Extraction Techniques-Solar Wind Volatiles
Professor G. L. Kulcinski
Feb. 16, 2004
The Solar Wind has been "blowing" on the planets (and Moons) of our solar system for some 4.5 billion years.

The Solar wind is ionized and therefore is deflected by the Earth's magnetic field.

- The Solar Wind Volatiles fall into two general classes:
  1) Biogenic elements (H, C, and N)
  2) Noble gases (He, Ne, Ar, Kr, & Xe)

http://sec.gsfc.nasa.gov/sec_resources_imagegallery.htm
The Solar Wind Has Been an Important Source of Resources for the Moon

- **Composition of Solar Wind:**
  - 96% H, 4% He, traces ($\approx 0.1\%$) of C, N, and O

- **Energy per particle**
  - 0.5-3 keV/amu (ave. $\approx 1$ keV/amu)
The Solar Wind Has Been an Important Source of Resources for the Moon

- Particle flux:
  - $\approx 1-8 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$
  - ave. $\approx 3 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$

- Number of solar wind particles that have hit the lunar surface in 4.5 billion years
  - $4 \times 10^{25}$ particles/cm$^2$

- This number of atoms is equal to the number of atoms in the first 2 meters of lunar regolith.
The Solar Wind Has Been an Important Source of Resources for the Moon

• The $^{3}\text{He}/^{4}\text{He}$ ratio in the solar wind is:
  – $4 \times 10^{-4}$ atomic
  – $3 \times 10^{-4}$ by weight

• This ratio is much different than on the Earth
  – (see Figure)
  – Source Wittenberg, 1989
The $^3$He/$^4$He ratio on the Earth can vary by orders of magnitude from the solar wind concentration.
The Concentration of Lunar Volatiles in the Apollo Soil Samples Covers a Wide Range of Values
The Inventory of Volatiles in the First 3 Meters of the Lunar Regolith Can be Substantial

Note: at the present SW flux, over 500 million tonnes of $^3$He hit the Moon over 4.5 billion years
Lunar Volatiles Have Many Applications

- **Hydrogen**: Water, Rocket Fuel, Hydrocarbons, Oxygen
- **Helium-3**: Fusion Energy (Propulsion, Electric Power, ...)
- **Helium-4**: Atmosphere Control, Cryogenics
- **Water**: Life Support, Oxygen
- **Nitrogen**: Food, Atmosphere Control, Reagents
- **CO, CO₂, CH₄**: Food, Hydrocarbons, Fuel
- **F₂**: Oxygen & Metal Production, Teflon
- **Cl₂**: Oxygen & Metal Production, Reagents
- **SO₂**: Metal Extraction, H₂SO₄, Explosives, Binder for Bricks
## What is Needed for Plants and Humans to Survive?

<table>
<thead>
<tr>
<th>Gaseous Component</th>
<th>Pressure-mbar</th>
<th>Explanation</th>
<th>Gaseous Component</th>
<th>Pressure-mbar</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plants</strong></td>
<td></td>
<td></td>
<td><strong>Humans</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>&gt;0.15</td>
<td>Lower limit set by photosynthesis, no upper limit</td>
<td>CO₂</td>
<td>&lt;10</td>
<td>Set by Toxicity</td>
</tr>
<tr>
<td>N₂</td>
<td>&gt;1-10</td>
<td>Nitrogen Fixation</td>
<td>N₂</td>
<td>&gt;300</td>
<td>Buffer Gas</td>
</tr>
<tr>
<td>O₂</td>
<td>&gt;1</td>
<td>Plant Respiration</td>
<td>O₂</td>
<td>&gt;130</td>
<td>Lower limit set by hypoxia</td>
</tr>
<tr>
<td>Total</td>
<td>&gt;10</td>
<td>Water + O₂ + N₂ + CO₂</td>
<td>Total</td>
<td>500-5,000</td>
<td>Upper limit set by flammability</td>
</tr>
</tbody>
</table>

It is Important to Minimize the Per Capita Loss Rate of Solar Wind Volatiles

<table>
<thead>
<tr>
<th>Compound</th>
<th>Use</th>
<th>Loss/Makeup Conditions</th>
<th>Loss Rate, kg/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Food Production</td>
<td>10%/y of waste not recoverable</td>
<td>&lt;3</td>
</tr>
<tr>
<td></td>
<td>Atmospheric Component</td>
<td>Earth-like atmosphere, 1% leakage/d</td>
<td>344</td>
</tr>
<tr>
<td>Oxygen</td>
<td>Food Production, Processing &amp; Waste Recycling</td>
<td>10%/y loss of food waste</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Atmospheric Component</td>
<td>Earth-like atmosphere, 1% leakage/d</td>
<td>95</td>
</tr>
<tr>
<td>CO₂</td>
<td>Food processing and waste recycling</td>
<td>10%/y loss in processed food</td>
<td>77</td>
</tr>
<tr>
<td>Water</td>
<td>Drinking, Food Production, Processing and Waste Recycling</td>
<td>10% loss of potable water/y</td>
<td>142</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td></td>
<td>716</td>
</tr>
</tbody>
</table>
The Total Amount of Volatiles Required to Support 1 Person-Year on the Lunar Surface Exceeds 700 kg/year

- Carbon Dioxide: 77 kg per Person-Year
- Water: 142 kg per Person-Year
- Oxygen: 150 kg per Person-Year
- Nitrogen: 347 kg per Person-Year

Efficient Recycle (Replacement Only)
It is Important to Minimize the Per Capita Loss Rate of Solar Wind Volatiles

<table>
<thead>
<tr>
<th>Element</th>
<th>Use</th>
<th>Loss Rate kg/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>Food, Atmosphere</td>
<td>347</td>
</tr>
<tr>
<td>O₂</td>
<td>Food, Water, Atmosphere</td>
<td>332</td>
</tr>
<tr>
<td>C</td>
<td>Food</td>
<td>21</td>
</tr>
<tr>
<td>H₂</td>
<td>Water, Food</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>716</strong></td>
</tr>
</tbody>
</table>
The Cost to Supply All the Volatiles Needed by a Base Camp of 10 People on the Moon is $\approx 1$ Billion/y

- Present cost to LEO is $\approx 10\text{-}20,000 \text{$/kg}$
- Sherwood and Woodcock, Boeing--1993, calculate that it will cost 7-10X as much to place cargo on the Moon
- The minimum life support mass (volatiles) is $\approx 700 \text{ kg/person-y}$
- The total cost to supply volatiles ranges from 50 to 150 $\text{M}$ per person year (today)
- A reasonable average cost is $\approx 100 \text{ $M /person-y}$ times 10 persons is $\approx 1 \text{ $B/y}$
Products That Could Be Derived from $1 \text{ m}^3$ of Lunar Regolith

350 liters $^4\text{He}$ @ STP

Global Average Annual Electricity Consumed per Capita–1995

modified from Jeff Taylor and Larry Haskin
There are at least 3 areas that could benefit from lunar volatiles in the near term:

- Life Support
- Transportation
- $O_2, H_2$ propellant to Mars
Man Factors go into the Calculation of the Amount of Solar Wind Volatiles That Can Be Recovered from the Moon

- **Flux of (SWV)$_i$ to the lunar surface**
  - $f(latitude, longitude, t)$

- **Geographic location of (host material)$_j$ on the Moon**
  - $f(latitude, longitude, depth, t)$

- **Fraction of (SWV)$_i$ retained by (host material)$_j$**
  - $f(t, T)$

- **Fraction of (host material)$_j$ that can be readily mined**
  - $f(depth, location, obstacles, grain size)$

- **Fraction of (SWV)$_i$ released from (host material)$_j$ after mining**
  - $f(T, t_{anneal})$
As the Moon passes in and out of the Solar Wind, and as a consequence of having one side always facing the Earth, the Solar Wind is distributed preferentially on the "far side" of the Moon. The "near side" collects only \( \sim 1/3 \) that of the "far side" (Swindle, 1992).

**The Relative Solar Wind Exposure Depends on the Lunar Latitude and Longitude**

Measured Helium Content in Lunar Samples

Wt ppm Helium

US Apollo Missions

USSR Missions

Maria

Highland and Basin Ejecta
Correlation of Helium Content With TiO2 in Lunar Regolith
Clementine Titanium Map of the Moon
Equal Area Projection

Near side

Far side

TiO₂ (wt.%)
J. Johnson et al. (1999) show that the Ti and maturity index can help identify potential locations of He-3.
Lunar Prospector data shows the distribution of H on the surface of the Moon.
The regolith in those regions is made up of very fine grains which has been gardened by meteorites over billions of years (NASA Photo).
The Median Survival Time of Most Rocks on the Lunar Surface is From 2-20 Million Years.
The Average Grain Size of Lunar Samples from the Apollo Missions Ranges from 40-130 Microns

Most of the Apollo 11, 12, 14, 15, 16, & 17 samples fall into this band

After Carrier and Mitchell, 1989
The Solar Wind Ions are Initially Deposited Within the First 320 Å of the Ilmenite Grains

Projected Range in Ilmenite Å

H: 138 Å
He-3: 265 Å
He-4: 318 Å
C: 253 Å
N: 244 Å
O: 251 Å

The Solar Wind ions Do Not Penetrate Very Deep Into the Lunar Regolith
The Concentration of Helium-3 in Apollo-11 Sample 10084 is Definitely Higher in Smaller Grains
Most of the Helium in the Apollo-11 Sample 10084 is Contained in Particles Below 50 Microns

After E. N. Cameron-1987
How Do We Calculate the Efficiency of Solar Wind Volatiles Evolution?

• One way is to maximize the amount of SWV’s evolved divided by the energy used to release the SWV’s
The Amount of Solar Wind Volatiles Available Depends on the Grain Size of the Host Material

- Define
  - $C_{SWV} = \text{conc. of SWV's in implanted zone of the host material}$
  - $f_i = \text{fraction of particles with radii between } r_i \text{ and } r_{i+1}$
  - $\Delta x = \text{depth of implanted zone}$
  - $r_i = \text{ave. radius of the particles with radii from } r_i \text{ to } r_{i+1}$

Then the maximum amount of SWV’s is:

$$= C_{SWV} \cdot \Delta x \cdot \sum_{i=1}^{N} f_i \cdot 4 \pi r_i^2$$
The energy required for Solar Wind Volatiles Evolution Also Depends on the Grain Size of the Host Material

- Define
  - $C_p = \text{Heat capacity of host material}$
  - $\Delta T = \text{Temperature increase needed to evolve the SWV’s}$

The energy needed to heat the SWV containing material to temperature $T$ is:

$$
= C_p \cdot \Delta T \cdot \sum_{i=1}^{N} f_i \cdot \frac{4 \pi r_i^3}{3}
$$
The Maximum SWV Return for a Given Energy Investment is Inversely Proportional to the Grain Size

\[
\left( \frac{C_{swv}}{C_p} \cdot \frac{\Delta x}{\Delta T} \right) \cdot \left( \frac{1}{r_i} \right)
\]
The Depth of the Regolith Varies Considerably from Site to Site

Depth from the surface - meters

-14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14

Apollo-11  Apollo-12  Apollo-14  Apollo-15  Apollo-16  Apollo-17

-4  -3  -8.5  -5  -9  -12
The Concentration of $^3$He in Apollo-15 Drill Core Samples Remains Reasonably Constant With Depth

Original data: Swindle et. al., U of AZ SERC report TM-90/1 (1990)
The Original Gas Release Pattern for the Apollo-11 Sample 10086,16 Was Very Complex

Source: Gibson and Johnson, Proc. 2nd Lunar Science Conf., 2, p. 1351(1971)
The Release of Lunar Volatiles (i.e. > 90%) Occurs Over a Wide Range of Temperatures

Noble Gases Can be Removed from Lunar Regolith by Heating to 800-1,200 °C

Temperature-°C

He-3
He-4
Ar-36
Kr-84
Xe-132

Original data-Pepin et. al., 1970
After K. Kuhlman-1996
The Peak Release Rate of Helium Isotopes from Apollo-11 Regolith Occurs at 500 °C

Original Data Pepin et. al., (1970)
Observations

• The solar wind could be a major source of life supporting elements such as H, C, N, and O on the Moon.
• Heating the regolith to high enough temperatures could cause the H to react with the oxygen in the lunar regolith to supply the water needed for early settlers on the Moon.
• Other SWV’s such as $^3$He and $^4$He could play important roles in the future of the Moon.
• Extraction of SWV’s will require significant thermal energy sources (solar? nuclear?).