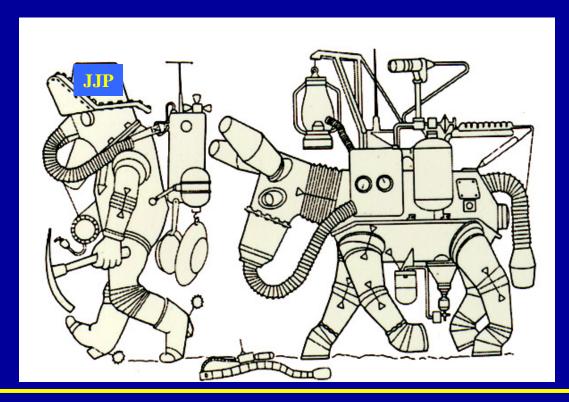
ISRU on the Moon by Larry Taylor

Planetary Geosciences Institute
University of Tennessee (lataylor@utk.edu)







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

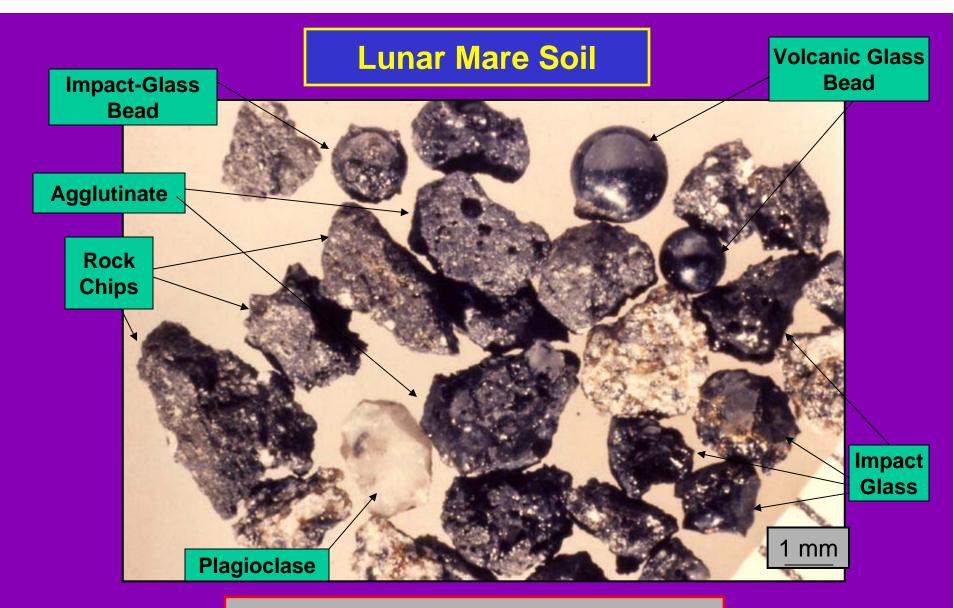
LUNAR SCIENCE IS THE ENTIRE BASIS FOR OUR KNOWLEDGE OF LUNAR RESOURCES

OUTLINE

LUNAR REGOLITH / SOIL: What it is??

Physically, Chemically, Mineralogically, Magnetically, Geotechnically

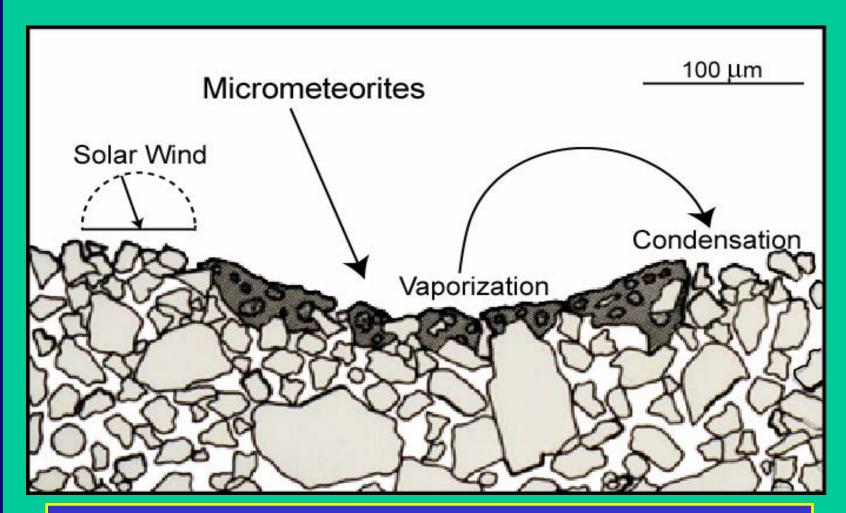
Recovering LLH and LUNOX; Mining Ice; Solar-Wind Hydrogen and Volatiles from Regolith; Oxygen from Regolith; Processing for Specific Products



Regolith: broken up rock material

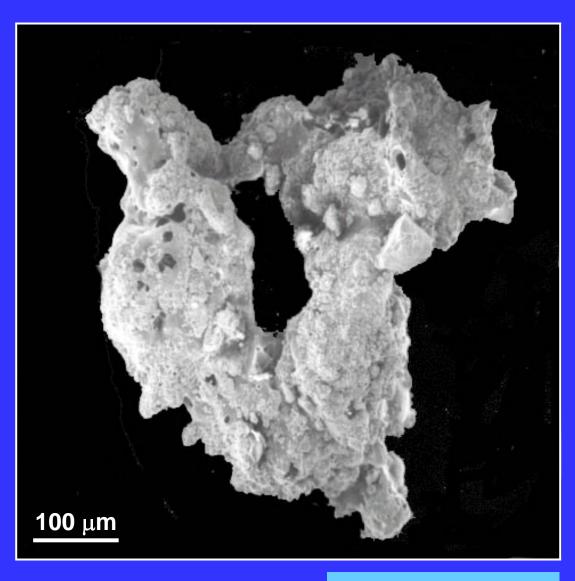
Soil: <1 cm portion of the Regolith

Lunar Soil Formation



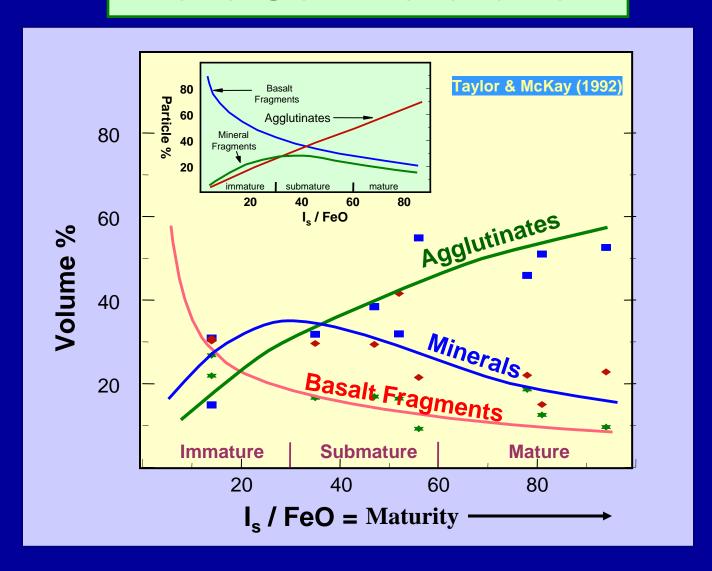
Comminution, Agglutination, & Vapor Deposition

Mare-Soil
Agglutinate

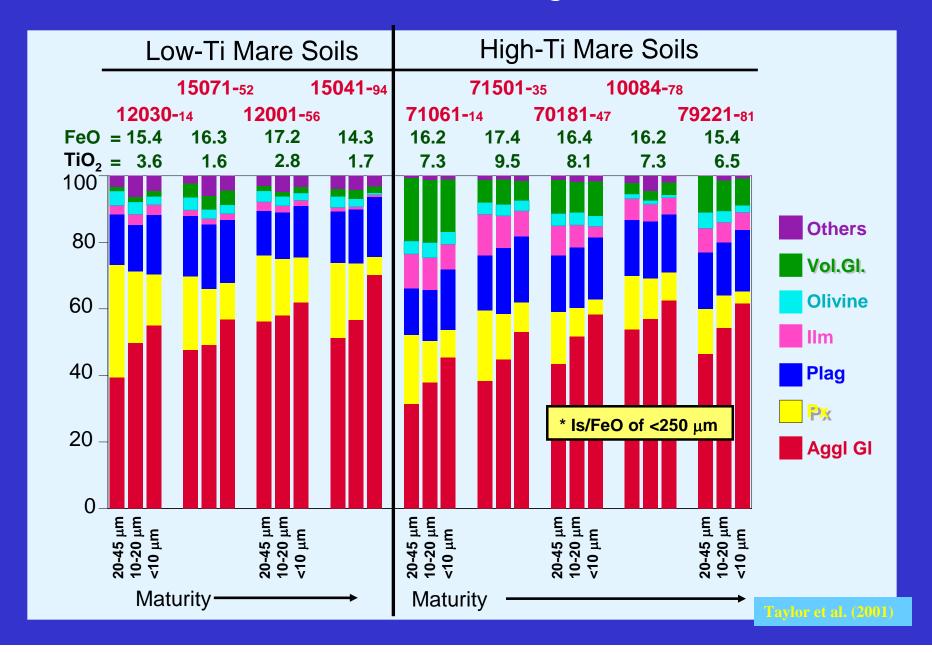


Courtesy - Dave McKay

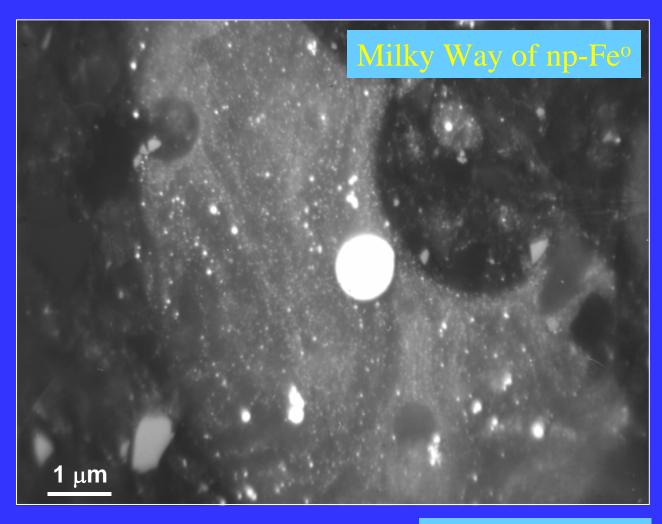
Mare Soil Maturation



Cumulative Modal Percentage of Mare Soils



SEM BSE-I mage of Mare Agglutinitic Glass



Courtesy – Dave McKay

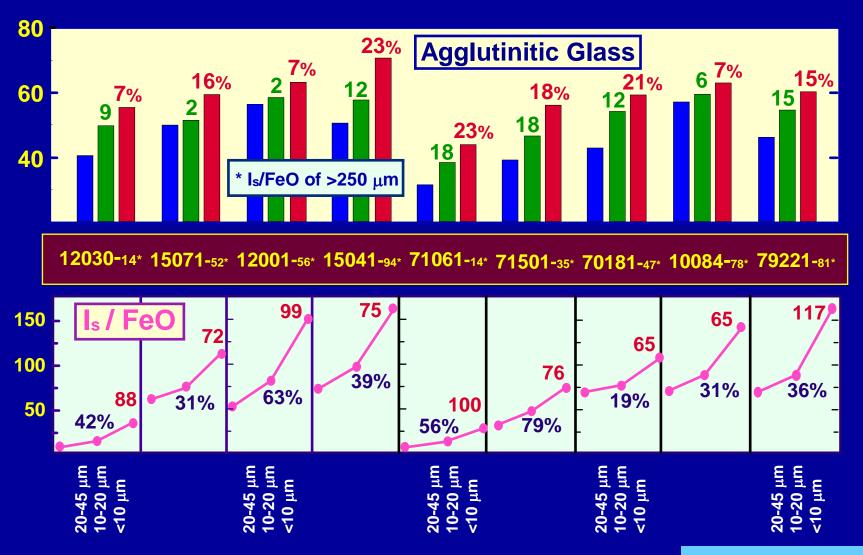
FORMATION OF NANOPHASE Fe^o in AGGLUTINITIC GLASS:

30 YEAR PARADIGM

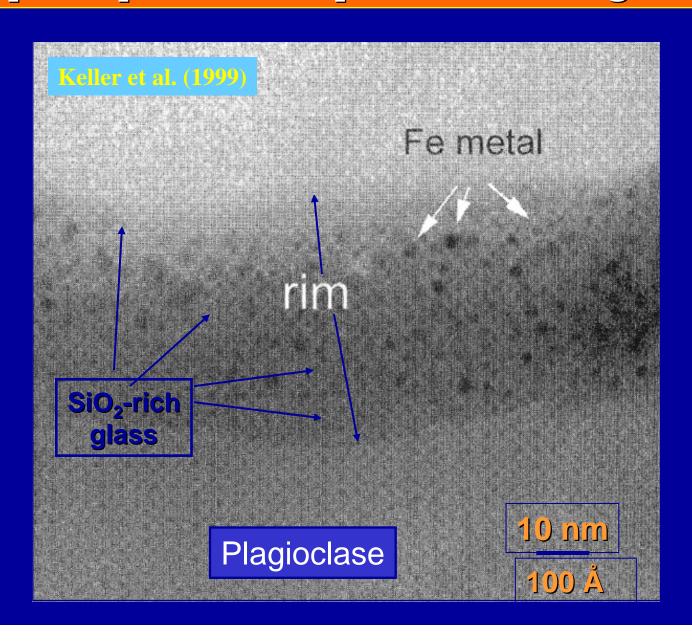
Auto-Reduction Reaction in Impact-Soil Melt "FeO_{melt}" + H_2 = Fe^0 + H_2O

Solar-Wind Implanted H⁺ in Lunar Soil Causes Reduction of Fe²⁺ to Fe^o in Micrometeorite-Produced Impact Melt

Is/FeO Values Versus Agglutinitic Glass Contents



Vapor-Deposited Nanophase Fe^o on Plagioclase



MAGNETIC PROPERTIES OF LUNAR SOLLS

- Magnetic Susceptibility of Soil Particles Increases as Grain Size Decreases;
- Effects of Vapor-Deposited Nanophase Fe^o 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.</p>

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??

MICROWAVE RADIATION

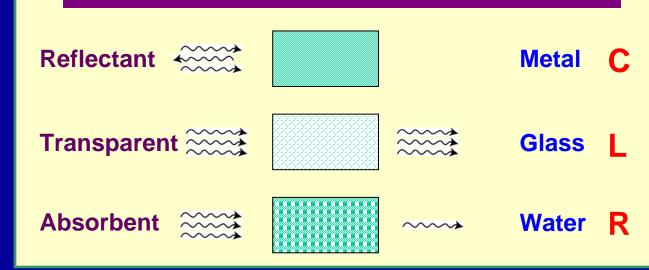
- There is an entire subculture of people who derive pleasure from putting strange things in microwave ovens
- Things that microwave oven manufacturers would strenuously suggest should not be put there.

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

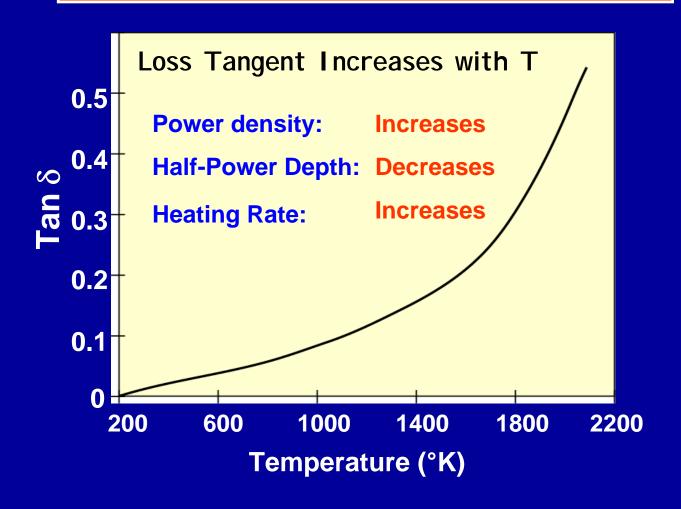
Interaction of Materials with Microwaves



LOSS TAN δ = Sum of Losses from All Mechanisms during Microwave Heating

MICROWAVE HEATING:

IMPORTANT PARAMETERS FOR MATERIAL RESPONSE DIELECTRIC CONSTANT, $\epsilon_{r},$ and loss tangent, tan δ



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;

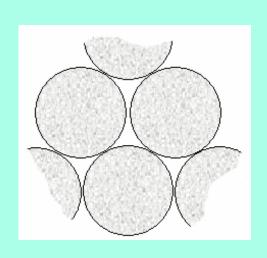
System is basically one of :

Small <u>conductors</u> of Fe⁰ insulated by

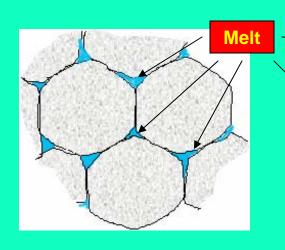
Intervening <u>dielectric glass</u>



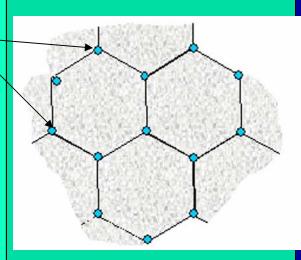
Sintering Progress of Powder Particles By Microwave Energy



Initial heating of particles

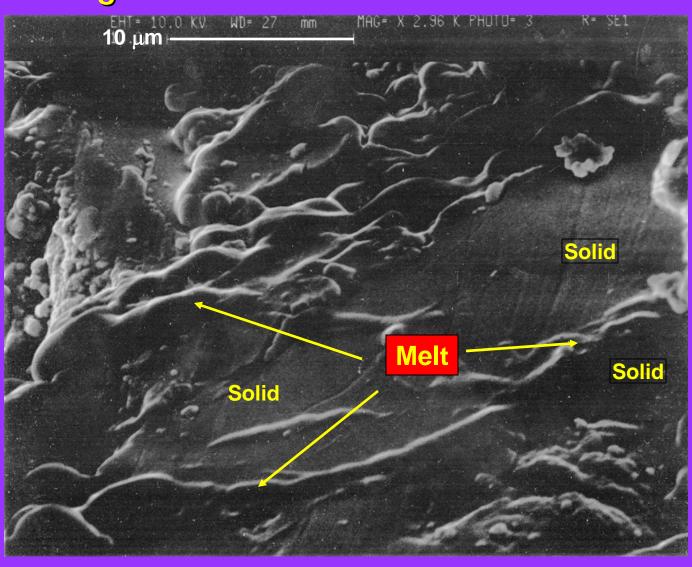


Solid-State Diffusion plus Introduction of liquid phase



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

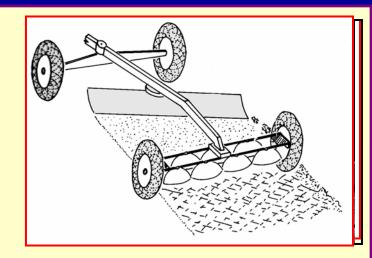
Bottom Line: LOWER ENERGY REQUIREMENTS

LUNAR SOIL PROCESSING & PRODUCTS

SINTERING and MELTING

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

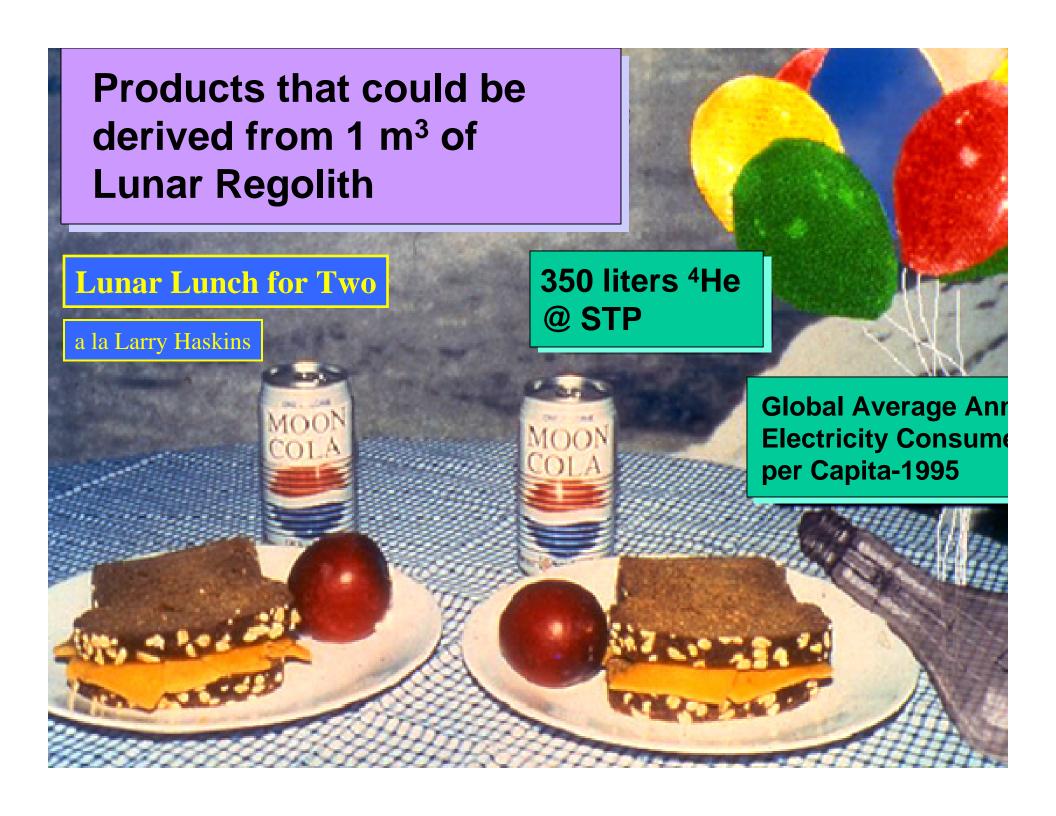
SUGGESTIONS??





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



Potential Processes for Oxygen Production on the Moon

Process	Reference			
Solid/Gas Interaction	Solid/Gas Interaction			
Ilmenite Reduction with Hydrogen Ilmenite Reduction with C/CO Ilmenite Reduction with Methane Glass Reduction with Hydrogen Reduction with Hydrogen Sulfide Extraction with Fluorine Carbochlorination Chlorine Plasma Reduction	Gibson & Knudsen (1985) Chang (1959); Shadman & Zhou (1988) Friedlander (1985) McKay et al. (1991) Dalton & Hohmann (1972) Burt (1988) Lynch (1989)			
Silicate/Oxide Melt Molten Silicate Electrolysis Fluxed Molten Silicate Electrolysis Caustic Dissolution & Electrolysis Carbothermal Reduction Magma Partial Oxidation Li or Na Reduction Ilmenite	Silicate/Oxide Melt Haskin (1985) Keller (1986) Dalton & Hohmann (1972) Rosenburg (1966); Cutler & Krag (1985) Waldon (1989) Sammells & Semkow (1987)			
Pyrolysis Vapor Pyrolysis Ion Plasma Pyrolysis Plasma Reduction of Ilmenite	Pyrolysis Steurer & Nerad (1983) Steurer & Nerad (1983) Allen et al., (1988)			
Aqueous Solutions HF Acid Dissolution H ₂ SO ₄ Acid Dissolution	Aqueous Solutions Waldron (1985) Christiansen et al. (1988); Sullivan (1991)			
Co-Product Recovery Hydrogen-Helium-Water from Soil.	Co-Product Recovery Christiansen et al. (1988) Taylor & Carrier			

Production of LUNOX by H2 Reduction of Ilmenite

recycle

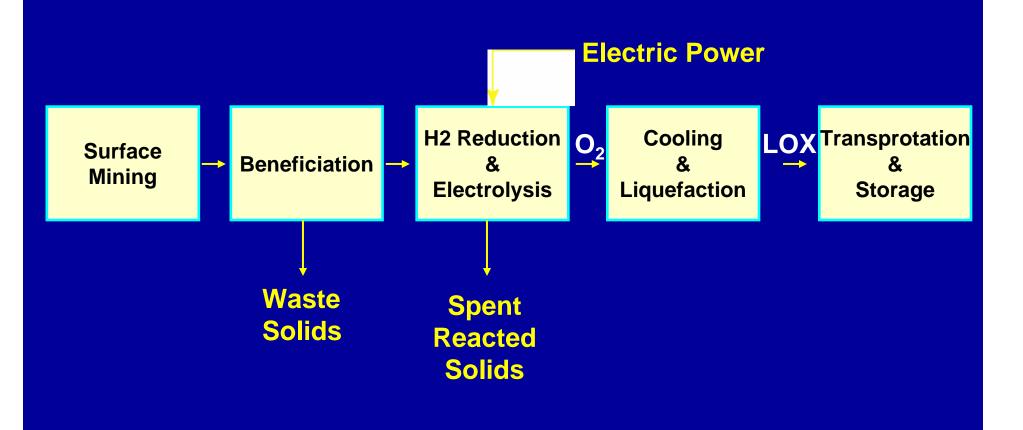
$$FeTiO_3 + \overset{v}{H_2} \rightleftharpoons Fe + TiO_2 + \overset{v}{H_2O} \xrightarrow{electrolysis} \overset{v}{H_2} + \overset{v}{1/2} O_2$$

Ilmenite feed

Solid Product Oxygen Product

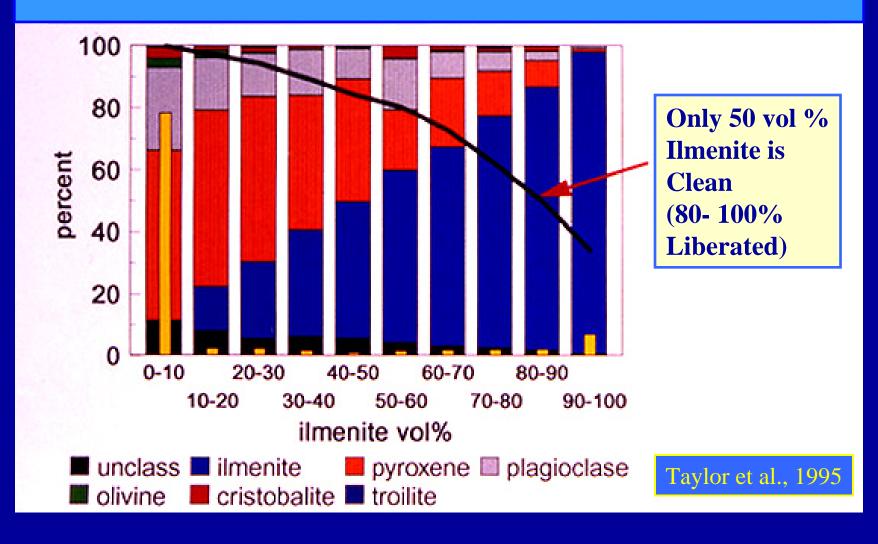


Block Flow – Ilmenite Processing



Beneficiation Studies

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



Concentrations of Solar-Wind Volatile Species in Lunar Regolith Samples, in ppm.

	Н	He	C	N	Ne	Ar
Apollo 11	20-100	20-84	96-216	45-110	2-11	1.3-12
Apollo 12	2-106	14-68	23-170	46-140	1.2-6	0.5-4.6
Apollo 14	67-105	5-16	42-225	25-130	0.14-1.6	0.4-2.2
Apollo 15	13-125	5-19	21-186	33-135	0.6-108	0.5-2.7
Apollo 16	4-146	3-36	31-280	4-209	0.4-1.2	0.6-3
Apollo 17	0.1-106	13-41	4-200	7-94	1.2-2.7	0.6-2.6

Haskin and Warren, 1991

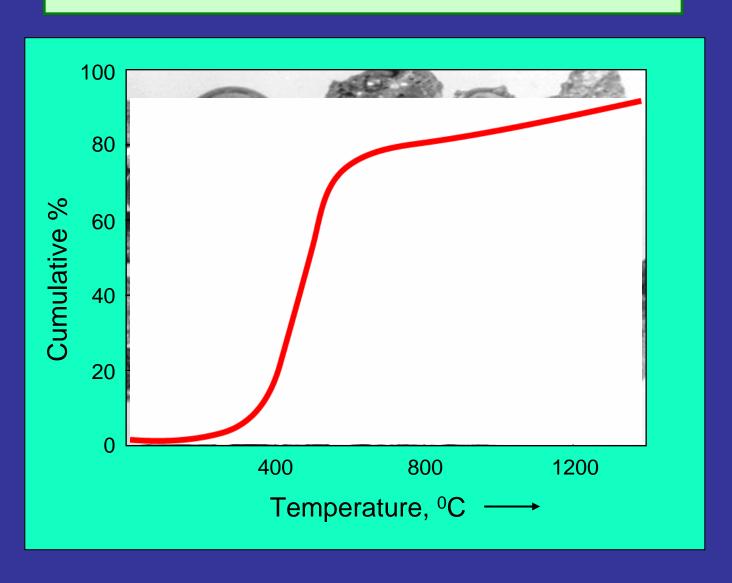
Abundance of Hydrogen in Mare Soil

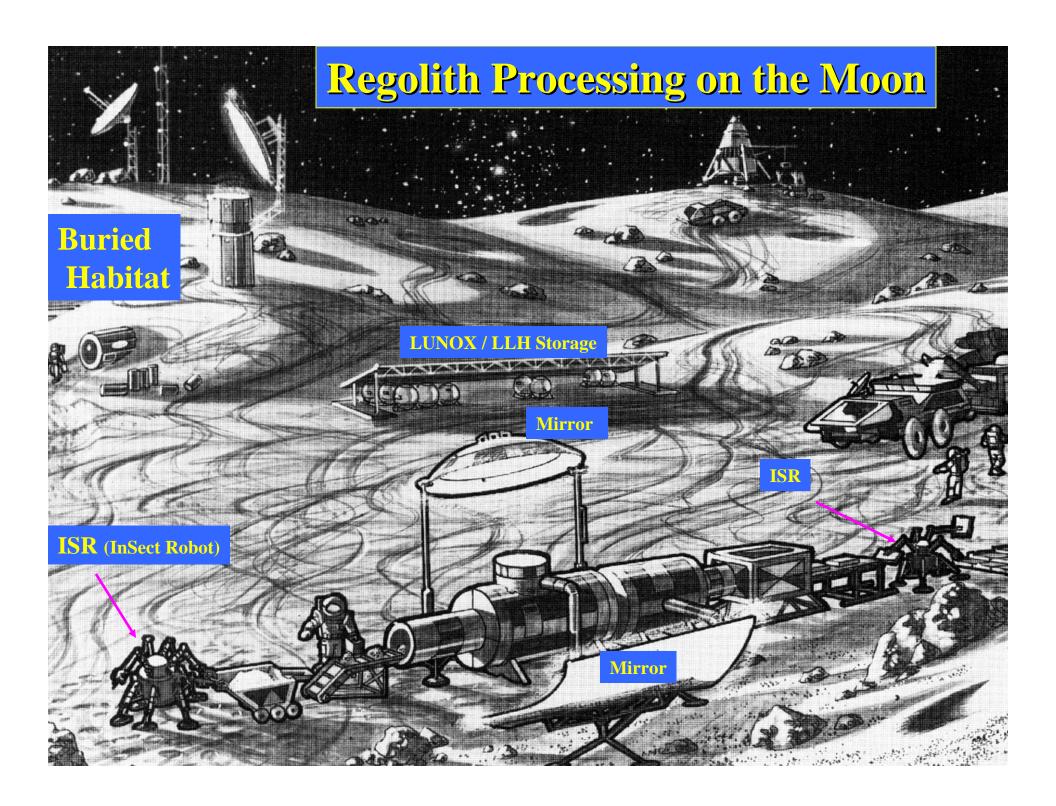
Premise: Need 20 tonnes of LLH hydrogen per year

```
Hydrogen in lunar soil = 200 ppm; 50\% recovery = 0.01 wt%
H in 1 m³ = [2.0 g/cc] x [10<sup>6</sup> cc/m³] X [1 x 10<sup>-4</sup>] = 2.0 x 10<sup>2</sup> g/m³
20 tonnes = 20t x 10<sup>3</sup> kg / t x 10<sup>3</sup> g/kg = 20 x 10<sup>6</sup> g
20 tonnes = 20 x 10<sup>6</sup>g / 2.0 x 10<sup>2</sup> g/m³ = 10 x 10<sup>4</sup> m³ = 10<sup>5</sup> m³
1 Football Field (Depth of 3m) = 5 x 10<sup>3</sup> m² x 3 = 15 x 10<sup>3</sup> m³
20 t LH = 6.2 Football Fields to 3 m depth
```

20 tonnes of LLH = \sim 6 Football Fields 0.03 km2 (1 / 30 th km²)

Gas Release from Lunar Mare Soil





Lo-Carb FOOD FOR THOUGHT Regolith Processing

- ◆ 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: H₂O-dominated ice In this case, physical properties of the regolith might be very different from those at Apollo sites

Polar Ice: Extraction and Purification

- 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???

Polar Ice

- * Effects of Ice on Regolith Physical Properties?
 - **♦ Composition of Ice:** Cometary? Lunar?
 - **▲ Ice form:** Crystalline? Amorphous? Thin films? Porefilling?;
 - **♦ 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 beneficiation! 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

<u>Bottom Line:</u> 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!