There Have Been Relatively Few Comprehensive Mining Equipment Studies for Lunar Resources

- **Solar Wind Volatiles**
  - University of Wisconsin

- **Oxygen Production**
  - Carbotek/JSC
  - Bureau of Mines
  - Shimizu

- **Hard metals Extraction**
  - Bureau of Mines
  - Los Alamos National Laboratory
Helium-3 Evolution from Lunar Regolith

Pepin et al.

% He3 Evolution

Regolith Temperature, °C

0 200 400 600 800 1000

0 20 40 60 80 100

75% 86% 95%
Miner Movie
- Depth of excavation: 3m
- Forward speed: 23 m/h
- Area excavated: 1 km²/y
- Mining hours/y: 3,942
- Excavation rate: 1,258 t/h
- Processing rate: 556 t/h
Process for Extracting Helium-3 from Lunar Regolith

6100 tonnes of Hydrogen (H₂) is available on the Moon, which can be processed to produce 1 tonne of Helium-3.

The process involves:
- Passing the Hydrogen (H₂) through a Radiator/Condenser at 300 °K.
- Cooling to 50 °K for Isotopic Separation.
- Further cooling to 1.5 °K to isolate 1 tonne of Helium-3.

The remaining materials:
- Water (H₂O) with 3300 tonnes
- Nitrogen (N₂) with 500 tonnes
- Carbon Dioxide (CO₂) with 1700 tonnes
- Methane (CH₄) with 1600 tonnes
- Carbon Monoxide (CO) with 1900 tonnes
- Helium-4 (Helium-4) with 3100 tonnes

These materials can be used for fuel, life support, and cryogenics on Earth.
The "Coldness" of Outer Space Can Be Used to Separate the Lunar Volatiles

- Mean Maximum Surface Temperature, 380 K
- Temperature @ 1.5 m Below Surface, 253 ±2 K
- Mean Surface Temperature Just Before Sunrise, 100 K
- "Temperature" of Outer Space, ~4 K

**Boiling Point of Some Lunar Volatiles**

- H$_2$O, 373 K
- CO$_2$, 194 K
- CH$_4$, 109 K
- CO, 81 K
- N$_2$, 77 K
- H$_2$, 20 K
- He, 4.2 K
One Mark II Miner Can Provide Enough $^3\text{He}$ to Power a 330 MW$_e$ Fusion Power Plant for a Full Year

- Earth mass of miner $18$ t
- Thermal energy $12.3$ MW$_t$
- Operating power $200$ kW$_e$
- Annual Production $^3\text{He}$ $33$ kg/y
- Volatile by-prod $600$ t/y
There Are at Least Three Major Applications for the Volatile By-products from Lunar $^3$He Mining

1) Fuel Cells
   - (H$_2$, O$_2$)

2) Life Support
   - (N$_2$, O$_2$, H$_2$O, CO$_2$)

3) Propulsion
   - (H$_2$, O$_2$, $^4$He)
The Mark-II Miner Could be Powered by a 200 kW_e Fuel Cell

• Operation Schedule
  – During lunar day only (≈14 earth days)
  – Assume 90% availability to account for sunrise and sunset as well as component failure

• Fuel Input
  – 200 kW_e requires
    • 17.1 g O_2/s
    • 2.1 g H_2/s
  – Total O_2 & H_2 is 23.2 tonnes/d
  – PV array for electrolysis ≈ 250 kW_e
In 1/3 of a Lunar Day, the Mining Unit Can Extract Enough H₂ and O₂ to Fill the 200 kWe Fuel Cell/Electrolyzer Loop.
After the First Lunar Day, the Entire Output of Volatiles Can Be Used For Support of the Lunar Settlement

Gases
- $\text{H}_2$, $\text{H}_2\text{O}$, $\text{He}$, $\text{He}$,$\text{N}_2$, $\text{CO}$, $\text{CO}_2$, $\text{CH}_4$

Evolved Gases

Solar Thermal

For Mechanical Power

Fuel Cell

H$_2$O

Electrolyzer

PV Cells

O$_2$

H$_2$
An Example of How a Solar Wind Volatiles ‘‘Mine’’ Might be Identified

-Mare Tranquillitatis-
Mare Traquillitatus
How Much of the Regolith in Mare Tranquillitatis can be Mined?

1) What is the depth of regolith?
2) How much of Tranquillitatis is covered by high-Ti regolith?
3) What percentage of Tranquillitatis is minable?
4) How much $^3$He is present in minable regolith?
Inferred Titanium Content of Regolith of Mare Tranquillitatis

- +7.5%
- 6.0 - 7.5%
- 3.0 - 6.0%

After G. Cameron
After G. Cameron

Figure 15. Map of Mare Tranquillitatis. Major structural features are less numerous in the area bounded by the area bounded by the heavy black line than in the remainder of the mare (cf. Figs. 5 and 6).
After G. Cameron

Figure 6. Reduced overlay of original of Figure 5. Craters 23.4 m or more in diameter (including ejecta halos where observed or inferred) shown by solid black circles. Mappable area plotted in terms of 400-meter square blocks (bounded by solid lines) and extensions (bounded by dashed lines).
Figure 7. Reduced overlay of original of Figure 5. Craters 23.4 m or more in diameter (including ejecta halos where observed or inferred) shown by solid black circles. Mappable area plotted largely in terms of 300-meter square blocks (bounded by solid lines) and extensions (bounded by dashed lines).
Approximately 1/5 of the Total Area of Mare Tranquillitatis is Occupied by Features that May Be Unminable

<table>
<thead>
<tr>
<th>Feature</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domes</td>
<td>0.6%</td>
</tr>
<tr>
<td>Ridges</td>
<td>5.6%</td>
</tr>
<tr>
<td>Craters</td>
<td>4.2%</td>
</tr>
<tr>
<td>Rilles</td>
<td>0.6%</td>
</tr>
<tr>
<td>Basement materials</td>
<td>2.0%</td>
</tr>
<tr>
<td>Ray materials</td>
<td>5.6%</td>
</tr>
<tr>
<td><strong>Misc. non-mare features</strong></td>
<td><strong>3.4%</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>22.0%</strong></td>
</tr>
</tbody>
</table>
The Smaller the Unit Mining Block the Larger the Percentage of Minable Area
### Minable Regolith and Helium Content of Mare Tranquillitatis

<table>
<thead>
<tr>
<th>Regolith Category</th>
<th>Area km²</th>
<th>Ave. He Content-wppm</th>
<th>Minable Regolith, tonnes</th>
<th>Helium tonnes</th>
<th>Helium-3 tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>84,000</td>
<td>38</td>
<td>252 x 10⁹</td>
<td>9,580,000</td>
<td>3,625</td>
</tr>
<tr>
<td>B</td>
<td>195,000</td>
<td>25</td>
<td>598 x 10⁹</td>
<td>14,960,000</td>
<td>5,754</td>
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<tr>
<td>Totals</td>
<td>279,000</td>
<td></td>
<td>850 x 10⁹</td>
<td>24,540,000</td>
<td>9,439</td>
</tr>
</tbody>
</table>

Note: He-3 content based on $^{4}\text{He}/^{3}\text{He} = 2600$ and average depth of regolith is 3 m
Another Approach to Lunar Volatiles Mining

-Spiral Mine Plots-
Spiral Mining System for Lunar Volatiles

VR: Volatile refining subsystems
HS: Habitat and crew work section
LP: Launch and landing platform
PS: Power subsystems
SA: Mobile Miner support arm

Solar Thermal Receiver
Mobile Miner
New Road
Old Road
Wheel Track
Temporary Road
Solar Concentrators and Reflectors
Regolith Filled Shield
Sealed SA Bearing
Adjustable Skirt
Spiral Miner Concepts (1)

• Mobile miner similar to Wisconsin Mark-II
• Power received from central station
• Daylight operation or nighttime with fuel cells
• Volatiles piped to central station
• Routine telerobotic operation
• Backup manual operation
Spiral Miner Concepts (2)

- Maintenance and repair at central station
- Possible transport of regolith through pipe to central station
- Look ahead radar to identify hidden boulders
- Unminable areas avoided by extending or contracting arm.
Spiral Mining/Central Station

- Could provide thermal and electrical power generation
- Command and control functions
- Processing of extracted volatiles
- Refined volatiles tanked for export or storage
- Regolith filled insulating shell
Spiral Mining/Permanent Support Base

- Administration and long term planning
- Volatile export planning
- Consumable import planning
- Region launch and landing coordination
- Agricultural production
- Manufacturing and shop support
- Major medical support
- Regional recreation center
Chamberlain et. al., (1993) have proposed an underground mining and sealing concept.

1. Portal
2. Tunnel
3. Chamber
4. Airlocks and sealed inner surface
5. Equipment and 2nd airlock separating processing site from mine
RETURN TO THE MOON

THIS TIME WE STAY

SECOND ANNUAL LUNAR DEVELOPMENT CONFERENCE JULY 20-21, 2000

ARTWORK CREATED FOR SPACE FRONTIER FOUNDATION BY MARK MAXWELL