In-Situ Resource Utilization (ISRU) And Lunar Surface Systems

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Previous ISRU Development & Implementation Roadmap

“Then a miracle occurs...”

“I think more work is needed in this step.”
Role of Moon in Human Exploration

Two Key Questions*
- Are there activities of economic value that can be carried out by humans living for extended duration on the Moon?
- Can in-situ resources be used in significant ways to support those activities?

**Economically Valuable Activities Feasible?**

<table>
<thead>
<tr>
<th>Use of In-Situ Resources Feasible?</th>
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<tbody>
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<td></td>
<td><strong>Yes</strong></td>
<td><strong>Space Settlement</strong></td>
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<td></td>
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<td><strong>Research Only</strong></td>
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<td></td>
<td><strong>Yes</strong></td>
<td><strong>Robotic or Human Tended Outpost</strong></td>
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*Adapted from Harry Shipman, Humans in Space (1980) and obtained from John Logsdon
ISRU & NASA’s Lunar Architecture

- **ISRU is a critical capability and key implementation of the VSE**
  - Enables the concept of “living off the land”
  - Has the potential to substantially reduce lunar downmass and logistics
  - Has the potential to further increase lunar downmass if LSAM Ascent Vehicle can be fueled from lunar ISRU
  - **ISRU Objectives rated highly as a result**

- **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**
  - Need to perform demonstrations to increase confidence in ISRU
  - Need to perform hydrogen/water resource prospecting ‘early’ for this resource to influence human exploration

- **Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired endstate**
  - Starts with gaining knowledge in Precursor missions
  - Continues with finding the hydrogen (location, form, concentration, etc)
  - Begins small scale demonstration
  - Hits the easy stuff first, like oxygen
  - Architecture is designed to be completely independent from ISRU, just in case it doesn’t pan out initially

- **Architecture is designed to be open enough to take advantage of ISRU from whatever source when available**
  - Scavenge spent LSAM tankage
  - Use ECLSS closed-loop byproducts
  - Design LSAM to have the capability to fuel at the Moon
  - Practice and demonstrate ISRU processes and techniques at every step
Global Lunar Strategy Objectives: Prioritized-Top 40

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<th>Overall Rank</th>
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<th>Category</th>
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<td>EVA Suit</td>
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<td>Characterize Dust Environment</td>
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Red = ISRU Objectives; Blue = Objectives Linked to ISRU Objectives
Objectives of Lunar ISRU Development & Use

1. **Identify and characterize resources on Moon** (especially polar region) that:
   - Can strongly influence mission phases, locations, and element designs to achieve maximum benefit of ISRU
   - Is synergistic with Science and space commercialization objectives

2. **Demonstrate ISRU** concepts, technologies, & hardware that reduce the mass, cost, & risk **for future Mars missions**
   - Excavation and material handling & transport
   - Volatile/hydrogen/water extraction
   - Thermal/chemical processing subsystems for oxygen and fuel production
   - Cryogenic fluid storage & transfer
   - Metal extraction and fabrication of spare parts

3. **Use Moon for operational experience** and mission validation **for Mars**
   - Pre-deployment & activation of ISRU assets
   - Making and transferring mission consumables (*propellants, life support, power, etc.*)
   - Landing crew with pre-positioned return vehicle or ‘empty’ tanks
   - ‘Short’ (<90 days) and ‘Long’ (300 to 500 days) Mars surface stay dress rehearsals

4. **Develop and evolve lunar ISRU capabilities** that *enable* exploration capabilities **from the start of the Outpost** phase
   - ex. Human and robotic hoppers for long-range surface mobility and global science access; power-rich distributed systems; enhanced radiation shielding, etc.

5. **Develop and evolve lunar ISRU capabilities** to support sustained, *economical space transportation*, presence on Moon, and **space commercialization** efforts
   - Lower Earth-to-Orbit launch needs
   - Enable reuse of transportation assets and single stage lander/ascent vehicles
     ➢ Lower cost to government thru government-commercial space commercialization initiatives
ISRU Capabilities for Human Lunar Exploration

Pre-Outpost

- Determine type, amount, and location of possible resources of interest (i.e. ilmenite, water, etc.) – link to Science objectives if possible
- Perform proof-of-concept and risk reduction demonstrations to certify ISRU capabilities for use at the Outpost - link to commercialization of space if possible
- Perform site characterization of topography, subsurface, and lighting conditions

Initial ISRU Capabilities to be pursued during early Outpost (first 5 years)

- Pilot-scale oxygen production, storage, & transfer capability (replenish consumables)
- Pilot-scale water production, storage, & transfer capability – assuming hydrogen source/water is accessible
- Demonstration of in-situ fabrication and repair demonstration
- Possible ISRU Capability under evaluation - Excavation & site preparation (i.e. radiation shielding for habitats, landing plume berms, landing area clearance, hole or trench for habitat or nuclear reactor, etc.)

Mid-Term ISRU Capabilities - Exploration growth (“Hub & Spoke”)

- Propellant production for LSAM, robotic sample return, or propulsive Hopper from Outpost
- Consumables for Pressurized rover
- Construction and fabrication demonstrations

Possible Long-Term Lunar Capabilities (Settlement)

- In-situ manufacturing and assembly of complex parts and equipment
- Habitat and infrastructure construction (surface & subsurface)
- In-situ life support – bio support (soil, fertilizers, etc.)
- Power generation for Moon and beyond: beaming, helium-3 isotope (³He) mining, etc.
Critical ISRU Connectivity

Construction & Manufacturing
- CFM technology common with ISRU
- Explosives
- Hydrocarbons for plastics
- Materials for concrete & metal structures
- Gas for pneumatic systems
- Thermal Energy

ECLSS technology common with ISPP
- Thermal Energy
- Backup water
- O₂ and N₂/Ar for Habitat & EVA suits
- Water and carbon waste from ECLSS

Environmental Control & Life Support System (ECLSS)
- Defines level of closed-loop ECLSS required

CFM technology common with ISRU
- Propellant (O₂ or O₂/fuel)
- Purge gas/tank pressurant
- Thermal Energy

Lander-Ascent & Hopper Propulsion
- N₂ and/or Ar for science instruments
- Gas for drills & hardware

Surface Mobility
- Defines resource excavation & transportation capabilities

Fuel cell technology common with ISPP
- Fuel cell reagents (O₂ and fuel)
- Water from fuel cell

Science Activities
- Gas for drills & hardware
- Explosives

Surface & Fuel Cell Power Generation
- Defines surface power needs and fuel cell reagents
Design & Implementation Impacts of ISRU on Outpost Elements

- **Life Support**
  - Degree of closed-loop air/water cycle and technologies/capabilities required depends on availability of ISRU water and oxygen. (ex. trade ISRU supplied water for ‘dirty’ water for propellant production)
  - Possible common water and air processing technologies and hardware
  - Amount of logistics required from Earth per year, size/mass of logistics carrier, and delivery rate
  - Disposal of trash and plastic waste – possible ISRU water, fuel production, and fabrication/repair feedstock by processing with ISRU oxygen

- **Extra Vehicular Activity (EVA)**
  - Liquid oxygen (LO$_2$) vs high pressure oxygen for Portable Life Support System (PLSS). LO$_2$ considered for PLSS only if available from ISRU
  - Water cooling/venting vs alternative cooling for PLSS. Availability of ISRU water or LO$_2$ could impact logistics and design
  - Amount of logistics required from Earth per year, size/mass of logistics carrier, and delivery rate

- **Surface Habitat & Mobile Power**
  - Consumable amount and storage concept for fuel cell reactants for night time power system (high pressure oxygen vs LO$_2$) different if ISRU is available (12% mass savings for LO2)
  - System capability to regenerate fuel cell reactants for surface mobility units (increase size of ISRU water electrolysis and storage system vs separate dedicated system)

- **Lunar Lander (LSAM) Propulsion**
  - ISRU O$_2$ (and possibly CH$_4$) enables resupply ascent vehicles
  - Use of LSAM descent tanks for ISRU storage minimizes downmass

- **Outpost Layout, Deployment, and Surface Operations**
  - Mobile Regolith transport systems for propellant/consumables production plant can double as road graders, landing site groomers, regolith shielding/insulating structure builders, etc
Lunar ISRU Development & Mission Strategy

- **LRO/LCROSS missions provide critical data for ISRU and water resource development and implementation strategies for the lunar Outpost**
  - LRO provides locations of primary interest for resource prospecting and slope/terrain information for mobility
  - Allows future global understanding of resource potential at other locations after ‘ground truth’ mission has been performed
  - LCROSS *could* provide early evidence of water on the Moon

- **For minimum implementation risk, Lunar ISRU should be demonstrated and incorporated into the Lunar architecture in 3 Phases:**
  - Phase 1 Proof-of-concept & Concept Validation
  - Phase 2 Risk Reduction for Outpost (1/10th Outpost scale min. & 6 months operation – provides EVA capability demonstration before Outpost)
  - Phase 3 Outpost Deployment and Operation (full scale and redundant)

- **Lunar ISRU technology and system development must be tied to other Surface Systems**
  - Consumable storage and transfer architecture for life support, fuel cell power (nighttime and mobile), EVA, propulsion, and habitat ECLSS make-up and resupply
  - Common technologies and hardware to reduce cost and logistics

- **Lunar resource objectives require separate but integrated development paths**
  - Oxygen extraction from regolith (anywhere on the Moon)
  - Hydrogen/water extraction (Polar region only)
    - If high concentration outside shadowed crater, evaluate resource extraction and use potential
    - If low concentration outside shadowed crater, perform prospecting in shadowed crater
  - Conversion of trash & plastics
Lunar Oxygen Production Overview

Production rate of 5 MT oxygen ($O_2$) & 1 MT water per year is baselined for the initial Outpost (2023) with buildup to 10 MT $O_2$ per year by 2027 with fuel:

- Initial capability supports EVA and habitat life support needs
- Build-up rate supports oxygen need for two LSAM ascent vehicles, EVA consumables, and habitat/life support backup

Mass of ISRU hardware required to produce 8 to 10 MT of oxygen per year is <2000 kg.
In-situ availability of water and hydrogen is of significant interest for human exploration
- Crew drinking/cleaning and degree of water processing required
- Extra-vehicular activity (EVA) suit cooling
- $O_2$ and $H_2$ from water for propulsion and fuel cells; also easily transferable to other locations for processing (orbital depots)
- Radiation shielding

Elevated hydrogen source most likely in permanently shadowed craters at lunar poles raising significant acquisition and processing issues
- Extremely cold-vacuum environment (40 to 100 K)
- Potentially at bottom of deep craters (4 to 8 km with 15 to 30 degree slopes) has impact on power and surface mobility
- Transition for sunlit to cold environment has impact on thermal control design
- Mixtures of water and regolith at low temperatures impacts excavation force and design

Currently developing resource acquisition, processing, and characterization hardware for possible use in future LPRP mission for science and exploration to determine:
- Regolith properties for future excavation and processing systems
- Volatile constituents, amounts, and distribution
- ISRU-related hardware performance on the Moon

Possible synergism with prospecting and extracting water on Mars for ISRU
ISRU Can Unite
Human Exploration, Science, & Space Commercialization

1. Joint Science/Human Exploration
   Direct
   • Remote & in-situ resource physical, chemical, and spatial characterization
   • Environment characterization
   • Resource/sample extraction and processing
   • Human/robotic interaction
   • Autonomous Operations
   Indirect
   • Access to bedrock and subsurface stratigraphy
   • Extended missions
   • Enhanced surface mobility
   • Enhanced or increased power availability
   • Increased payload or sample return size
   • Infrastructure for long-term operations

2. Joint Human Exploration/Space Commercialization
   • Knowledge of resources and ‘market’ potential
   • Risk reduction demonstrations
   • High-leverage products with ‘return on investment’
     – Propellants
     – Life support consumables
     – Power
   • Robust and affordable transportation architecture
   • Long-term operations and goals
   • Infrastructure and capability growth

3. Joint Science/Space Commercialization
   • Resource characterization/prospecting
   • Resource/sample extraction and processing
   • Infrastructure for long-term operations

4. Needs Common to All
   • Resource information (sample return)
   • Resource/sample extraction
   • Maximize payload/return mass
   • Maximize power availability
   • Human/robotic interaction
   • Reduced development and mission cost
Near & Far Term Space Commercial Applications

- **Remote Sensing**
  - Earth viewing
  - Astronomical observatories

- **Self-Sustaining Colonies**
  - Tourism
  - Resort construction & servicing

- **Power Generation**
  - Power beaming from lunar surface
  - Helium-3

- **Cis-Lunar Transportation & Propellant**
  At Earth-Moon L1 for following:
  - NASA Science & Human Exploration Missions
  - Debris Management
  - Military Space Control (servicing; moving, etc.)
  - Commercial Satellite Delivery from LEO, Servicing, & Refueling
  - Delivery of resources/products for Space Solar Power
Path to Commercialization

- **Initiate NASA-Government Tasks to Enable Space Commercialization**
  - Demonstrations to validate concepts & build business case
  - Regulation reforms: tax incentives, property rights, liability, ITAR / export control

- **Utilize Multiple Methods for ‘Commercializing’ ISRU**
  - Traditional development BAA/Contracts
  - NASA Innovative Partnership Program (IPP)
  - Contract for ‘services’
  - Government-Industry Consortiums (Comsat or Galileo)
  - Government-Industry “Infrastructure” Partnerships (railroad, air-mail, highways, etc.)
  - Prizes
  - Creation of Earth, LEO, and Lunar-based ISRU test & development laboratories

- **Establish a committee of representatives from NASA, industry, and academia**
  - Define the roles that NASA and Industry will have as space exploration matures.
  - Promote enactment of regulations and policy that enable short and long-term lunar commercialization goals
  - Initiate and establish policies, procedures and incentives to turn over Lunar infrastructure assets to industry so NASA can focus on exploring beyond the Moon.
  - Prioritize technology development & demonstrations which best meet goals of both reduced costs to NASA human exploration & space commercialization
  - Define scope and charter for Government-Industry Space Consortiums

➢ **Early engagement of NASA/commercial partnerships is required to maximize commercial benefits**
Customers & Connectivity

Customers & Stakeholders
- ESMD Technology Development Program
- Lunar Architecture and Mission Planners
- Lunar Robotic Precursor Program (LPRP)
- Constellation Program (LSAM & Surface Systems)
- Other US Government Agencies
- International Partners
- Commercial Space Industry

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Conclusion: ISRU Strongly influences Architecture & Critical Technologies

- **ISRU is a critical capability and key implementation of the VSE**
  - 5 of top 40 Objectives identified for returning to the Moon; strongly tied to 7 more
  - ISRU is an integral part of all six Themes for returning to the Moon (Extend Human Presence, Exploration Preparation, Scientific Knowledge, Global Partnership, Economic Expansion, Public Outreach)

- **ISRU Strongly effects Outpost logistics, design and crew safety**
  - Potential to reduce logistics consumables for EVA/life support of 1000 to 4000 kg/year (2000 to 8000 kg w/ logistics carrier mass);
    - Significant payload impact if crewed LSAM down mass capability is only ~6000 kg.
  - Availability of liquid oxygen from ISRU allows EVA suits and mobile/night time power more volume and mass efficient (12% mass savings for power module)
  - Availability of ISRU oxygen/water provides functional redundancy to life support systems
  - Ability to move regolith could increase crew safety through increased radiation shielding, landing area clearing, and exhaust plume protection
  - Ability to produce oxygen (and fuel) for propulsion expands long-term surface exploration and payload delivery/return options

- **ISRU Strongly effects Outpost critical technologies**
  - LSAM ascent & descent propulsion
  - CO₂ and water life support system
  - EVA space suit portable life support system
  - Surface power reactant storage and regeneration for Outpost and mobile fuel cells

- **ISRU mass investment is minimal compared to immediate and long-term architecture delivery mass and reuse capabilities provided**
  - **Investment in ISRU constitutes a commitment to the mid and long term future of human exploration**