>
<td>ECLSS &amp; Env. Monitoring</td>
<td>Trash and waste feedstock</td>
<td>Consumables (quality, type, amount)</td>
<td>CO₂, water, and trash mgmt and processing</td>
</tr>
<tr>
<td>Entry, Descent, and Landing</td>
<td>Landing accuracy for resource assessment</td>
<td>Aeroshell from space resources</td>
<td>Plume modeling &amp; mitigation testing</td>
</tr>
<tr>
<td></td>
<td>Plume exhaust interaction with surface</td>
<td>Landing pads/berms</td>
<td></td>
</tr>
<tr>
<td>Power &amp; Energy Storage</td>
<td>Electrical (and thermal) energy</td>
<td>Fuel cell consumables. Energy generation &amp; storage from in-situ materials</td>
<td>Fuel cell reactant regeneration; solid oxide fuel cells and water electrolyzers</td>
</tr>
<tr>
<td>Radiation</td>
<td>Requirements for radiation shielding</td>
<td>Approaches for radiation shielding</td>
<td>Radiation material effectiveness testing</td>
</tr>
<tr>
<td>Thermal (incl. Cryo Fluid Management)</td>
<td>Consumable liquefaction, storage, transfer; thermal management in shadowed regions</td>
<td>Requirements; Waste heat; in-situ thermal storage approaches</td>
<td>Lunar night and polar region survival and/or operation</td>
</tr>
<tr>
<td>Fire Safety</td>
<td></td>
<td></td>
<td>Hazard mitigation and sensors</td>
</tr>
<tr>
<td>Propulsion</td>
<td>Requirements for propellants</td>
<td>Consumables (quality, type, amount)</td>
<td>Propulsion, storage, and transfer testing</td>
</tr>
<tr>
<td>ISRU</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

G. Sanders, (281) 483-9066, gerald.b.sanders1@jsc.nasa.gov
MARCO POLO (Mars Atmospheric & Regolith COllector/PrOcessor for Lander Operations) is a combined Mars ISRU atmosphere & soil processing demonstration which includes a rover for excavation and science/prospecting.

Atm. Processing Module:
- CO$_2$ capture using freezing
- Sabatier converts H$_2$ and CO$_2$ into Methane and water

Soil Processing Module:
- Soil Hopper handles 30kg
- Soil dryer uses sweep gas and <500 deg C to extract water

Liquefaction Module:
- Common bulkhead tank for Methane and Oxygen liquid storage

Water Cleanup Module:
- Cleans water prior to electrolysis
- Provides clean water storage

Water Processing Module:
- Electrolyze water into H$_2$ & O$_2$

Excavator/Science Rover
- Collects soil for processing
- Can include science instruments

Notional MARCO POLO Design Characteristics
- Nom. Mission Life = 90 Mars days (sols)
- Mass = 200+ kg
- Dimensions = Modular; fit on top of 3 m diameter lander
- Ave. Power; >2000 W
- Production = Up to 0.5 kg O$_2$/hr
Mars ISRU Pathfinder Demo Payload Options

- Mars Atmosphere Processing (O₂ only)
  - Electrostatic precipitator w/ regenerative HEPA filter
  - CO₂ collection (freezing)
  - CO₂ processing: Solid Oxide Electrolysis
  - CO/CO₂ separation and recycling to increase performance
  - O₂ liquefaction
  - O₂ storage

- Mars Atm/Soil Processing (O₂/CH₄)
  - Electrostatic precipitator w/ regenerative HEPA filter
  - CO₂ collection (freezing)
  - CO₂ processing: Sabatier Reactor
  - Rover/Excavation
  - Soil processing reactor (up to 450 C)
  - Water separation/cleanup module
  - Water electrolysis (Cathode Feed PEM)
  - O₂ & CH₄ product dryer
  - O₂ & CH₄ liquefaction & Storage
# ISRU Demo Payload Results Summary

## Mars Atm ISRU Demo

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>Power (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Production rate: 0.45 kg/hr;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtration</td>
<td>1.23</td>
<td>0.00025</td>
</tr>
<tr>
<td>CO₂ Collection/Freezer</td>
<td>173</td>
<td>2.23</td>
</tr>
<tr>
<td>SOE Processor</td>
<td>5.6</td>
<td>3.7</td>
</tr>
<tr>
<td>SOE Recirculation system</td>
<td>34.6</td>
<td>0.187</td>
</tr>
<tr>
<td>O₂ Liquefaction and Storage</td>
<td>70</td>
<td>0.6</td>
</tr>
<tr>
<td>Secondary Structure (15%)</td>
<td>42.7</td>
<td></td>
</tr>
<tr>
<td>Solar Arrays (2)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Power conditioning/batteries*</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Thermal Management/Radiators</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>372.1</td>
<td>6.72</td>
</tr>
</tbody>
</table>

## Mars Soil ISRU Demo

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>Power (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Production rate: 0.48 kg/hr;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rover Excavator**</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Soil Processor &amp; Water Cleanup</td>
<td>193</td>
<td>3.1</td>
</tr>
<tr>
<td>Water Electrolysis (2)</td>
<td>40</td>
<td>2.8</td>
</tr>
<tr>
<td>O₂ Dryer</td>
<td>4.1</td>
<td>0.064</td>
</tr>
<tr>
<td>O₂ Liquefaction and Storage</td>
<td>72</td>
<td>0.7</td>
</tr>
<tr>
<td>Secondary Structure (15%)</td>
<td>71.9</td>
<td></td>
</tr>
<tr>
<td>Solar Arrays (2)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Power conditioning/batteries*</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Thermal Management/Radiators</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>596.0</td>
<td>6.66</td>
</tr>
</tbody>
</table>

## Combined Atm/Soil ISRU Demo

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>Power (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ Production rate: 0.48 kg/hr;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtration</td>
<td>1.3</td>
<td>0.00025</td>
</tr>
<tr>
<td>CO₂ Collection/Freezer</td>
<td>43</td>
<td>0.574</td>
</tr>
<tr>
<td>Sabatier Microchannel Reactor</td>
<td>1</td>
<td>0.082</td>
</tr>
<tr>
<td>Rover Excavator**</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Soil Processor &amp; Water Separation</td>
<td>193</td>
<td>1.7</td>
</tr>
<tr>
<td>Water Capture/Temp Storage</td>
<td>3.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Water Electrolysis (2)</td>
<td>40</td>
<td>2.8</td>
</tr>
<tr>
<td>O₂ and CH₄ Dryers</td>
<td>5</td>
<td>0.098</td>
</tr>
<tr>
<td>O₂ Liquefaction and Storage</td>
<td>72</td>
<td>0.7</td>
</tr>
<tr>
<td>CH₄ Liquefaction and Storage</td>
<td>58</td>
<td>0.42</td>
</tr>
<tr>
<td>Secondary Structure (15%)</td>
<td>88.1</td>
<td></td>
</tr>
<tr>
<td>Solar Arrays (2)</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Power conditioning/batteries*</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Thermal Management/Radiators</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>720.1</td>
<td>6.9</td>
</tr>
</tbody>
</table>

## ISRU Plant Only

<table>
<thead>
<tr>
<th>Component</th>
<th>Atm</th>
<th>Soil</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>246.59</td>
<td>272.67</td>
<td>330.05</td>
</tr>
<tr>
<td>Power (KW)</td>
<td>6.12</td>
<td>5.96</td>
<td>5.75</td>
</tr>
</tbody>
</table>

*Mass and power available for batteries
**Rover not optimized for soil excavation or production rate

Rover oversizes for mission

Human mission would include 3 units

Rover not included
Oxygen and Methane are ‘space’ storage (i.e. heating or cooling is minimal to maintain its state) for the Earth, Moon, and Mars.

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