Keck
INSTITUTE FOR SPACE STUDIES
CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY

Three Dimensional (3D) Additive Construction for Space using In-Situ Resources - Shortcourse

Resources for 3D Additive Construction on the Moon, Asteroids and Mars

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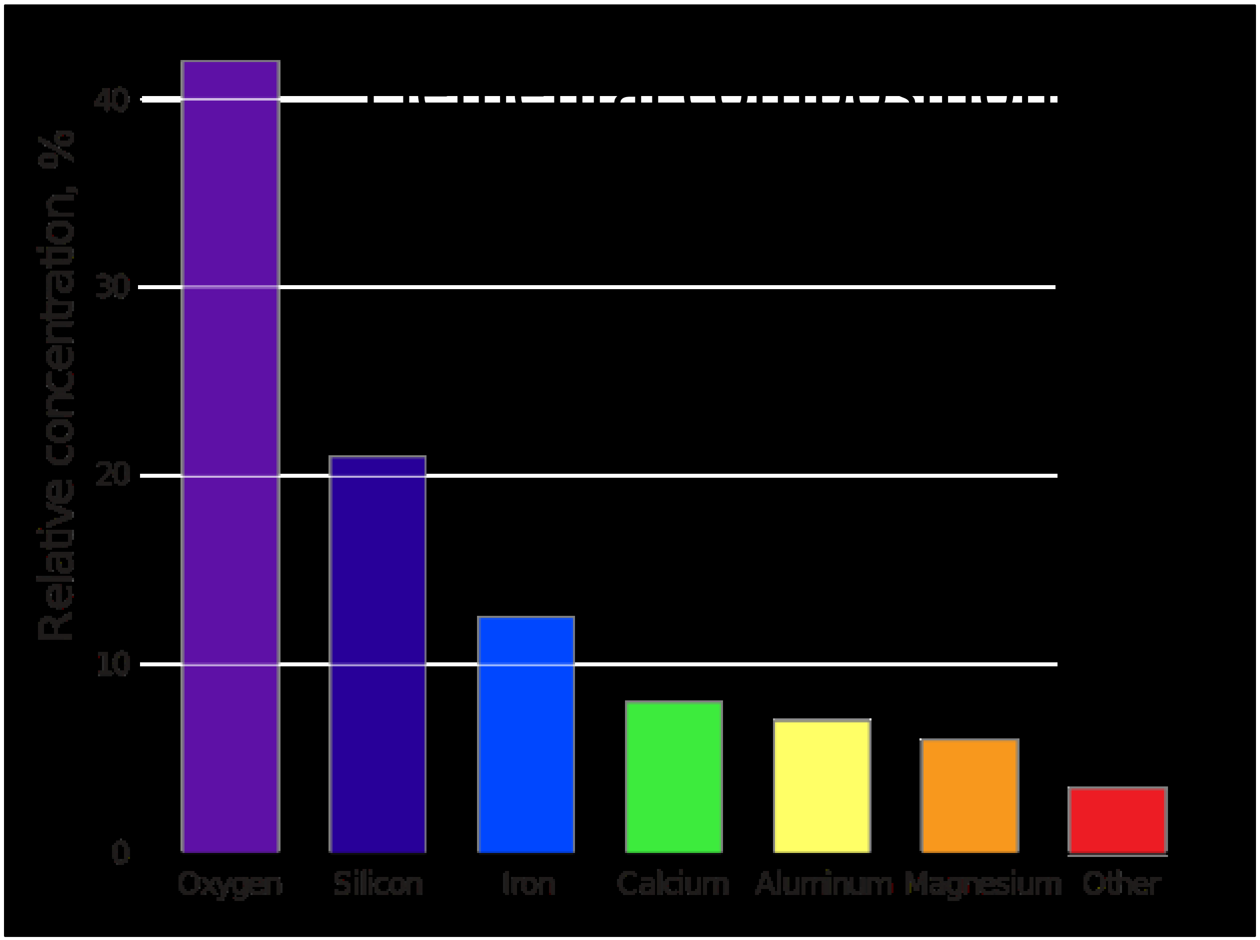
SWAMP WORKS
NASA KENNEDY SPACE CENTER

The Moon

The Moon's Resources

- Sunlight
- Regolith
- Volatiles
- Exotics
  - Asteroids?
  - Recycled spacecraft
- Derived resources
- Vacuum

Global Average Elemental Composition



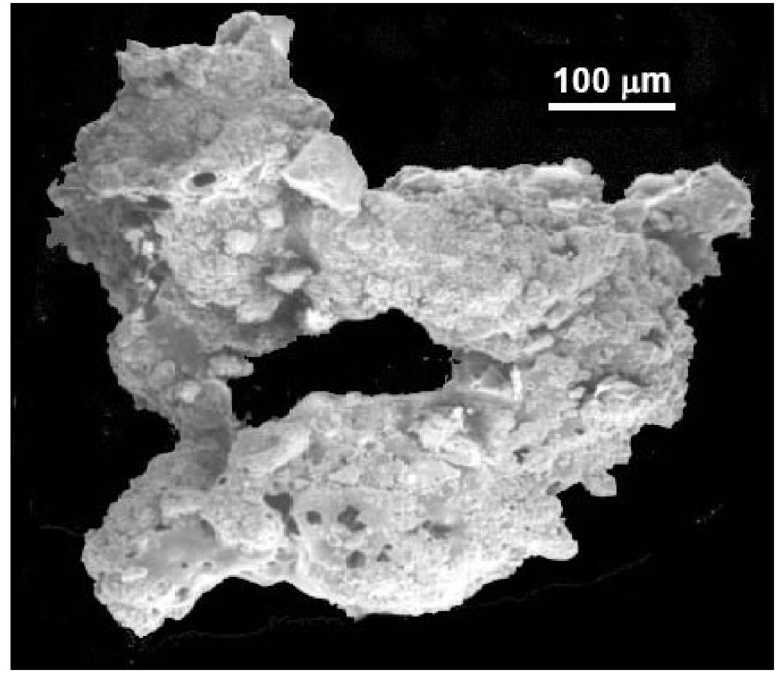
This is supplemented by lunar ice, which provides Hydrogen, Carbon and Nitrogen (plus many other elements)

Terminology

- **Regolith**: broken up rocky material that blankets a planet, including boulders, gravel, sand, dust, and any organic material
- **Lunar Soil**: regolith excluding pieces larger than about 1 cm
  - On Earth, when we say "soil" we mean material that has organic content
  - By convention "lunar soil" is valid terminology even though it has no organic content
- **Lunar Dust**: the fraction of regolith smaller than about 20 microns (definitions vary)
- Lunar geology does not generally separate these

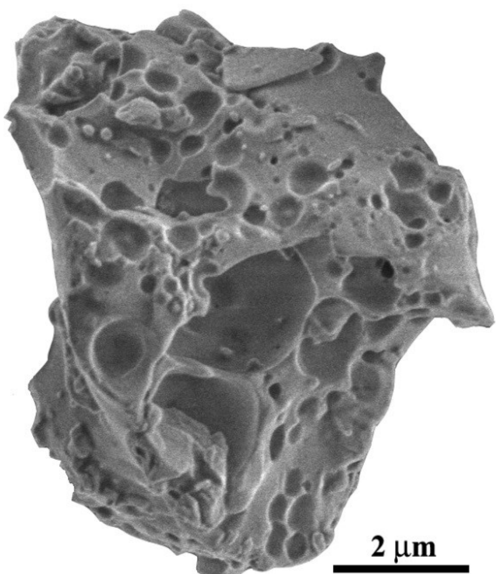
Regolith Formation

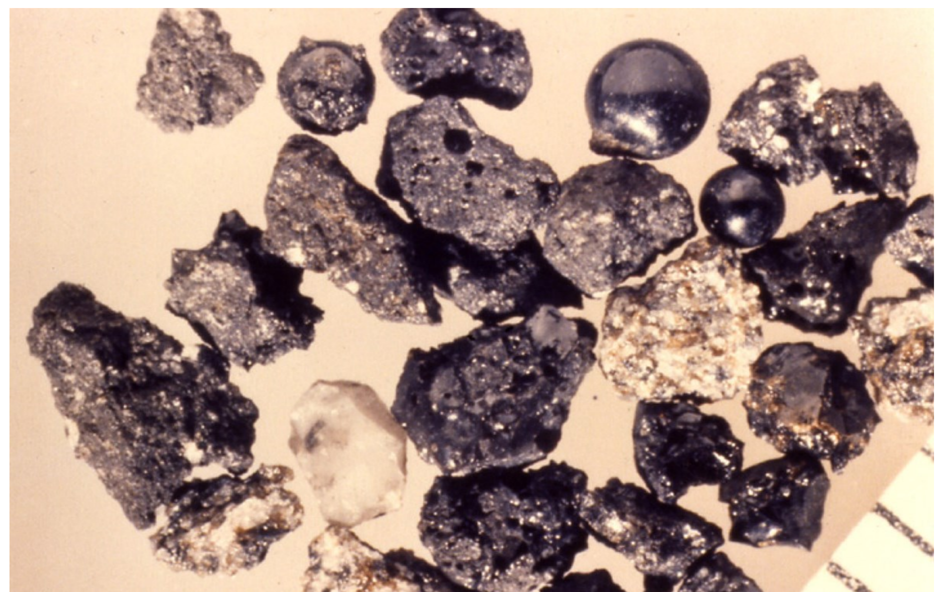
- Impacts are the dominant geological process
- Larger impacts (asteroids & comets)
  - Fracture bedrock and throw out ejecta blankets
  - Mix regolith laterally and in the vertical column
- Micrometeorite gardening
  - Wears down rocks into soil
  - Makes the soil finer
  - Creates glass and agglutinates
  - Creates patina on the grains via vapor deposition
- Lunar soil is completely unlike terrestrial soil
  - No lunar soil simulant can meet every need
  - Too expensive, $10K - $100K per ton for the best simulants
  - We must design simulants to meet specific needs



Source: David McKay, NASA/JSC

Source: Yang Liu





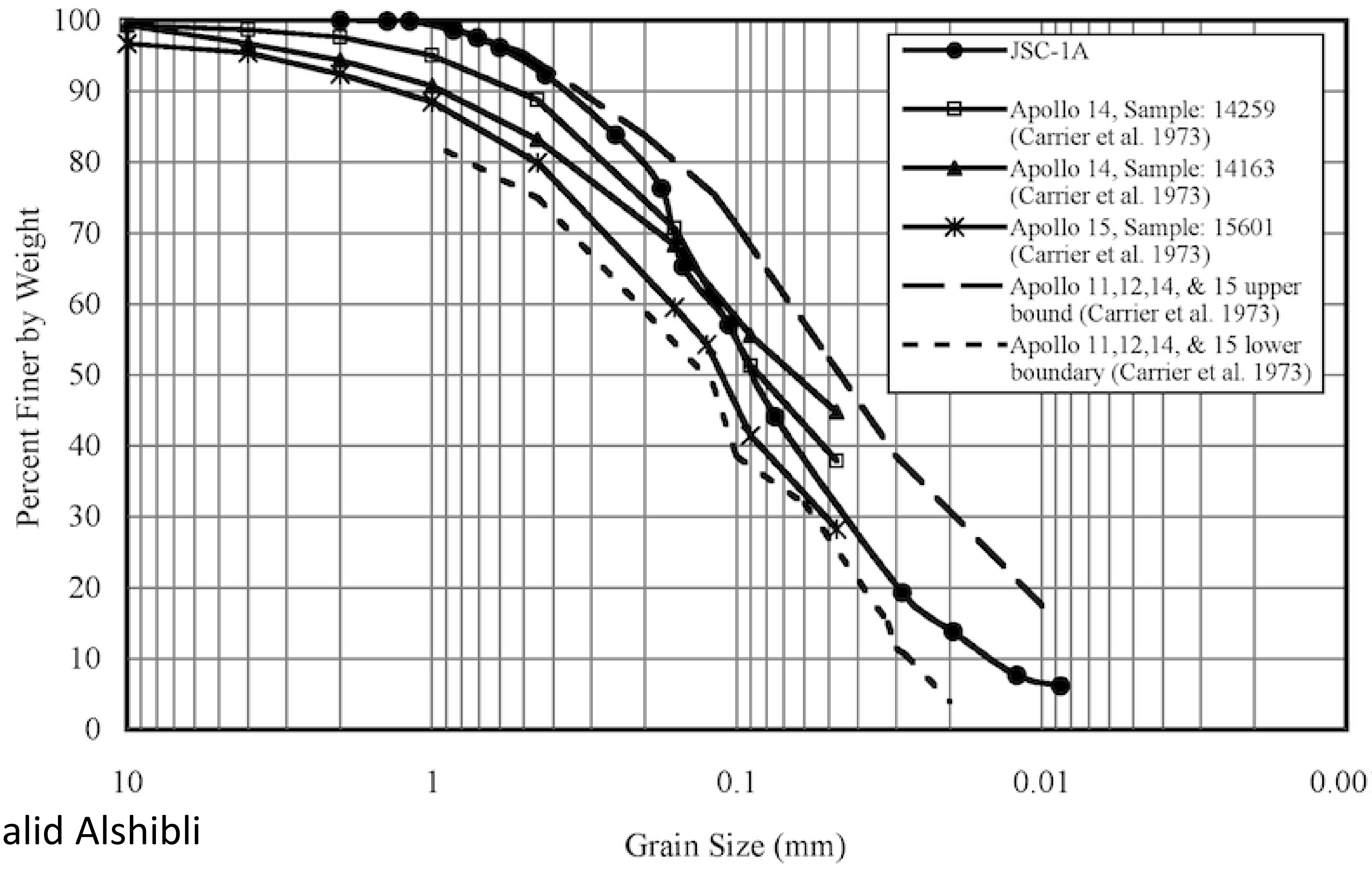
Source: Larry Taylor

Boulders & Cobbles

- Rock fields usually around young craters
- Exposed rocks slowly "dissolve" into regolith by micrometeoroid impacts
- Buried rocks can survive long times
- <u>Soil</u> <u>rakes</u> may extract them from the regolith

Source: http://www.ion-tracks.de/nuc/6/6/1.html

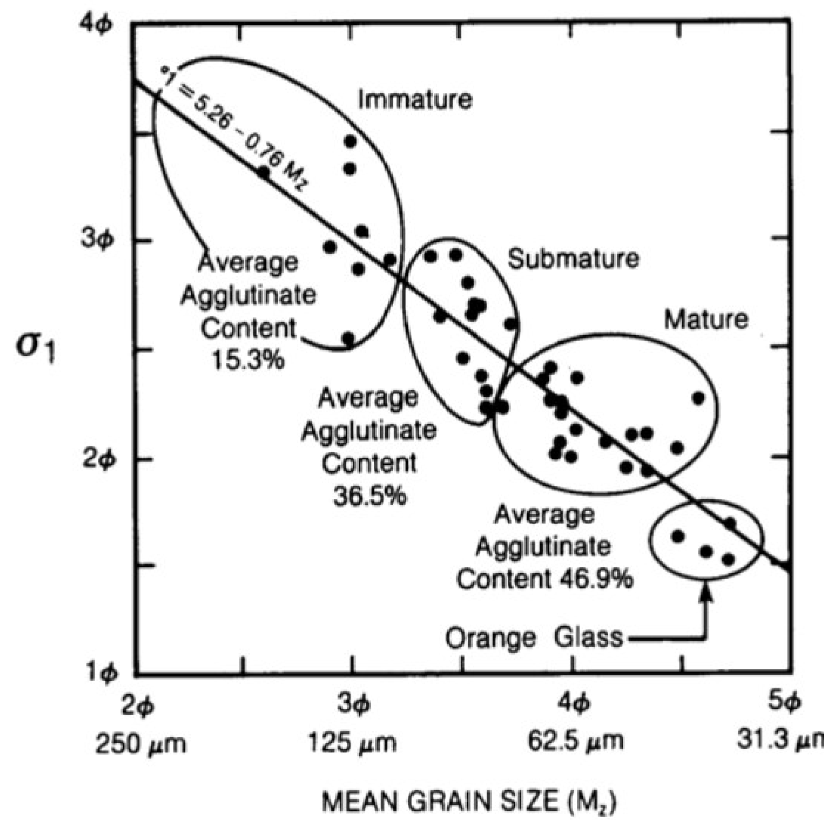
Soil Particle Size Distribution



Credit: Khalid Alshibli

Soil Maturity

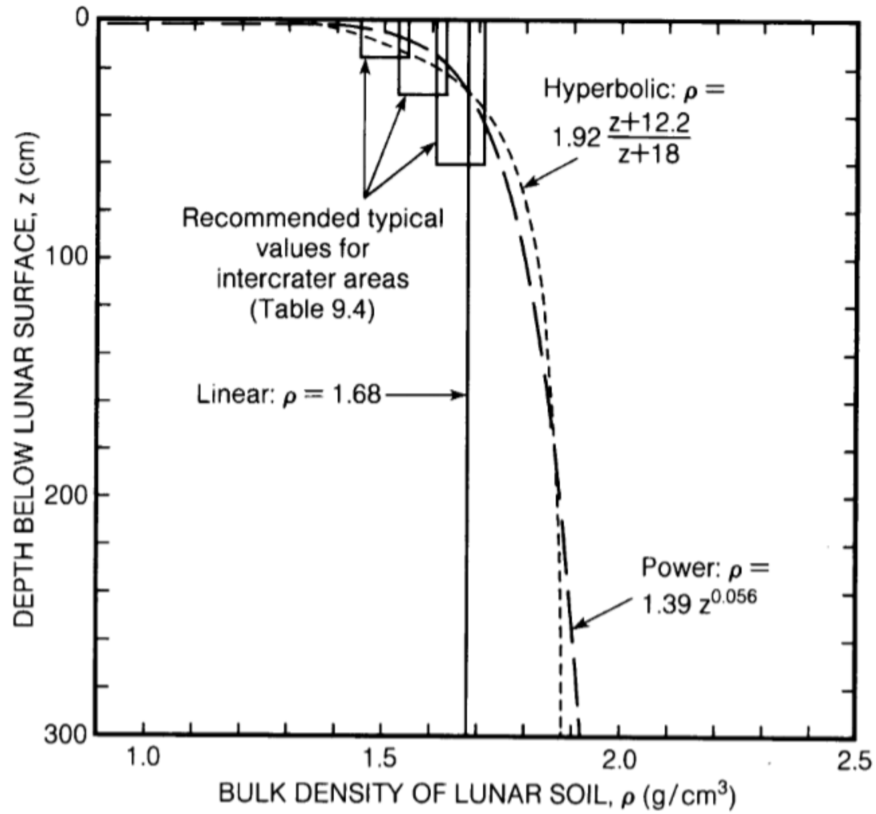
- Soil formed by a recent impact is *immature*
  - Coarser, less glass content, fewer agglutinates, less nanophase iron
- Exposure to micrometeorite garding makes it *submature* then *mature*



Source: Lunar Sourcebook

Soil Compaction

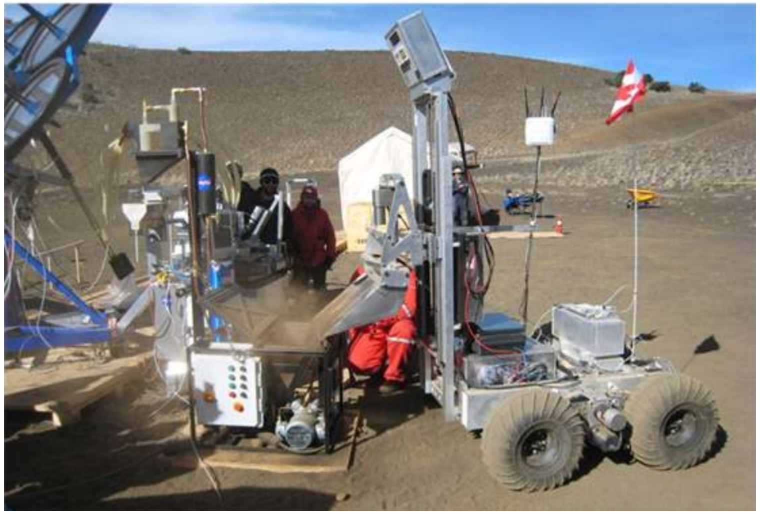
- Loose on the surface
- Generally increases in compaction with depth
- Looser at the rims of young craters
- May be looser in the permanently shadowed craters and areas of low insolation



Source: Lunar Sourcebook

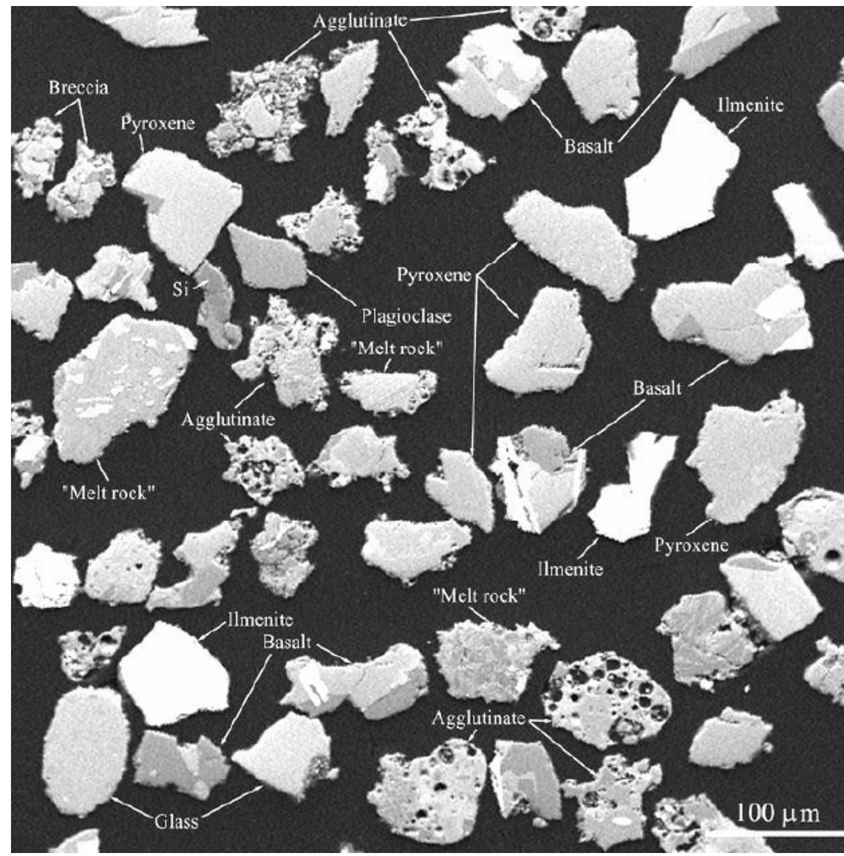
Flowability of Lunar Soil

- Lunar soil does not flow well
  - Sharp, angular particles = high friction
  - Dust content = high cohesion
  - Low Gravity
- Lunar soil simulants often flow too easily
  - JSC-1A flows far too easily
  - NU-LHT series much better but very expensive
- Technologies developed to keep it from jamming
  - Pneumatic
  - Magnetic
  - Vibration (risk of compacting)



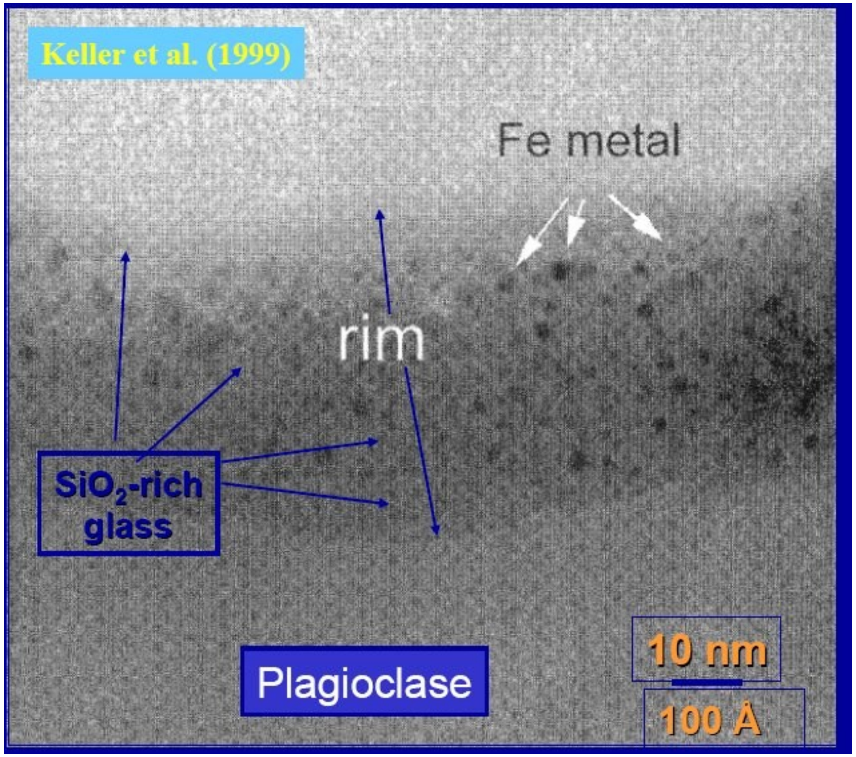
Composition of Lunar Soil

- Mixture of minerals, rock fragments, glass spherules, breccias, and agglutinates
- Minerals include pyroxene, plagioclase, ilmenite, basalt, etc.
- Mixed laterally by impacts
  - Every location on the Moon contains soil particles from every part of the Moon
- Nevertheless, soil composition varies both locally and regionally
  - Highlands vs. Mare
- Can we somehow sort the minerals? (Beneficiation)



Magnetic Susceptibility of Lunar Soil

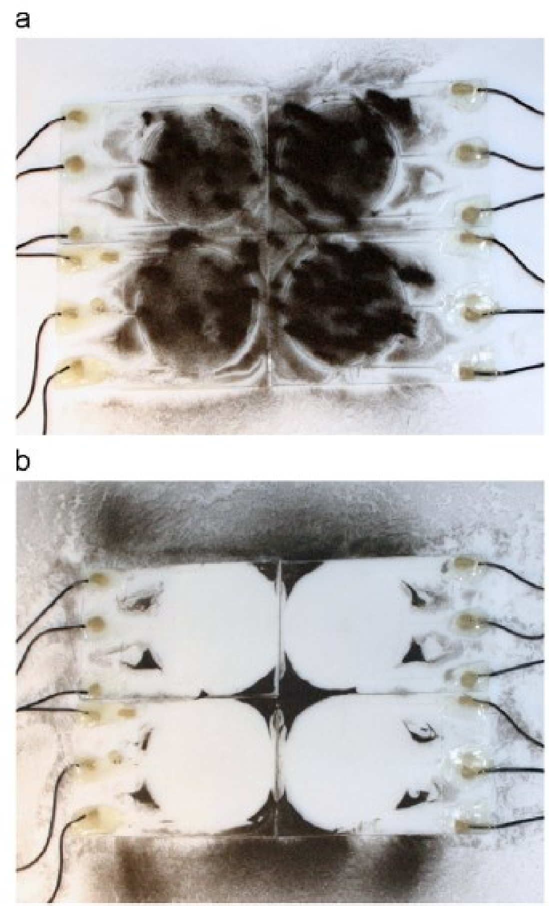
- Particles coated with a glass patina or rim from impact vapor deposition
- Rims contain nanophase iron particles, npFe
- npFe is superparamagnetic, dominates among fines
- Larger particles may be paramagnetic
- L. Taylor's research showed a null result (so far) in magnetic beneficiation of minerals



Source: Credit: Keller et al, 1999, via Larry Taylor

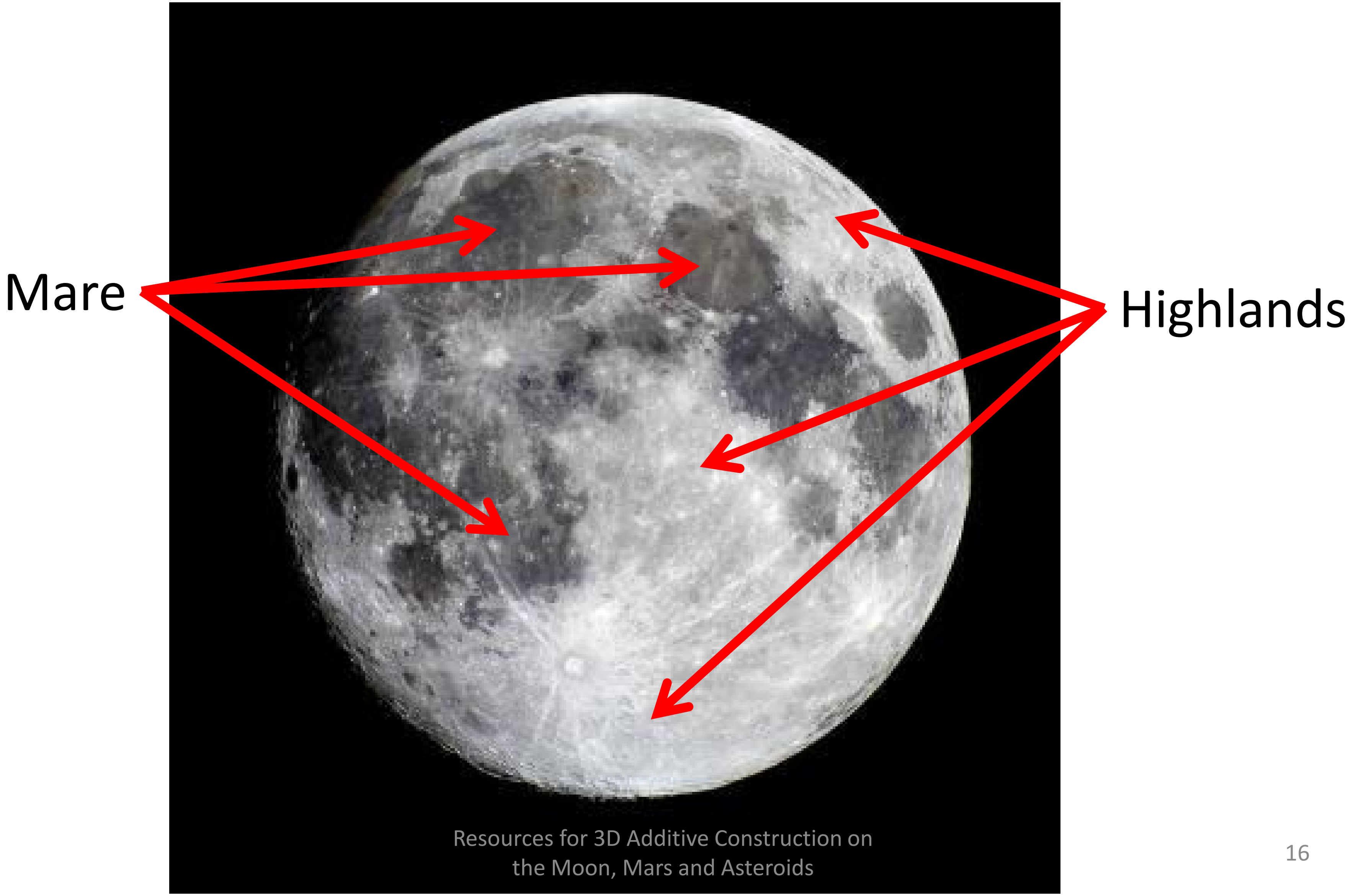
Electrostatics of Dust

- Dust becomes electrically charged via:
  - UV light (photocharging)
  - Friction (tribocharging)
- Electrostatic charge can make dust cling to surfaces
- Electrodynamic dust screens developed to move dust by its charge
- Electrostatic beneficiation
  - Quinn, et al successfully concentrated desirable minerals
  - Others in the community have disputed this result



Source: NASA

Mare and Highlands



Regional Composition Variations

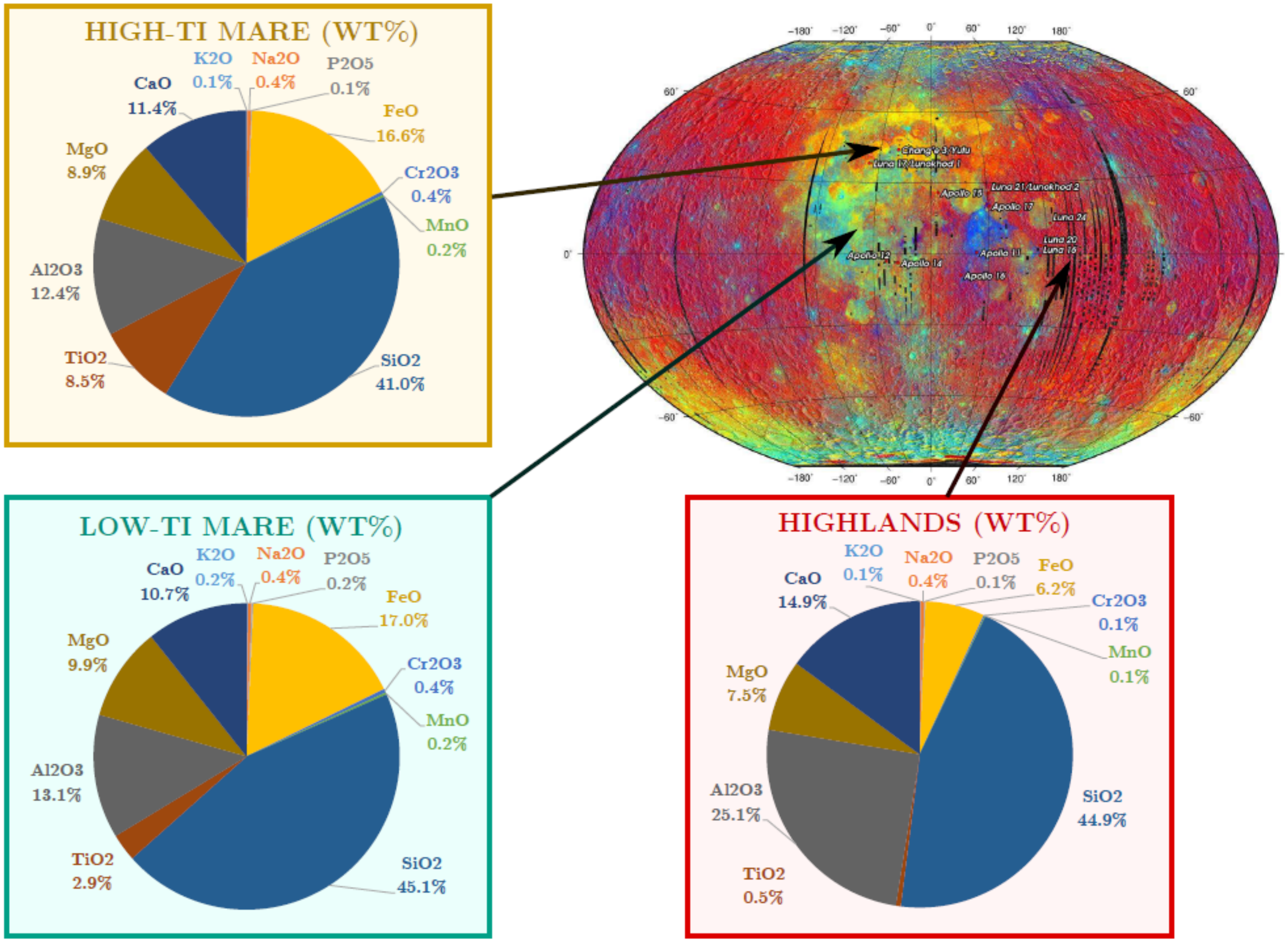
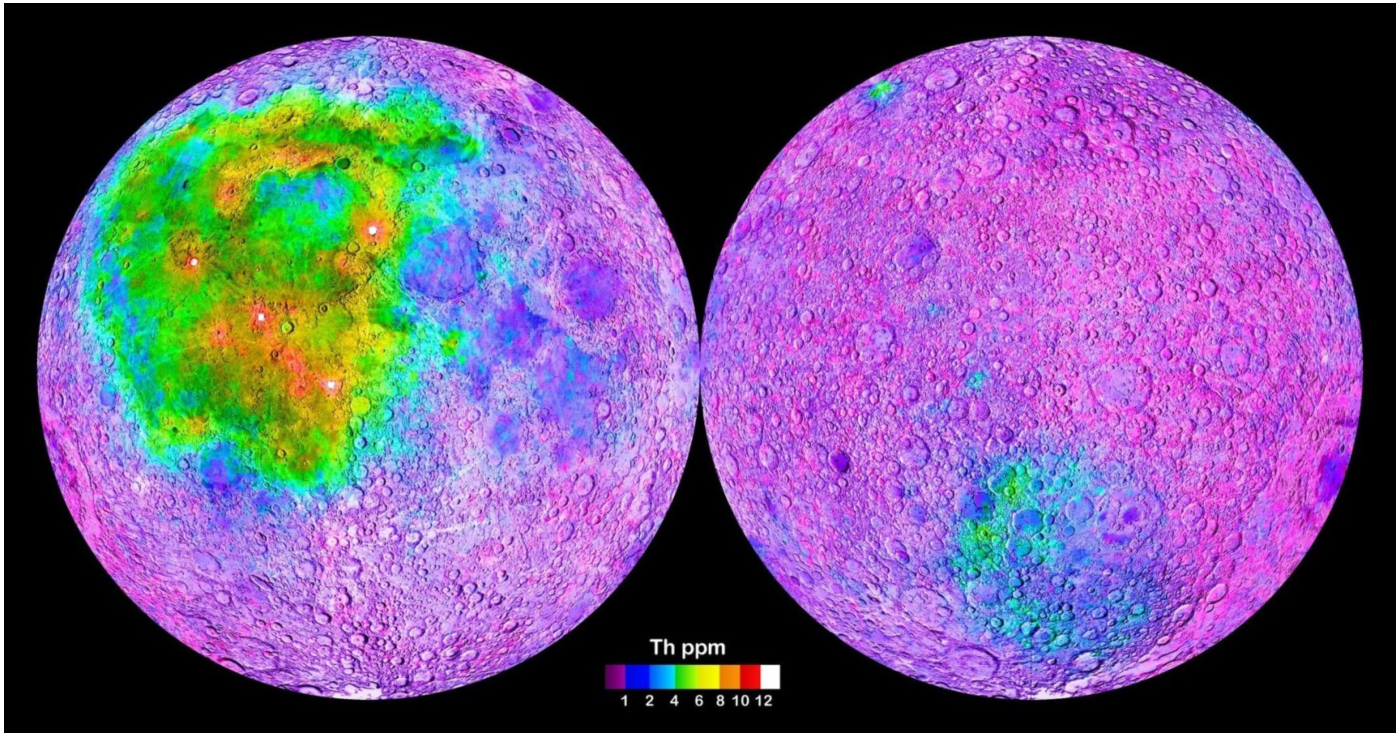


Figure 2-2: The composition of lunar regolith by oxide type for three different regions: High-Titanium Mare (yellow), Low-Titanium Mare (cyan), and Highlands (red). Composition data from Apollo and Luna missions [111] and imagery data from Clementine UVVIS instrument [72].

From S. Schreiner, “Molten Regolith Electrolysis Reactor Modeling and Optimization of In-Situ Resource Utilization Systems”, PhD Dissertation, MIT, 2013.

Procellarium KREEP Terrane

- KREEP = Potassium (K), Rare Earth Elements (REE), and Phosphorus (P)
- Corresponds to region of high uranium, thorium (see map), and potassium



Credit: NASA

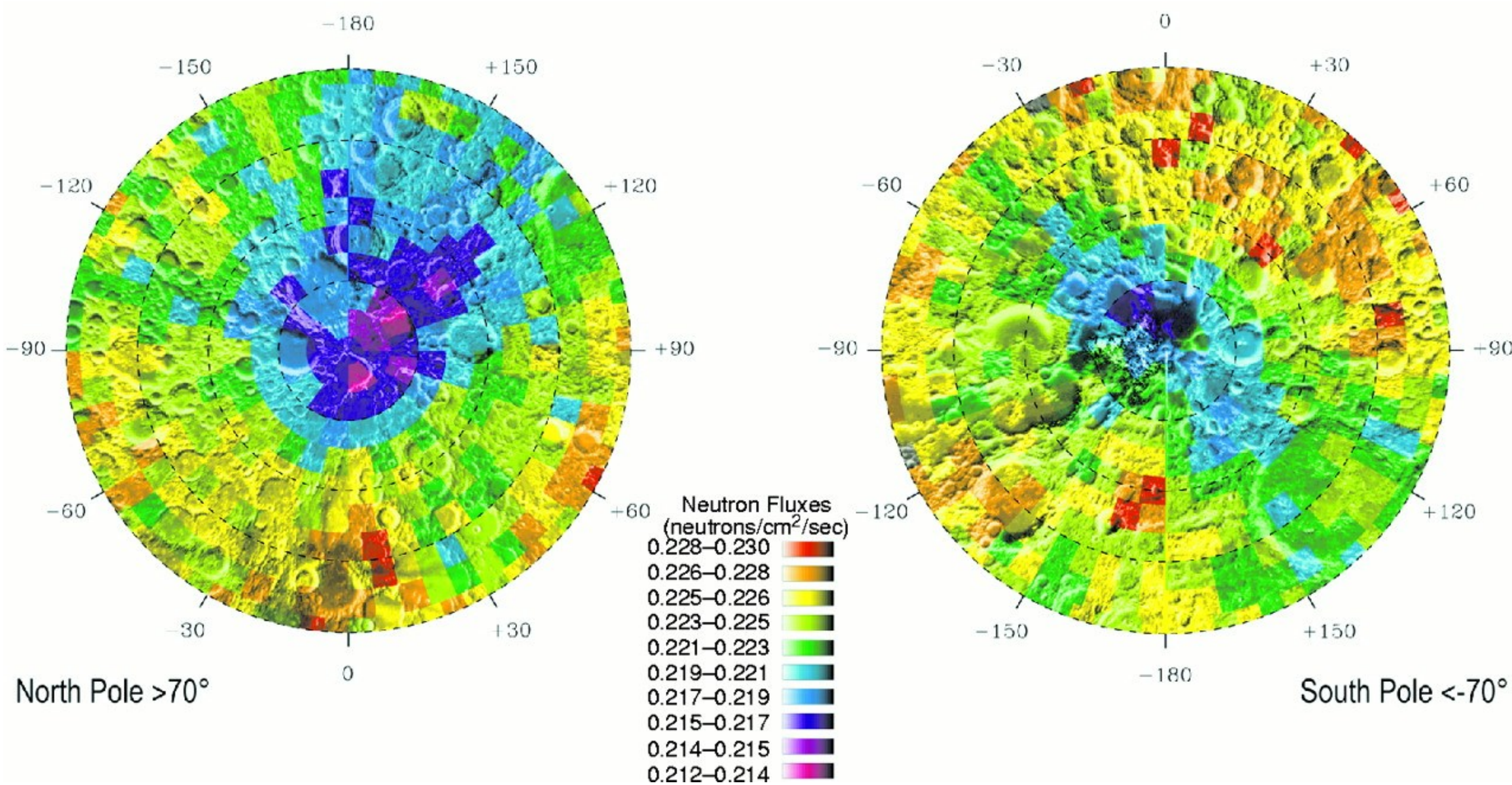
Binders on the Moon?

- No clay minerals
  - May be formed by artificial chemical weathering of plagioclase minerals
  - Never has been tested
- Sulfur
  - 0.16% to 0.27% in mare soils
  - May be extracted (along with solar wind implanted volatiles) via heating
  - Lunar daytime temperatures approach its melting point
- Basalt fibers have been spun from simulants but the process needs more development
- Others? This is a key challenge in additive construction!

Lunar Volatiles

- Hydrogen (H, OH, H_2O) has been implanted via solar wind and other processes
  - 65 ppm equatorially
  - Averaging about 120 to 150 ppm near the poles
  - A monolayer or worked into the bulk?
- Ice deposits in the bulk regolith inside the permanently shadowed regions (PSRs)
- Possibly also surface frost in the PSRs

Figure 8 Overlay of epithermal* counting rates in each 2° by 2° equal area pixel poleward of ±70° with surface relief maps of the lunar poles (28).



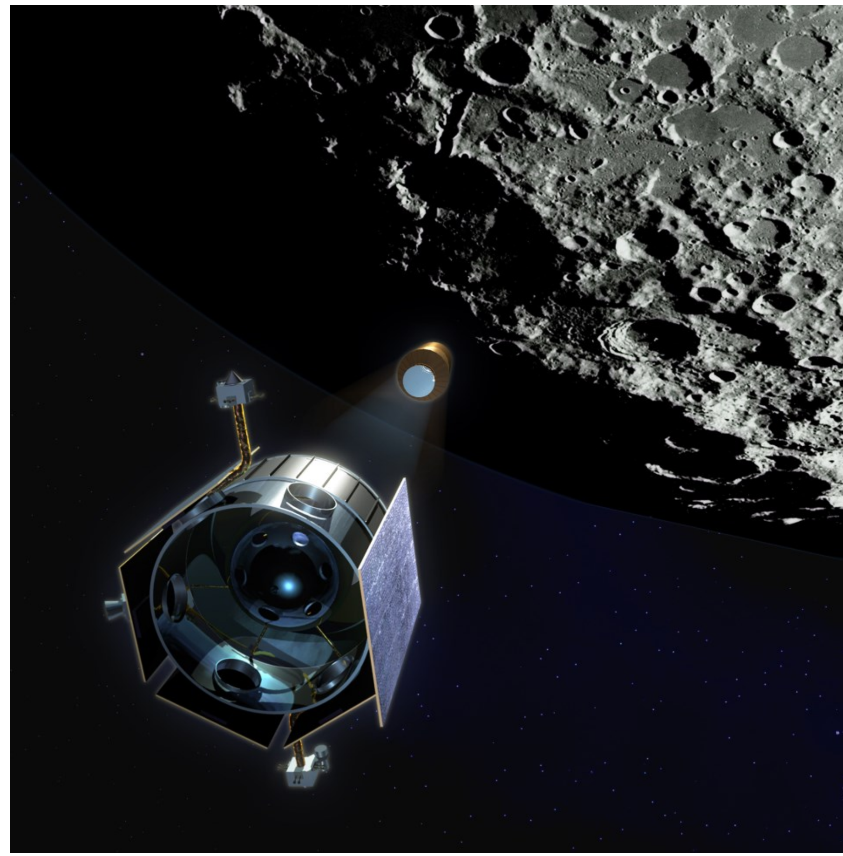
W. C. Feldman et al. Science 1998;281:1496-1500

Science AAAS

Published by AAAS

LCROSS Impact

- 4 to 6 MT material ejected
- Volatiles comprised much as 20% of mass
- Not just water
  - CH_4, NH_3, H, CO_2, CO
  - Metals including sodium, silver and mercury
- Physical state of the ice is unknown



Source: NASA

Other resources

- Asteroid remnants on the Moon?
  - A paper in Nature suggests 25% of asteroid impactors did not vaporize and the fragments exist in the central uplift peaks of the craters
- Recycling old spacecraft parts
  - But the historic lunar sites (Apollo, Surveyor, Ranger, and presumably the Soviet sites) are protected for their historic and cultural value

Derivative Lunar Resources

- Plastics made from lunar volatiles via Fischer Tropsh process
- Metals refined from lunar soil
- Ceramics
- Processing for these derivative materials requires significant infrastructure and energy

Molten Regolith Electrolysis

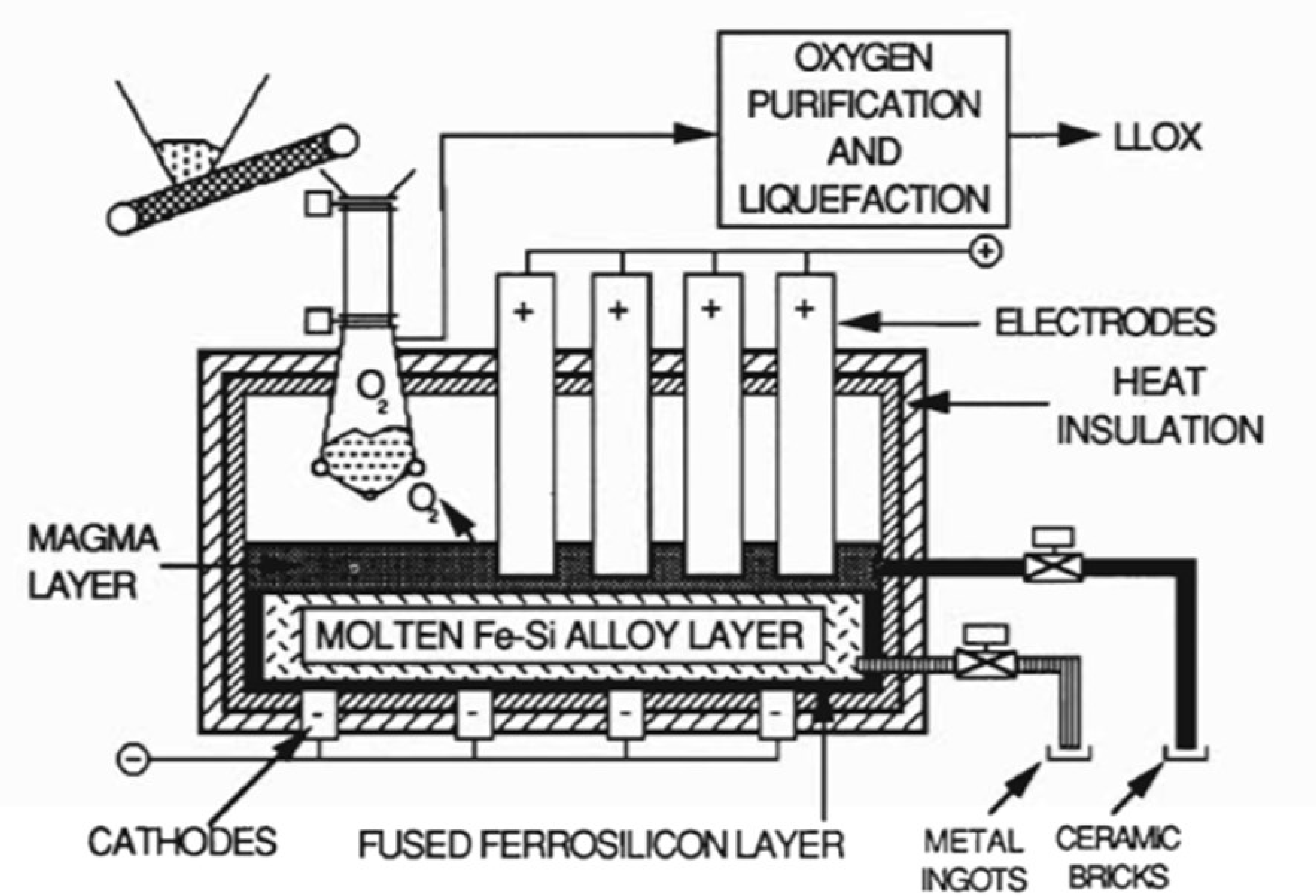
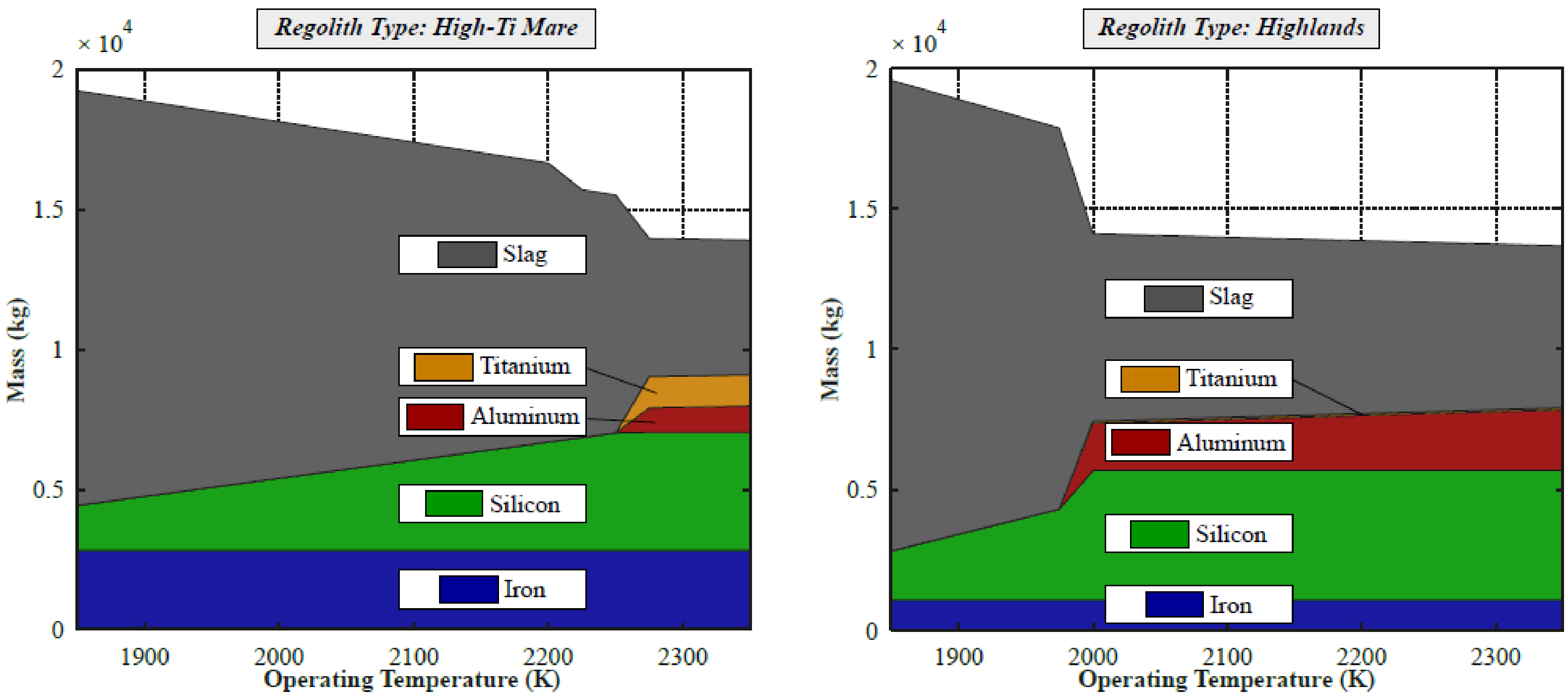


Figure 5. Magma electrolysis cell design for the production of LLOX from lunar regolith, modified after McCullough and Mariz (1990).

Source: Taylor, Lawrence A., and W. David Carrier III. "Oxygen production on the Moon: an overview and evaluation." *Resources of near-earth space* 1 (1993): 69-108.

Molten Regolith Electrolysis



From S. Schreiner, "Molten Regolith Electrolysis Reactor Modeling and Optimization of In-Situ Resource Utilization Systems", PhD Dissertation, MIT, 2013.

Figure 2-30: The amount of metal produced by an MRE reactor operating on Mare (left) and Highlands (right) regolith. As operating temperature increases, more oxides can be reduced to produce more molten metal.

The metals and silicon will be dissolved in the iron, not separated. A subsequent processing stage such as vacuum distillation is needed to isolate elements.

Molten Regolith Electrolysis

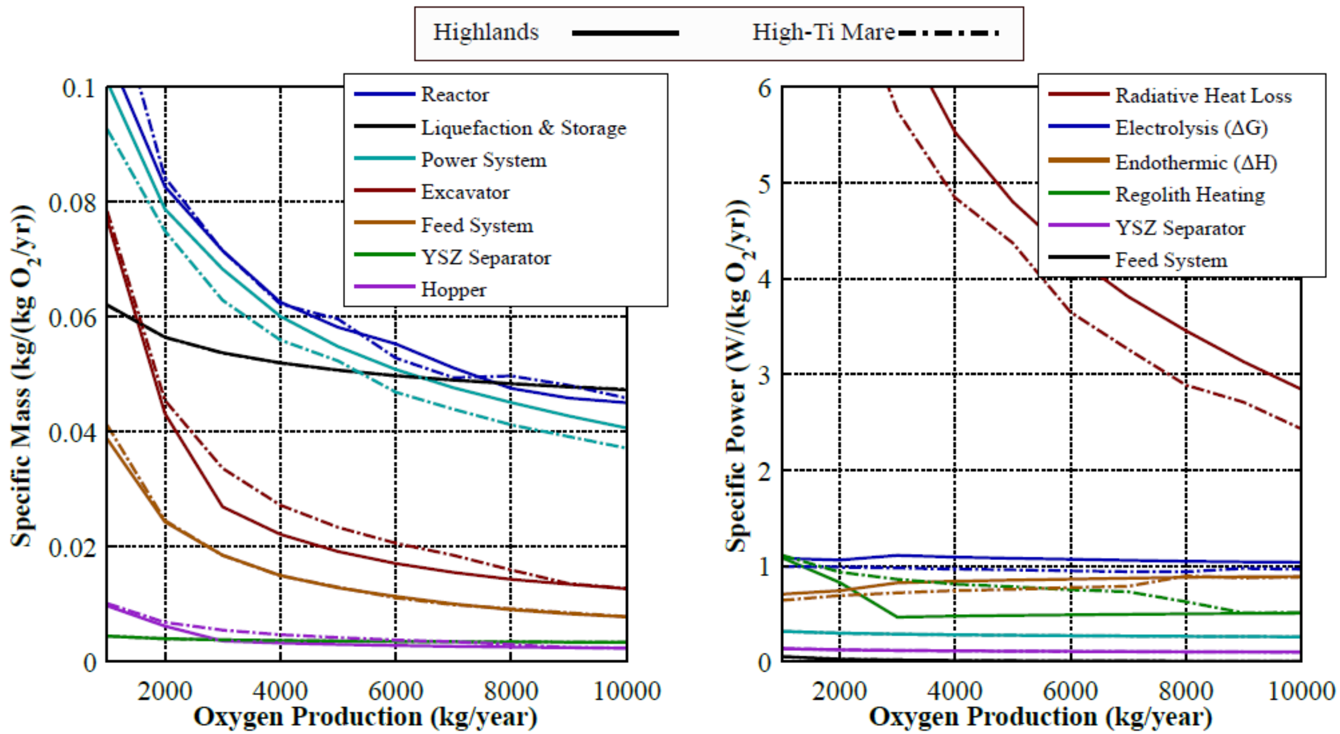
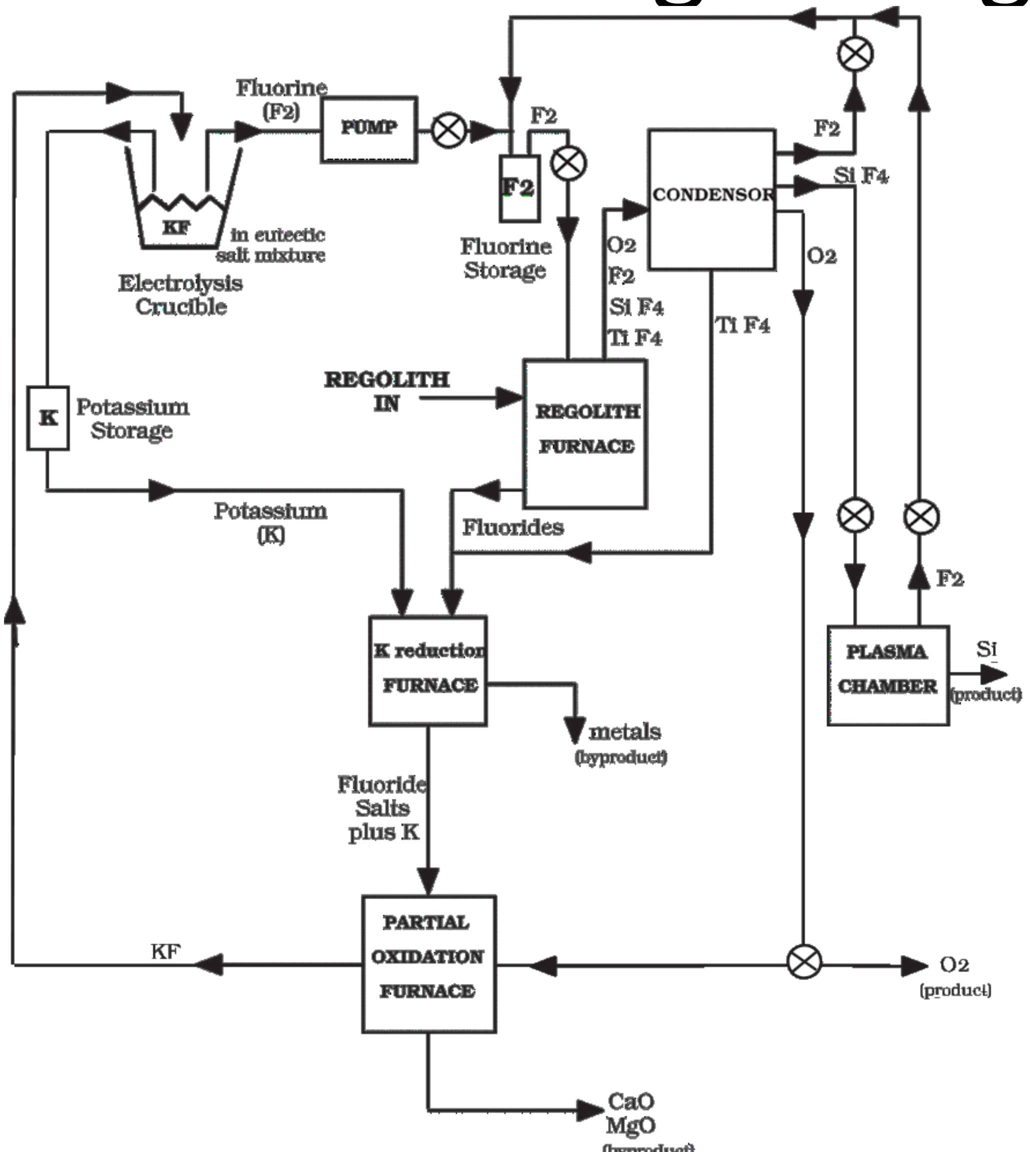


Figure 3-11: The specific mass and power for each subsystem in the ISRU system for systems optimized for Highlands regolith (solid line) and Mare regolith (dashed line).

From S. Schreiner, "Molten Regolith Electrolysis Reactor Modeling and Optimization of In-Situ Resource Utilization Systems", PhD Dissertation, MIT, 2013.

Using reasonable assumptions, it takes 5x more energy to extract a "mongrel alloy" than to make aluminum using terrestrial bauxite

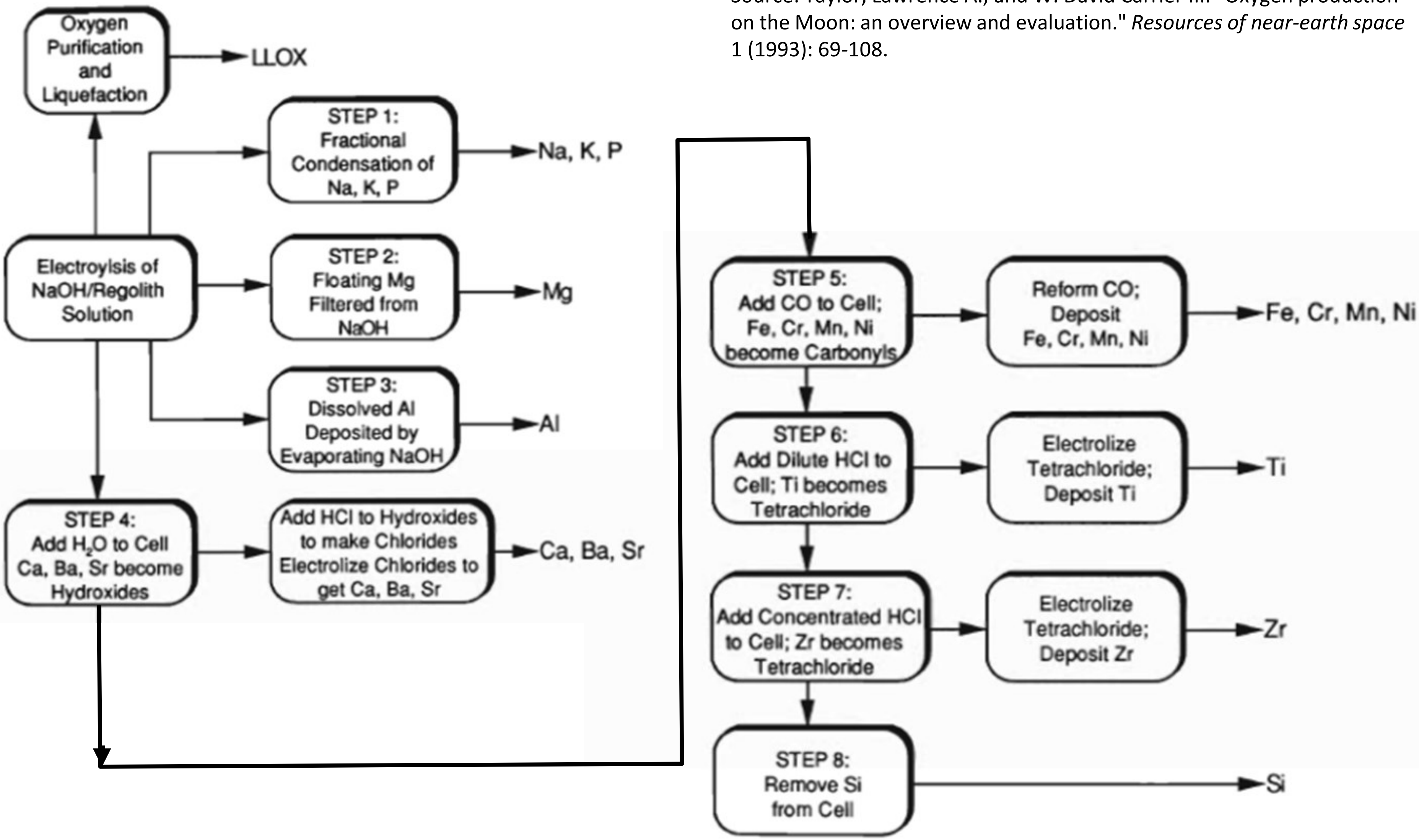
Fluorine Processing of Regolith



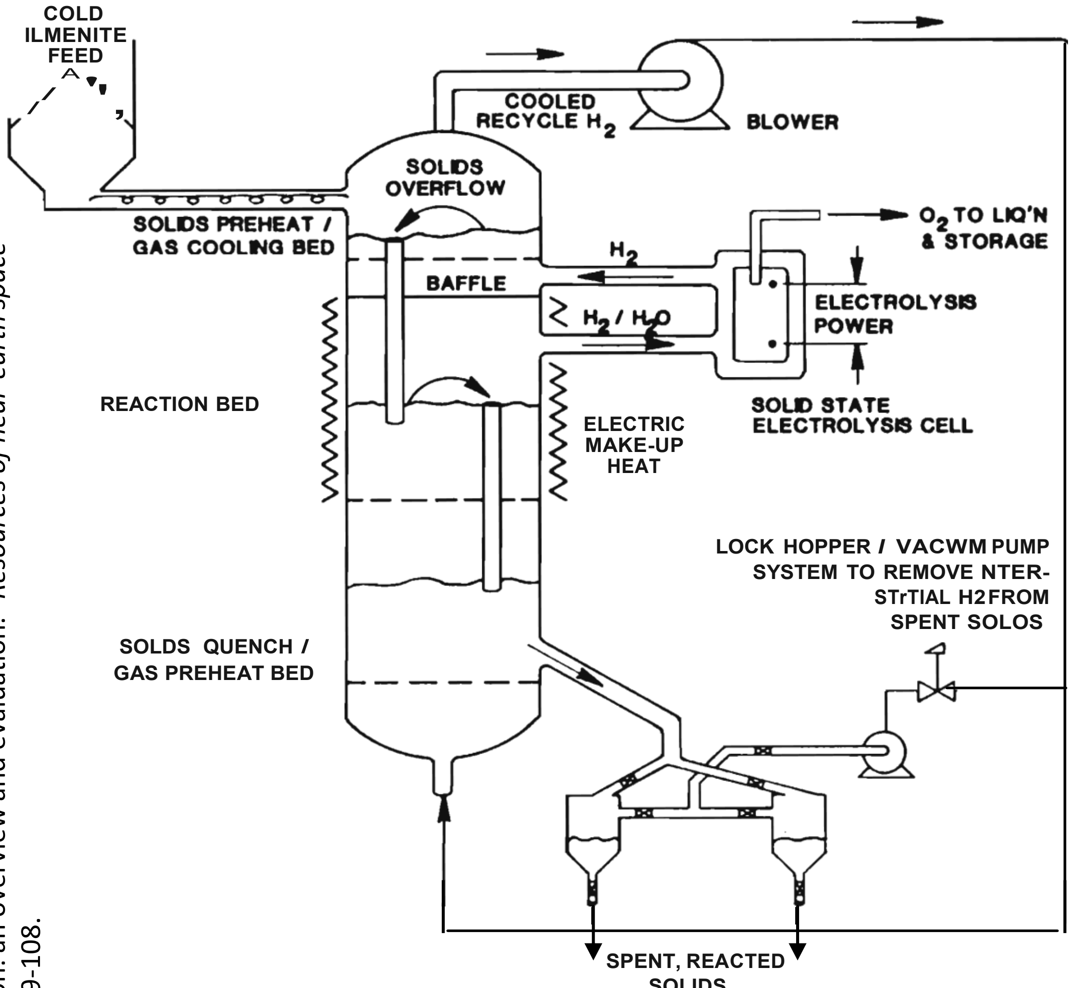
Source: Taylor, Lawrence A., and W. David Carrier III. "Oxygen production on the Moon: an overview and evaluation." *Resources of near-earth space* 1 (1993): 69-108.

Caustic Dissolution & Electrolysis

Source: Taylor, Lawrence A., and W. David Carrier III. "Oxygen production on the Moon: an overview and evaluation." *Resources of near-earth space* 1 (1993): 69-108.



Hydrogen Reduction of Ilmenite



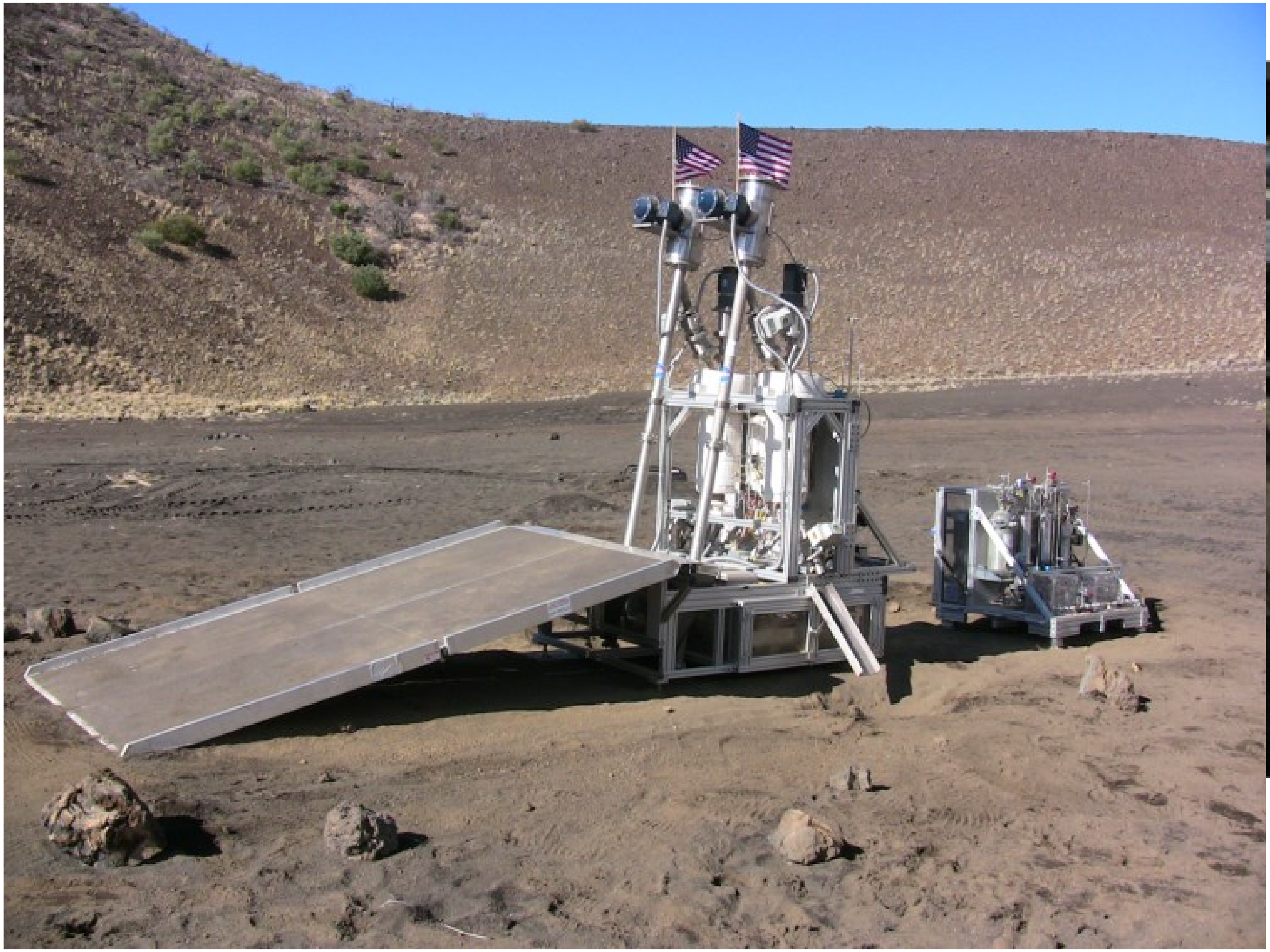
Source: Taylor, Lawrence A., and W. David Carrier III. "Oxygen production on the Moon: an overview and evaluation." *Resources of near-earth space* 1 (1993): 69-108.

$$FeTiO_3 + H_2 \leftrightarrow Fe + TiO_2 + H_2O$$

$$H_2O \leftrightarrow H_2 + \tfrac{1}{2} O_2$$

- Requires beneficiation to isolate ilmenite, otherwise it is less energy efficient and the spent solids are mixed minerals
- Much of the ilmenite is left unreduced
- Useful for oxygen production but probably not for metal production
- A version has been field tested on Mauna Kea in the 2008 ISRU Field Test

2008 ISRU Field Test
ROXYGEN: Hydrogen Reduction



Methane Reduction of Ilmenite

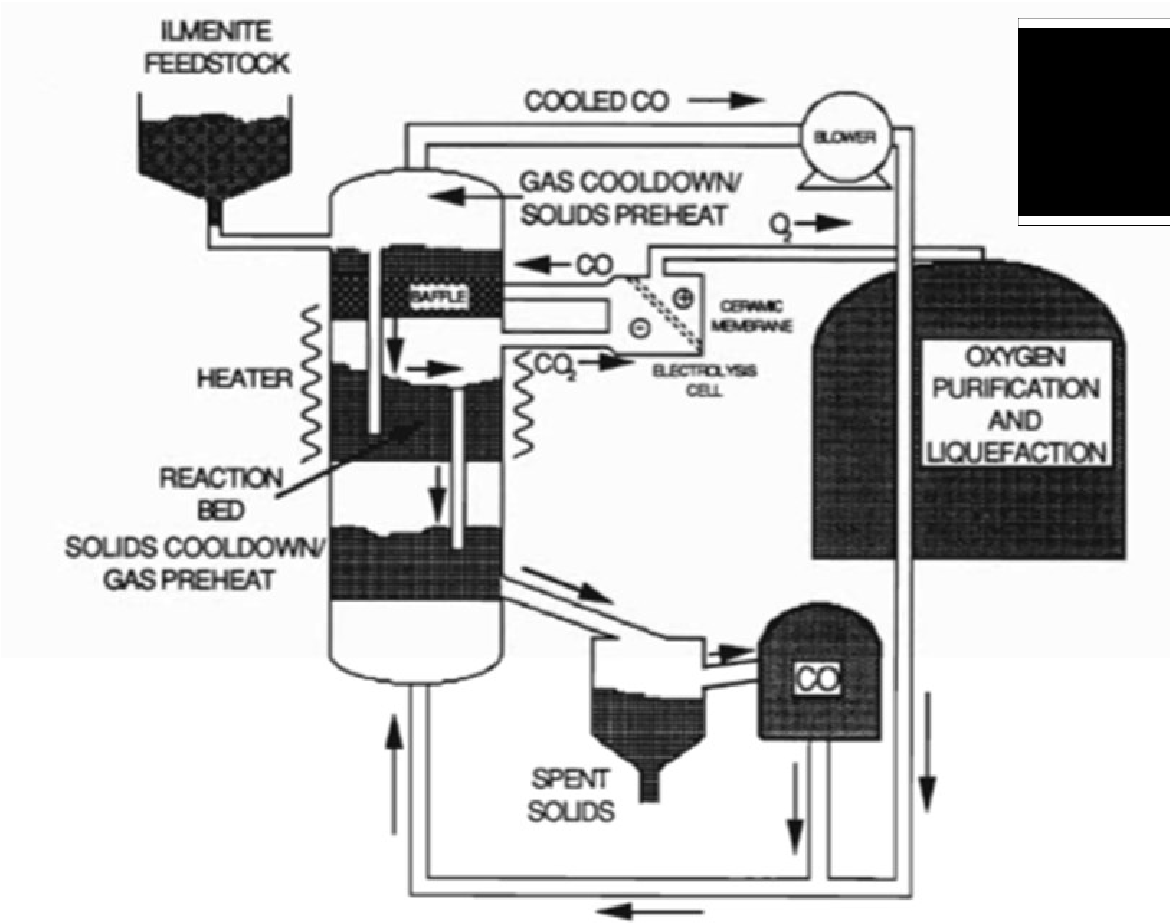


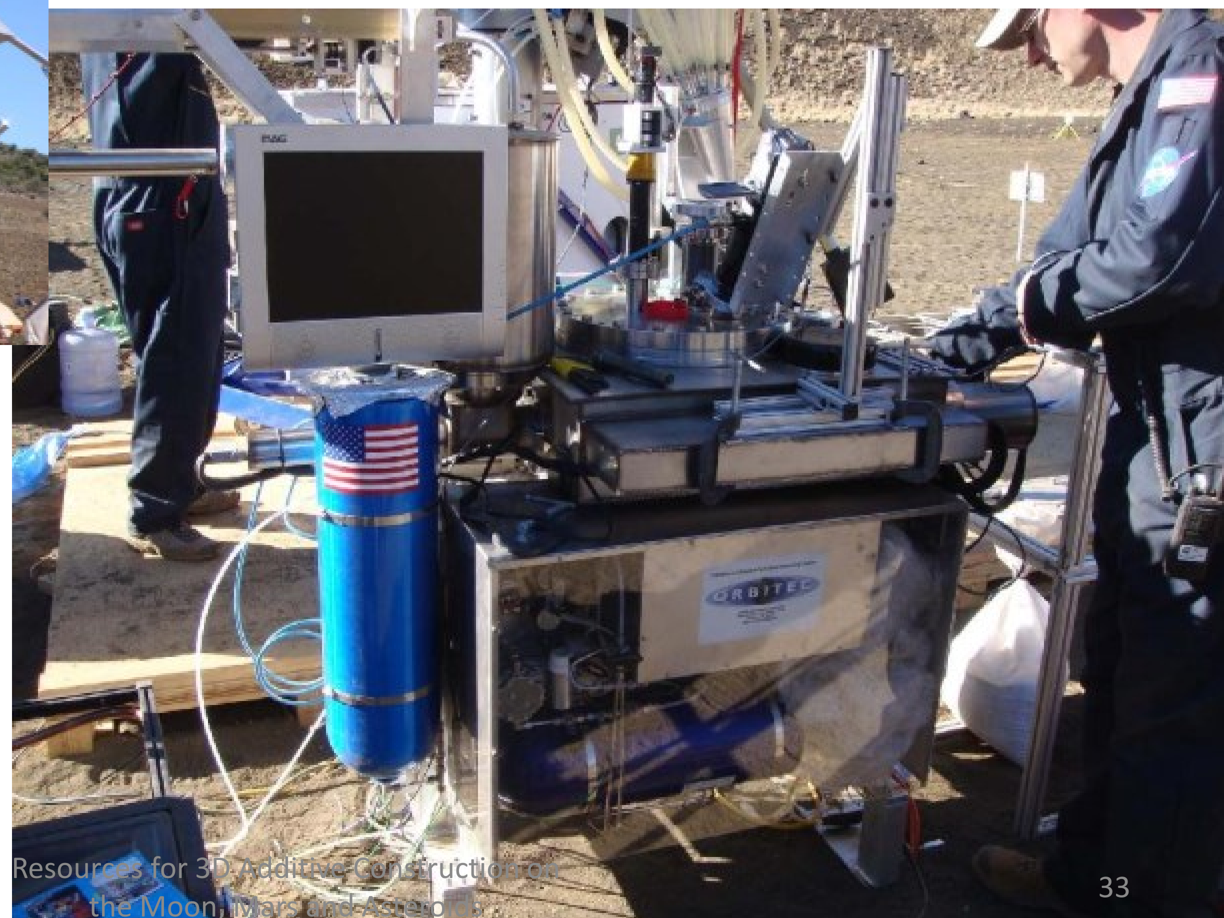
Figure 3. Carbon monoxide reduction of ilmenite for the production of LLOX, using fluidized-bed processing. The use of methane as the reductant, or the reduction of glass with hydrogen, could have the same configuration.

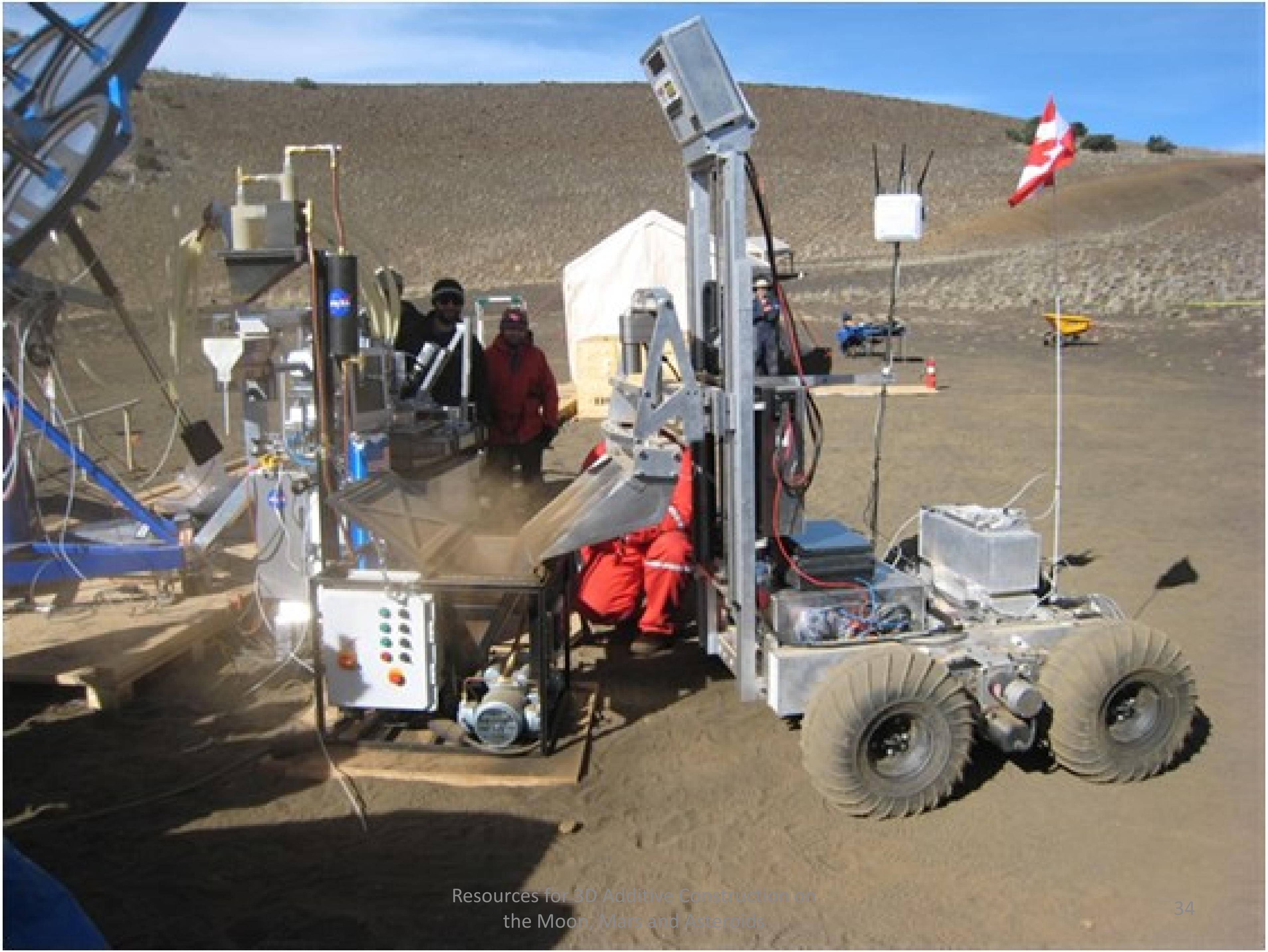
[redacted]

- “Carbothermal”
- Requires beneficiation to isolate ilmenite
- Useful for oxygen production but probably not for metal production
- A version has been field tested on Mauna Kea in the 2010 ISRU Field Test

Source: Taylor, Lawrence A., and W. David Carrier III. "Oxygen production on the Moon: an overview and evaluation." *Resources of near-earth space* 1 (1993): 69-108.

2010 ISRU Field Test
Carbothermal: Dust-to-Thrust





1980 Ames Summer Study

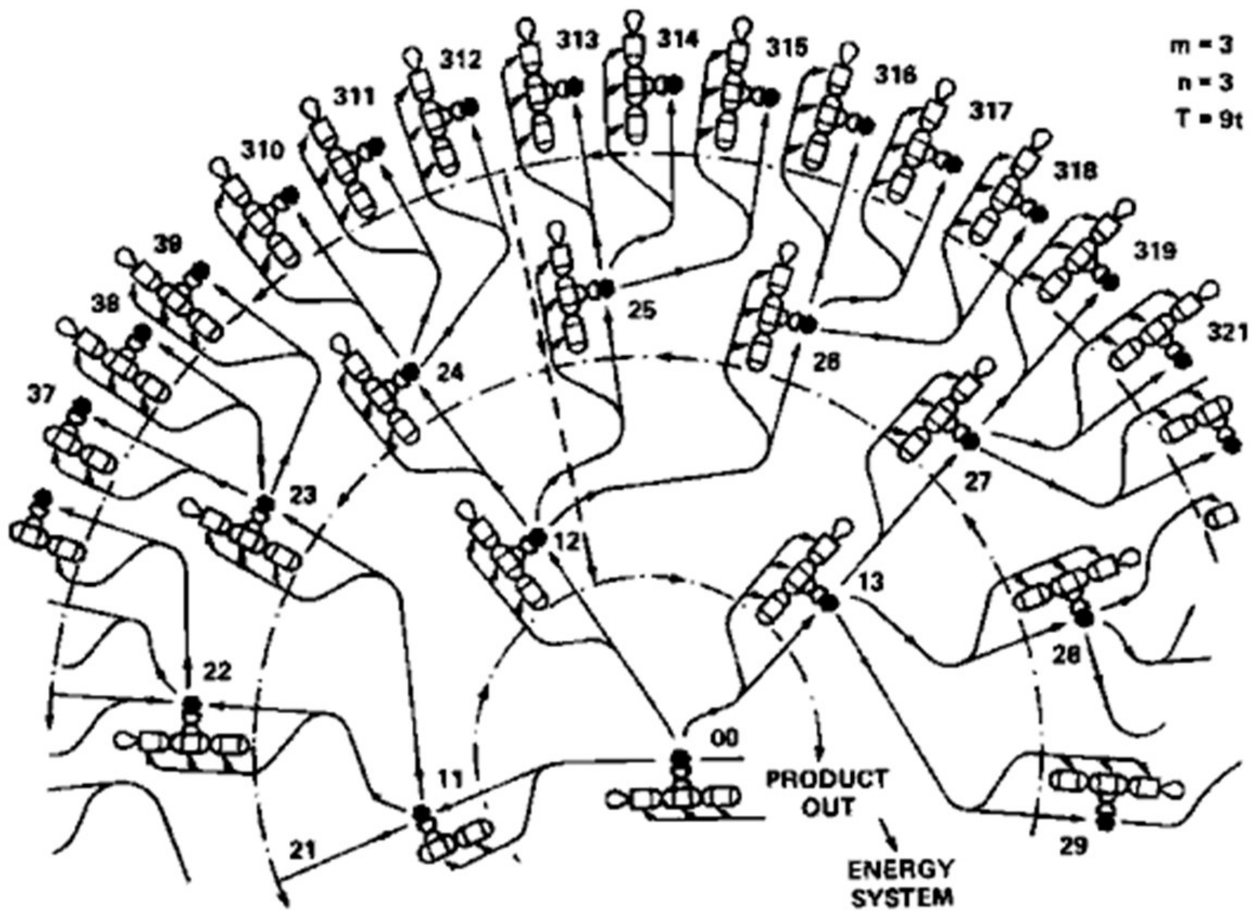
100 Ton, Self-replicating Lunar Factory, 80% Closure

Credit: NASA

Lunar Factory Components

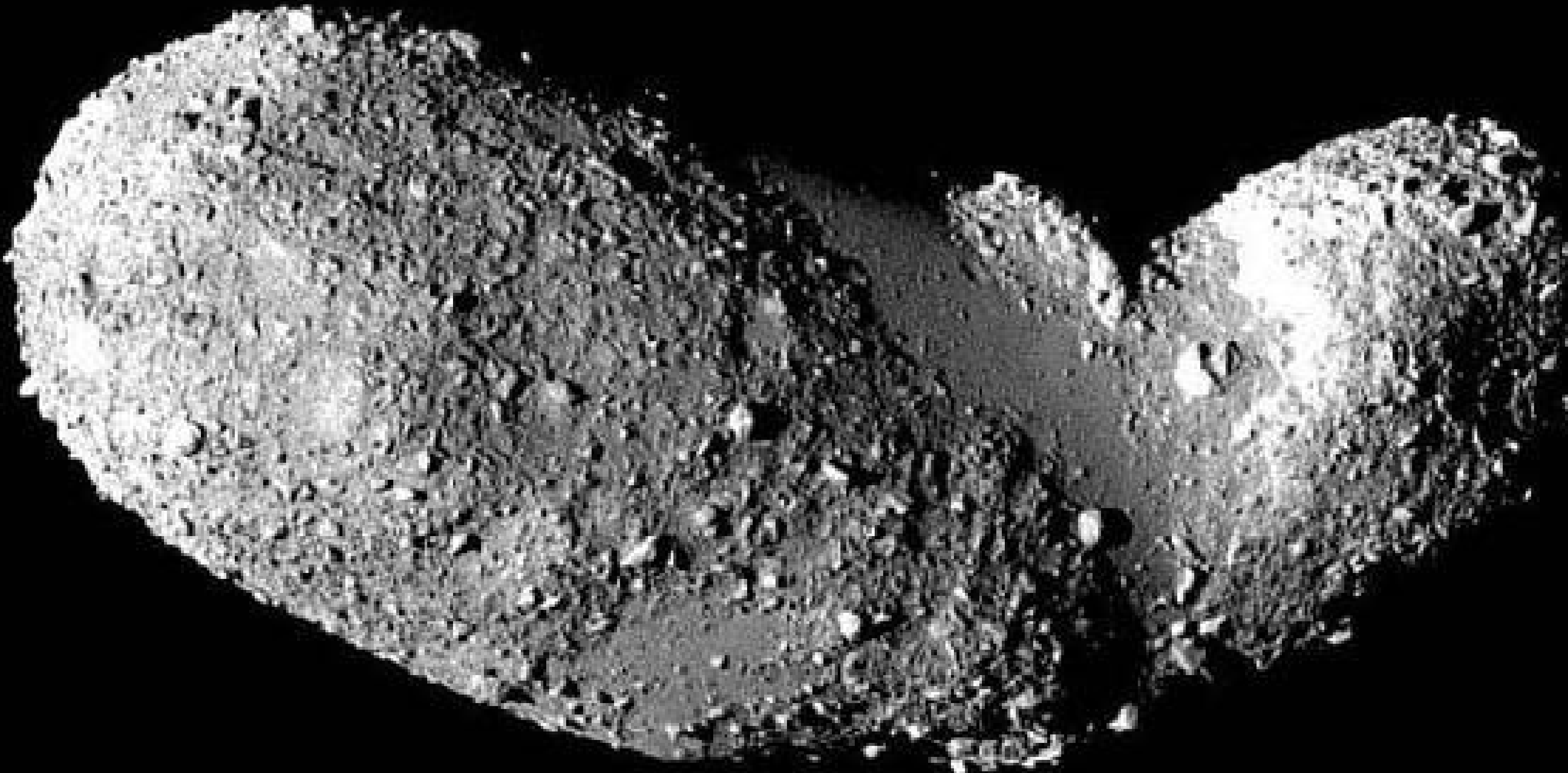
- Mining robots
- Paving robots
- Solar cell makers
- Assembly robots
- Factory warehouse robots
- Traditional manufacturing (“subtractive”)
- Etc.

Self-Replicating Lunar Factories



Credit: NASA

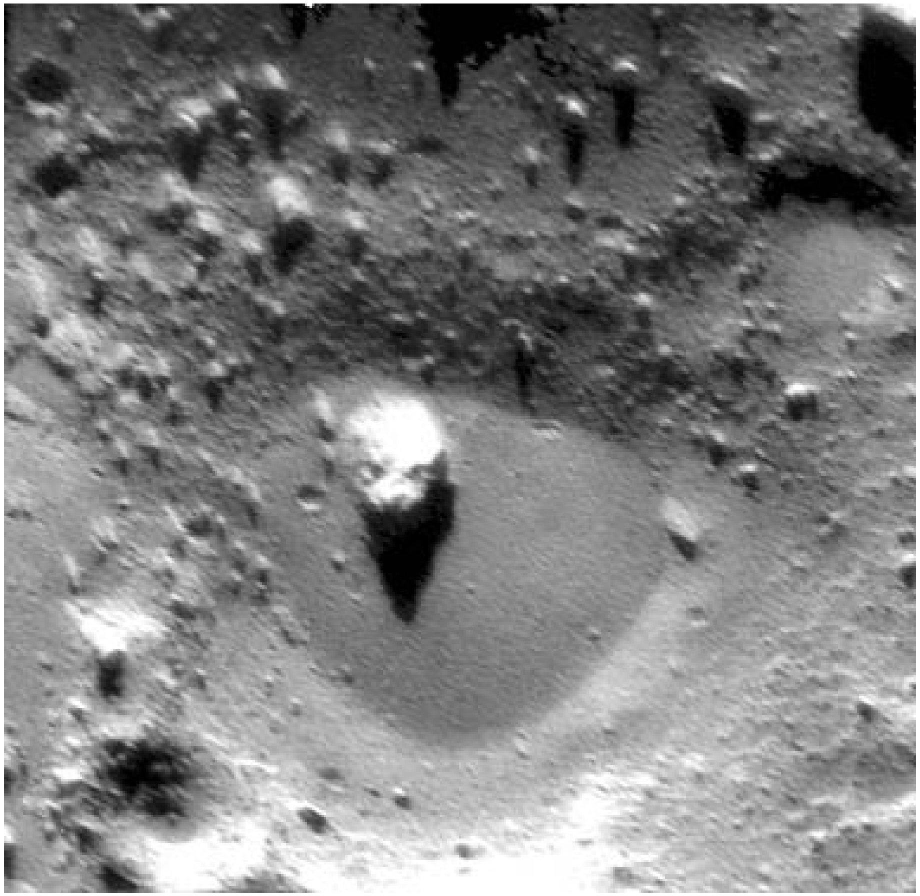
Asteroids



Some Basics

- Many (or most?) asteroids are covered with regolith
  - Apparently formed by thermal fatigue (rocks cracking by thermal cycling) and impact processes
- Many asteroids are rubble piles
- Asteroids are divided into many spectral classes
  - Meteorites give compositional insight into these classes
- Asteroids are divided into many trajectory classes

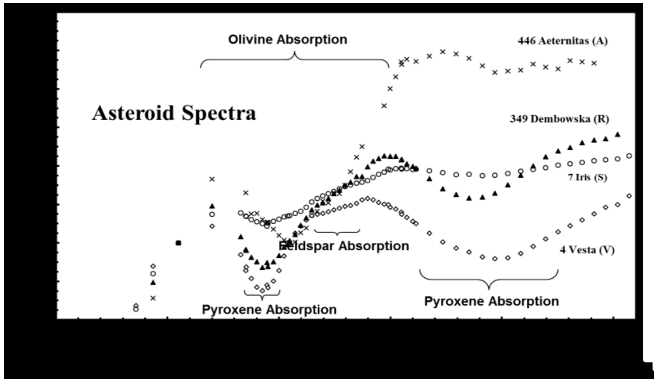
Regolith

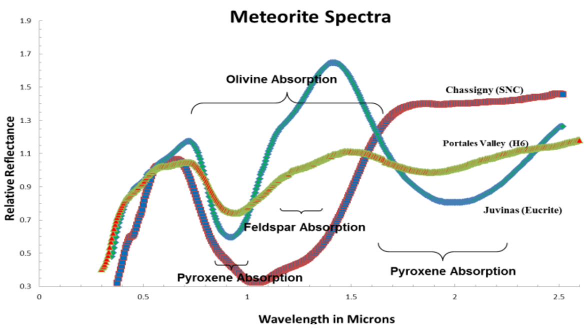


Credit: Mark Robinson, Northwestern University

- Boulders, cobbles, gravel
- Not sure how much fine material (sand)
- Electrostatics and solar wind might winnow off the dust and even sand
- “Dust ponds”
- New regolith constantly generated

Asteroid Spectral Classes





Some major Near-Earth Asteroid Classes	Inferred Major Surface Minerals
S	Olivine, pyroxene, metal
Q	Olivine, pyroxene, metal
C (dry)	Olivine, pyroxene, carbon compounds
C (wet)	Clays, carbon, organics, ice
M	Metal, enstatite
B	Clays, carbon, organics
D	Organics, silicates, ice
P	Organics, silicates, ice
K	Olivine, orthopyroxene, opaques
E	Mg-Pyroxene

Source: Dan Britt, UCF

Iron Meteorites

Source:
http://www.arizonaskiesmeteorites.com/AZ_Skies_Links/Meteorite_Photos/Irons/

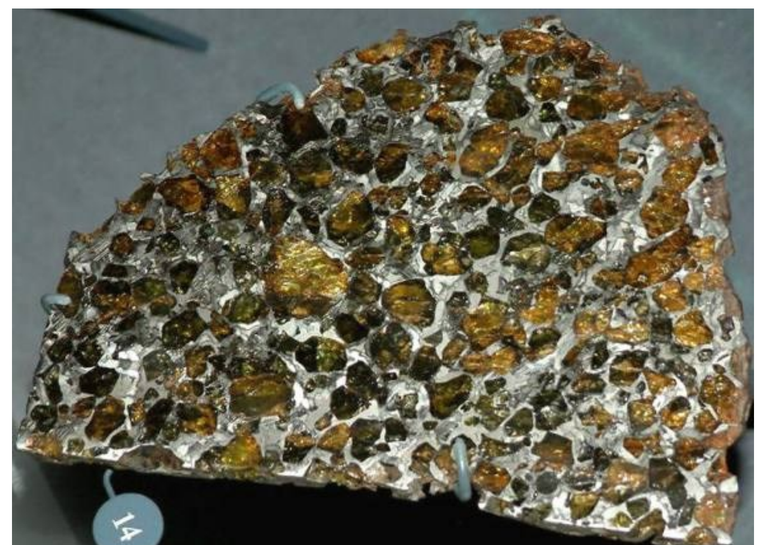
Credit: Wikimedia

Composition: metals, primarily iron, nickel and cobalt

Stony-Iron Meteorites

Source: http://www.earthsciences.hku.hk/shmuseum/
earth_evo_02_meteorities.php

Source: Smithsonian Museum

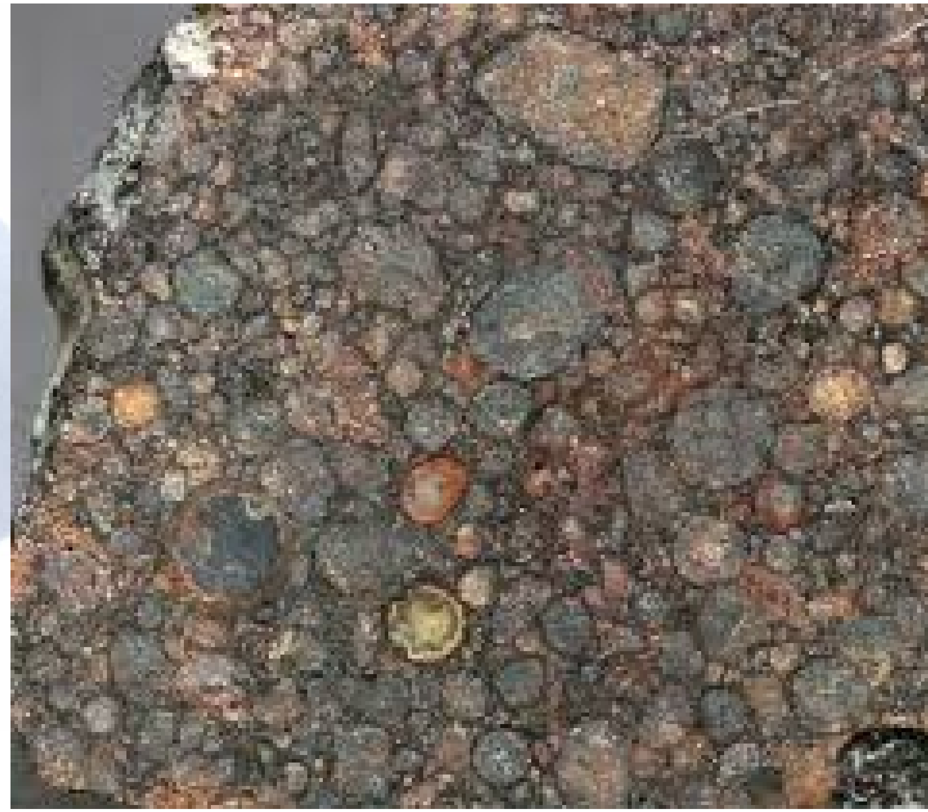


Metal: nickel-iron
Silicates: primarily olivine

Source: https://glacialtill.wordpress.com/2011/04/25/meteorite-monday-stony-iron-meteorites-or-space-rock-bling/

Stony Chondritic Meteorites

Source: http://www.arizonaskiesmeteorites.com/
Meteorite-Identification/



Source: http://www.thaicosmic.com/
product.detail_289387_en_1473192

Composition: iron, iron oxide, olivine, pyroxenes, and other minerals

Stony Achondritic Meteorites

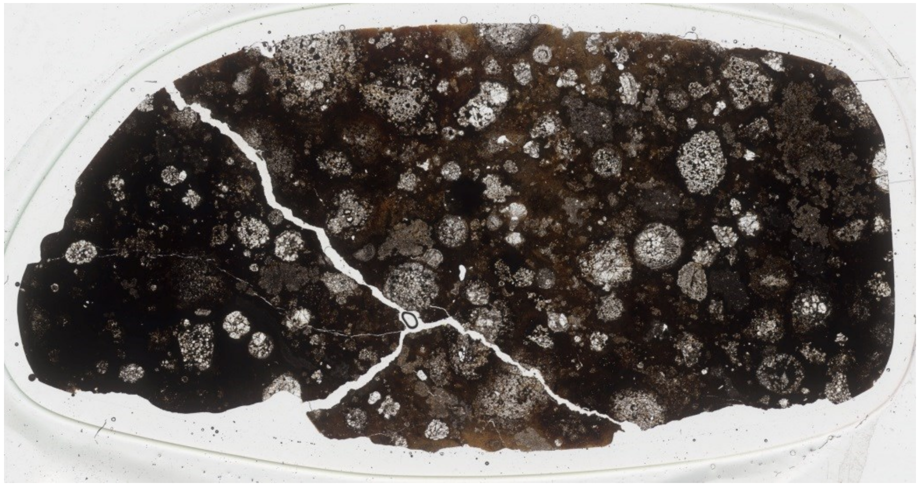
Source: https://www.pinterest.com/pin/171277592049583349/

Source: http://www.astro.washington.edu/users/smith/Astro150/Labs/Meteorites/

Silicate mineralogy varies between subgroups

Carbonaceous Chondrite Meteorite

Source: Wikimedia https://commons.wikimedia.org/wiki/File:Murchison_crop.jpg



Source: https://glacialtill.wordpress.com/tag/meteorite-monday/

Olivine, serpentine (a clay), iron oxides such as magnetite, complex organics. The clay contains water in its structure.

Asteroid Simulants

- NASA has funded development of asteroid simulants
  - Both regolith and competent rocks
  - Several spectral classes
- Workshop to guide the simulant development will be held at UCF in Orlando, FL, Oct. 6-7. If interested, please contact Steve Covey, Dan Britt or myself.

"Best" Spectral Classes for Mining?

- Depends on the business case
- Here are a few asteroid types that have been mentioned:
  - Carbonaceous – water, clay minerals, organic compounds (source of carbon), some metal
  - S Class compositionally similar to LL Chondrites – highest in PGMs despite being low in metals, water
  - M Class – metal, but very hard; will require high energy to cut and process

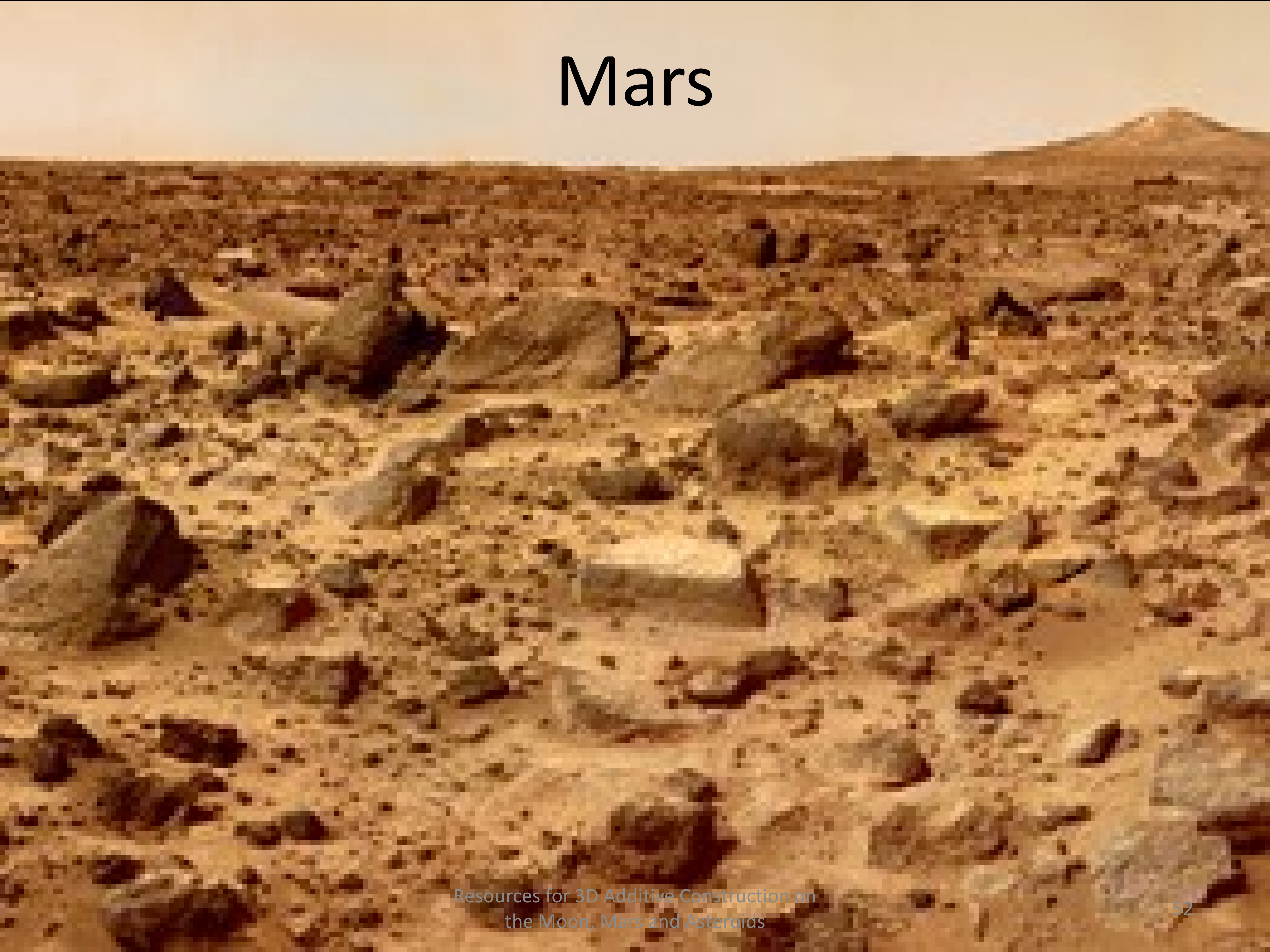
Phobos and Deimos

- Phobos appears to be a captured D-Type asteroid
  - Carbonaceous, possibly with water in its interior
- Deimos may be a captured D-Type or C-Type asteroid
- It is unclear how much water can be obtained on Phobos or Deimos
  - Need ground truth!

Regolith 3D Printing on Phobos

Credit: Pat Rawlings and KSC Swamp Works

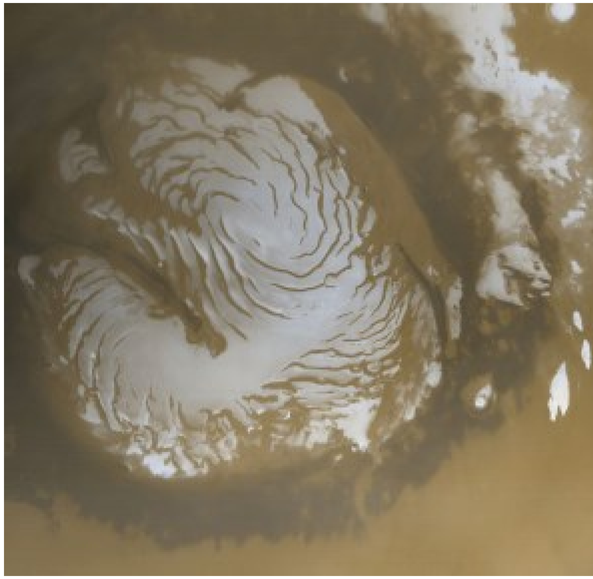
Mars



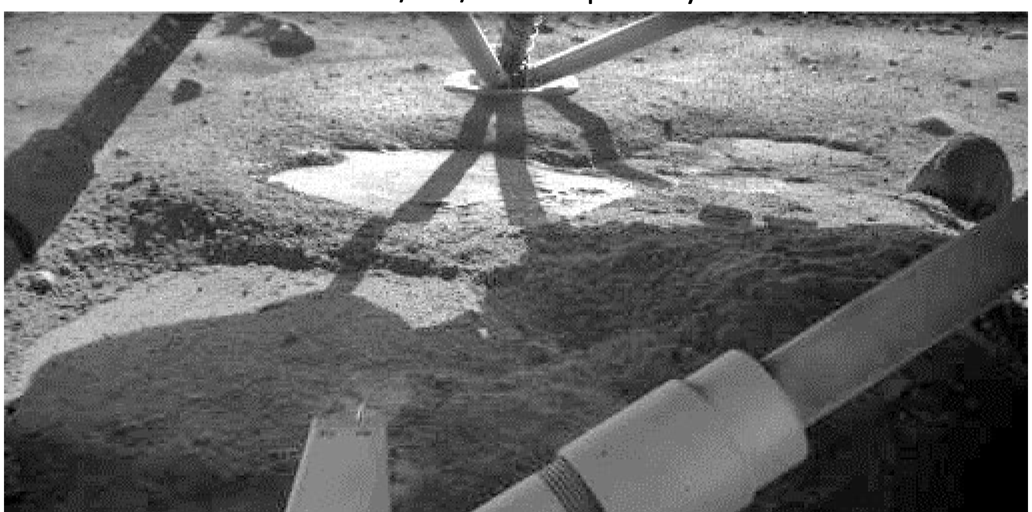
Mars Resources

- Ore bodies may have formed on Mars
- Silicate minerals
  - metals may be refined from the rocks
  - Clay minerals, which may be used as binder
  - Martian geology is diverse
- Sulfates
- Water ice
  - Easy to access at high latitudes
  - Shallow subsurface at Phoenix Lander site
  - On the surface at the poles
  - Very deep at equatorial locations
  - Can ice be a building material?
- Atmosphere: CO_2 (95%), N_2 (3%)

Mars H_2O Resources



Source: NASA/JPL/Malin Space Systems



Source: NASA/JPL-Caltech/University of Arizona

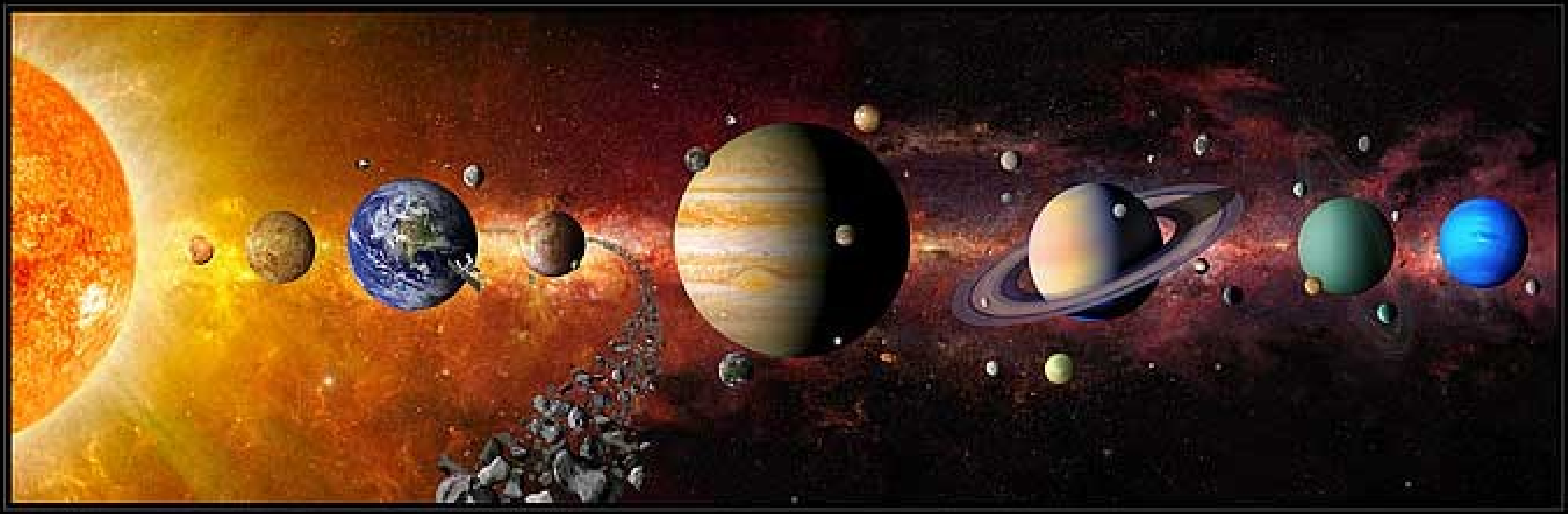
Source: NASA/JPL-Caltech/University of Arizona/Texas A&M University

MARCO-POLO on Mars

Credit: Pat Rawlings and KSC Swamp Works

Resource Processing on Mars

- Lunar processes generally apply to Mars, too
  - E.g., molten regolith electrolysis can work on Mars with some re-optimization for the new minerals
  - Make metals and ceramics
- Water cleanup for the ice
  - Probably contains salts, varied chemistry
  - Need to ground-truth the ice
- Atmospheric capture for CO2
  - Condense and store as liquid
- Crack CO2 for the carbon, electrolyze H2O for the hydrogen, then form the CH4
- Fischer-Tropsch process to polymerize CH4 in to complex hydrocarbons, plastics, rubbers



Think Outside the Sphere