Space Resource Utilization and Human Exploration of Space

Presentation for the Planetary & Terrestrial Mining Sciences Symposium (PTMSS)

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Gerald (Jerry) Sanders
ISRU Chief Engineer
NASA/Johnson Space Center, Houston, TX, 77058  USA
gerald.b.sanders@nasa.gov
NASA Strategic Goals:

- Extend and sustain human activities across the solar system
- Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere.
- Create the innovative new space technologies for our exploration, science, and economic future

Affordable and Sustainable
Critical for exploration beyond low Earth orbit
- Robotics & Automation
- Power Systems
- Propulsion
- Habitation & Life Support
- Space Resource Utilization
“Fifty years after the creation of NASA, our goal is no longer just a destination to reach. Our goal is the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite. And in fulfilling this task, we will not only extend humanity’s reach in space -- we will strengthen America’s leadership here on Earth.”

- President Obama, April 2010
Sustainable Human Space Exploration
NASA’s Building Blocks to Mars

Earth Reliant
Missions: 6 to 12 months
Return: hours

Proving Ground
Missions: 1 month up to 12 months
Return: days

Earth Independent
Missions: 2 to 3 years
Return: months

U.S. companies provide affordable access to low Earth orbit

Mastering the fundamentals aboard the International Space Station

Pushing the boundaries in cis-lunar space

Developing planetary independence by exploring Mars, its moons, and other deep space destinations

The next step: traveling beyond low-Earth orbit with the Space Launch System rocket and Orion crew capsule

U.S. companies provide affordable access to low Earth orbit

Mastering the fundamentals aboard the International Space Station

Pushing the boundaries in cis-lunar space

Developing planetary independence by exploring Mars, its moons, and other deep space destinations

The next step: traveling beyond low-Earth orbit with the Space Launch System rocket and Orion crew capsule
Evolvable Mars Campaign: Enabling Technologies

**Transportation**
- Oxygen-Rich Staged Combustion (ORSC) Engine Technology
- Chem Prop (In-Space): LOX/Methane Cryo (Propulsion & RCS)
- Solar Electric Propulsion & Power Processing
- 10-100 kW Class Solar Arrays
- Cryo Propellant Acquisition & ZBO Storage
- AR&D, Prox Ops & Target Relative Navigation
- EDL, Precision Landing, Heat Shield
- Autonomous Vehicle Systems Management
- Mission Control Automation beyond LEO

**Staying Healthy**
- Advanced, High-Reliability ECLSS
- Long-Duration Spaceflight Medical Care
- Long-Duration Spaceflight Behavioral Health & Performance
- μ-G Biomedical Counter-Measures for Long-Duration Spaceflight
- Deep Space Mission Human Factors & Habitation
- In-Flight Environmental Monitoring
- Human SPE & GCR Radiation Exposure Prevention & Protection
- Fire Prevention, Detection, Suppression (Reduced Pressure)

**Working in Space**
- Autonomy beyond LEO
- High Data Rate Forward Link Communications
- High-Rate, Adaptive, Internetworked Proximity Communications
- In-Space Timing & Navigation for Autonomy
- Fission Surface Power (FSP)
- ISRU (Atmospheric & Regolith)
- Mechanisms (low-temp), Dust Mitigation
- Tele-robotic Control of Robotic Systems with Time Delay
- Robots Working Side-By-Side with Suited Crew
- Robotics & Mobility EVA Exploration Suit and PLSS
- Electro-Chemical Power Systems
- Advanced Fire Protection Systems
- Deep Space Suit & Mars Surface Suit (EVA)
- Surface Mobility
- Suit Port, u-G tools & anchoring
- Advance Software Development/Tools
What are Space Resources?

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

- **Energy**
  - Permanent/Near-Permanent Sunlight
    - Stable thermal control & power/energy generation and storage
  - Permanent/Near-Permanent Darkness
    - Thermal cold sink for cryo fluid storage & scientific instruments

- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
  - High Thermal Gradients

- **Location**
  - Stable Locations/‘Real Estate’:
    - Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth
    - Electromagnetic noise, hazardous testing & development activities (nuclear, biological, etc.), extraterrestrial sample curation & analysis, storage of vital information, etc.
**Space Resources**

**Four major resources on the Moon:**
- **Regolith**: oxides and metals
  - Ilmenite 15%
  - Pyroxene 50%
  - Olivine 15%
  - Anorthite 20%
- Solar wind volatiles in regolith
  - Hydrogen 50 – 150 ppm
  - Helium 3 – 50 ppm
  - Carbon 100 – 150 ppm
- **Water/ice** and other volatiles in polar shadowed craters
  - 1-10% (LCROSS)
  - Thick ice (SAR)
- Discarded materials: **Lander and crew trash and residuals**

**Resources of Interest**
- **Oxygen**
- **Water**
  - Hydrogen
  - Carbon/CO₂
  - Nitrogen
  - Metals
  - Silicon

**Three major resources on Mars:**
- **Atmosphere**:
  - 95.5% Carbon dioxide,
  - 2.7% Nitrogen,
  - 1.6% Argon
- **Water in soil**: concentration dependant on location
  - 2% to dirty ice at poles
- Oxides and metals in the soil

**~85% of Meteorites are Chondrites**

**Ordinary Chondrites**
- FeO:Si = 0.1 to 0.5
- Fe:Si = 0.5 to 0.8

**Source metals (Carbonyl)**
- Pyroxene
- Olivine
- Plagioclase
- Diopside
- Metallic Fe-Ni alloy
- Troilite - FeS

**Carbonaceous Chondrites**
- 8%
- Highly oxidized w/ little or no free metal
- Abundant volatiles: up to 20% bound water and 6% organic material

**Enstatite Chondrites**
- 5%
- Highly reduced; silicates contain almost no FeO
- 60 to 80% silicates; Enstatite & Na-rich plagioclase
- 20 to 25% Fe-Ni
- Cr, Mn, and Ti are found as minor constituents

**Easy source of oxygen (Carbothermal)**
Vision for Using Space Resources

Moon

Mars

Phobos

NEAs

Commercial
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.

Five Major Areas of ISRU

- **Resource Characterization and Mapping**
  Physical, mineral/chemical, and volatile/water

- **Mission Consumable Production**
  Propellants, life support gases, fuel cell reactants, etc.

- **Civil Engineering & Surface Construction**
  Radiation shields, landing pads, roads, habitats, etc.

- **In-Situ Energy Generation, Storage & Transfer**
  Solar, electrical, thermal, chemical

- **In-Situ Manufacturing & Repair**
  Spare parts, wires, trusses, integrated structures, etc.

- ‘ISRU’ is a capability involving multiple technical discipline elements (mobility, regolith manipulation, regolith processing, reagent processing, product storage & delivery, power, manufacturing, etc.)

- ‘ISRU’ does not exist on its own. By definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.
Potential Lunar ISRU Mission Capabilities

- Excavation & Regolith Processing for O₂ and Metal Production
- Consumable Depots and Waypoints for Crew & Power
- Polar Ice/Volatile Prospecting & Mining
- Solar and Thermal Energy Storage Construction
- Landing Pads, Berm, and Road Construction
- Structure and Habitat Construction
Space ‘Mining’ Cycle: Prospect to Product

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

Communication & Autonomy

Site Preparation & Infrastructure Emplacement

Mining

Maintenance & Repair

Crushing/Sizing/Beneficiation

Processing

Waste

Spent Material Removal

Remediation

Product Storage & Utilization
- Power
- Propulsion
- Life Support & EVA
- Depots
Space Resources Utilization Changes How We Can Explore Space

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

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

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

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

- Solves Terrestrial Challenges & Enables Space Commercialization
  - Develops alternative & renewable energy technologies
  - New renewable construction
  - CO₂ remediation
  - Green metal production
  - Provides infrastructure to support space commercialization
  - Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

- Space Resource Utilization
  - CO₂ remediation
  - Green metal production

- New renewable construction

- CO₂ remediation

- Green metal production

- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

- Reduces dependence on Earth
Make It vs Bring It – A New Approach to Exploration

**Reduces 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 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

**Increases Performance**
- Longer stays, increased EVA, or increased 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
- Decreased logistics and spares brought from Earth

**Increases Science**
- Greater surface 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 eliminating consumable delivery

**Increases Sustainability/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

**Supports Multiple Destinations**
- Surface soil processing operations associated with ISRU applicable to Moon and Mars
- ISRU subsystems and technologies are applicable to multiple destinations and other applications
- Resource assessment for water/ice and minerals common to Moon, Mars, and NEOs
How ISRU Enables Future Moon & Mars Missions

Every 1 kg of product made on the Moon or Mars saves 7.5 to 11.3 kg in Low Earth Orbit

- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

A Kilogram of Mass Delivered Here...

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

Estimates based on Aerocapture at Mars

1 kg propellant on Mars

1.9 kg used for EDL

2.9 kg prior to Mars EDL

8.4 kg used for TMI propulsion

226 kg on Earth

11.3 kg in LEO
Implementation Strategy for Space Resource Utilization

- Three phases of ISRU implementation to minimize risk to human exploration plans
  - **Phase 1: Scout and Demonstrate** – *Mission Feasibility*
    - Evaluate potential exploration sites: terrain, geology/resources, lighting, etc.
    - Demonstrate critical technologies, functions, and operations
    - Evaluate environmental impacts and long-term operation on hardware: dusty/abrasive/electrostatic regolith, radiation/solar wind, day/night cycles, polar shadowing, etc.
  - **Phase 2: Pilot Scale Demonstration** – *Mission Enhancement*
    - Perform critical demonstrations at scale and duration to minimize risk of utilization
    - Obtain design and flight experience before finalizing human mission element design
    - Pre-deploy and produce product before crewed missions arrive to enhance mission capability
  - **Phase 3: Utilization Operations** – *Mission Enabling*
    - Produce at scale to enable ISRU-fueled reusable landers and support extended duration human surface operations
    - Commercial involvement or products bought commercially based on Phase 2

- Identify technologies and systems for multiple applications (ISRU, life support, power) and multiple mission (Moon, Mars, NEOs)

- Multinational (government, industry, and academia) involvement for development and implementation leading to space commercialization
Stepwise Approach to Utilizing Space Resources

Or mineral maps for oxygen/metals

**Stepwise Approach to Utilizing Space Resources**

Select Site for Prospecting

Perform Mining Feasibility

Start Mining for Product

Perform Exploratory Assessment

Perform Focused Assessment

Mining Feasibility results were promising

Focused Assessment results were promising

Focused Assessment results were not favorable

Exploratory Assessment results were not favorable

**Neutron Depletion**

**Depth to Stable Ice (m)**

**Days of Sunlight**

**Comm Visibility (Days)**

**Slopes at 25 m Scale (deg)**

- Neutron Depletion
- Depth to Stable Ice (m)
- Days of Sunlight
- Comm Visibility (Days)
- Slopes at 25 m Scale (deg)
ISRU Capability-Function Flow Chart

Survey/Prospect

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

In-Situ Construction

- Produce Feedstock for Construction
- Resource Excavation/Transfer
- Gas Resource Preparation
- Solid Resource Preparation

In-Situ Manufacturing

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

Consumable Production

- Extract Oxygen and/or Metals
- Extract Water/Volatiles
- Produce O₂, Fuel, and/or water

Primary Process

- 3D Construction Material
- Shielding Material

Secondary Process

- Concrete
- Metallurgical Mat’l
- Trash/Granular
- Granular Mat’l
- Atn/Gas
- Volatiles
- H₂, He, etc.
- Organics
- CO, CO₂, Gases

Products

- Oxygen
- Water
- Oxygen
- Water
- Fuels
- Life Support Gases
- Gases
- Precursors
- Plastic
- Ceramics
- Plastic
- Precursors
- Steel
- Ceramic
- Concrete
- 3D Construction Material
- Shielding Material

Secondary Processes

- Metal Processed Mat’l
- In-Situ Manufacturing
- In-Situ Construction
- Site Imaging/Characterization
- Locate Sample/Mining Locations
- Select Mining Site/Anchor to Surface
- Physical/Mineral/Volatile Assessment
- Resource Analysis & Mapping

Resource Acquisition

- Survey/Prospect
- Select Mining Site/Anchor to Surface
- Locate Sample/Mining Locations
- Resource Analysis & Mapping

Primary Processes

- Produce Feedstock for Construction
- Gas Resource Preparation
- Solid Resource Preparation
- Resource Excavation/Transfer
- Resource Acquisition
# Moon, Mars, & Near Earth Objects (NEOs)

<table>
<thead>
<tr>
<th></th>
<th>Moon</th>
<th>Mars</th>
<th>NEOs</th>
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</thead>
<tbody>
<tr>
<td><strong>Gravity</strong></td>
<td>1/6 g</td>
<td>3/8 g</td>
<td>Micro-g</td>
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<tr>
<td><strong>Temperature</strong></td>
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<tr>
<td>(Max)</td>
<td>110 °C/230 °F</td>
<td>20 °C/68 °F</td>
<td>110 °C/230 °F</td>
</tr>
<tr>
<td>(Min.)</td>
<td>-170 °C/-274 °F</td>
<td>-140 °C/-220 °F</td>
<td>-170 °C/-274 °F</td>
</tr>
<tr>
<td>(Min. Shade)</td>
<td>-233 °C/-387.4 °F</td>
<td>-233 °C/-387.4 °F</td>
<td>-233 °C/-387.4 °F</td>
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<tr>
<td><strong>Solar Flux</strong></td>
<td>1352 W/m²</td>
<td>590 W/m²</td>
<td>Varied based on distance from Sun</td>
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<tr>
<td><strong>Day/Night Cycle</strong></td>
<td>28+ Days - Equator Near Continuous Light or Dark - Poles</td>
<td>24.66 hrs</td>
<td>Varied - hrs</td>
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<tr>
<td><strong>Surface Pressure</strong></td>
<td>1x10⁻¹² torr</td>
<td>7.5 torr</td>
<td>1x10⁻¹² torr</td>
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<tr>
<td><strong>Atmosphere</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td></td>
<td></td>
<td>CO₂, N₂, Ar, O₂</td>
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<tr>
<td><strong>Soil</strong></td>
<td>Granular</td>
<td>Granular &amp; clay; low hydration to ice</td>
<td>Varied based on NEO type</td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td>Regolith (metals, O₂)</td>
<td>Regolith (metals, O₂)</td>
<td>Regolith (metals, O₂)</td>
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<tr>
<td></td>
<td>Hydrated Soils</td>
<td>Hydrated Soils</td>
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<td>H₂O/Volatile Icy Soils</td>
<td>H₂O/Volatile Icy Soils</td>
<td>H₂O/Volatile Icy Soils</td>
</tr>
</tbody>
</table>

- The Moon has aspects in common with Mars and NEOs/Phobos
- All destinations share common technologies, processes, and operations
- NEO micro-gravity environment is the largest difference between destinations
# ISRU Development Areas vs Mission Applications

## ISRU Development Areas

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<tr>
<td>Regolith-Soil Extraction</td>
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<td>Regolith (granular) Excavation &amp; Transfer</td>
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<td>Hard Material Excavation &amp; Transfer</td>
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<td>Hydrated Soil /Material Excavation &amp; Transfer</td>
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<td>Resource Characterization</td>
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<td>Physical Property Evaluation</td>
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<tr>
<td>Mineral/Chemical Evaluation</td>
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<tr>
<td>Volatile-Product Analysis</td>
<td>X</td>
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<tr>
<td>Regolith-Soil Processing (Volatile, O₂, Metal)</td>
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<tr>
<td>Crushing</td>
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<td>Size Sorting</td>
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<td>Beneficiation/Mineral Separation</td>
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<td>Solid/Gas Processing Reactor</td>
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<td>Solid/Liquid Processing Reactor</td>
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<td>Contaminant Removal</td>
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<td>Gas Processing</td>
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<td>Dust/Particle Filtration</td>
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<td>CO₂ Capture - Separation</td>
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<td>CO₂ Conversion into CO-O₂</td>
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<td>CO/CO₂ Conversion into H₂O-CH₄</td>
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<td>H₂-CH₄ Separation</td>
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<td>Water Processing</td>
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<td>Water Capture</td>
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<td>Water Cleanup - Purity Measurement</td>
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<td>Water Electrolysis</td>
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<td>Regenerative Dryers</td>
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<td>Support Systems</td>
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<td>Extended Operation Power Systems</td>
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<tr>
<td>Extended Operation Thermal Systems</td>
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<tr>
<td>Cryogenic Liquefaction, Storage, and Transfer</td>
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</tbody>
</table>

**Main Discriminators:** material (physical, mineral) water content/form (ice, hydration, surface tension), gravity (micro, low), pressure, (vacuum, atm.), and weathering
Notional Mission Evolution with ISRU
(for planning)

- Resource Prospector (RESOLVE)
- International Space Station
- Asteroid Retrieval
- NEA Resource Prospecting
- In-Space Manufacturing
- Mars ISRU Demo
- Lunar Sample Return
- Mars Surface Pathfinder
- Propellant Production on Mars Surface
- NEA Resource Extraction
- NEA Resource Prospecting
- In-Space Propellant Depot
- Propellant Production on Phobos
- Human Cis-Lunar Missions
- Human NEA Missions
- Human Mars Missions

- Polar Volatiles &/or Oxygen from Regolith
Lunar and Space Exploration Vision for Space Resource Utilization

- Affordable and Sustainable Human Exploration requires the development and utilization of space resources.

- The search for potential resources (Prospecting) and the production of mission critical consumables (propellants, power reactants, and life support gases) is the primary focus of NASA technology and system development since they provide the greatest initial reduction in mission mass, cost, and risk.

- Two approaches to implement space resources into human space missions
  - Scout/Demonstrate, Pilot-operations in non-mission critical role, Utilize in mission
  - Exploratory assessment, focused assessment, and Mining Feasibility

- Selection of common technologies and processes for multiple destinations is recommended.

- Plans for developing ISRU through an evolution of missions starting with the lunar Resource Prospector Mission and Asteroid Retrieval Mission has been proposed to minimize risk
  - Several missions in this evolutionary plan have been initiated or are in the planning stage.
Questions?