The Moon: Stepping Stone to the Planets

William A. Ambrose
Houston Geological Society
May 10, 2017

Why Return to the Moon?

● **Earth’s closest neighbor**
  - Three-day trip
  - Technology already exists to return to the Moon
  - Less than 0.1% surface area visited by humans

● **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 Mars
  - Mining
  - Space-power systems
The Moon
Surface Mineralogy

Chandrayaan-1
NASA Moon Mineralogy Mapper
September 2009

Fe-rich basalt

Ti-rich basalt

H, OH−

Feldspathic Highlands
LUNAR Soil Composition

- **O$_2$**: 42%
- **Si**: 21%
- **Fe**: 13%
- **Ca**: 8%
- **Al**: 7%
- **Mg**: 6%
- **Other**: 3%

**Apollo 17 Geologist**
**Harrison Schmitt**
Lunar Helium-3


>270,000 km² minable (high- and medium-grade)

One Space Shuttle load could power the U.S for 6 months

Lewis (1996)
Lunar He-3 Distribution

>270,000 km² minable (high- and medium-grade)

*Lewis (1996)*

Oceanus Procellarum

Tranquillitatis

*Johnson et al. (1999)*
Lunar He-3 Mining

Matt Gujda et al. (2006)

Mass 9.7 tons
350 kW power usage
Handles 30° slopes

Solar Powered!

### Mass of Volatiles Extracted (tonnes/yr @ 10ppb)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mass (tonnes/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>108.9</td>
</tr>
<tr>
<td>N₂</td>
<td>16.5</td>
</tr>
<tr>
<td>CO₂</td>
<td>56.1</td>
</tr>
<tr>
<td>H₂</td>
<td>201.3</td>
</tr>
<tr>
<td>⁴He</td>
<td>102.3</td>
</tr>
<tr>
<td>CH₄</td>
<td>52.8</td>
</tr>
<tr>
<td>CO</td>
<td>62.7</td>
</tr>
<tr>
<td>³He</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Assumed 10ppb! Actual >20ppb
A ~0.4-mi$^2$ (1-km$^2$) area of mare regolith at 40-ppm hydrogen could be mined to a depth of ~3.3 ft (1 m) to extract an equivalent amount of hydrogen for launching the Space Shuttle (Spudis, 1996).
Hydrogen-Producing Station

Spudis (1996)
Volatiles at the Poles

Impacts from Comets

10^{13} \text{ kg water past 2 Ga (Arnold, 1979)}

Bussey and Spudis (2006)
View from the Moon’s South Pole

Kaguya Photograph
Mission to Shadowed Crater
Lunar Ice Drill

1-2 m depth of investigation
Luna-27 lander in 2020: -140°C
LCROSS
Impact Site Selection near South Pole

Depth to Stable Ice (m)

Water Equivalent Hydrogen

Elphic et al. (2011)

1 cm

> 1 m

Eke et al. (2009)

100 km
Lunar Polar Crater Anomalies

Modified from Spudis et al. (2013)

North Pole
≥80°N

South Pole
≥80°S

Shadowed Craters

Neutron Spectrometer
Red: High Hydrogen

Neutron + CPR
Off-axis Polar Hydrogen

Modified from Siegler et al. (2016)
Procellarum KREEP Terrane

Jolliff, et al. (2000)

Spudis (2005)
Thorium Silicic Domes

Mons Gruithuisen

LOLA M117752970ME

Yamashita (2009)
Compton Belkovich Lava Domes

Modified from Jolliff et al. (2011)

40-55 ppm Th
**Mars: Surface Radiation Risks**

**RAD on Mars Curiosity**

Galactic Cosmic Rays, Solar Particle Events

Radiation equivalent to whole-body
Computation Axial Tomography (CAT) scan every 5 days
Lifetime cancer risk increase of 5%
Lunar Base Designs

Sinterhab

ESA/Foster + Partners (2013)

Inflatable Lunar Base
Distribution of Lunar Pits

Modified from Wagner and Robinson (2014)

- Mare pits
- Highland pits
- Impact melt pits

1,000 km
Mars: Collapsed Lava Tubes

Pit Chains in Tharsis

© ESA/DLR/FU Berlin (G. Neukum)

Mars Express (2012)
Global Space Economy

- $330 Billion in 2015
  - Commercial activities: 76 percent
  - Global navigation systems
  - Infrastructure and support
  - Transportation systems (ISS, Space Tourism)

- NASA: $19.3 Billion: 2016 (0.5% US Federal Budget)

Falcon 9: May 18, 2015
Private Space Sector

Offworld: Robots
Shackleton Energy Company: Ice Mining
Bigelow Aerospace: Habitation Modules, Lunar Base
SpaceX: Launch vehicles
Odyssey Moon: Rovers
Infinite Space Dynamics, Planetary Resources: NEAs
Deep Space Industries: Space manufacturing, solar
Mars One: Mars colonization
B330 Habitation: Bigelow Aerospace

330 m³ volume (ISS 900 m³): Arrived at ISS, April 10, 2016
BEAM
Bigelow Expandable Activity Module

May 28, 2016
Luna Ring: Shimizu Corporation

Energy Conversion Facilities

Microwaves
Lasers

Energy Transmission Facilities

Modified from Shimizu Corporation (2016)
Luna Ring: Close View

Shimizu Corporation (2016)
Cislunar Space and Economic Potential

Modified from Duke et al. (2003); Kutter (2015)

LEO Remote Sensing
Communications
Observations
Debris Mitigation
Propellant Transfer

GEO Communications
Solar Power
Observations
Satellite Life Extension

L1 and L2 Fuel Depot
Communication Link
Lunar Observations
Repair Station

Moon Mining
Fuel Depots
Manufacturing
Habitations
Solar Power to Earth

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

Aerobraking
Propellant Costs

Based on $3 million per ton at LEO

Kutter (2015)

Earth-LEO: 8.0 kms⁻¹

LEO-Moon: 6.3 kms⁻¹

Resource Cost ($k/kg)

Cost from Earth

Cost from Moon

$0.001k

$0.5k
Future Lunar Outpost
For Additional Information, see the EMD-AAPG Memoir 101


Especially Chapter 1, 8, and 9:

William A. Ambrose, Bureau of Economic Geology, University of Texas at Austin, Chapter 1
http://i2massociates.com/downloads/CHAPTER01.pdf

David R. Criswell, University of Houston, Chapter 8
http://www.i2massociates.com/downloads/CHAPTER08.pdf

Michael D. Campbell, I2M Associates, llc, and others, Houston, Chapter 9

http://bit.ly/2r7RhPf

I2M Web Portal: Search Results for “Moon”.