ISRU at a Lunar Outpost: Implementation and Opportunities for Partnerships and Commercial Development


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Vision for Space Exploration: ISRU is an Integral Part

- **ISRU Supports and Enables the four main Goals and Objectives of the U.S. Vision for Space Exploration (VSE)**
  - Implement a *sustained* and *affordable* human and robotic program to explore the solar system and beyond;
  - Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
  - Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
  - Promote international and *commercial participation* in exploration to further U.S. scientific, security, and economic interests.

- **ISRU is integral to the success of all of the ‘Themes’ for Why we are going to the Moon?**
  - Extend sustained human presence to the Moon to enable eventual settlement
  - Pursue scientific activities to address fundamental questions
  - Use the Moon to prepare for future human missions to Mars and other destinations
  - Expand Earth’s economic sphere to encompass the Moon, and pursue lunar activities with direct benefits to life on Earth.
  - Strengthen existing and create new global partnerships
  - Engage, inspire, and educate the public
ISRU: Decisions from Lunar Architecture Development

- ISRU is a critical capability and key implementation of the VSE and sustained human exploration.

- At the same time, ISRU on the Moon is an unproven capability for human lunar exploration and can not be put in the critical path of architecture until proven.

- Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired endstate.

- Architecture is designed to be open enough to take advantage of ISRU from whatever source when available.
“I think more work is needed in this step.”
Three Pronged Approach to ISRU Development & Incorporation

- Identify how ISRU fits into Architecture for Sustained human presence on the Moon
  - Non-critical path initially with fall back strategy
  - Evolutionary with growth in:
    - Capability
    - Criticality
    - Ties to Mars
    - Ties to Space Commercialization

- Build confidence in ISRU early and often
  - Multiple generations of hardware and systems developed
  - Extensive ground and analog site testing for operations, maintenance, and interconnectivity
  - Robotic precursors if possible to reduce risk AND
    - Tie to common science objectives for regolith, mineral, and volatile characterization
    - Tie to long-term operations associated with Outpost deployment and operation

- Early NASA involvement in all aspects of ISRU with transition to industry
  - Ensures NASA is ‘smart’ buyer
  - Ensures lessons learned from ground and flight demonstrations are transferred to all of industry (unless pre-agreement established for commercialization aspect)
  - Ensures long-term industry involvement
What is Lunar 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.

In-Situ Lunar Resources

- ‘Natural’ Lunar Resources:
  - Regolith, minerals, metals, volatiles, and water/ice
  - Sunlight, vacuum, thermal gradients/cold sinks

- Discarded Materials
  - LSAM descent stage fuel residual scavenging, tanks, etc. after landing (with Power)
  - Crew trash and waste (after Life Support processing is complete)

Lunar ISRU Products and Services (Lunar Architecture Team findings)

- Site Preparation and Outpost Deployment/Emplacement
  - Site surveying and resource mapping
  - Crew radiation protection (in-situ water production or bulk regolith)
  - Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
  - Area and road clearing to minimize risk of payload delivery and emplacement

- Mission Consumable Production
  - Complete Life Support/Extra Vehicular Activity closure for Oxygen (O2) and water
  - Propellant production for robotic and human vehicles
  - Regenerate and storage life support and fuel cell power consumables (in conjunction with Life Support and Power)

- Outpost Growth and Self-Sufficiency
  - Fabrication of structures that utilize in-situ materials (in conjunction with Habitats)
  - Solar array, concentrator, and/or rectenna fabrication (in conjunction with Power)
  - Thermal energy storage & use from processed regolith (in conjunction with Power)
  - Production of feedstock for fabrication and repair (in conjunction with Sustainability)
ISRU - Related Surface Elements & Activities

Red Header = Within scope of current ISRU Project
Blue Header = Out of scope of current ISRU Project
Brown Header = Funded by other ETDP Project

Resource & Site Characterization

Regolith Excavation

Regolith Transport

Regolith Processing

Site Preparation
(roads, pads, berms, etc.)

Mobile Transport of Oxygen

Habitats & Shelters

Life Support Systems

Oxygen & fuel for life support, fuel cells, & propulsion

Power Source
(Solar Array or Nuclear Reactor)

In-Situ Energy Generation & Storage

Manufacturing & Repair

Manufacturing feedstock

Non-Regolith Resource Processing

Residuals & hardware scavenging

Product Storage

(Modified LSAM Cargo Lander)

Crew trash & waste

Mission consumables

Surface Construction

Construction feedstock

Surface Mobility Asset

Surface Construction feedstock

Non-Regolith Resource Processing

In-Situ Energy Generation & Storage

Power Source

Life Support Systems

Product Storage

Mobile Transport of Oxygen

Habitats & Shelters

Life Support Systems

Oxygen & fuel for life support, fuel cells, & propulsion

Power Source
(Solar Array or Nuclear Reactor)
Possible Excavation Needs & Requirements for the Outpost

- **Excavation for Oxygen Production**
  - Evaluated a number of excavation options
  - Parametrics presented are based on a front-end/overshot loader that scoops and dumps into bin on back of chassis
  - If operate continuously, primary difference between small and large chasses is rate of drain on battery
    - Very inefficient to dig slowly/small amounts per scoop - lifting arm and dumping into bin is primary energy drain

- **Excavation for Outpost: Landing pads and berms**
  - Largest outpost emplacement excavation requirement over life of Outpost
  - If landers are not moved, a new pad needs to be prepared every 6 months
  - Capability Manifested on 1st landed mission

- **Excavation for Outpost: Habitat protection**
  - Multiple options if regolith shielding for radiation or thermal is desired
  - Trenching and inflatable covers evaluated for excavation impact

- **Excavation for Outpost Emplacement**
  - Excavate ramp or hole for nuclear reactor emplacement/shielding
  - Prepare pathways for transferring cargo from lander
  - Prepare trenches for cables

- **Excavation for Science**
  - Prepare trenches for subsurface geologic/stratigraphy access for Science
  - Core extraction drilling for subsurface sample acquisition (resource characterization)
  - Site preparation for antenna deployment
ISRU Consumable Production for Lunar Architecture

- **O₂ Production from Regolith**
  - 2 MT/yr production rate for surface mission consumables – 1 MT/yr for ECLSS/EVA and 1 MT/yr to make water
  - **Capability manifested on 6th landed mission (before start of permanent presence)**
  - Increased production to 10 MT/yr during Outpost operation could also support refueling 2 ascent vehicles per year to further increase payload delivery capability

- **In-Situ Water Production**
  - Scavenge minimum of 55 kg of hydrogen (max. ~252 kg) from each LSAM descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water
  - Polar water extraction not evaluated in Lunar Architecture Phase II effort. Not needed unless large scale in-situ propellant (O₂ & H₂) production is required

- **In-Situ Methane Production**
  - Pyrolysis processing of plastic trash and crew waste with in-situ oxygen can make methane
  - Capability supports LSAM Ascent ‘top-off’ in case of leakage, power loss, or increased payload to orbit

### ISRU Processing Requirements kg/yr (min.)

<table>
<thead>
<tr>
<th>ISRU Processing Requirements</th>
<th>kg/yr (min.)</th>
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<tbody>
<tr>
<td><strong>Oxygen Production</strong></td>
<td></td>
</tr>
<tr>
<td>For ECLSS &amp; EVA</td>
<td>1000</td>
</tr>
<tr>
<td>For Water Production</td>
<td>800</td>
</tr>
<tr>
<td>For LSAM Ascent Propulsion</td>
<td>7600</td>
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<tr>
<td><strong>Water Production</strong></td>
<td></td>
</tr>
<tr>
<td>For ECLSS &amp; EVA (from in-situ O₂ + Scavenged H₂)</td>
<td>900</td>
</tr>
<tr>
<td>Required H₂ Scavenged from LSAM Descent Stage</td>
<td>100</td>
</tr>
<tr>
<td>For radiation shielding (<em>one time production need</em>)</td>
<td>1000 to 2000*</td>
</tr>
<tr>
<td><strong>Water Electrolysis</strong></td>
<td></td>
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<tr>
<td>For ISRU</td>
<td>1125</td>
</tr>
<tr>
<td>For Night time Power</td>
<td>7335</td>
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<tr>
<td>For Pressurized Rover Power (45 kg/mission)**</td>
<td>1260</td>
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<tr>
<td><strong>Methane Production</strong></td>
<td></td>
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<tr>
<td>For LSAM Ascent Propulsion (max)</td>
<td>2160</td>
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</table>

** 28 excursions per year with at least 1 MPU
Lunar Architecture ISRU Systems & Technologies

**Solar Concentrators**
- Lightweight or inflatable collectors
- Thermal management

**Oxygen Extraction from Regolith**
- Solid/gas processors
- Water electrolysis
- CO₂/methane processors & reagent regeneration
- Contaminant removal
- Thermal management & Radiators
- Dust tolerant sealing

**H₂ Scavenging to Make Water**
- Dust tolerant O₂ disconnects
- Dust tolerant H₂ disconnects

**Oxygen Storage-Transfer**
- High pressure O₂
- O₂ cryocoolers
- Liquid O₂ storage
- Thermal management
- Dust tolerant O₂ disconnects

**Site Preparation, Berm Building, & Reactor Burial**
- Surface Mobility
- High-cycle life, high-power density power systems
- End-effectors w/ dust tolerant mechanisms
- Autonomous control

**Regolith Excavators/Haulers**
- Surface mobility platforms
- High-cycle life, high-power density power systems
- End-effectors w/ dust tolerant mechanisms
- Autonomous control

**Small vs Large Rovers**
Lunar Regolith Excavation Development

Soil Preparation and Controlled Testing

Surveyor Arm/Scoop Re-fabrication and Controlled Laboratory Testing at GRC

Excavation Hardware – Small Rover-based

Cratos Small Excavator at GRC  Cratos w/ Hard Regolith Cutter Concept  Buckwheer Testing At NORCAT  Bucketwheel Excavator at CSM  Bucketdrum Excavator at LMA (IR&D)

Excavation Hardware – Large Rover-based

Chariot (Chassis C) Vehicle  Area Clearing Blade on Chariot  Multi-purpose End-effector on Chariot
Regolith Beneficiation

- **Regolith Iron-Oxide Beneficiation (KSC)**
  - Feldspar: (Na,K)AlSi₃O₈·SiO₂ 40%
  - Spodumene: LiAlSi₂O₆ 40%
  - Olivine: (Mg,Fe)₂SiO₄ 10%
  - Ilmenite: FeTiO₃ 10%
  - Reade Advanced Materials ~ 300 mesh sieved
  - Further sieved to 50-75 µm size range

- **Beneficiated Regolith after 1st Pass (PTFE Charger)**

- **Important for H₂ Reduction to increase efficiency**

Lunar Simulant Development

- **OB1 Highland Simulant (NORCAT/UNB)**
- **Lunar Highland (LHT) Simulant (MSFC-USGS)**
- **JSC1a (ORBITEC)**
- **Artificial Agglutinate from JSC1a (ORBITEC)**
- **Glass Agglutinate from LHT (USGS)**

Regolith Mitigation

- **Transparent electrodes on glass with lunar simulant; Raman spectrum not attenuated negatively**
- **Integration of electrode/window into Metering Device/Crusher for RESOLVE EBU#2 now in work**

Before activation

After activation
ISRU $O_2$ Extraction from Regolith Development

**H$_2$ Reduction Rotating Reactor System (PILOT-LMA)**

- PILOT Hydrogen Reduction Kinetic Reactor
- Reactor-Regolith Handling/Transport Testbed

**CH$_4$ Carbothermal Reduction Reactor System (PILOT-ORBITEC)**

- Regolith Handling/Transport Testbed
- PILOT Carbothermal Reactor Testbed
- Methane Regeneration Reactor

**H$_2$ Reduction Fluidized-Bed Reactor System (ROE & ROxygen - NASA)**

- Hydrogen Reduction Fluidized Subscale Reactor Testbed
- Water Electrolysis Breadboard
ISRU O₂ Extraction from Regolith Development (Cont.)

Regolith Salt & Molten Electrolysis

Ilmenox (FFC Process) Cell at FIT

Molten Electrolysis Cell at MIT

Low-Temperature Electrolysis Cell at KSC

Early Electrolysis Cell Test at MSFC

Outpost O₂ Extraction Plant Concept with Solar Concentrator & O₂ Storage

Robotic Precursor O₂ Extraction Plant Concept with Micro Excavator (LMA)

Robotic Precursor O₂ Extraction Subscale Demo
ISRU Development & Integration Strategy

- Develop ISRU through phased ground development without requiring LPRP missions
  - LPRP missions would reduce risk of resource, process, and environment uncertainties that ground facilities could not adequately replicate
  - Technology and System development tasks be directed at Outpost applications but will also anticipate (not preclude) possible LPRP scale applications

- ISRU Technology and Systems developed in 4 Phases (2-3 years each phase)
  - Phase I: Demonstrate Feasibility
  - Phase II: Evolve System w/ Improved Technologies
  - Phase III: Develop 1 or more systems to TRL 6 Before Start of Flight development
  - Phase IV: Flight Development for Outpost

- Be prepared to participate in robotic precursor missions should opportunity arise
  - Site characterization, resource mapping, and/or ISRU precursor
  - Outpost ‘dress rehearsal’ mission

Regolith Excavation & Oxygen Extraction from Regolith

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<td>Fit. Protype TRL 5-6</td>
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<td>Element Need Date (PDR)</td>
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<td>LPRP (Notional)</td>
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<td>Adv. Dev. TRL 4-5</td>
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<td>Element Need Date (PDR)</td>
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ISRU Precursor Demonstration (O₂ Production and Resource/Site Characterization)

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<td>Prototype Unit</td>
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Utilize laboratory and analog site demonstrations to:

- Demonstrate needed capabilities and operations for Lunar Outpost and technology/system ‘customers’
- Demonstrate evolution and incremental growth in technologies and systems for Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness).
- Unite separate technology development efforts within NASA
- Develop partnerships and relationships across NASA and other US government agencies, and with International Partners, Industry, and Academia

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<tr>
<th>Site Preparation &amp; Outpost Construction</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
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<tr>
<td>COTS blade on Chariot rover @ JSC</td>
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<td>Inflatable habitat burial</td>
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<td>Area clearing/berm building filed demonstration</td>
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<td>Reactor mockup burial</td>
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<th>2007</th>
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<th>2009</th>
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<tr>
<td>PILOT H₂ reduction reactor field test @ Desert RATS</td>
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<tr>
<td>ROxygen H₂ reduction field test @ Desert RATS</td>
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<tr>
<td>Integrated Carbothermal reduction reactor &amp; Solar Concentrator RESOLVE H₂ reduction field test</td>
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<tr>
<td>Upgraded ROxygen reactor with Solar Concentrator</td>
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<tr>
<td>Full-scale Carbothermal reduction reactor &amp; Solar Concentrator</td>
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<tr>
<th>Site Characterization &amp; Resource Prospecting</th>
<th>2007</th>
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<td>K10s with GPR and 3D lidar at Haughton</td>
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<tr>
<td>RESOLVE drill integration onto CMU rover at CMU</td>
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<tr>
<td>K10s with GPR and Neutron Spectrometer at ARC</td>
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<tr>
<td>RESOLVE drill/CMU rover field test at CMU</td>
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<tr>
<td>Combined K10 and RESOLVE/CMU field test</td>
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▲ = In-Situ Resource Utilization (ISRU)-led Demo  
◆ = Human-Robotic Systems (HRS)-led Demo  
● = Structures & Mechanics-led Demo
ISRU System & Surface Operations Ground Demo Plan

**Site Preparation & Outpost Deployment**

- **2007**
  - Inflatable Shelter concept

- **2008**
  - Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation (At JSC)

- **2009**
  - Perform area clearing and berm building with Chassis C & ISRU Blade (At JSC & Hawaii)

- **2010**
  - Add Autonomy & increased capabilities (ex. dig hole for reactor)

- **2011**
  - Add Autonomy & increased capabilities and durations

**Oxygen Extraction from Regolith**

- **2007**
  - Excavation and oxygen production from regolith with H₂ Reduction at 250 kg to 1000 kg per year rate for 1 to 5 days (At Meteor Crater)

- **2008**
  - Excavation and oxygen production from regolith using carbothermal reduction at 250 to 1000 kg per year with solar power (At Meteor Crater or Hawaii if in-situ material can be used)

**ISRU Precursor & Site/Resource Characterization**

- **2007**
  - Integrate RESOLVE drill on CMU rover (At CMU)

- **2008**
  - Integrate complete RESOLVE package on CMU rover (At Hawaii-permafrost)

- **2009**
  - Possible:
    1. Add Advanced Power system to Rover
    2. Perform joint demo with ARC K-10 rovers

**Notional:** Integrate other science instruments for prospecting on single platform (ex. GPR, Neutron Spec. etc.)
Possible Approaches for International Partnership with ISRU

A. Joint instrument/missions for:
   - Resource mapping & characterization
   - ISRU demonstrations for consumable production, energy production, habitat & surface construction

   Ex. CSA drill on NASA lunar prospecting mission

B. Separate but coordinated missions and capabilities
   - Different hardware to do same capability but shared lessons learned (ex. different oxygen extraction method from regolith)

C. Pre-agreed upon lead roles of strategic interest to each Partner
   - Partners provide critical capability not provided by US

   Ex. International Partner provides excavator/surface mobility platform to bring regolith to NASA oxygen extraction plant
Existing and Potential Partnerships

- **Corporations: Lockheed Martin**
  - Possible joint ISRU/Surface Mobility demonstration of excavation unit in FY08

- **Other US Government Agencies: Department of Energy, Dept. of Defense**
  - Possible leveraging of work performed on alternative fuel production (such as ethane or ethylene for propulsion)
    - Pacific Northwest National Laboratory (PNNL)
  - Leverage existing work in molten electrolysis for titanium and aluminum extraction from ore

- **Canadian Space Agency**
  - Joint development of lunar/Mars drilling technology through RESOLVE project
    - Agreement: Each providing funding and understanding to minimize overlap

- **Japanese Aerospace and Exploration Agency (JAXA)**
  - Possible technology development and lunar simulant leveraging
  - Possible joint Lunar flight opportunities

- **European Space Agency (ESA)**
  - Possible technology development leveraging
  - Possible joint flight hardware and opportunities (lunar & Mars)