ISRU on the Moon by Larry Taylor

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MOON is an enormous Earth-orbiting Space Station [Moon = EOSS], a natural satellite outside of Earth’s gravity well, with raw materials that can be put to practical use, as humanity expands outward into the Solar System.
Regolith for Feedstock: Processing and Products

LUNAR SCIENCE IS THE ENTIRE BASIS FOR OUR KNOWLEDGE OF LUNAR RESOURCES

OUTLINE

LUNAR REGOLITH / SOIL: What it is??
Physically, Chemically, Mineralogically, Magnetically, Geotechnically

SOUTH POLE: Water-Ice versus Only Hydrogen
Recovering LLH and LUNOX; Mining Ice; Solar-Wind Hydrogen and Volatiles from Regolith; Oxygen from Regolith; Processing for Specific Products
**Lunar Mare Soil**

- Impact-Glass Bead
- Volcanic Glass Bead
- Agglutinate
- Rock Chips
- Plagioclase

**Regolith**: broken up rock material

**Soil**: <1 cm portion of the Regolith

1 mm
Lunar Soil Formation

Comminution, Agglutination, & Vapor Deposition

Micrometeorites

Solar Wind

Condensation

Vaporization
Mare-Soil
Agglutinate

100 µm

Courtesy – Dave McKay
Mare Soil Maturation

Taylor & McKay (1992)
Cumulative Modal Percentage of Mare Soils

<table>
<thead>
<tr>
<th>Low-Ti Mare Soils</th>
<th>High-Ti Mare Soils</th>
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<tr>
<td></td>
<td>15071-52</td>
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<tr>
<td></td>
<td>12030-14</td>
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<tr>
<td>FeO</td>
<td>15.4</td>
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<tr>
<td>TiO₂</td>
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<td></td>
<td>12001-56</td>
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<td>FeO</td>
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<tr>
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<td></td>
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<td>FeO</td>
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<td>TiO₂</td>
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<td></td>
<td>12001-56</td>
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<tr>
<td>FeO</td>
<td>17.2</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.7</td>
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</tbody>
</table>

* Is/FeO of <250 μm

Taylor et al. (2001)
SEM BSE-Image of Mare Agglutinitic Glass

Milky Way of np-Fe°

1 μm

Courtesy – Dave McKay
FORMATION OF NANOPHASE $\text{Fe}^0$ in AGGLUTINIC GLASS:

30 YEAR PARADIGM

Auto-Reduction Reaction in Impact-Soil Melt

$\text{``FeO}_{\text{melt}}$'' + $\text{H}_2 = \text{Fe}^0 + \text{H}_2\text{O}$

Solar-Wind Implanted $\text{H}^+$ in Lunar Soil Causes Reduction of Fe$^{2+}$ to Fe$^0$
in Micrometeorite-Produced Impact Melt
Is/FeO Values Versus Agglutinitic Glass Contents

Taylor et al. (2001)
Vapor-Deposited Nanophase Fe° on Plagioclase

Keller et al. (1999)
MAGNETIC PROPERTIES OF LUNAR SOILS

- Magnetic Susceptibility of Soil Particles Increases as Grain Size Decreases;

- Effects of Vapor-Deposited Nanophase Fe° are a Direct Function of Surface Area and Most Pronounced in the Finest Grain Sizes;

- Virtually All <10 µm Particles are Easily Attracted by a Simple Hand-held Magnet, Plg, Pyx, Ol, and Agglutinitic Glass alike.
Lunar Dust Effects: Must be Addressed before any Commercial Presence on the Moon can be Fully Evaluated.

- Potential for coatings, on seals, gaskets, optical lens, windows, electrical components, et cetera;
- Abrasiveness, with regards to friction-bearing surfaces;
- Potential for settling on all thermal and optical surfaces, such as Solar cells and mirrors; and
- Physiological effects on humans, especially with respect to the lungs, the lymph system, and potentially the cardiovascular system, in the case of extremely fine particles.

SOLUTION: Magnetic brushes
There is an entire subculture of people who derive pleasure from putting strange things in microwave ovens.

Things that microwave oven manufacturers would strenuously suggest should not be put there.

In the hands of these people:
- Table grapes produce glowing plasmas;
- Soap bars mutate into abominable soap monsters;
- Compact discs incandesce;
- Even ‘Wet Poodles’ have been known to “explode.”
**Microwave Principles**

\[ I_{\text{out}} = f \left[ \begin{array}{l} C \quad L \quad R \end{array} \right] \text{Total Current} \]

**Interaction of Materials with Microwaves**

- Reflectant: Thermally Insulating Material
  - Metal: \( C \)

- Transparent: Let Light Through
  - Glass: \( L \)

- Absorbent: Absorbs Heat
  - Water: \( R \)

**Loss Tan \( \delta \)** = Sum of Losses from All Mechanisms during Microwave Heating
MICROWAVE HEATING:

IMPORTANT PARAMETERS FOR MATERIAL RESPONSE
DIELECTRIC CONSTANT, $\varepsilon_r$, AND LOSS TANGENT, $\tan \delta$

Loss Tangent Increases with $T$

- Power density: Increases
- Half-Power Depth: Decreases
- Heating Rate: Increases
Microwave Heating of Lunar Soil:

NanoPhase Fe⁰ in Silicate Glass

Fe⁰ grain size is so small as to be below the effective “skin depth” of microwave penetration;

System is basically one of:

Small conductors of Fe⁰ insulated by Intervening dielectric glass

GREAT MICROWAVE COUPLING!
Sintering Progress of Powder Particles By Microwave Energy

- Initial heating of particles
- Solid-State Diffusion plus Introduction of liquid phase
- Combination of Solid-State and Liquid-Phase Sintering
Microwave Melting
Along Grain Boundaries of Mare Soil
BENEFITS OF MICROWAVE OVER CONVENTIONAL HEATING

- **RAPID HEATING RATES** [ >1000 °C/min ]
- **HIGH TEMPERATURES** [ 2000 °C ]
- **ENHANCED REACTION RATES** [ Faster Diffusion Rates ]
- **FASTER SINTERING KINETICS** [ Shorter Sintering Times ]
- **LOWER SINTERING TEMPERATURE** [ Energy Savings ]
- **FINE MICROSTRUCTURES** [ Improved Mechanical Properties ]
- **CONSIDERABLY REDUCED PROCESSING TIME**
- **PROCESS SIMPLICITY**
- **LESS LABOR COSTS**

**Bottom Line:** LOWER ENERGY REQUIREMENTS
LUNAR SOIL PROCESSING & PRODUCTS

SINTERING and MELTING

- Roads
- Satellite Dishes
- Shielding
- Welding
- Recovery of Volatiles
- Glass Fiber Production
- Solar Cells (Ilmenite)

SUGGESTIONS ??

[Image of road construction equipment]
RESOURCE USE AT FIRST LUNAR BASE

- **LUNOX** experiments and initial production
- **LLH Recovery**
- **Photo-Voltaic Cell** production
- **Regolith for radiation protection**: digger, mover, transporter, role of microwave processing
- **Production of cast basalt and sintered regolith** by microwave processing
- **Rover / robotics** – geosciences / resource evaluation
Products that could be derived from 1 m³ of Lunar Regolith

Lunar Lunch for Two
a la Larry Haskins

350 liters ⁴He @ STP

Global Average Annual Electricity Consumption per Capita-1995
## Potential Processes for Oxygen Production on the Moon

<table>
<thead>
<tr>
<th>Process</th>
<th>Reference</th>
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<tr>
<td><strong>Solid/Gas Interaction</strong></td>
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<tr>
<td>Ilmenite Reduction with Hydrogen</td>
<td>Gibson &amp; Knudsen (1985)</td>
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<tr>
<td>Ilmenite Reduction with C/CO</td>
<td>Chang (1959); Shadman &amp; Zhou (1988)</td>
</tr>
<tr>
<td>Ilmenite Reduction with Methane</td>
<td>Friedlander (1985)</td>
</tr>
<tr>
<td>Glass Reduction with Hydrogen</td>
<td>McKay et al. (1991)</td>
</tr>
<tr>
<td>Reduction with Hydrogen Sulfide</td>
<td>Dalton &amp; Hohmann (1972)</td>
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<tr>
<td>Extraction with Fluorine</td>
<td>Burt (1988)</td>
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<tr>
<td>Carbochlorination</td>
<td>Lynch (1989)</td>
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<td><strong>Silicate/Oxide Melt</strong></td>
<td>Silicate/Oxide Melt</td>
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<tr>
<td>Molten Silicate Electrolysis</td>
<td>Haskin (1985)</td>
</tr>
<tr>
<td>Fluxed Molten Silicate Electrolysis</td>
<td>Keller (1986)</td>
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<tr>
<td>Caustic Dissolution &amp; Electrolysis</td>
<td>Dalton &amp; Hohmann (1972)</td>
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<tr>
<td>Carbothermal Reduction</td>
<td>Rosenberg (1966); Cutler &amp; Krag (1985)</td>
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<tr>
<td>Magma Partial Oxidation</td>
<td>Waldon (1989)</td>
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<tr>
<td>Li or Na Reduction Ilmenite</td>
<td>Sammells &amp; Semkow (1987)</td>
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<td><strong>Pyrolysis</strong></td>
<td>Pyrolysis</td>
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<td>Vapor Pyrolysis</td>
<td>Steurer &amp; Nerad (1983)</td>
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<td><strong>Aqueous Solutions</strong></td>
<td>Aqueous Solutions</td>
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<td>HF Acid Dissolution</td>
<td>Waldron (1985)</td>
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<tr>
<td>$\text{H}_2\text{SO}_4$ Acid Dissolution</td>
<td>Christiansen et al. (1988); Sullivan (1991)</td>
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<td><strong>Co-Product Recovery</strong></td>
<td>Co-Product Recovery</td>
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<tr>
<td><strong>Taylor &amp; Carrier, 1992</strong></td>
<td></td>
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</tbody>
</table>
Production of LUNOX by H2 Reduction of Ilmenite

\[
\text{FeTiO}_3 + H_2 \overset{\text{electrolysis}}{\longrightarrow} \text{Fe} + \text{TiO}_2 + H_2O \quad \text{Oxygen Product}
\]

Ilmenite feed  recycle  Solid Product
LUNOX

Block Flow – Ilmenite Processing

- Surface Mining → Beneficiation → H2 Reduction & Electrolysis
- O2
- Spent Reacted Solids
- LOX
- Transportation & Storage

Waste Solids

Electric Power
Beneficiation Studies

Ilmenite Liberation for the 45 – 90 µm Size Fraction of Hi – Ti Basalt 71055

Only 50 vol % Ilmenite is Clean (80-100% Liberated)

Taylor et al., 1995
Concentrations of Solar-Wind Volatile Species in Lunar Regolith Samples, in ppm.

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<thead>
<tr>
<th></th>
<th>H</th>
<th>He</th>
<th>C</th>
<th>N</th>
<th>Ne</th>
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<tr>
<td>Apollo 11</td>
<td>20-100</td>
<td>20-84</td>
<td>96-216</td>
<td>45-110</td>
<td>2-11</td>
<td>1.3-12</td>
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<td>Apollo 12</td>
<td>2-106</td>
<td>14-68</td>
<td>23-170</td>
<td>46-140</td>
<td>1.2-6</td>
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<td>Apollo 14</td>
<td>67-105</td>
<td>5-16</td>
<td>42-225</td>
<td>25-130</td>
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<td>0.4-2.2</td>
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<td>Apollo 15</td>
<td>13-125</td>
<td>5-19</td>
<td>21-186</td>
<td>33-135</td>
<td>0.6-108</td>
<td>0.5-2.7</td>
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<td>Apollo 16</td>
<td>4-146</td>
<td>3-36</td>
<td>31-280</td>
<td>4-209</td>
<td>0.4-1.2</td>
<td>0.6-3</td>
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<tr>
<td>Apollo 17</td>
<td>0.1-106</td>
<td>13-41</td>
<td>4-200</td>
<td>7-94</td>
<td>1.2-2.7</td>
<td>0.6-2.6</td>
</tr>
</tbody>
</table>

Haskin and Warren, 1991
Abundance of Hydrogen in Mare Soil

Premise: Need 20 tonnes of LLH hydrogen per year

Hydrogen in lunar soil = 200 ppm; 50% recovery = 0.01 wt%

\[ H \text{ in } 1 \text{ m}^3 = [2.0 \text{ g/cc}] \times [10^6 \text{ cc/m}^3] \times [1 \times 10^{-4}] = 2.0 \times 10^2 \text{ g/m}^3 \]

20 tonnes = 20t \times 10^3 \text{ kg} / t \times 10^3 \text{ g/kg} = 20 \times 10^6 \text{ g}

20 tonnes = 20 \times 10^6 \text{ g} / 2.0 \times 10^2 \text{ g/m}^3 = 10 \times 10^4 \text{ m}^3 = 10^5 \text{ m}^3

1 Football Field (Depth of 3m) = 5 \times 10^3 \text{ m}^2 \times 3 = 15 \times 10^3 \text{ m}^3

20 t LH = 6.2 Football Fields to 3 m depth

20 tonnes of LLH = ~6 Football Fields

0.03 km² (1 / 30 \text{ th} \text{ km}²)
Gas Release from Lunar Mare Soil
Regolith Processing on the Moon

Buried Habitat

LUNOX / LLH Storage

ISR (InSect Robot)

Mirror

ISR
The Nature of Lunar Resources and the Types of Feedstocks that can be Feasibly Produced Must be Factored into the Engineering Design for the Particular Production Process

- Simplicity of Overall Process – Batch vs Continuous mode
- Resupply Mass from Earth – Reagent makeup + Attrition
- Plant Mass & Energy Requirements – $f$ (mass needed); solar vs RTG energy
- Evaluation of Feedstock – Mare vs Highland; Rocks vs Soils; Beneficiation; Product mass; Energy needs
Polar Regions

Two cases:

- **Hydrogen enrichment: solar-wind hydrogen only**
  Properties of regolith may be similar to elsewhere on the Moon, from our Apollo studies; new information may not be needed; possibility of unexpected effects of extreme cold (25-100 K); major considerations for processing tools at 50 K.

- **Hydrogen enrichment: H$_2$O-dominated ice**
  In this case, physical properties of the regolith might be very different from those at Apollo sites.
Once ice deposits are identified and characterized, extraction experiments are needed:

- Heating methods
- Volatile handling
- Further processing of other gases
- Gas storage
- Separation of impurities from
- Electrolysis of H₂O to produce LLH and LUNOX

Demonstration Experiments on the Moon???
Effects of Ice on Regolith Physical Properties?

- **Composition of Ice:** Cometary? Lunar?
- **Ice form:** Crystalline? Amorphous? Thin films? Pore-filling?;
- **Soil Particles:** Binding by Ice? Loose? Granular? Coherent?
- **Geotechnical Properties:** variations with depth (drill cores)? Ice Properties!
- **Physical Properties of Regolith:** cohesion, shear strength, grain-size distribution, bulk density, porosity, etc.
SUBJECTS TO PONDER

✓ WHAT IS NEEDED FOR FURTHER EVALUATION OF:
  REGOLITH RESOURCES??
  REGOLITH PROCESSES??

✓ WHAT DO WE NEED TO KNOW IN ORDER TO PLAN RESOURCE RECOVERY??
  Site Evaluation! Subsurface knowledge! Nature of Regolith!

✓ “PROOF-OF-CONCEPT” ISRU EXPERIMENTS NEEDED FOR A LANDER??

✓ REGOLITH PROCESSING?? Regolith moving! Mineral benefic-
  iation! Oxygen production! Solar-wind measurements!
  Microwave Processing (sintering, melting, glass)!
  PV Cell production .......... 

✓ ENERGY FOR LANDERS FROM SOLAR CELLS VERSUS RTGs?
TO DO: ASAP

♦ Develop / Demonstrate Material Science Processing for Utilization of Lunar Resources, Including Oxygen / Hydrogen Production; Ceramics / glass / brick – HOW?
♦ Begin ASAP with Focused Applied Material Science / Engineering Program to Research the Chemical Reactions / Physical Processes / Etc.
♦ Evaluate Competitive ISRU Processes
♦ PROOF – IN -- CONCEPT DEMONSTRATIONS
  Production of Oxygen / Hydrogen from Soil
  Measurement of Solar-Wind Components in Soil
  Release and Capture of Solar-Wind Components
  Microwave Processing of Soil; Volatile; Shielding; Bricks

Bottom Line: Lunar Resources are known in a preliminary sense, largely thru extensive scientific studies. However, further exploration for & confirmation of resources and demonstration of their practical utility will be required!