Extraction Techniques for Minerals in Space

- Mining on Earth
- Mining in Space - General
- Mining in Space - The Lunar Regolith
- The Asteroids

Review of Mining on Earth

- 3-D workplace that must be: safe, well drained and ventilated with necessary power and transportation
- Also must be able to produce ore at steady rate and quality

Extraction Constraints

- Orebody shape is function of its mode of formation (and subsequent history):
  - 2-D sheet-like or tabular bodies
  - linear or rod-like bodies
  - irregular 3-D masses
- Mining depends on:
  - thickness, attitude, depth, strength of ore and host materials

Blasting

- an individual explosion removes cone of material
- more explosives lead to smaller rock but not more excavation
- amount of breakage should be controlled or keyed to requirements of subsequent treatment
- timed blasting:
  - to remove material from an open pit bench
  - to advance a face underground

Open Pit/Quarry - OH-1

- f(overburden thickness, topography, nature of ore)
- pit wall angle: 45° for rock; 30° for unconsolidated material - f(gravity)
- pit vs underground: f(geometry of ore body; grade of the ore)
- pits may lead up to underground operations (or the reverse) over time
  - originally too expensive, now infrastructure in place and paid for
  - postpone the ecological day of reckoning
- Surface mines are likely scenario on the moon.

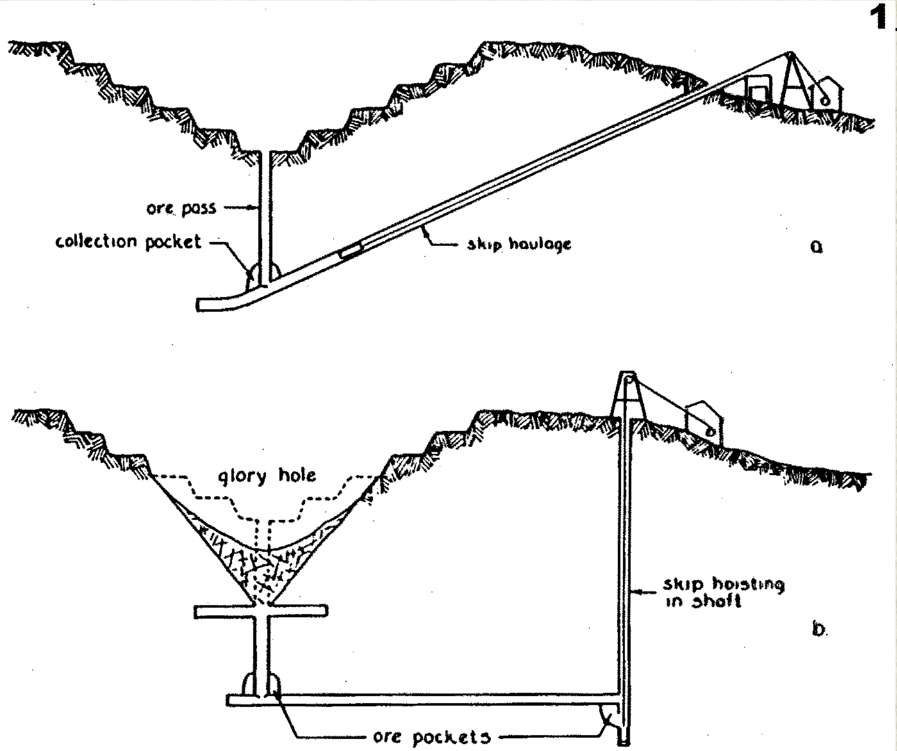


Figure 6.4. Transition to deep mining from an open pit.

Underground Operations

- details depend strongly on geometry and grade of ore and the nature of the gangue
- usually need to leave ore behind as pillars
- gravity is commonly used to help reduce handling
- must start with access system of drifts and shafts (usually in footwall)
- extraction done in rooms (stopes) connected by drifts, raises
- artificial supports commonly needed

Traditional Underground Methods

- **What is a major advantage** of underground mining on the moon?

[1] Shrinkage Stope - OH-2

- method takes advantage of the fact that
- broken ore occupies 30-50% more volume than parent material
- keep minimum headroom by drawing down the muck pile
- see Figure 6.9

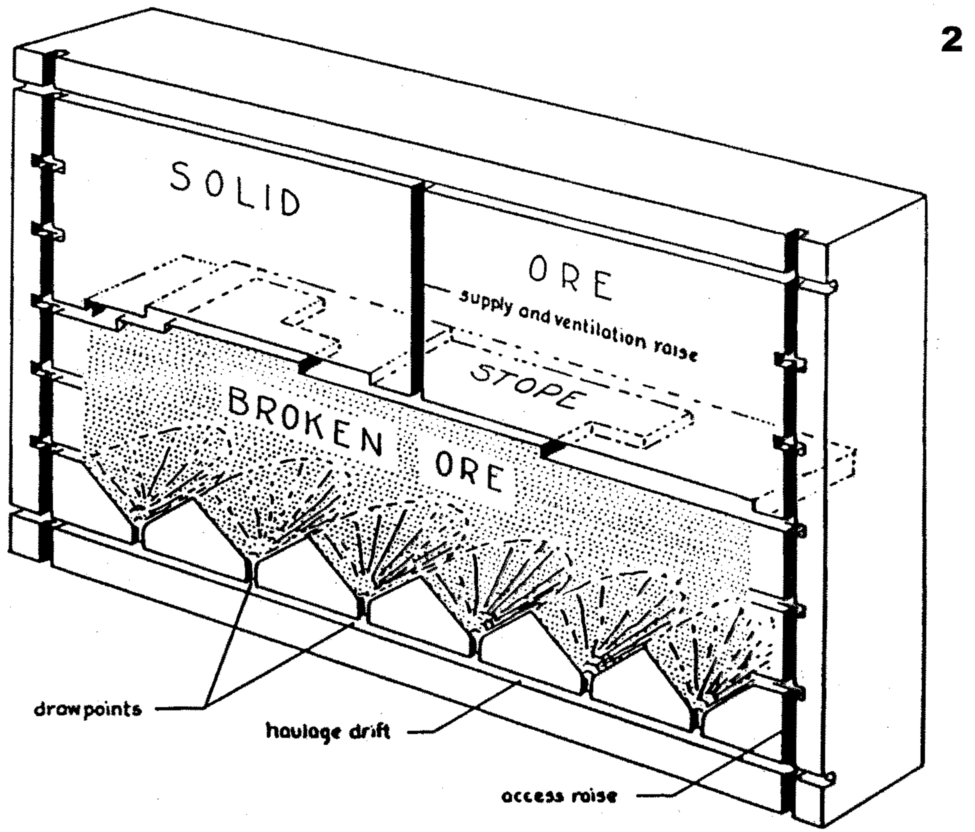


Figure 6.9. Layout of a shrinkage stope.

[2] Cut and Fill - OH-3

- fill mined area with waste rock or cemented tailings
- very versatile, commonly used
- development costs relatively low
- pillars can be recovered
- takes care of some of the waste disposal problem

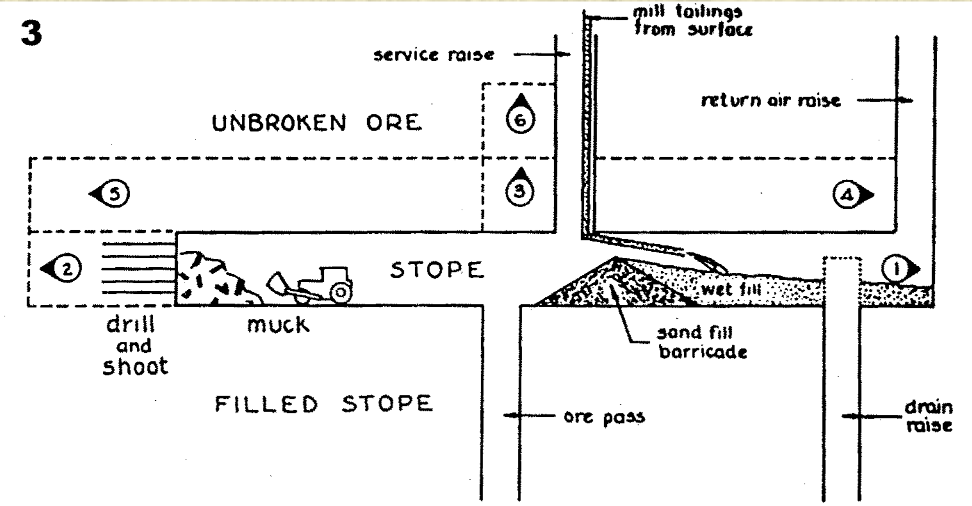


Figure 6.10. Cut and fill stoping; the sequence of operations is indicated by the arrowed numbers.

- Both Shrinkage Stoping and Cut and Fill work well on vertical, tabular ores which are not likely to be found on the moon.

[3] Sublevel/Block Caving- OH-4

- used in weak ore which may not be safe to mine in other ways
- low cost
- LOTS of premining development needed
- problems with ore dilution and surface disturbance

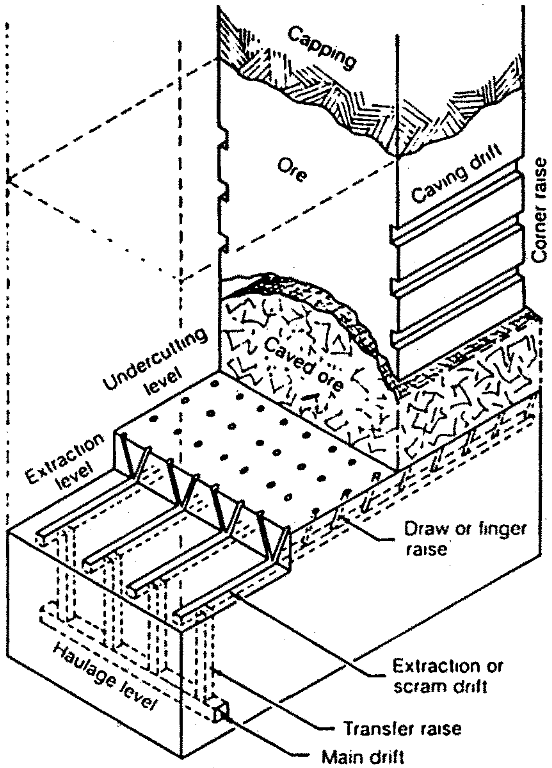


Figure 6.12. Block caving. (*Source:* From William H. Dennen and Bruce Moore, *Geology and Engineering*. Copyright © 1986 Wm. C. Brown Publishers, Dubuque, Iowa. All rights reserved. Reprinted by permission)

[4] Advance or Retreat Mining

- advance more common because quicker return on investment
- retreat common in some coal mines
- may lead to surface subsidence
- See Fig. 6.13 - OH-5

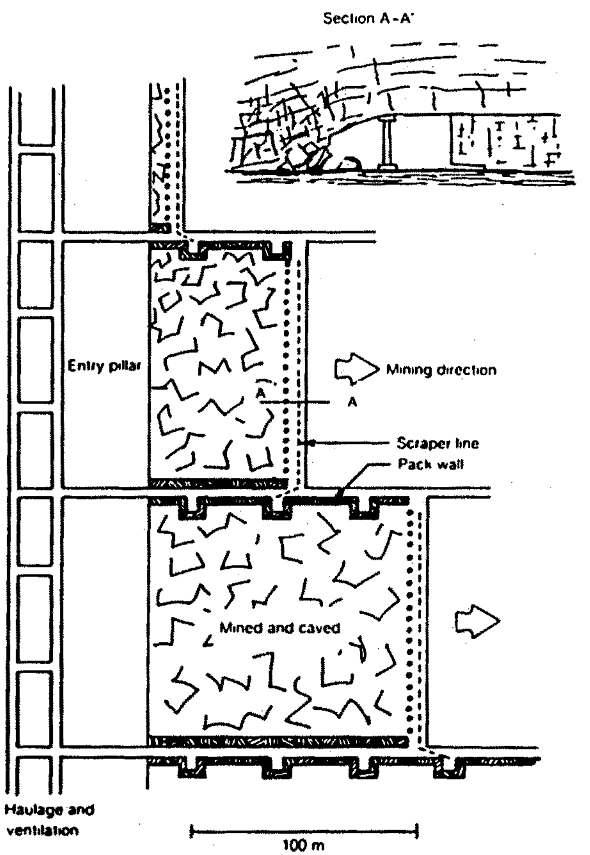
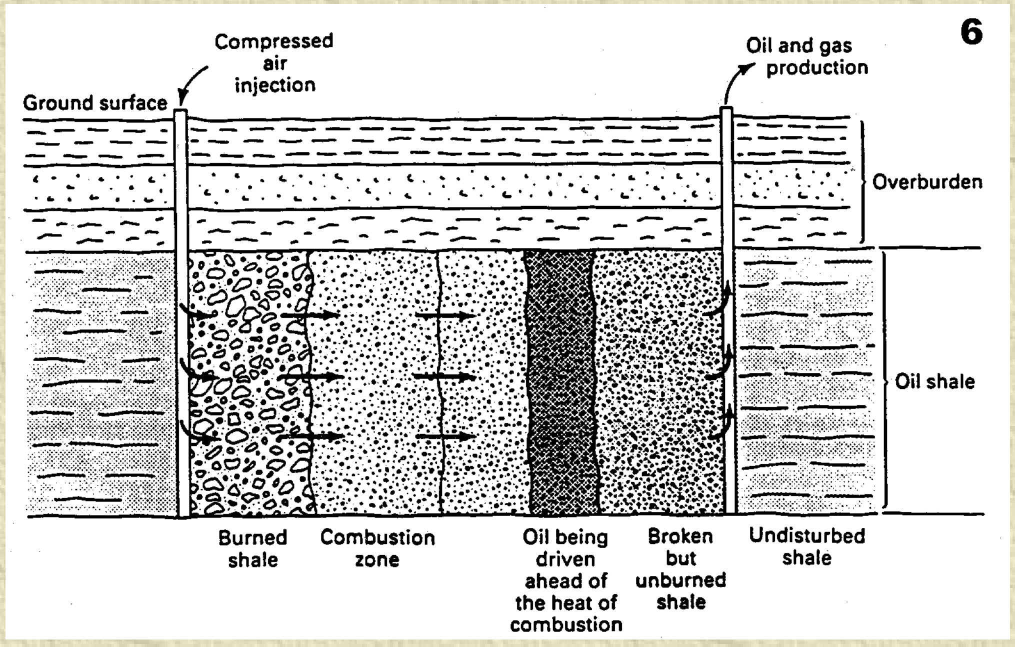


Figure 6.13. Mine plan, longwall advancing. (*Source:* From William H. Dennen and Bruce Moore, *Geology and Engineering*. Copyright © 1986 Wm. C. Brown Publishers, Dubuque, Iowa. All rights reserved. Reprinted by permission)

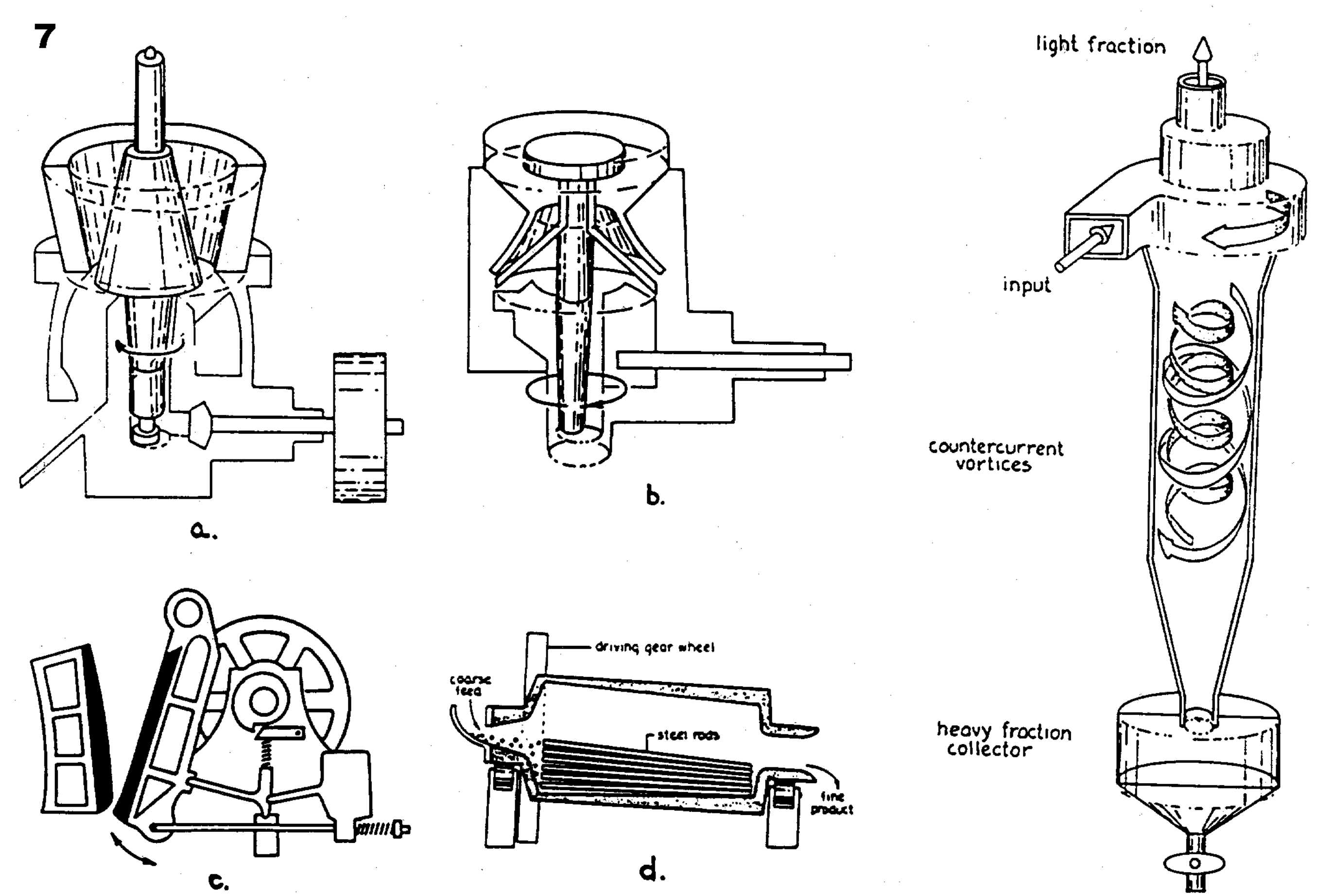
Still Others - OH-6

- [5] In-situ recovery: possible for oil shale (burn front) see Figure
- [6] Heap Leaching as The Cheapest Way


6
Compressed air injection
Oil and gas production
Ground surface
Overburden
Oil shale
Burned shale
Combustion zone
Oil being driven ahead of the heat of combustion
Broken but unburned shale
Undisturbed shale

Milling: Sizing & Separation-OH-7

- "bust it up and classify it"
- breaking method depends on tensile and compressional strengths
- classifying depends on size, shape, density, magnetic properties, ...
- various types of crushers: gyratory, cone, jaw, ball/rod mill
- sorters: grizzlies, screens, cyclones, flotation, settling velocity, shaker table
- hydrometallurgy, pyrometallurgy

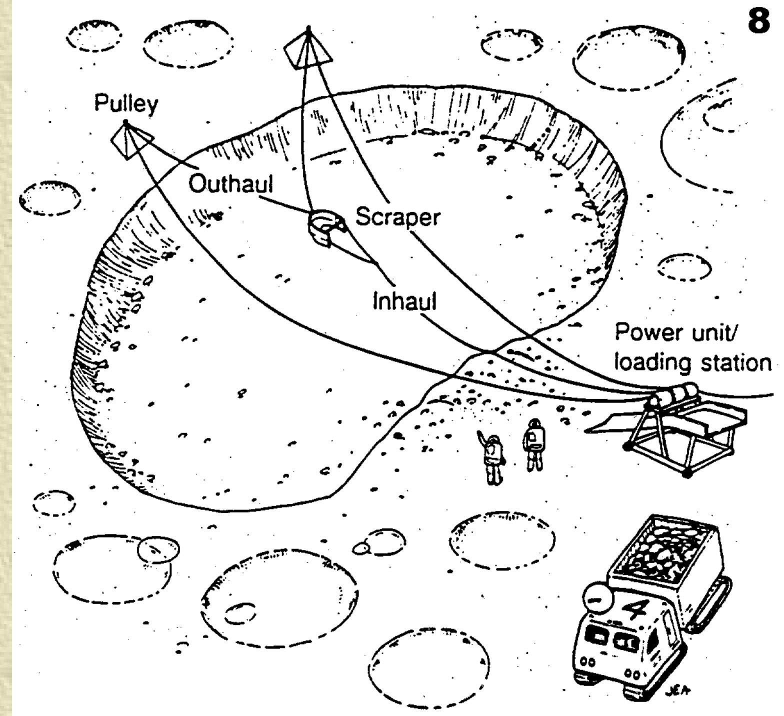

7
light fraction
input
countercurrent vortices
heavy fraction collector
a.
b.
driving gear wheel
coarse feed
steel rods
fine product
c.
d.

Lunar Sizing and Separation

- Magnetic separators - Fe/Ni particulates - 0.1%
  - agglutinate problem
- Electrostatic processes
- Sieving - need a fluid
  - Liquid O_2?

Lunar Regolith - 1 - OH-8

- Mobile Slusher
  - able to move from site to site as needed
- Stationary Slusher
  - simpler, lighter
  - would need help getting around
- Both are 3-drum cable tools which can reach any area defined by the location of the power unit and the 2 anchor pylons


8
Pulley
Outhaul
Scraper
Inhaul
Power unit/
loading station

Lunar Regolith - 2

- Scraper fills because of combination of in-haul forces and weight of the scraper
- Looks like a simple operation but at present this would probably have to be run by people either on site or by teleoperation. We still couldn't automate even this simple process.
- Ability to change from scraper to rake to ripper to plow.
  - Lower levels of regolith will probably need to be broken up.
  - Explosives? Design of ripper or plow?

Weight, mass, inertia, friction, traction -1

- Inertia not weight is the real problem with moving things and, as this is a function of mass not weight, the lack of gravity is not a real bonus
- Fracturing and evacuation equipment on Earth uses gravity as the hold-down mechanism. Something else will have to take its place.
- On Earth, loading equipment operates near its traction limit
- Reduced gravity creates a less favorable inertia: traction ratio

Weight, mass, inertia, friction, traction -2

- Can increase traction by increasing mass (which makes for inertia problems)
- Once anchored, the slusher fills basically in response to the in-haul force which is traction independent. The bucket will have to be more massive but this may be accomplished by using onsite rocks for ballast.
- Fracturing provides initial velocity to rock particles/pieces. On Earth these pieces rapidly loose their V and accumulate; at zero gravity you have an out-of-control 3-D billiard game.

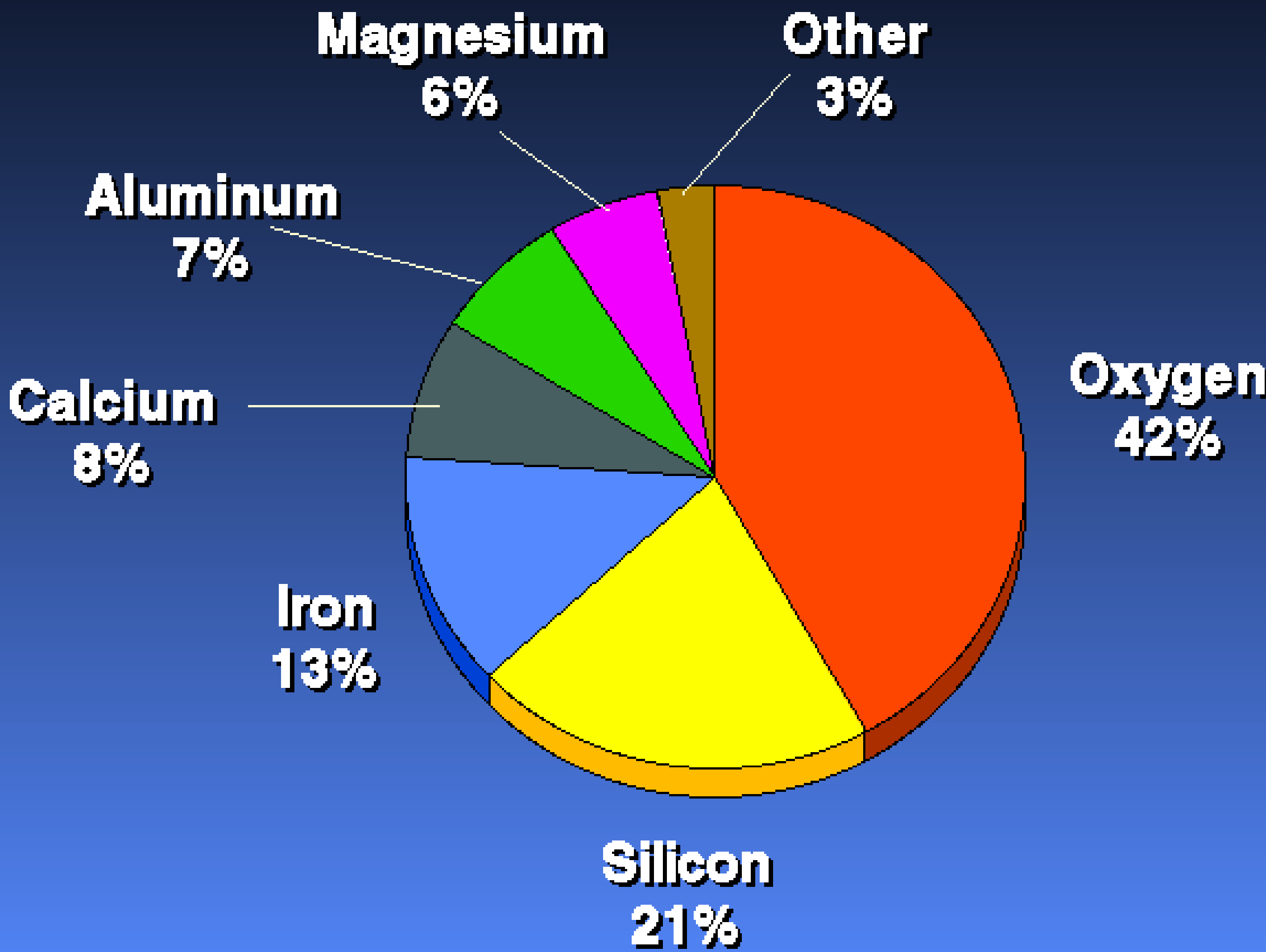
Specific Lunar Examples: Ti, Fe, Al, Ca

- Where do these elements come from on Earth?
- Titanium recovered from rutile TiO_2 or ilmenite $FeTiO_3$ - both primary igneous minerals.
- Iron recovered from simple oxides or carbonates or sulfides - both sedimentary and igneous sources
- Aluminum recovered from oxides and hydroxides - deep weathering, or possibly from the pre-weathering igneous rock
- Calcium (for cement) recovered from sedimentary limestone

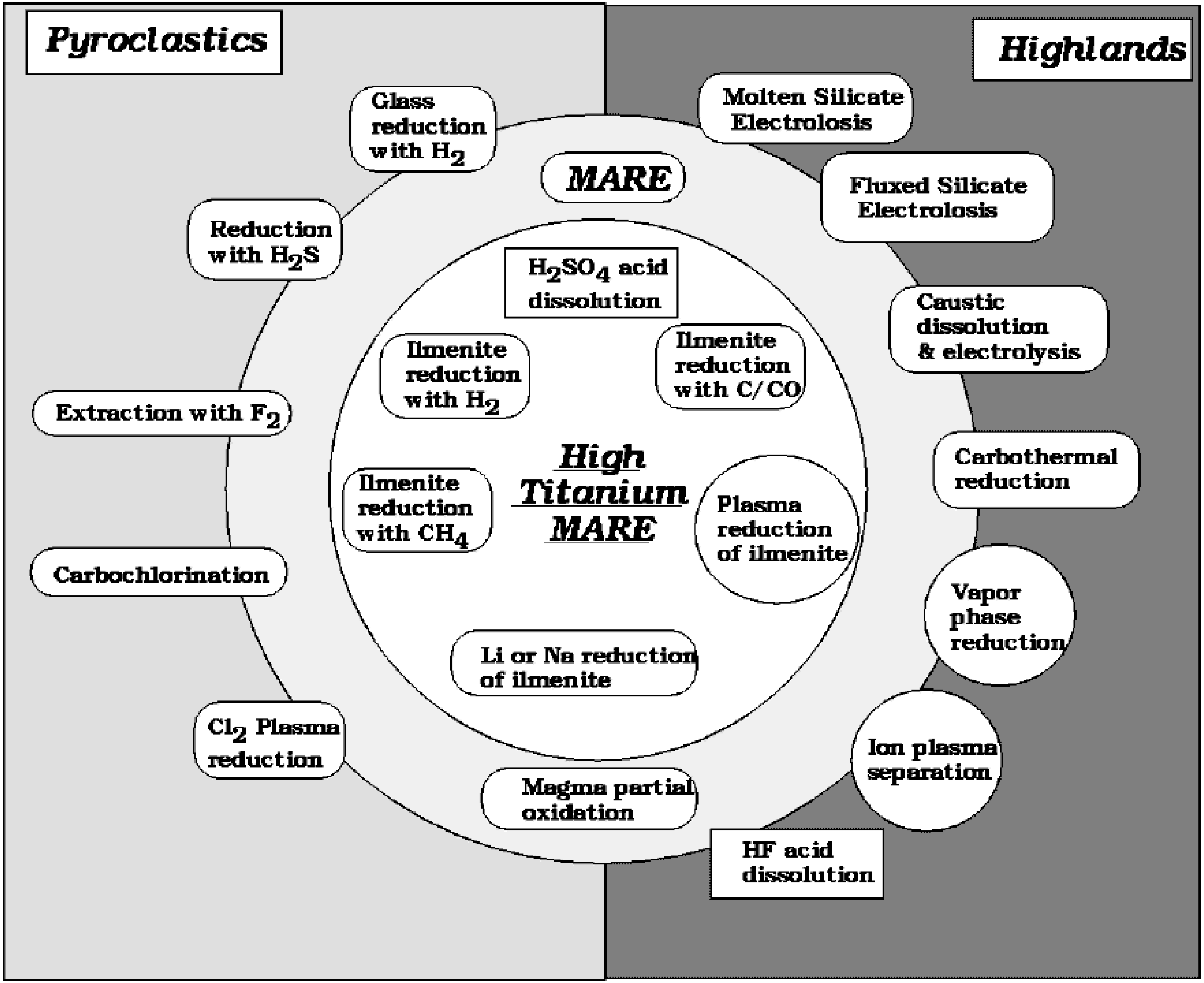
Lect. 13 Recap - 1

- The lunar soil composition pie chart (Lec. 13, Slide 3) shows what is most available.
- Lec. 13, Slide 5 pointed out that O_2 could be recovered from all the different lunar rock types and thus we might be processing any of these
- The metal-oxygen bond strength graphic (Lec. 13, Slide 6) applies whether you are trying to recover oxygen or the metals

Lunar Soil Composition



The Feedstocks for Oxygen Production Can Come From Different Locations and Host material

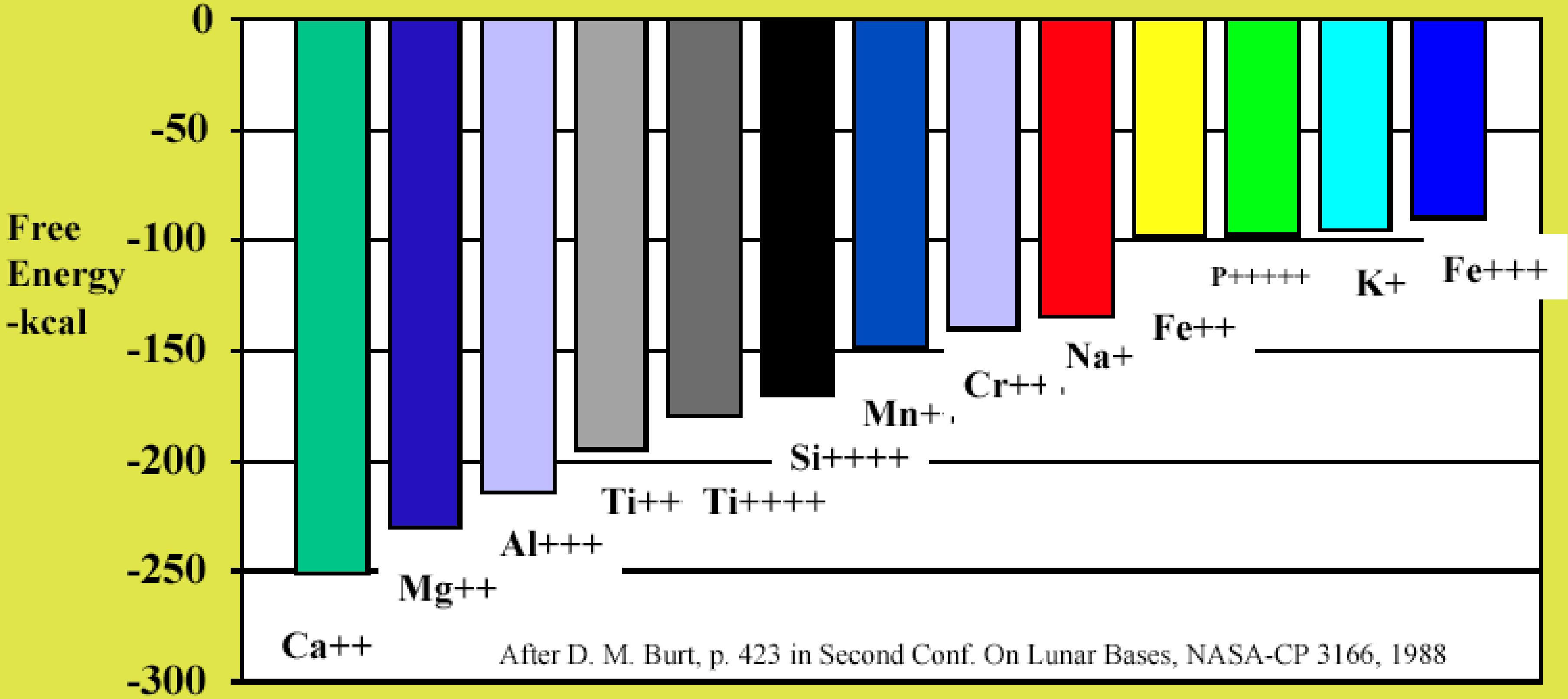


There at Least 20 Ways to Extract Oxygen from Lunar Material

Taylor & Carrier (1993)

	Solid/Gas Interaction	Silicate/Oxide Melt	Pyrolysis	Aqueous Solutions
Most Favored	Ilmenite Reduction With H2 Glass Reduction With H2	Molten Silicate Electrolysis Fluxed Silicate Electrolysis	Vapor Phase Reduction	
Possible	Ilmenite Reduction C/CO Ilmenite Reduction CH_4 Plasma Reduction Cl_2 Reduction H_2S	Caustic Dissolution & Electrolysis Carbothermal Reduction	Ion Plasma Separation	
Long Shot	Carbochlorination Extraction with F_2	Magma Partial Oxidation Li or Na Reduction of Ilmenite	Plasma Reduction of Ilmenite	HF H_2SO_4

It is Hardest to Extract Oxygen from Ca and Easiest from Fe



Lect. 13 Recap - 2

- Fig. 7 schematically shows production of TiO_2 from ilmenite - next stop, Ti?
- Figures 13, 14, and 15 show variations on melting lunar source materials and generating either ceramics (=bricks?) or metals by electrolysis
- Other possibilities:
  - platinum group elements from the meteoritic component of the regolith
  - native iron from old mature regolith

The Use of Hydrogen to Reduce Ilmenite for the Production of Oxygen Was First Proposed by Williams in 1979

- Ideal formula-$FeTiO_3$
- Actual Ilmenite composition-Apollo-12

TiO_2	52-54%
FeO	45%
Al_2O_3	0.3-0.4%
Cr_2O_3	0.2-0.4%
MgO	0.1-0.4%
MnO	0.3-0.4%

(Can be beneficiated from Mare Basalt rocks and Mare soils)

Reduction Reaction

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

Oxygen Can Be Extracted From Molten Silicates

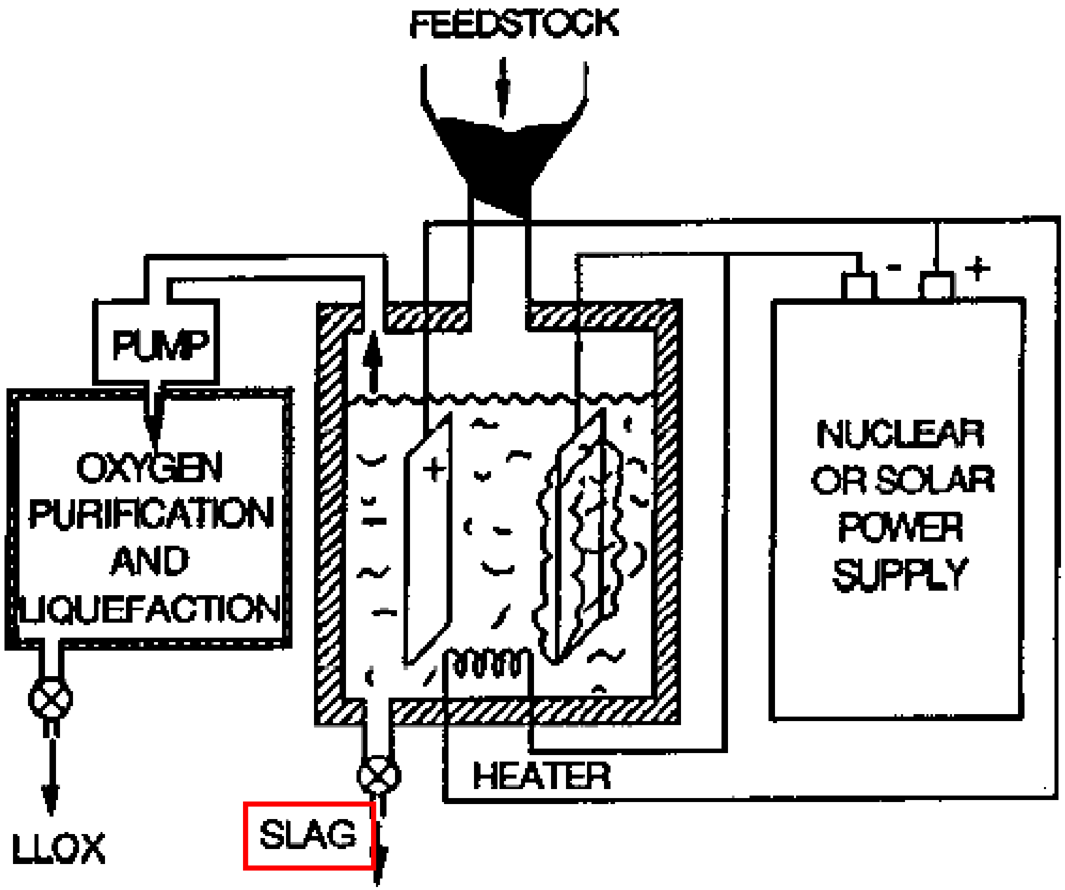
Anorthite
$CaAl_2Si_2O_8$

Olivine
$(Mg,Fe)_2SiO_4$

Pyroxene
$Ca(FeMg)Si_2O_6$

Chromite
$FeCr_2O_4$

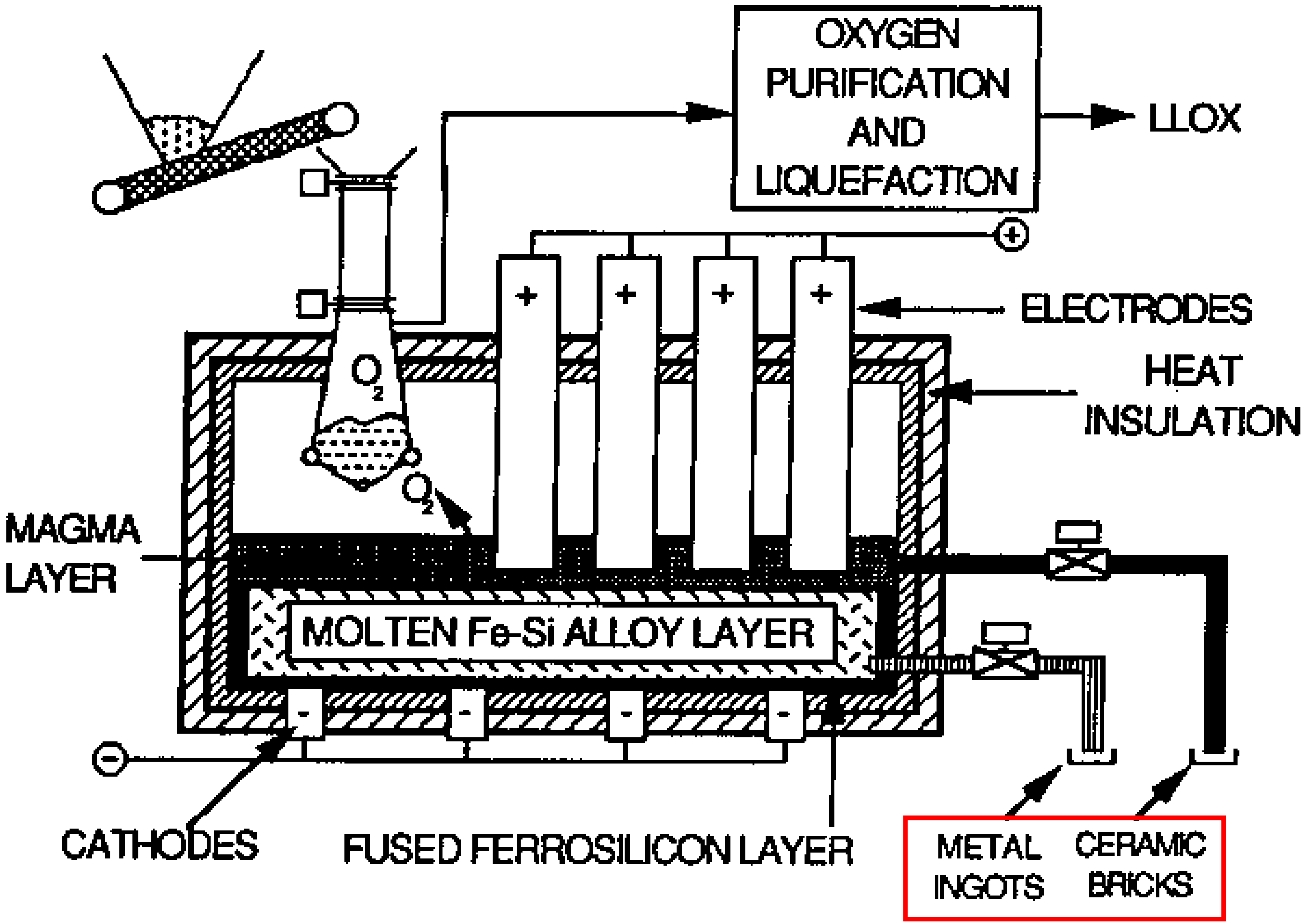
Ilmenite
$FeTiO_3$



- **Advantages: No moving parts, one step oxygen production**
- **Disadvantages: High temperatures, 1300-1700 °C, corrosion**

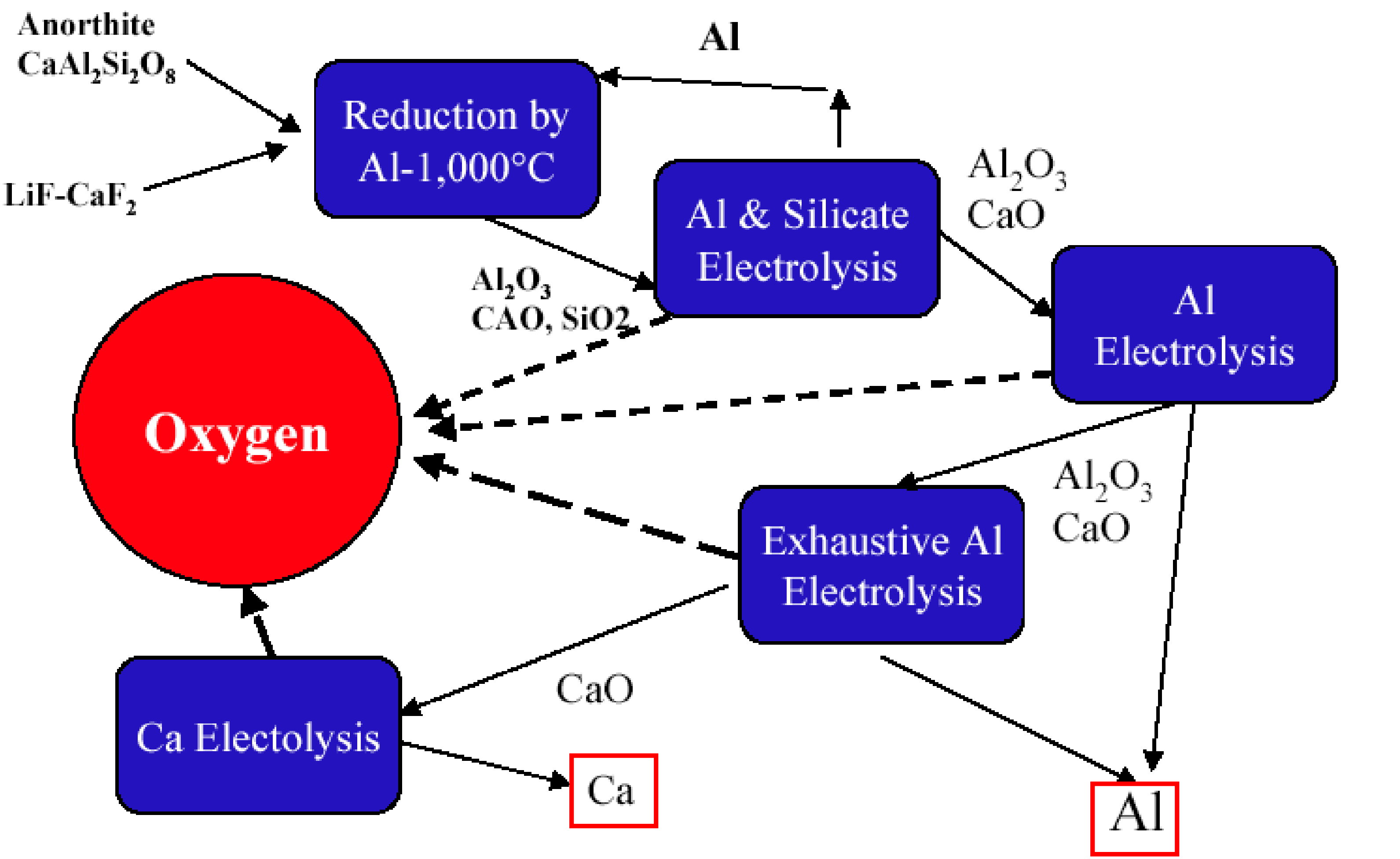
After L. A Taylor and W. D. Carrier III, in Resources of Near-Earth Space, Univ. of Arizona Press, (1993)

Many Other Useful Products Can be Derived From the Molten Silicate Process



After McCullough and Mariz (1990), "Lunar Oxygen Production via Magma Electroysis", in Engineering, Construction and Operations in Space II: Proc. Space 90 (New York: Amer. Soc. of Civil Engrs.), pp. 347-356.

The Fluxed Molten Silicate Process Can Produce Oxygen More Efficiently at Lower Temperatures



Asteroidal Mining

- Probably start with a near-earth Amor, Apollo, or Aten asteroid
- Some asteroidal material is very easily crushed and may be processed easily
  - long lead time increases expenses
  - long duration manned mission
  - automated or teleoperated mission

Asteroidal Mining

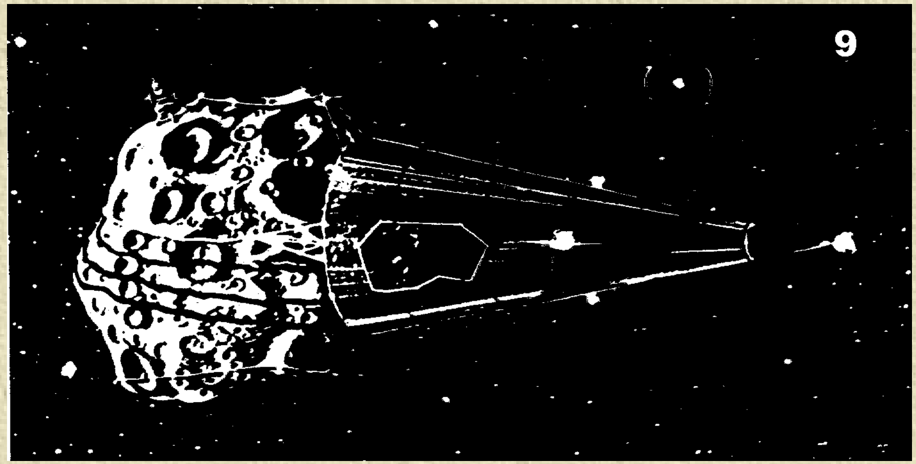
- slow long low DeltaV equipment arrival combined with faster high DeltaV manned portion
- Problems with manned mission:
  - long exposure to zero gravity
  - solar radiation
  - life support
  - manned deep space vehicle

Problems with automation or teleoperation

- slow progress on doing this on Earth
- so many unknowns which might require a human touch to overcome
- time lag of teleoperation may make it impossible to respond soon enough to keep disaster at bay

Possible solution to low gravity problems

- Cable the mining equipment to the small asteroid.
- The cable holds both the fracturing/removal equipment and the collecting `bag' to the surface of the asteroid. The bag maintains its shape because the asteroid is spinning; this spinning also helps collect the broken material into the bag.
- Material needs to be boosted with enough energy to pass the synchronous orbit limit so that centripetal force collects it into the bag.
- Blasting could be an alternative but would have to be done very carefully. - OH-9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Extraterrestrial Mining Problems for Research - 1

- How should mechanical equipment be modified for operation in reduced gravity? (excavation, loading, moving)
- Remote and automated mining. What progress has been made on Earth?
- Environmental effects: extremes of heat and cold
- Applicability of terrestrial techniques to low gravity, no atmosphere situations.

Extraterrestrial Mining Problems for Research - 2

- Changes in traction and how to compensate:
  - traction is function of gravity and friction
- Changing role of blasting in low gravity settings; vacuum will also affect blast
- Wear resistant materials

Extraterrestrial Mining Problems for Research - 3

- Particle size reduction in low gravity settings
  - design of crushers; substitute for wet grinding and separating?
  - Classifiers
- Rock drilling: - OH-10
  - conventional drilling: drilling mud? friction?
  - melting and vaporization; chemical reaction; heat induced spalling; mechanical stress; spark cratering

6. Rock drilling on the Moon