Assessing the Resource Potential of the Moon: The Case for a Decadal-Scale Robotic Lunar Exploration Program

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Annual LEAG Workshop Sep 14-16, 2010

Space Resource Roundtable and Planetary and Terrestrial Mining Science Symposium
Someday We Will Settle the Moon
“Everything has changed but our way of thinking” – Neil A Einstein
A Game Changer: Water and other Volatiles Confirmed on the Moon

• The lunar cold traps are:
  – Potentially the coldest locations in the solar system
  – Potentially the most stable reservoirs for long-term volatile storage in the solar system
The Resource Potential of the Moon

Q1: Can lunar resources make space operations and exploration – within and beyond cis-lunar space – more affordable?

Q2. Can lunar resources help to solve problems for the Earth?
Contents

1. Introductory remarks
2. Architecture and Concept of Operations for robotic lunar exploration program that meets exploration goals and supports national education objectives
3. Some thoughts on lunar resources and their applications
4. Conclusions
Architecture and Concept of Operations

Space Resource Roundtable
and
Planetary and Terrestrial Mining Science Symposium
ISRU Cycle (Space Mining)

Remote Survey → Resource Prospecting and Definition → Extraction Mining

Product → Processing → Beneficiation

Waste
Thermal Wadis and Compact Rovers
A New Kind of Exploration Program
Proposed Decadal Exploration/Resource Prospecting Program

• Develop extensive resource maps
  – Tens of standard class rovers providing prospecting functions
    • With potentially unique combinations of instruments (spectrometers, core drilling, ground penetrating radar, etc)

• Operated by students and other members of the public
  – Under the guidance/direction of PIs that are trained in lunar science
  – Operating from and involving universities, high schools and informal science centers
  – Additionally investigating broader issues such as the eventual settlement of the Moon
Proposed Decadal Exploration/Resource Prospecting Program
Proposed Decadal Exploration/Resource Prospecting Program

• Outcomes
  – Larger numbers of students drawn into and graduated with degrees in the STEM (Science, Technology, Engineering and Mathematics) disciplines
  – Using resource maps and the results of technology demonstrators, combined with economics and business studies, we will develop an understanding of the resource potential of the Moon
Some Thoughts on Lunar Resources and Applications

Space Resource Roundtable and
Planetary and Terrestrial Mining Science Symposium
Potential Lunar Ore Resources

Solar Wind Implanted Volatiles
- H, He, C, N, Ne, Ar, Kr, Xe
- All alkali elements (except Na), alkaline-earth elements (except Ca), the Rare Earth Elements (REE), B, Zr, Nb, Sn, Hf, Ta, U, Th

Incompatible Trace Elements

Major and Minor Components
- O, Si, Al, Fe, Mg, Ca, Na, Ti, P, Sc, V, Cr, Mn, Ga, Sr

Vapor-Mobilized Elements
- S, the halogens, Cu, Zn, As, Se, Ag, Cd, In, Te, Hg, Tl, Pb, Bi

Siderophile Elements
- Fe, Co, Ni, Ge, Mo, Ru, Rh, Pd, Sb, W, Re, Os, ir, Pt, Au

Incompatible Trace Elements

Objective 1: China’s Market Dominance May Affect Future U.S. Availability of Rare Earth Materials

- Some government and rare earth industry officials believe that China plans on greater vertical integration of the rare earth materials market in the future, which would increase China’s total market power and dominance.
- While China is currently exporting rare earth oxides and metals, some rare earth industry officials believe that in the future China will only export finished rare earth material products with higher value.

**Incompatible Trace Elements**

**Apollo 11 Data for Five Rare Earth Elements**

<table>
<thead>
<tr>
<th></th>
<th>Lunar Basalt</th>
<th>Lunar Breccias</th>
<th>Lunar Soil</th>
<th>Earth Crust</th>
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<tr>
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• KREEP materials can be further concentrated using fractional crystalization and separated/purified using solvent extraction

Q: Where are the highest concentrations of KREEP on the lunar surface?
Fractional Crystallization

- Partial melting enriches ITEs
- Volatiles are off-gassed
## Vapor Mobilized Elements

### Apollo 11 Data for Five VMEs

<table>
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<th>Element</th>
<th>Unit</th>
<th>Lunar Basalt</th>
<th>Lunar Breccias</th>
<th>Lunar Soil</th>
<th>Earth Crust</th>
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<tr>
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<td>18</td>
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<tr>
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<td>ppb</td>
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<td>5</td>
<td>&lt;10</td>
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<td>0.05</td>
</tr>
</tbody>
</table>

### Question

Q: Will VMEs be found in higher concentrations in polar regions, within or in the vicinity of cold traps?
Conclusions

• Discussed an architecture for participatory lunar robotic exploration that:
  – Supports national educational objectives (STEM education)
  – Provides the information that defines the resource potential of the Moon

• Discussed the possibility that lunar resources might help to solve problems on the Earth
  – National Security technologies
  – Sustainable energy systems

• Raised the hypothesis that other VMEs – including those of interest for sustainable energy systems (e.g., Te, In, etc) -- will be found in the coldest locations on the Moon