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

Presentation to National Academy of Sciences Workshop on Research Enabled by the Lunar Environment

June 14, 2007

Jerry Sanders  JSC  gerald.b.sanders@nasa.gov
Bill Larson  KSC  william.e.larson@nasa.gov
Kurt Sacksteder  GRC  kurt.r.sacksteder@nasa.gov
“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>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>Space Tourism and Research</td>
<td>Space Settlement</td>
</tr>
<tr>
<td>No</td>
<td>Research Only</td>
<td>Robotic or Human Tended Outpost</td>
</tr>
</tbody>
</table>

*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

<table>
<thead>
<tr>
<th>Overall Rank</th>
<th>Objective ID Number</th>
<th>Category</th>
<th>Short Title</th>
<th>Overall Rank</th>
<th>Objective ID Number</th>
<th>Category</th>
<th>Short Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mCAS2</td>
<td>Crew Activity Support</td>
<td>EVA Suit</td>
<td>21</td>
<td>mSM1</td>
<td>Surface Mobility</td>
<td>Surface Mobility for Crew &amp; Cargo</td>
</tr>
<tr>
<td>2</td>
<td>mLSH3</td>
<td>Life Support &amp; Habitat</td>
<td>Closed Loop ECLSS (physiochemical)</td>
<td>22</td>
<td>mLRU7</td>
<td>Lunar Resource Utilization</td>
<td>Produce Propellants &amp; Other Consumables</td>
</tr>
<tr>
<td>3</td>
<td>mEHM1</td>
<td>Environmental Hazard Mitigation</td>
<td>Radiation Shielding (Background &amp; Solar Flares)</td>
<td>23</td>
<td>mLRU1</td>
<td>Lunar Resource Utilization</td>
<td>Characterize Lunar Resource Potential</td>
</tr>
<tr>
<td>4</td>
<td>mLSH1</td>
<td>Life Support &amp; Habitat</td>
<td>Habitation Systems</td>
<td>24</td>
<td>mLRU3</td>
<td>Lunar Resource Utilization</td>
<td>Demonstrate ISRU Technologies</td>
</tr>
<tr>
<td>5</td>
<td>mHH2</td>
<td>Human Health</td>
<td>Lunar Environment Effects on Humans</td>
<td>25</td>
<td>mPE7</td>
<td>Program Execution</td>
<td>Program Execution Flexibility</td>
</tr>
<tr>
<td>6</td>
<td>mOPS1</td>
<td>Operations, Test &amp; Verification</td>
<td>Human Surface Ops (Make EVA easier)</td>
<td>26</td>
<td>mPE3</td>
<td>Program Execution</td>
<td>Maximize Synergy</td>
</tr>
<tr>
<td>7</td>
<td>mHH1</td>
<td>Human Health</td>
<td>Fundamental Biological &amp; Physiological Studies</td>
<td>27</td>
<td>mTRANS3</td>
<td>Transportation</td>
<td>Cryo Fluid Management</td>
</tr>
<tr>
<td>8</td>
<td>mOPS10</td>
<td>Operations, Test &amp; Verification</td>
<td>Lunar Repair Techniques</td>
<td>28</td>
<td>mGEO8</td>
<td>Geology</td>
<td>Characterize Potential Resources</td>
</tr>
<tr>
<td>9</td>
<td>mPWR1</td>
<td>Power</td>
<td>Power Generation, Storage, &amp; Distribution</td>
<td>29</td>
<td>mOPS2</td>
<td>Operations, Test &amp; Verification</td>
<td>Remote Training</td>
</tr>
<tr>
<td>10</td>
<td>mHH3</td>
<td>Human Health</td>
<td>Lunar Health Care</td>
<td>30</td>
<td>mCAS5</td>
<td>Crew Activity Support</td>
<td>Teleoperations &amp; Telepresence</td>
</tr>
<tr>
<td>11</td>
<td>mPE2</td>
<td>Program Execution</td>
<td>Exploration Strategy</td>
<td>31</td>
<td>mPE4</td>
<td>Program Execution</td>
<td>Emphasize System Performance</td>
</tr>
<tr>
<td>12</td>
<td>mTRANS2</td>
<td>Transportation</td>
<td>Autonomous Lander</td>
<td>32</td>
<td>mGEO7-1</td>
<td>Geology</td>
<td>Characterize Lunar Volatiles</td>
</tr>
<tr>
<td>13</td>
<td>mEHM2</td>
<td>Environmental Hazard Mitigation</td>
<td>Dust Mitigation Techniques</td>
<td>33</td>
<td>mSM2</td>
<td>Surface Mobility</td>
<td>Surface Mobility for Outpost</td>
</tr>
<tr>
<td>14</td>
<td>mCAS3</td>
<td>Crew Activity Support</td>
<td>Human Machine Partnership</td>
<td>34</td>
<td>mENVMON1</td>
<td>Environmental Monitoring</td>
<td>Monitor Space Weather</td>
</tr>
<tr>
<td>15</td>
<td>mPE6</td>
<td>Program Execution</td>
<td>Affordability &amp; Sustainability</td>
<td>35</td>
<td>mCAS4</td>
<td>Crew Activity Support</td>
<td>Autonomous Robotic Support for EVA &amp; Long Range</td>
</tr>
<tr>
<td>16</td>
<td>mOPS9</td>
<td>Operations, Test &amp; Verification</td>
<td>Crew-Centered Control</td>
<td>36</td>
<td>mLRU9</td>
<td>Lunar Resource Utilization</td>
<td>Lunar Elements that Use ISRU</td>
</tr>
<tr>
<td>17</td>
<td>mCOM1</td>
<td>Communications</td>
<td>Scalable Communications</td>
<td>37</td>
<td>mNAV1</td>
<td>Navigation</td>
<td>GNC Lunar Capabilities</td>
</tr>
<tr>
<td>18</td>
<td>mHH4</td>
<td>Human Health</td>
<td>Reduced Lunar Habitation Pressure Effects</td>
<td>38</td>
<td>mENVCH3</td>
<td>Environmental Characterization</td>
<td>Characterize Surface Radiation Environment</td>
</tr>
<tr>
<td>19</td>
<td>mLRU6</td>
<td>Lunar Resource Utilization</td>
<td>Tools, Technologies, &amp; Systems for ISRU</td>
<td>39</td>
<td>mEHM4</td>
<td>Environmental Hazard Mitigation</td>
<td>Thermal Protection</td>
</tr>
<tr>
<td>20</td>
<td>mOPS3</td>
<td>Operations, Test &amp; Verification</td>
<td>Mars Analog</td>
<td>40</td>
<td>mENVCH5</td>
<td>Environmental Characterization</td>
<td>Characterize Dust Environment</td>
</tr>
</tbody>
</table>
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
- Hydrocarbons for plastics
- Materials for concrete & metal structures
- Gas for pneumatic systems
- Explosives

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

Lander-Ascent & Hopper Propulsion
- Propellant (O₂ or O₂/fuel)
- Purge gas/tank pressurant
- Thermal Energy

Surface Mobility
- Defines resource excavation & transportation capabilities

In-Situ Resource Utilization (ISRU)
- Fuel cell reagents (O₂ and fuel)
- N₂ and/or Ar for science instruments
- Water from fuel cell
- Gas for drills & hardware
- Explosives

Fuel cell technology common with ISPP
- Defines surface power needs and fuel cell reagents

Science Activities
- Defines propellant options & propulsion capabilities

Surface & Fuel Cell Power Generation
- Defines surface mobility

Gerald. B Sanders/JSC, gerald.b.sanders@nasa.gov

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 (LO₂) vs high pressure oxygen for Portable Life Support System (PLSS). LO₂ considered for PLSS only if available from ISRU
  - Water cooling/venting vs alternative cooling for PLSS. Availability of ISRU water or LO₂ 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 LO₂) 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 O₂ (and possibly CH₄) 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 (O₂) & 1 MT water per year is baselined for the initial Outpost (2023) with buildup to 10 MT O₂ 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

Level 0 Architecture & Outpost Requirements

Mass of ISRU hardware required to produce 8 to 10 MT of oxygen per year is <2000 kg.
Lunar Volatile & Water Resource Overview

- 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
  - \( \text{O}_2 \) and \( \text{H}_2 \) 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 Consortiaus (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

<table>
<thead>
<tr>
<th>Requirements Connectivity</th>
<th>Hardware Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion Systems</td>
<td>Propellant Storage &amp; Valving</td>
</tr>
<tr>
<td></td>
<td>Solar Collectors</td>
</tr>
<tr>
<td>Life Support/EVA Systems</td>
<td>Consumable Storage &amp; Valving</td>
</tr>
<tr>
<td></td>
<td>Water Processing/Electrolysis</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide Processing</td>
</tr>
<tr>
<td></td>
<td>Liquid/Gas Separation</td>
</tr>
<tr>
<td></td>
<td>Solar Collectors</td>
</tr>
<tr>
<td></td>
<td>Mobility Platforms</td>
</tr>
<tr>
<td>Surface Mobility</td>
<td>Consumption Quantity</td>
</tr>
<tr>
<td></td>
<td>Consumable Type</td>
</tr>
<tr>
<td></td>
<td>Waste Products/Trash</td>
</tr>
<tr>
<td></td>
<td>Storage Capability</td>
</tr>
<tr>
<td>Surface Power</td>
<td>Daylight Power Amount</td>
</tr>
<tr>
<td></td>
<td>Nighttime Power Amount</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell Storage Capacity</td>
</tr>
<tr>
<td></td>
<td>Nuclear Reactor Placement/Shielding</td>
</tr>
<tr>
<td>Habitat</td>
<td>Placement</td>
</tr>
<tr>
<td></td>
<td>Shielding/Protection</td>
</tr>
<tr>
<td></td>
<td>Assembly/Inflation Capacity</td>
</tr>
</tbody>
</table>
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