Oxygen and Metals Processing on the Moon:
Will Materials Science Change our future in space?

Laurent Sibille, ASRC Aerospace
Donald R. Sadoway, MIT
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
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, material, etc. after landing
  - Crew trash and waste (after Life Support processing is complete)

Lunar ISRU Products and Services

- 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 ($O_2$) 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)
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 for spin-in and spin-off applications
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

<table>
<thead>
<tr>
<th>ISRU Processing Requirements</th>
<th>kg/yr (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen Production</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>
</tr>
<tr>
<td>Water Production</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 (*one time production need)</td>
<td>1000 to 2000*</td>
</tr>
<tr>
<td>Water Electrolysis</td>
<td></td>
</tr>
<tr>
<td>For ISRU</td>
<td>1125</td>
</tr>
<tr>
<td>For Night time Power</td>
<td>7335</td>
</tr>
<tr>
<td>For Pressurized Rover Power (45 kg/mission)**</td>
<td>1260</td>
</tr>
<tr>
<td>Methane Production</td>
<td></td>
</tr>
<tr>
<td>For LSAM Ascent Propulsion (max)</td>
<td>2160</td>
</tr>
</tbody>
</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**
### ISRU System & Surface Operations Ground Demo Plan

<table>
<thead>
<tr>
<th>Year</th>
<th>Site Preparation &amp; Outpost Deployment</th>
<th>Oxygen Extraction from Regolith</th>
<th>ISRU Precursor &amp; Site/Resource Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
<td>2008</td>
<td>2009</td>
</tr>
<tr>
<td></td>
<td>Site Preparation &amp; Outpost Deployment</td>
<td>Oxygen Extraction from Regolith</td>
<td>ISRU Precursor &amp; Site/Resource Characterization</td>
</tr>
<tr>
<td></td>
<td>Include Inflatable Shelter concept</td>
<td>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)</td>
<td>Integrate RESOLVE drill on CMU rover (At CMU)</td>
</tr>
<tr>
<td></td>
<td>(At JSC)</td>
<td></td>
<td>Integrate complete RESOLVE package on CMU rover (At Hawaii- permafrost)</td>
</tr>
<tr>
<td></td>
<td>Cover inflatable shelter with material using Caterpillar and micro-excavator before inflation</td>
<td>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)</td>
<td>Possible: 1. Add Advanced Power system to Rover 2. Perform joint demo with ARC K-10 rovers</td>
</tr>
</tbody>
</table>

**Notional:** Integrate other science instruments for prospecting on single platform (ex. GPR, Neutron Spec. etc.)
Rover/Lift System Interface

- Rover returns from excavation site and delivers fresh regolith to lift system
- Lift system dumps previous batch's spent regolith into rover bed
- Lift systems hoists fresh material up to auger as rover heads off to dump and dig next batch

Delivery of fresh material

Collection of spent material
Auger/Reactor Interface

1. Valves Open
2. Auger moves in
3. Lift bed moves up

INITIAL CONDITION

Lift bed mates to auger face plate

LOADING REACTOR

Regolith feeds into reactor (Valves are protected)

Reactor spins
Auger spins

LOCKHEED MARTIN
Auger/Reactor Interface

**WHILE PROCESSING**

1. Lift bed lowers

2. Auger moves out

3. Valves Close

**UNLOADING REACTOR**

- Reactor spins
- Auger spins
- Regolith feeds out of reactor (Valves are protected)
PILOT Hardware

Regolith Handling Test

Hydrogen Reduction Reactor

Photos Courtesy of Lockheed Martin Astronautics
Excavation Areas

Areas assume a 4% yield O2 from regolith

Excavation area 5 cm deep for 300 kg O2 using 4 kg/day PILOT plant (11.4 m dia circle or 10m x 10m square) = 7,500 kg regolith excavated

Excavation area 5 cm deep for 730 kg O2 (1 year) using 4 kg/day PILOT plant (17.3 m dia circle or 15m x 15m square) = 18,250 kg regolith excavated

Excavation area 5 cm deep for 2000 kg O2 using 2 mt/yr plant (28.2 m dia circle or 25m x 25m square) = 50,005 kg regolith excavated
PILOT
Carbothermal Reactor (Orbitec)

Regolith Handling Model

Regolith Handling Prototype

Carbothermal Reactor

Photo Courtesy of Orbitec
Oxygen and Metals Processing on the Moon (PART II):
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Integrated COSRS-RWGS-Electrolyzer System During Operation.
From left: LabView® display screen, RWGS-Electrolyzer, COSRS Fe Oxide Reduction Reactor System.

Vertical Carbothermal Reduction in Operation.
Regolith Oxygen Extraction

Funded under RESOLVE in FY06 - Moving to O2 funding in FY 07

- Fluidized Bed Reactor
- 0.5" DIA Heater
- Reactor Vessel (note pen for scale)
- ROX Hardware Under Test
Regolith Electrolysis
## Key O2 System Goals

<table>
<thead>
<tr>
<th>Key Performance Parameter</th>
<th>State of the Art</th>
<th>Performance Target (full success)</th>
<th>Performance Target (min. success)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production rate, kg/hr</td>
<td>Not Measured Yet</td>
<td>2.3 kg/hr</td>
<td>1.15 kg/hr</td>
</tr>
<tr>
<td>Electrical Energy Usage KW/Kg</td>
<td>Not Measured Yet</td>
<td>1.5 KW/Kg</td>
<td>2.0 KW/Kg</td>
</tr>
<tr>
<td>Operation Duration, days</td>
<td>Lab Test, 10's to 100's of minutes</td>
<td>1095 earth days</td>
<td>180 earth days</td>
</tr>
<tr>
<td>Mean Time Between Repair, days of operation</td>
<td>No Tests to Failure</td>
<td>365 earth days</td>
<td>180 earth days</td>
</tr>
<tr>
<td>Reactant Losses</td>
<td>8% to 15%</td>
<td>0.5%</td>
<td>5%</td>
</tr>
</tbody>
</table>
Direct Molten Oxide Electrolysis

\[ \text{Fe}^{2+} + 2 \text{e} \rightarrow \text{Fe}_{(l)} \]

\[ \text{Si}^{4+} + 4 \text{e} \rightarrow \text{Si}_{(l)} \]

\[ \text{O}^2- \rightarrow \frac{1}{2} \text{O}_2(g) + 2 \text{e} \]

\( T \approx 1600^\circ\text{C} \)

cathode
anode

electrolyte (solvent)
molten regolith

cell wall
Direct Molten Oxide Electrolysis

T ≈ 1600°C

\[ \text{O}_2^- \rightarrow \frac{1}{2} \text{O}_2(g) + 2 \text{e}^{-} \]

- Goals of direct electrolysis of molten silicates.
  - determine most active anode catalyst for OER.
  - find inert (non consumable) anode.
  - determine current density, voltage and power requirements for scale up.
  - quantitative and qualitative analysis of oxygen
Relative amounts of regolith constituents and energy cost associated with electrowinning of each

Change in molten regolith properties with electrolysis

- $2\text{CaO} \rightarrow 2\text{Ca} + \text{O}_2$
- $\frac{2}{3}\text{Al}_2\text{O}_3 \rightarrow \frac{4}{3}\text{Al} + \text{O}_2$
- $2\text{MgO} \rightarrow 2\text{Mg} + \text{O}_2$
- $\text{SiO}_2 \rightarrow \text{Si} + \text{O}_2$
- $2\text{FeO} \rightarrow 2\text{Fe} + \text{O}_2$
- $2\text{Na}_2\text{O} \rightarrow 4\text{Na}^+ + \text{O}_2$

Dissociation Potential (V)

grams $\text{O}_2$ produced

0 100 200 300 400 500

0 0.5 1 1.5 2 2.5
Electrolysis Cell Setup

Furnace power supply

Potentiostat

Hot zone

Ar in

Ar out

Ar bubblers

Chiller (for furnace cap)
Redesigning cell cap for oxygen capture

Double o-ring seal
Electrolysis in Molten Oxides (trial four)

Mo cathode (after trial 3)
Pt RE (after trial 3)
mullite tubes

Mo cathode (after trial 4)
alumina tubes

Anode tube (after trial 4)
Iridium Current Density vs. Applied Potential in a Variety of Melts

\[ i = i_0 \left( e^{\frac{\alpha_f F \eta}{RT}} - e^{\frac{-\alpha_b F \eta}{RT}} \right) \]

\[ i_o = F A k^0 C^{*\alpha_f}_{O^2-\text{(melt)}} C^{*\alpha_b}_{O_2\text{(melt)}} \]

Increasing optical basicity (OB \( \alpha [O^2^-] \))
Optical Basicity of Lunar Regolith and Rocks
(higher optical basicity=higher \([\text{O}^2-]\) =higher current)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Basicity 1</th>
<th>Basicity 2</th>
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</thead>
<tbody>
<tr>
<td>Apollo 12</td>
<td>0.620</td>
<td>0.607</td>
</tr>
<tr>
<td>Apollo 14</td>
<td>0.600</td>
<td></td>
</tr>
<tr>
<td>Apollo 11</td>
<td>0.616</td>
<td>0.619</td>
</tr>
<tr>
<td>Apollo 17</td>
<td>0.625</td>
<td>0.630</td>
</tr>
<tr>
<td>Apollo 16</td>
<td>(deep drill) 0.589</td>
<td>0.586</td>
</tr>
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</table>
As part of an In-Situ Resource Utilization infrastructure on the lunar surface, the production of oxygen and metals by various technologies is under development within NASA projects. Such an effort reflects the ambition to change paradigms in space exploration to enable human presence for the long-term. Sustaining such presence involves the acceptance of a new concept in space activities; crews must be able to generate some of their consumables from local resources. The balance between accepting early development risks and reducing long-term mission risks is at the core of the technology development approach. We will present an overview of the technologies involved and present their possible impact on the future of human expansion in the solar system.