Extraction Techniques for Minerals in Space

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

- Orebody shape is function of its mode of formation (and subsequent history):
  - 2-D sheetlike 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

- $f(\text{overburden thickness, topography, geometry and grade of ore})$
- pit wall angle: $45^\circ$ for rock; $30^\circ$ for unconsolidated material - $f(\text{gravity, cohesion})$
- pits may lead up to underground operations (or the reverse) over time
  - once infrastructure in place and paid for…
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 (tunnels), raises (shafts)
- artificial supports commonly needed
What would be a major advantage of underground mining on the moon?

- Temperature control?
- Radiation control?
- Live in the excavation - Badgers again!
[1] Shrinkage Stope

- The 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.
[2] Cut and Fill

- 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
Lunar Applicability?

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

- **Because** “vertical tabular” generally means “veins” formed by hydrothermal fluids - these are likely to be absent on the moon

- Is anything on the moon likely to be “waste” once it is picked up and processed?
[3] Sublevel or Block Caving

- used in weak ore which may not be safe to mine in other ways
- low cost
- LOTS of pre-ore recovery development needed
- problems with ore dilution and surface disturbance
Advance or Retreat Mining

- **Advance** more common because quicker return on investment
- **Retreat** common in some coal mines
- May lead to surface subsidence
- Figure a Plan view
Unlikely Methods in Space but…

- [5] *In-situ* recovery: solution mining (+bugs)
  - *in situ* burning possible for oil shale
- [6] **Heap Leaching** as The Cheapest Way
Milling: Sizing and Separation

- "bust it up and classify it"; **most energy used here**
- 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
Lunar Sizing and Separation

- Magnetic separators - Fe/Ni particulates - 0.1%
  - agglutinate problem and size problem
- Electrostatic processes
- Sieving - need a fluid
  - Liquid O₂?
Lunar Regolith - 1

- 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
3-Drum Cable Slusher
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?
Because *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.
Can increase traction by increasing mass (which makes for inertia problems of the equipment)

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.

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.
Rock Breakage

- a. Spalling
- b. Melting and Vaporization
- c. Mechanical Stress
- d. Chemical Reaction
- e. Spark Cratering
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 Regolith Composition

Lunar Soil Composition

- Oxygen: 42%
- Silicon: 21%
- Iron: 13%
- Calcium: 8%
- Aluminum: 7%
- Magnesium: 6%
- Other: 3%
The Feedstocks for Oxygen Production Can Come From Different Locations and Host material

**Pyroclastics**
- Glass reduction with $\text{H}_2$
- Reduction with $\text{H}_2\text{S}$
- Extraction with $\text{F}_2$
- Carbochlorination
- $\text{Cl}_2$ Plasma reduction

**MARE**
- $\text{H}_2\text{SO}_4$ acid dissolution
- Ilmenite reduction with $\text{H}_2$
- Ilmenite reduction with C/CO
- Plasma reduction of ilmenite
- Li or Na reduction of ilmenite
- Magma partial oxidation
- HF acid dissolution

**High Titanium**

**MARE**

**Highlands**
- Molten Silicate Electrolysis
- Fluxed Silicate Electrolysis
- Caustic dissolution & electrolysis
- Carbothermal reduction
- Vapor phase reduction
- Ion plasma separation
Fig. 7 schematically shows production of TiO$_2$ from ilmenite - next stop, Ti metal?

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$_2$O$_3$ 0.3-0.4%
  - Cr$_2$O$_3$ 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

$$\text{FeTiO}_3 + \text{H}_2 \leftrightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O}$$
Oxygen Can Be Extracted From Molten Silicates

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

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

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

- **Anorthite CaAl₂Si₂O₈**
- **LiF-CaF₂**

**Oxygen**

- **Ca Electrolysis**
- **Al Electrolysis**

**Reduction by Al-1,000°C**

**Al & Silicate Electrolysis**

- **Al₂O₃ CaO**
- **Al₂O₃ CaO, SiO2**

**Exhaustive Al Electrolysis**

- **CaO**
- **Ca**
- **Al**
Asteroidal Mining
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.
Tag it and Bag it
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:
  - conventional drilling: drilling mud? friction?
  - melting and vaporization; chemical reaction; heat induced spalling; mechanical stress; spark cratering