Exploration Sustainability
Benefits and Hurdles of Incorporating In-Situ Resource Utilization

Presentation to LEAG Workshop
Houston, TX. Nov. 16, 2009

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“Sustainability”

For a human exploration program to the Moon to be successful and sustainable, it must achieve both the Exploration (the “How”) and Programmatic (the “What & Why”) perspective objectives.

It can be argued that while Apollo and the International Space Station (ISS) may have achieved many Exploration perspective objectives, it did not achieve many Programmatic perspective objectives.
Attributes of Exploration Sustainability

- **Continually improve performance and capability**
  - Increase payload mass, stay duration, number of crew
  - Increase access and duration to wide and varied surface locations
  - Stepwise advancement with visible and concrete results

- **Continually reduce risk to mission and crew**
  - Redundancy in key functions
  - Increased mission flexibility and failure recovery (Redundancy in key elements by Partners)

- **Continually reduce cost for performing missions and operations; Increase “Value”**
  - Increase life and reliability of hardware
  - Reusability
  - Standards, modularity, common interfaces, and common technologies/hardware across multiple assets
  - Commercial involvement

- **Continually reduce dependence on Earth supplied logistics and infrastructure**
Attributes of Programmatic Sustainability

- Establish common ‘Vision’ and long-term plan that public supports
  - Credible and based on realistic expectations
  - Balance and integrate robotic and human exploration
  - Needs to support multiple objectives and constituents (science, exploration, national security, economic)
  - Long-term objectives (exploration, commerce, etc.) need to drive near-term decisions and designs

- Continually engaging and exciting the public (thereby support for Government activities)
  - Continually do ‘new’ things (new ‘1st s’; evolve at rate that keeps public engaged (ex. ISS buildup was too long)
  - Participatory exploration (‘direct involvement’)
  - Promote space tourism capabilities
  - Promote education (STEM)

- Increase benefits to Countries supporting exploration and the Earth
  - Revenue and jobs (tourism, aerospace industry, technology spin-offs, etc)
  - Energy, resources, and security

- Robust & Flexible: Allow for new ideas and flexibility in priority schedules
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, water/ice, sunlight, cold-traps
- Discarded Materials: residual propellants, discarded landers, trash/waste

Lunar ISRU Products and Services

- Resource Prospecting
- Site Characterization, Site Preparation, and Outpost Deployment/Emplacement
- Mission Consumable Production (Life Support, Propellants, Power)
- Radiation Protection
- Outpost Growth and Self-Sufficiency (Construction, Energy, Manufacturing Recycling)

- **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.** There must be Customers, and by definition it must connect and tie to multiple uses and systems to produce the desired capabilities and products.
# Pros & Cons of ISRU for Lunar Exploration

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td>Enables Reusability &amp; Flexibility</td>
<td>Higher initial risk</td>
</tr>
<tr>
<td>Increased delivered payloads/reduced consumables from Earth</td>
<td>Higher upfront costs</td>
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<tr>
<td>Interdependence – common hardware, interfaces, and standards</td>
<td>Interdependence - common failure modes across multiple subsystems</td>
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<tr>
<td>Long-term growth/reduced life cycle costs</td>
<td>Does not benefit short trips/stays</td>
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<tr>
<td>Linked objectives w/ Science; increased Science rationale and capabilities</td>
<td>Concern about impacting lunar environment for science</td>
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<tr>
<td>Supports Commercial involvement/reduced costs</td>
<td>International agreement/Legal issues</td>
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<tr>
<td>Mars Forward</td>
<td>Lunar/Mars must consider from start</td>
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<tr>
<td>Public Outreach &amp; Interest. Not repeating Apollo</td>
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<tr>
<td>Technology Spin-In and Spin-off</td>
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</table>
The Current Problem with ISRU for Lunar Exploration

- **ISRU is a critical capability and key implementation** of the Vision for Space Exploration 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 end-state

- **Architecture** needs to be designed to be **open enough to take advantage of ISRU** when available
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This is the tough part!
Is Abort-to-Surface (vs Abort-to-Orbit) a Viable Option? If yes:
– Ascent propellant production and transfer to increase payload to surface is possible

Is Reusable Transportation a Long-term Objective? If yes:
– Landing/ascent pads and surface propellant depots
– Large scale propellant production
  • If O₂/H₂ propellants -> Need polar water or H₂ delivery from Earth
  • If O₂/CH₄ propellants -> Need O₂ from regolith and CH₄ from trash/waste/plants or CH₄ delivery from Earth
– Propellant depots in LLO
– Surface hopping to other locations (and back)

How Much Radiation Shielding is Adequate for Crew Protection from Solar and GCR?
– Water/hydrogen scavenging
– Habitat burial or regolith shielding of habitats

Is Space Commercialization and Long-term Settlement of the Moon a Goal?
– Commercial operations for consumables, propellants, transportation, communications, etc.
– In-situ fabrication, metal extraction, and assembly (including feedstock production)
– Structure and habitat construction
– In-situ energy production and storage
– Plant growth, fish, livestock

Is Mars Forward the Primary Goal for Lunar Exploration?
– Demonstrate Mars applicable technologies, systems, and applications
– Demonstrate remote/uncrewed and long-duration operations
Current Approach to Incorporating ISRU into Lunar Architecture

- Identify limitations to current architecture which ISRU can help to solve
  - Increase stay time, power, payload, range of exploration, and amount of samples returned

- Identify high risk and mass reduction candidates for ISRU
  - Reduce damage, radiation risk, and spare parts from Earth

- Identify ISRU applications for long-term Sustainability
  - Enable reusability, commercialization, construction, manufacturing, and Earth spinoff applications
  - Utilize commonality and modularity across surface system fluid and processing architecture

- Identify ISRU processes and applications for Mars Forward
  - Water prospecting & extraction, propellant production, nuclear power,

- Integrate ISRU functions and products into lunar architecture from the start, even if initially supplied from Earth

- Utilize phased approach to incorporate ISRU with minimum risk to mission success
Each ISRU Function may support more than one ISRU Application

Each Application of ISRU requires:
- One or more ISRU Functions to provide the necessary product or service
- Close coordination with other surface elements and disciplines to maximize benefits and minimize overlap

### ISRU Functions

<table>
<thead>
<tr>
<th>ISRU Applications</th>
<th>ISRU Functions</th>
<th>Mission Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geotechnical &amp; Resource Characterization</td>
<td>Repoth Excavation &amp; Material Delivery</td>
<td>Pilot Utilize</td>
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<tr>
<td>Repoth Sintering &amp; Modification</td>
<td>O₂</td>
<td>H₂O</td>
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<tr>
<td>Q₁ Extraction from Regolith</td>
<td>Solar Wind Volatile Extraction</td>
<td>Lander Propellant Scavenging</td>
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<tr>
<td>Regolith &amp; Preparative Manufacturing</td>
<td>Regolith &amp; Preparative Manufacturing</td>
<td>Regolith &amp; Preparative Manufacturing for Manufacturing</td>
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<tr>
<td>Life Support/EVA Consumables Production</td>
<td>Propellant Production (Topping Off, Ascent, Hoppers)</td>
<td>ISRU-Power-Utility Waystation</td>
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<tr>
<td>Fuel Cell Reagent Production/Regeneration</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>O₂</td>
</tr>
<tr>
<td>Science &amp; Cleaning Gases</td>
<td>Demo Utilize</td>
<td></td>
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<tr>
<td>Radiation shielding</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Thermal Energy Storage</td>
<td>Solar Array Fabrication</td>
<td>Structure/Habitat Construction</td>
</tr>
<tr>
<td>Landing Pad/Runway Clearing</td>
<td>X</td>
<td>X</td>
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<tr>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Demo Utilize</td>
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<td>Demo Early Utilize Late</td>
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<tr>
<td>Food Production (plants, fish, livestock)</td>
<td>H₂O</td>
<td>H₂O</td>
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</tbody>
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*Polar water may contain NH₃, HCN, CH₃, and other hydrocarbons
S = Provides byproduct of interest

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Phased Approach to ISRU Incorporation

**Purpose**
- Verify critical processes & steps
- Verify Critical engineering design factors (forces, energy required, etc.)
- Address unknowns or Earth based testing limitations (simulants, 1/6 g, contaminants, etc.)
- Characterize local material/resources

**Purpose**
- Enhance or extend capabilities/reduce mission risk
- Verify production rate, reliability, and long-term operations
- Verify integration with other surface assets
- Verity use of ISRU products

**Mission Criticality**
- Robotic Precursors
- Sorties
- Extended Sorties
- Repeat visit sites
- Sites of extreme access difficulty
- Outpost
- Commercial space operations

- Earth Supplied
  - 100%
- Mission Criticality
  - 0%

100%
0%

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Lunar Surface System Elements, Modules, & Interconnectivity

Can common requirements, interfaces, and sizes be established that meet everyone’s needs?

Science, Survey, Prospecting, Excavation

ISRU - O₂ from Regolith

H₂ Reduction

H₂O

Evaluate Commonality & Integration

&/or

Lg Mobile Platform

Lander

Propellant Scavenging

Evaluate Integration

Surface Logistics

Outpost Power System

Mobile Utility Pallet
(Power/Life Support)

Evaluate Integration

Mobile Power

Pressurized Rover

Combine with

ISRU Waystation

Solid Waste

Habitat

Water-Trash Processing

Life Support – Physical/Chemical & Biological (plants/algae)

Plant growth light

For Crew, EVA, & Radiation shielding

Waste

Civil Engineering

SRU – CH₄ from Waste/Trash

CH₄ Reduction

H₂O

Evaluate Commonality & Integration

Sm Mobile Platform

Sm Mobile Platform

Sm Mobile Platform

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ISRU Insertion Approaches

- Evolve Sustainability - ISRU When It's Ready (current approach)
  - No reusable transportation elements at the start of the architecture
  - ISRU & propellant depots not in initial critical path to mission success
  - Demonstrate ISRU capabilities early
  - Design Architecture to incorporate ISRU products and services when adequately demonstrated

  **Low Risk but High Life Cycle Costs**

- Sustainability as Driver - ISRU From Start
  - Develop reusable transportation elements, propellant depots, and ISRU in critical path; human and cargo landers synergistic with Mars
  - Utilize Earth supplied propellants for depot until ISRU is fully demonstrated

  **Higher Upfront Costs & Delayed Human Exploration**
Conclusions

**ISRU Can be Enabling for Lunar Exploration & Sustainability**

- Minimize impact of uncertainties, shortfalls, and development costs in lunar architecture Elements during design and development
- Increase Crew Safety & minimize impact of Critical Failures
- Growth in Lunar Architecture Stay, Range, Payloads,
- Increased Science
- Reduced Cost/Commercialization

**ISRU Needs to Be Planned from the Start**

- Reusable Transportation Elements with ISRU-Compatible Propellants
- Operations: Abort-to-Surface, Propellant Depots, etc.
- Surface Elements Fluid System Commonality and Requirements
Backup
# ISRU Functions & Purpose

<table>
<thead>
<tr>
<th>ISRU Functions</th>
<th>Purpose</th>
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<tbody>
<tr>
<td><strong>1</strong> Resource Prospecting/Mapping</td>
<td>Measure and map potential resources for site selection and ISRU planning; Opportunistic Science</td>
</tr>
<tr>
<td>1a Chemical/Mineral Characterization &amp; Mapping</td>
<td>Measure and map regolith geotechnical and mineral/chemical attributes of surface regolith and subsurface down to 0.5 m to select feedstock for ISRU functions (supports lunar science objectives)</td>
</tr>
<tr>
<td>1b Hydrogen/Water Characterization &amp; Mapping in Permanently-shaded Craters</td>
<td>Measure and map geotechnical and hydrogen/water volatiles down to 1 meter to assess potential for large scale extraction</td>
</tr>
<tr>
<td><strong>2</strong> Consumable Production</td>
<td>Reduce Earth delivery logistics; Enable new exploration</td>
</tr>
<tr>
<td>2a Oxygen Extraction from Regolith</td>
<td>Produce oxygen for crew, EVA, and propulsion</td>
</tr>
<tr>
<td>2b Water/Hydrogen/He Scavenging from Altair Lander</td>
<td>Convert residual propellants into water; Produce water with excess hydrogen and in-situ oxygen; Scavenge helium pressurant from tanks</td>
</tr>
<tr>
<td>2c Solar Wind Volatile Extraction from Regolith</td>
<td>Extract and separate hydrogen, nitrogen, helium, carbon, etc. from regolith</td>
</tr>
<tr>
<td>2d Water/Hydrogen Volatile Extraction from Permanently-shaded Crater Regolith</td>
<td>Extract and separate hydrogen, water, ammonia, methane, hydrogen cyanide, etc. from regolith</td>
</tr>
<tr>
<td>2e Methane/Carbon Dioxide Production From Trash/Crew Waste Processing</td>
<td>Process trash and crew waste to produce methane and carbon dioxide</td>
</tr>
<tr>
<td>2f Metal/Silicon Extraction from Regolith for Manufacturing</td>
<td>Produce silicon, iron, aluminum, etc from regolith as feedstock for in-situ manufacturing</td>
</tr>
<tr>
<td>2g Cement and Modified Regolith for Construction</td>
<td>Produce feedstock from construction thru modification of bulk regolith</td>
</tr>
<tr>
<td>2h Plant/Fish/livestock Growth Support</td>
<td>Provide infrastructure and feedstock to support plant growth and fish/livestock food production</td>
</tr>
<tr>
<td><strong>3</strong> Civil Engineering &amp; Construction</td>
<td>Reduce mission and crew risk; Enable infrastructure growth</td>
</tr>
<tr>
<td>3a Excavate and transport regolith consumable production (2a, 2b, 2c, 2d, 2f, &amp; 2g)</td>
<td>Provide regolith for in-situ processing</td>
</tr>
<tr>
<td>3b Construct landing pads &amp; roads (clear areas, berms, sintering)</td>
<td>Protect hardware from plume damage; Mitigate dust around surface infrastructure</td>
</tr>
<tr>
<td>3c Utilize regolith for Radiation Protection (burial or covering)</td>
<td>Bury/cover habitats to protect crew from solar/galactic radiation; Bury/cover nuclear reactors with regolith</td>
</tr>
<tr>
<td>3d Construct Structures from In-situ Materials</td>
<td>Modify regolith and construct structures for hardware protection and crew</td>
</tr>
<tr>
<td><strong>4</strong> Energy Production and Storage</td>
<td>Reduce mission risk; Enable infrastructure growth</td>
</tr>
<tr>
<td>4a Construct Thermal Energy Storage from In-Situ Materials</td>
<td>Modify regolith for use as thermal storage media for energy storage and generation</td>
</tr>
<tr>
<td>4b Construct solar arrays from In-Situ Materials</td>
<td>Modify regolith and fabricate solar arrays on lunar surface for power generation growth</td>
</tr>
<tr>
<td><strong>5</strong> Manufacturing &amp; Reuse</td>
<td>Reduce Earth delivery logistics; Reduce mission risk</td>
</tr>
<tr>
<td>5a Hardware Scavenging and Recycling</td>
<td>Remove fluid and electrical components from dead landers and infrastructure for reuse (modularity required)</td>
</tr>
<tr>
<td>5b Rapid Prototype Part Fabrication</td>
<td>Produce spare parts from powdered metals and plastics</td>
</tr>
</tbody>
</table>
Power, Habitation, & ISRU System Modules & Options

Unique Modules

- Solar Concentrator Module
- Solar Array Module
- CH₄ Module
- H₂ Module
- O₂ Module
- H₂O Module
- Fuel Cell Module
- Water Electrolysis Module
- Regolith O₂ Module
- Excavation Attachment
- CO₂ Processing Module
- Trash/Plastic Processing Module

Primary Systems

- Mobility – Science, Survey, Prospecting, Excavation, Exploration
- ISRU – O₂ from Regolith
- Fuel Cell System
- Solar Power
- Utility Pallet (Power/Life Support)

Civil Engineering

- ISRU – CH₄ from Waste/Trash

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Lunar Surface System Element and Module Integration

ISRU – \( \text{O}_2 \) from Regolith (\( \text{H}_2 \) Reduction & Volatile Capture)

ISRU – \( \text{CH}_4 \) from Waste/Trash

Life Support – Physical/Chemical & Biological (plants/algae)

Water-Trash Processing

Solid Waste

Habitat

Portable Utility Pallet (Power/Life Support)

Propellant & Fuel Cell Scavenging

Integrated-MODULE

Integrated Habitat Life Support-ISRU for \( \text{O}_2 \) & Trash

Solar Thermal

Integrated-Modular ISRU-Power-Utility System

Waste

For Crew, EVA, & Radiation shielding

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