THE INFLUENCE OF LUNAR OUTPOST OBJECTIVES ON OUTPOST CAPABILITIES AND SITING

J. B. Plescia

The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD

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Why Are We Going to the Moon?

The Problem:

NASA does not have (or can not articulate) a well-defined reason for going to Moon or what will be done there.

Human Civilization, Scientific Knowledge, Exploration Preparation, Global Partnerships, Economic Expansion, Public Engagement

The Issue: The objective is what controls site selection, capabilities, and possible international contributions.

Commerce
Tourism
Science
Waypoint to Further Exploration
Security / Prestige
Be There
Scientific Questions

Lunar Exploration Analysis Group (LEAG)
Understand the environmental impacts of lunar exploration.
Development and implementation of sample return technologies and protocols.
Characterize the environment and processes in lunar polar regions.
Understand the dynamical evolution and space weathering of the regolith.
Understand lunar differentiation.
Understand volcanic processes.
Understand the impact process.
Determine the stratigraphy, structure, and geological history of the Moon.
Understand formation of the Earth-Moon system.
Understand the impact history of the Inner Solar System as recorded on the Moon.
Regolith as a recorder of extra-lunar processes.

Scientific Context for Exploration of the Moon: Final Report
Bombardment history of the inner solar system uniquely revealed on the Moon.
Structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated body.
Key planetary processes are manifested in diversity of lunar crustal rocks.
The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history.
Lunar volcanism provides a window into the thermal and compositional evolution of the Moon.
The Moon is an accessible laboratory for studying the impact process on planetary scales.
The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies.
Processes involved with the atmosphere and dust environment of the Moon are accessible for scientific study while the environment remains in a pristine state.

These really require global access and multiple samples.
What Really Needs to Be Measured at the Moon?

Apollo-like Sorties

Polar

*Enabling:* Geodetic control, Topography, Lighting

*Enhancing:* High-resolution imaging (hazards)

Non-Polar

*Enabling:* Nothing

*Enhancing:* High-resolution imaging

Outpost – Being There (Just land safely)

Polar

*Enabling:* Geodetic control, Topography, Lighting

*Enhancing:* High-resolution imaging

Non-Polar

*Enabling:* Nothing

*Enhancing:* High-resolution imaging

Global

*TBD:* Dust toxicity / Electrical charging
What Really Needs to be Measured at the Moon?

Outpost with Resource Utilization
Resource distribution (ore characterization)
  - H form, concentration, distribution in polar regions
  - Highlands composition
  - Pyroclastic composition
  - Regolith physical properties
    - Pyroclastics, Permanently shadowed

Polar
*Enabling*: Geodetic control, Topography, Lighting
*Enhancing*: High-resolution imaging

Non-Polar
*Enabling*: Nothing
*Enhancing*: High-resolution imaging

Global
*TBD*: Dust toxicity / Electrical charging
Let’s Suppose...

Waypoint to Further Exploration

Learn to live off planet
Cut the ties to Earth
Facilitate lunar, cis-lunar, solar system exploration

In Situ Resource Utilization

Power – Solar
Life support gases and liquids (O$_2$, H$_2$O, C$_2$H$_5$OH) – H, O, N, C
Fuel production (H$_2$:O or O$_2$:CH$_4$) – H, O, N, C

Reduce Earth launch mass – lower the cost
Resources

Oxygen can be found globally and relatively uniformly
   Oxygen significant fraction of lunar crust (45% by mass)
   Multiple processes of oxygen extraction (mare and highlands)

Hydrogen distribution variable
   Local concentrations
     Polar region
     Pyroclastics
     High-Ti Basalts

Light – Solar Power
   Local areas of extended sunlight at the poles

Hydrogen is the key unknown
   Transport from Earth
   Lunar storage
   Water is simple storage medium

LP/LRO NS data indicate average polar H content of ~150 ppm
   NS pixels are large
   Could be solar wind origin and uniformly distributed
   Could be solar wind or cometary and cold trapped

Pyroclastics may have high H content
   Apollo 17 black glass (devitrified orange glass)
## Solar Wind Implanted Volatiles

<table>
<thead>
<tr>
<th>Site / Rock Type</th>
<th>Range (Average) microgram / gram</th>
<th>H</th>
<th>C</th>
<th>N</th>
<th>He</th>
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</thead>
<tbody>
<tr>
<td>A11 Basalt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0192-0.47</td>
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<tr>
<td>A12 Basalt</td>
<td>1.5-9</td>
<td>5.3-45 (33)</td>
<td>0.6-44</td>
<td></td>
<td>0.026-0.089</td>
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<tr>
<td>A15 Basalt</td>
<td>1.2-12</td>
<td>7.7-22</td>
<td>3.5-125</td>
<td></td>
<td></td>
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<tr>
<td>A17 Basalt</td>
<td>1-3.8</td>
<td>3-80</td>
<td>0-105</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luna 20 Basalt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.199-0.97</td>
</tr>
<tr>
<td>A11 Soil / Regolith Breccia</td>
<td>20-100</td>
<td>96-216 (154)</td>
<td>45-110 (78)</td>
<td>19.6-84 (46)</td>
<td></td>
</tr>
<tr>
<td>A12 Soil / Regolith Breccia</td>
<td>1.9-106</td>
<td>23-170 (115)</td>
<td>46-140 (89)</td>
<td>14-68</td>
<td></td>
</tr>
<tr>
<td>A14 Soil / Regolith Breccia</td>
<td>67-105 (80)</td>
<td>42-225 (131)</td>
<td>25-130 (91)</td>
<td>5.2-15.9 (10.6)</td>
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</tr>
<tr>
<td>A15 Soil / Regolith Breccia</td>
<td>13-125</td>
<td>21-186 (109)</td>
<td>33-135 (86)</td>
<td>4.5-18.7 (11.2)</td>
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<tr>
<td>A16 Soil / Regolith Breccia</td>
<td>3.9-146</td>
<td>31-280 (112)</td>
<td>4-209</td>
<td>3-36</td>
<td></td>
</tr>
<tr>
<td>A17 Soil / Regolith Breccia</td>
<td>0.1-106</td>
<td>3.5-200</td>
<td>7.3-94</td>
<td>13-41 (23.9)</td>
<td></td>
</tr>
<tr>
<td>A14 Polymict Breccia</td>
<td></td>
<td>21-170</td>
<td>2.5-99</td>
<td>0.021-19.5</td>
<td></td>
</tr>
<tr>
<td>A15 Polymict Breccia</td>
<td>12-60</td>
<td>11-210</td>
<td>23-102</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A17 Polymict Breccia</td>
<td>1-56</td>
<td>12-157</td>
<td>30-120 (72)</td>
<td></td>
<td></td>
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<tr>
<td>Mature soil</td>
<td></td>
<td>50</td>
<td></td>
<td>50</td>
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</tbody>
</table>

Concentration is a function of surface area and resistance to radiation damage from solar X rays. Highest concentrations in “ilmenite” rich soils; Isotopic ratios indicate solar wind origin.
Could make a choice today based on what we know. But ....

Apollo 11 – Mare Tranquillitatis

Shackleton Crater South Pole
Exploration Strategy

LRO

**Polar Lander** (e.g., illuminated rim of Shackleton)
- Analytically determine H content of illuminated regolith
  - If H content ~150 ppm $\rightarrow$ H of solar wind origin and uniformly distributed
    - No need to explore shadowed areas
  - if H content <<150 ppm $\rightarrow$ H is segregated in cold traps
    - Small-scale distribution and form of H still uncertain
    - Need to explore shadowed areas to understand form and distribution
- Understand physical polar environment

**Pyroclastic Lander**
- Analytically determine H content of pyroclastic material

**PSR Rover**
- Determine the form, concentration and distribution of H

**Resource Ore Decision – Shadowed Polar Area or Pyroclastics**

ISRU demonstration / Regolith handling
- Collect and physically process the regolith / ice
- Demonstrate O and H release at relevant scale
- Demonstrate O and H storage (fluid transfer, cryostorage, etc.)

**Can we really do large scale ISRU? Is it worth it?**

**Determine the location of the outpost.**
But... See Dr. Bussey for details on real estate options.
Volatile Assessment

POLAR SHADOWED AREAS

Measure volatile content of permanently shadowed regolith (form, concentration)
- Independent measurements at $N$ samples
- $N$ is defined by the level of statistical uncertainty (i.e., risk)
- Determine $H_2O$ and other volatile species
  - Sample below $\sim 10$ cm and well into $H$ containing zone
  - Avoid geologic effects
- Sub-surface sample acquisition (i.e., drill)
- Mass Spectrometer (measure content and isotopic ratios)

Map lateral and vertical distribution of volatile phases in the shadowed areas
- Sub-surface sample acquisition (i.e., drill)
- Remote Sensing (tie sub-surface samples together)
  - Neutron Spectrometer
  - Electromagnetic Sounding

Determine geotechnical properties of shadowed regolith
- Drill and/or arm with end effectors

PYROCLASTIC DEPOSITS

Regolith H (and other rare gases) Content
- Drill (need to penetrate below desiccated layer and geologic effects)
  - 1-2 m depth
- Mass Spectrometer (measure amount and isotopic ratios)

Neutron Signature
- Neutron spectrometer

Surface Morphology / Lighting (Polar sites)
- Mast mounted stereo imaging system
- Solstice to solstice (1 year goal)

Geotechnical Properties
- Uses drill / arm to measure properties in situ with exchangeable end-effectors

Regolith Radiation Shielding / Secondary Radiation Generation
- Radiation detector buried in disturbed regolith

Levitated Dust
- TBD (passive experiment)

Dust Properties
- TBD (active analysis on acquired sample)

Regolith reactivity
Pyroclastic deposits may have high H content
Apollo 17 orange glass and Apollo 15 green glass enriched in volatile elements
Black glass contains illmenite – enhanced H retention
ISRU Demonstration / Regolith Excavation

Demonstrate
  - Excavation and transport
  - Recovery of volatiles
  - Oxygen production
  - Fuel production
  - Cryogenic storage and transfer

Requires advanced power, mobility, large landed payload capacity
Outpost

Permanent presence
Mobility 100s km
Extended surface operations

*Impact cratering history*
   Extensively explore numerous craters of different size
   Melt material to allow dating of the crater
   Glass-lined craters
Conclusions

NASA Lunar raison d’être remains undefined

If one selects the objective:

Learn to life off-planet / Facilitate exploration of solar system

*In situ* fuel development is critical

Power, Oxygen and **hydrogen** key elements

Understand ore potential and process requires *in situ* analysis / demonstration

Site selection depends upon a critical analysis of the complete costs, logistics, and energy considerations.
Vaya con el hidrógeno!