Return to the Moon: Resources, Risks, and Rewards*

William Ambrose

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Abstract

A sustained human presence on the Moon will be an important first step in settling Mars and other bodies in the Solar System. This long-term mission will be to prove scientific and exploration technologies, provide life support for human settlements, and extract resources at cost-effective levels. Factors that will impact sustainability of lunar outposts include power generation and energy storage, radiation and micrometeorite shielding, and food cultivation. All of these factors will also have to be considered in Martian habitations. Health hazards imposed by fine-grained lunar dust represent a critical problem for human settlement. These hazards will involve not only impaired breathing as experienced in the Apollo 17 mission, but also damage to equipment, dispersal from engine blasts, and reduced mobility. Underground installations, either excavated from lunar regolith or located in subsurface lava tubes, will be necessary to mitigate radiation and impacts from micrometeorites. The Moon contains mineral and volatile resources for construction materials and propellant manufacture. Detailed mapping of pyroclastic volcanic vent deposits has identified volcanogenic elements that include iron, zinc, cadmium, mercury, lead, copper, and fluorine. Rare metals and platinum-group elements may also reside in low concentrations in regolith breccias, highland impact breccias, and possibly in layered mafic intrusives. Thorium is relatively abundant in Oceanus Procellarum, associated with late-stage melts rich in KREEP (Potassium/Rare-Earth-Elements/Phosphorus) constituents. Exhalatives and some impact breccias contain volatiles such as nitrogen and carbon, the building blocks of plastics and foodstuffs. Other volatiles, including water, also occur in lunar pyroclastic glasses and in cold, permanently shadowed areas near the poles. Lunar orbital depots for fuel and life-support materials can serve as temporary accumulation areas for transport of materials derived from volcanogenic sources to Earth’s surface. Future advances in technology and planetary engineering on the Moon, a perfect proving ground, will offer humans a steppingstone to Mars, ultimately leading to a sustained human presence in space.

References Cited


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William A. Ambrose
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Bureau of Economic Geology

AAPG Astrogeology Committee

ESA
Return to the Moon

- Earth’s closest neighbor
  - Three-day trip
  - Technology already exists to return to the Moon
  - Human missions: <0.1% surface area visited

- Abundant resources
  - Water and volatiles for human settlement and rocket fuel
  - Metals for Moon Base and solar power facilities

- Technology Development
  - Settlements: Learning experiences for other planets
  - Mining
  - Space-power systems
# The Moon: Private Sector

<table>
<thead>
<tr>
<th>Company</th>
<th>Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bigelow Aerospace</td>
<td>Habitation modules, Lunar base</td>
</tr>
<tr>
<td>Lockheed</td>
<td>Orion-based lunar lander</td>
</tr>
<tr>
<td>SpaceX</td>
<td>Launch vehicles</td>
</tr>
<tr>
<td>Odyssey Moon</td>
<td>Robotic lander/rover</td>
</tr>
<tr>
<td>Honeybee Robotics</td>
<td>Ice drilling/testing/extraction</td>
</tr>
<tr>
<td>Cislunar Space Development</td>
<td>Space tugs, shuttles</td>
</tr>
</tbody>
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Mark Maxwell
Helium-3 from Solar Wind

Solar Helium

$^3\text{He}$ Generation and Lunar Accumulation

Earth Shielded

Lunar He-3 Distribution

Global: $6.5 \times 10^8$ kg
(715 million short tons)

Fa and Jin (2007)
Lunar He-3 and Hydrogen Mining

artstation.com
Volatiles at the Poles

Impacts from volatile-rich comets/asteroids
$10^{13}$ kg water: past 2 Ga (Arnold, 1979)
Polar Illumination

Within 2° latitude: White areas: sunlight >50% lunar day

North Pole

South Pole

Shoemaker

Shackleton

3-14% water ice

Hermite A

Hinshelwood

Whipple

de Gerlache

Peary

Peary

Hermite A

Hinshelwood

Whipple

de Gerlache
LRO-Based Photo-Mapping of Permanent Shadow

- South Polar Region (60-90° S. Lat.)
  - 91,409 km²

- North Polar Region (60-90° N. Lat.)
  - 169,508 km²

- Total: 260,917 km²

- Potential Helium-3 resources at 40 ppb
  - 33,563 tonnes

- Areas minable to 3 m based on 50% of area of smooth plains > 25 km²

Schmitt (2014)  Kaguya Photograph
South Polar Temperature

LCROSS Impact Site
5.6 ± 2.9% H₂O

Colaprete et al. (2010)
Polar Surface Water Ice

Kornuta et al. (2019)

North

South

- M³, LOLA, Diviner
- M³, LOLA, Diviner, LAMP
Water Ice Extraction: Solar Power

Heliostats

Collection: IHOP*

*Hydrogen Oxygen Production

Room.eu.com (2017)

Kornuta et al. (2019)
Lunar TiO$_2$ Basalts

- TiO$_2$ >7 wt.%
- TiO$_2$ 3-7 wt.%
- TiO$_2$ <2 wt.%
- Old highlands/ejecta
- Recent ejecta

Rolf Wahl Olsen
Thorium: Silicic Domes

Yamashita (2009)

Mons Gruithuisen

LOLA M117752970ME

>90 ppm

Yamashita (2009)
Lunar Habitations

Sinterhab Design

Installation

ESA/Foster + Partners
Mare Pits

MODIFIED FROM
Haruyama et al. (2011)
Distribution of Lunar Pits

Modified from Wagner and Robinson (2014)
Modified from Duke et al. (2003); Kutter (2016)
Propellant Costs

Based on $3 million per ton at LEO
Kutter (2016)
Kornuta et al. (2019)

Resource Cost ($k/kg)

Aerobraking

Earth-LEO: 8.0 kms⁻¹
LEO-Moon: 6.3 kms⁻¹

Kutter (2016)
Kornuta et al. (2019)

Cost from Earth
Cost from Moon

450 metric tons lunar propellant yr⁻¹: $2.4 Billion revenue
Return to the Moon: Timeline

- NASA Space Launch System: 2020
- NASA Crewed Lunar Orbit: 2025
- Short-Stay Human Missions: 2030
- First Habitats with Support Systems: 2035
- Semi-permanent Lunar Settlement: 2035

Gibney (2018)
Summary

- **Resources**
  - Helium-3
  - Hydrogen
  - Ti-rich basalts
  - Thorium and Uranium

- **Lunar Bases**
  - Polar facilities
  - Sinterhab/Inflatable designs
  - Mare Pits

- **Private Sector**
  - Lunar landers
  - Habitation modules
  - Navigational and transportation systems