Harvesting NEOs: The Mining Engineering Perspective

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Outline

• Mining terms
• Small-body classification for mining
• Unit operations
• Stages in the life of an asteroid mine
• Mining methods
Mining

• mining = extraction of geologic materials for use

• mining engineering = applying science, engineering fundamentals, and appropriate technology to recover geologic materials
Mineral deposit = a naturally occurring concentration of geologic material

- ore = anything that can be mined for a net benefit
  - may include one or several target substances
- most mineral deposits are not ore, because
  - the concentrated material is not of interest; or
  - the deposit is too small; or
  - the material is in an un-extractable form

- gangue = unwanted material intermixed with the target substance
More Mining Terms

• reserves vs. resources
  – reserves = ore known to exist, and available to mine
  – resources = potential ore

• recovery = proportion of in-place target substance that can be separated from waste material

• dilution = amount of waste material inextricably bound to target substance
Small-Body Classification for Mining
Apply to All Asteroids and Comets

- **Group 0. Ice composites**
  - Very weak, mostly ices with or without organic compounds.

- **Group 1. Friable rock**
  - Similar to Group 0, but with low volatile amounts. Weak.

- **Group 2. Hard rock**
  - Strong and brittle, the most similar to materials encountered in terrestrial mining practice.

- **Group 3. Metallic:**
  - 3a. Massive metal – may be ductile.
  - 3b. Rock-metal composites – would fracture mainly at rock-metal interfaces.
Group 0 Example: Comet Churyumov-Gerasimenko
Group 1 Example: Mathilde(?)

(Student宿舍)
Group 2 Example: Ida(?)
Group 3b Example: Lutetia(?)
Unit Operations
Mining Unit Operations

• generic fundamental activities to acquire ore while minimizing handling of gangue

• terrestrial basics:
  – fragmentation – detach ore from surrounding mass
  – excavation – remove ore from surroundings – often combined with fragmentation
  – transportation – move ore through the process
  – beneficiation – increase the concentration of target substance
  – support activities
Fundamental Constraints

• terrestrial:
  – unidirectional, constant-magnitude gravity vector
  – energy scarcity
  – mass abundance
  – difficult deposit access
  – originally derived from human physical capabilities

• asteroids:
  – variable gravity vector
  – energy abundance
  – launch mass limitations
  – difficult location access
  – difficult human participation
Example: Sand & Gravel Pit

• fragmentation, excavation, and some transportation accomplished by track hoes
• beneficiation is by simple size separation
• further transportation is by truck
• site maintenance is by bulldozer
Example: Large Open-Pit Gold Mine

- fragmentation is by drilling-and-blasting
- excavation is by hydraulic excavator
- transport is by truck
- liberation is by crushing and grinding
- separation is by carbon adsorption & cyanide leaching
Example: Underground Copper Mine

- fragmentation is by drilling-and-blasting
- excavation is by load-haul-dump
- transportation is by truck, conveyor, & hoist
- liberation is by crushing and grinding
- separation is by froth flotation
Example: Underground Salt Mine

- liberation is by chemical dissolution
- transport is by slurry pipeline
- concentration is by evaporative precipitation
Stages in the Life of an Asteroid Mine
Asteroid Mining Sequence: Prospecting

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO

6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation
Asteroid Mining Sequence: Exploration

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
   a) surface properties
   b) internal properties
   c) orbital properties
5. prepare NEO
6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation
Asteroid Mining Sequence: Development

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
   a) anchor and tether
   b) control NEO motion
   c) restrain NEO
5. prepare NEO
   d) install operations platforms
   e) bag all or part of NEO
   f) install support equipment
6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation
Asteroid Mining Sequence: Acquisition

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
   a) access the ore
   b) remove the ore
7. ore beneficiation
8. transport
9. closure & reclamation
Asteroid Mining Sequence: **Beneficiation**

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO

6. mining operations
7. ore beneficiation
   a) liberation
   b) separation
8. transport
9. closure & reclamation
Asteroid Mining Sequence:

Transport

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
7. ore beneficiation
8. transport
   a) supplies & support
   b) mining
   c) processing
   d) marketing
9. closure & reclamation
Asteroid Mining Sequence: Closure

1. decide on target substance
2. locate target NEOs
3. gain access to NEO
4. characterize NEO
5. prepare NEO
6. mining operations
7. ore beneficiation
8. transport
9. closure & reclamation
   a) remove/recycle equipment
   b) prevent future problems
Mining Methods
Mining Method

• how the unit operations are accomplished for a given deposit type
  – same unit operations can be accomplished by various technologies
  – take advantage of environment and orebody characteristics – terrestrial examples:
    • block caving uses gravity and the fracturability of the rock mass to fragment and excavate the ore
    • longwall mining uses differences in fracturability of coal and sandstone to control stability of the rock mass
    • mills built on hillsides use gravity to transport ore through beneficiation steps
Target: Volatile Ices

• mining method derived from in situ solution and block caving

• likely asteroids:
  – Group 0

• mining sequence:
  – primary fragmentation
  – bagging of major fragments
  – heating
  – fragmentation of refractory portion(s)
  – repeat as needed
Target: REEs

- mining method derived from bulk mining of disseminated metal orebodies
- likely asteroids:
  - Groups 1-3
- mining sequence for spin caving:
  - maintain or increase body spin
  - set up two opposing bags sized for half the body
  - blast even-massed layers off both ends simultaneously – repeat
  - wind up and release inter-bag tether to segregate fragments
Target: PGEs

- mining method derived from narrow-vein deposit methods
- likely asteroids:
  - large, cohesive Group 2 bodies
- mining sequence:
  - locate vein outcrops
  - fragment & excavate with gripper-based continuous miner
Target: Native Metals

- mining method derived from smelting
- likely asteroids:
  - Group 3a, some Group 3b
- mining sequence:
  - bag the body
  - solar concentrator for differential heating
What About Rubble Pile Asteroids?

- it depends on particle compositions & sizes
- gain experience with small, monolithic bodies
  - mineral economics determines minimum size
  - orbital dynamics and rock strength determine maximum size
- then “move up” to multi-component bodies
Mining Method w.r.t. Asteroid Size

• smallest bodies likely to be monolithic and free of regolith cover
• intermediate-sized bodies may require hierarchical approach:
  – fragment into sizes amenable to small-body methods
• largest bodies may be amenable to underground mining techniques
  – especially if ore occurs in narrow veins
Questions?
Backup Slides
Generic Resource Extraction

1. Resource Assessment
   - Prospecting
     - 1.1
   - Exploration
     - 1.2
   - Development
     - 1.3

2. Resource Acquisition
   - Atmospheric Gases
     - 2.1
   - Subsurface Liquids & Gases
     - 2.2
   - Regolith
     - 2.3
   - Rock
     - 2.4
   - Mixed Materials
     - 2.5
   - Openings as Product
     - 2.6
   - Waste Materials
     - 2.7

3. Resource Beneficiation
   - Phase Change
     - 3.1
   - Particle Size Change
     - 3.2
   - Separation
     - 3.3
   - Materials Handling
     - 3.4

4. Site Management
   - Site Planning
     - 4.1
   - Dust Control
     - 4.2
   - Anchoring & Tethering
     - 4.3
   - Ground Stability
     - 4.4
   - Transportation and Storage
     - 4.5
   - Monitoring
     - 4.6
   - Auxiliary Operations
     - 4.7
   - Waste Management
     - 4.8
   - Closure & Reclamation
     - 4.9
Resource Assessment Components

- Prospecting
  - Compilation of Previous Data
    - Direct Methods
    - Indirect Methods
  - Direct Methods
  - Indirect Methods

- Exploration
  - Direct Methods
  - Indirect Methods

- Development
  - Detailed Site Information
    - Extraction Method Selection
    - Development
  - Extraction Method Selection
  - Development
Resource Extraction Components

- Subsurface Fluids
  - Interior
  - Exterior
  - Material Handling

- Rock
  - Fragmentation
  - Excavation
  - Material Handling

- Openings as Product
  - Surface-Access
  - Subsurface-Access

- Auxiliary Operations
  - Ground Stability
  - Anchoring
  - Dust Control

- Anchoring
- Mixed Materials
  - Volatiles from Regolith
  - Mixed Waste Materials

- Waste Materials
  - Gaseous Waste
  - Liquid Waste
  - Solid Waste

- Mined Waste Handling

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Resource Beneficiation Components

Phase Change
- Gases → Other Phases
  - 3.1.1
- Liquids → Other Phases
  - 3.1.2
- Solids → Other Phases
  - 3.1.3
- Process Monitoring
  - 3.1.4

Particle Size Change
- Comminution
  - 3.2.1
- Agglomeration
  - 3.2.2
- Process Monitoring
  - 3.2.3

Separation
- Plasma Separation
  - 3.3.1
- Gaseous Separation
  - 3.3.2
- Liquid Separation
  - 3.3.3
- Granular Solids Separation
  - 3.3.4
- Other Methods
  - 3.3.5
- Process Monitoring
  - 3.3.6

Materials Handling
- Batch Transport
  - 3.4.1
- Continuous Transport
  - 3.4.2
- Storage
  - 3.4.3
Mine Site Management

- Dust Control
  - Interior
  - Exterior

- Ground Stability
  - Surface
  - Subsurface
  - Whole-Body

- Site Monitoring
  - Infrastructure Performance
  - Ground Stability
  - Environmental Quality

- Waste Management
  - Disposal Site Preparation
  - Material Handling

- Closure & Reclamation
  - Site Closure
  - Reclamation
  - Long-Term Stabilization
  - Long-Term Monitoring

- Site Planning
  - Site Logistics
    - Site Preparation
  - Anchoring & Tethering
    - In Regolith
    - In Rock
    - Other Approaches
  - Transport & Storage
    - Batch Mode
    - Continuous Mode
    - Storage

- Auxiliary Operations
  - Power
    - Equipment Maintenance
  - Communications
    - Infrastructure Maintenance
  - Parts and Supplies
Mining

- mineral deposits form when natural processes segregate substances
  - if it's a substance humans can use, then the deposit is a potential orebody
  - most mineral deposits are not of interest, so aren't studied or mined

- natural segregation accomplishes part of the beneficiation required for extraction
  - can be as simple as the carbonaceous chondrite proportion of the NEO population
  - or as complex as PGE* veins in multi-lithology breccia

*platinum-group element
Mining Methods

• classified by access type
  – surface
  – underground

• classified by ground support type
  – naturally supported
  – artificially supported
  – unsupported, allowed to fail

• classification by deposit type
  – same unit operations often accomplished by various technologies / methods
Mining Methods by Access

• surface
  – open-pit
  – quarry
  – area mine

• underground
  – categorized by support type (next slide)
Mining Methods by Support Type

• naturally supported
  – room-and-pillar
  – sublevel stoping
  – longhole open stoping

• artificially supported
  – cut-and-fill
    • overhand
    • underhand
  – shrinkage stoping
  – vertical crater retreat

• unsupported – allowed to fail
  – longwall/shortwall
  – sublevel caving
  – block/panel caving
Mining Methods by Deposit Type

• fuel minerals
  – coal
  – uranium

• nonfuel minerals
  – base metals
  – precious metals
  – industrial minerals
  – construction materials

• rock type
  – hard rock (> 50-100 MPa)
  – soft rock

• petroleum

• water
  – fresh surface water
  – salt surface water
  – groundwater