Asteroid Mining Methods

Brad R. Blair
Mining Engineer, Mineral Economist
Space Studies Institute

Leslie S. Gertsch
Deputy Director, Rock Mechanics and Explosives Research Center
Missouri University of Science and Technology

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Overview

- What is **Mining**?
- Who is the **Customer**?
- How to **Mine Asteroids**?
- Preliminary **Requirements and Constraints** (mining vs. civil engineering of space objects)
- **Mining** and **Planetary Defense** – natural allies
- **Conclusions**

Mining Defined

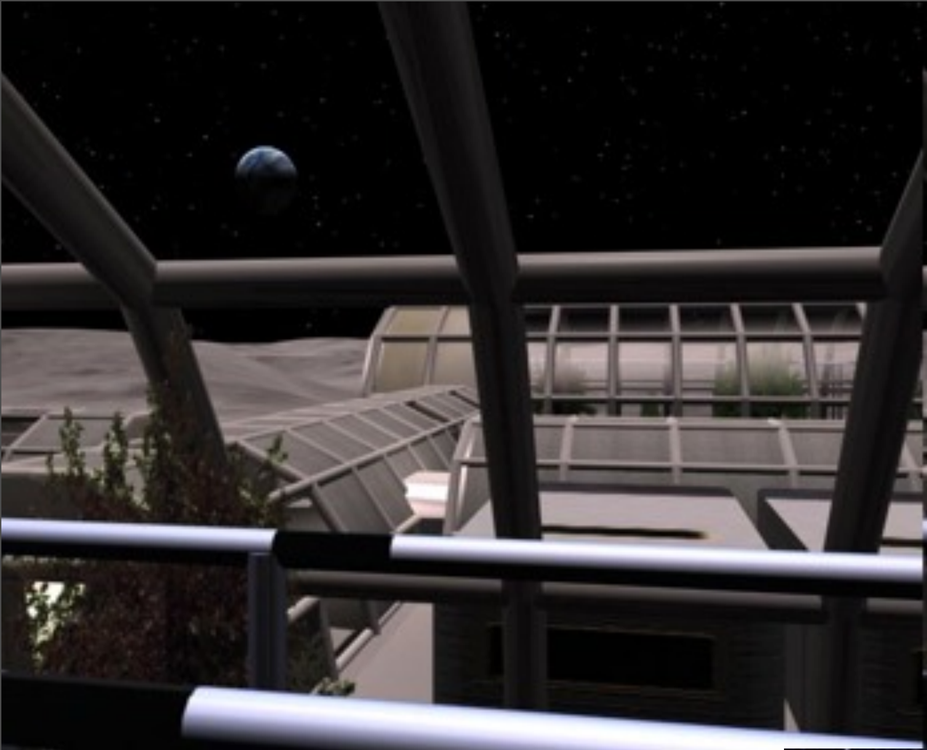
- Definition of **mining**
  - The extraction of *valuable minerals*, other geological materials, or any non-renewable resource
- Definition of **ore**
  - Any material that can be mined for a *net benefit*
- Mining is an ***economic activity***

Asteroid Customer Profiles

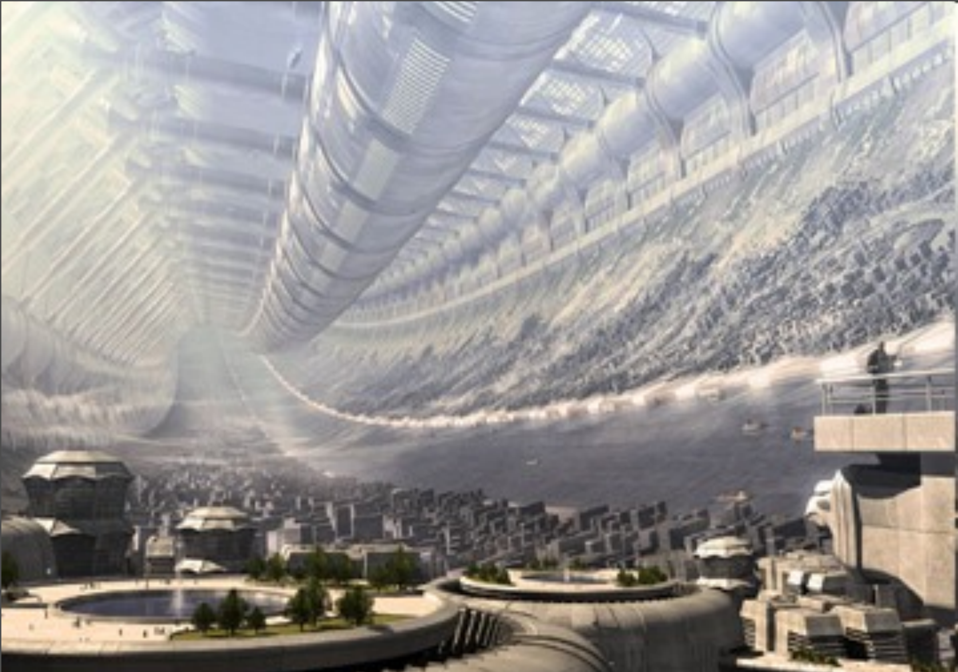
- Classified by **commodity** type (and limited by asteroid classification)
  - **PGMs** for terrestrial markets
  - **Volatiles** for propellant, life support
  - **Metals** for tanks, structures, construction, etc.
  - **Silicates** for ceramic composites
  - **Hydrocarbons** for plastics, propellant, food, etc.

- Classified by **consumer** type
  - Planetary **defense** apps (a.k.a. *Civil Engineering*)
  - Human space **exploration** & military uses of asteroid materials
  - **Construction** materials for G.K. O'Neil space colonies
  - Feedstock for Orbiting **Shipyards**
  - **Settlement** needs: fuel, food, water, housing, entertainment, etc.

sustainable space settlement ***duplicates most terrestrial activities***




Ark I Lifeboat Foundation Ark I




Preliminary Requirements Analysis

- Mining
  - Fragmentation
  - Moving / hauling
  - Separation
  - Melting
  - Containment
  - Processing
- Planetary Defense
  - Fragmentation
  - Moving / hauling
  - Containment
  - Separation

Note level of commonality between mining and planetary defense

Also note that this list is notional - more work is needed to capture a complete set of systems requirements and constraints

First-order Constraints

- Astrodynamics
  - Manifolds vs. Hohmann transfers
  - Earth-Moon vs. Earth-Sun Lagrange points destination
- Environmental conditions
  - Very low gravity, variable gravity vector
  - High vacuum
  - Hard radiation
  - Thermal cycling
  - Available sunlight & diurnal cycle
- Launch systems (payload mass & volume)
- Available energy (power sources)
- Maintenance & Repair (service life)
- Communication delays
- *Other system constraints will likely be identified as asteroid exploration and development advances…*

Asteroid Mining Process Steps

- Mine **development** and site **preparation**
  - Anchor to the NEO and attach tether
  - NEO motion control
    - partial or complete de-spin and de-wobble
  - Emplace body/fragment restraint system
  - Construct operations platform system
  - Emplace processing system
  - Emplace auxiliary and support equipment
- **Extraction**/modification operations
  - Mining
  - Beneficiation and Processing
  - Transport
- Orbit modification (**transport**)
  - Main body
  - Fragments

Required first

Simultaneous

Process steps, cont'd

- Principles of terrestrial mining include
  - Max productivity + revenues
  - Min costs + need for reclamation
  - Actions that lower risk are typical
  - Low maintenance / complexity technology is often preferred over higher productivity (perception of longer service life)
- Mine design process
  - Planning and sequencing of unit operations in time and 3D space
  - Extract the mineral of interest at the maximum net benefit (total benefits minus costs)
  - The capabilities required to make the mining method work are the first-order determinants
  - Mining methods are refined to the second and third orders by the constraints imposed by the technology choices made

Developing Mining Methods for Asteroids

- Types of mining methods:
  - Classified by fragmentation energy storage
    - Self-supporting
    - Artificially supported
    - Caving
  - Classified by access
    - Surface
    - Underground
  - Classified otherwise
    - Spin-assisted
    - Others?

- Mining method selection
  - Market (output) controls
    - Demand rate
    - Location
  - Geologic (input) controls

What to produce?
Who's buying it?

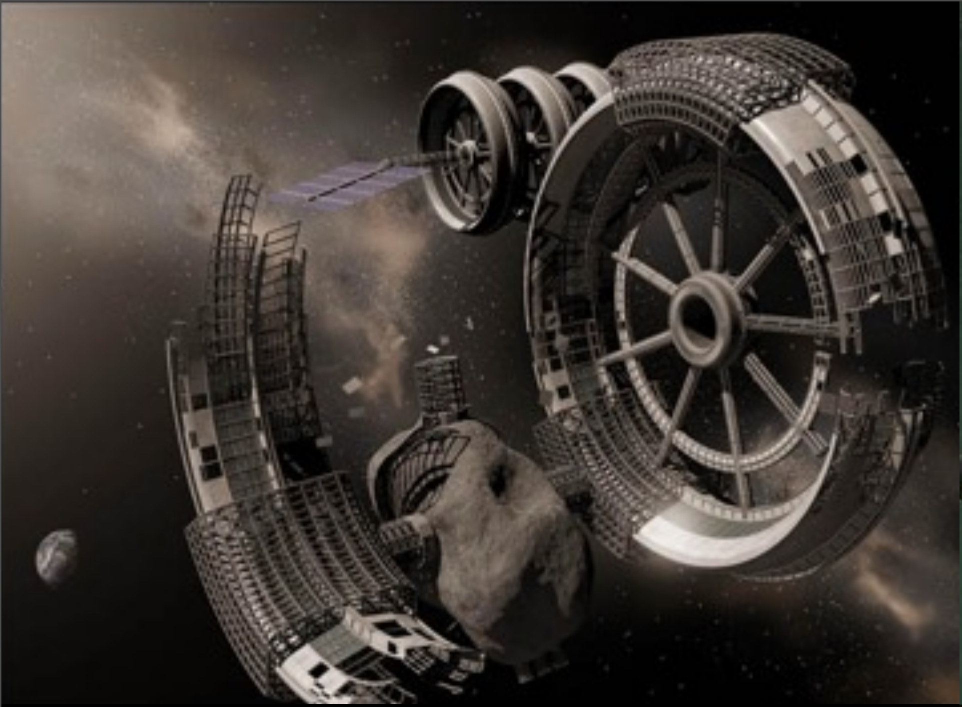
The answers determine the mining method

Asteroid mining methods

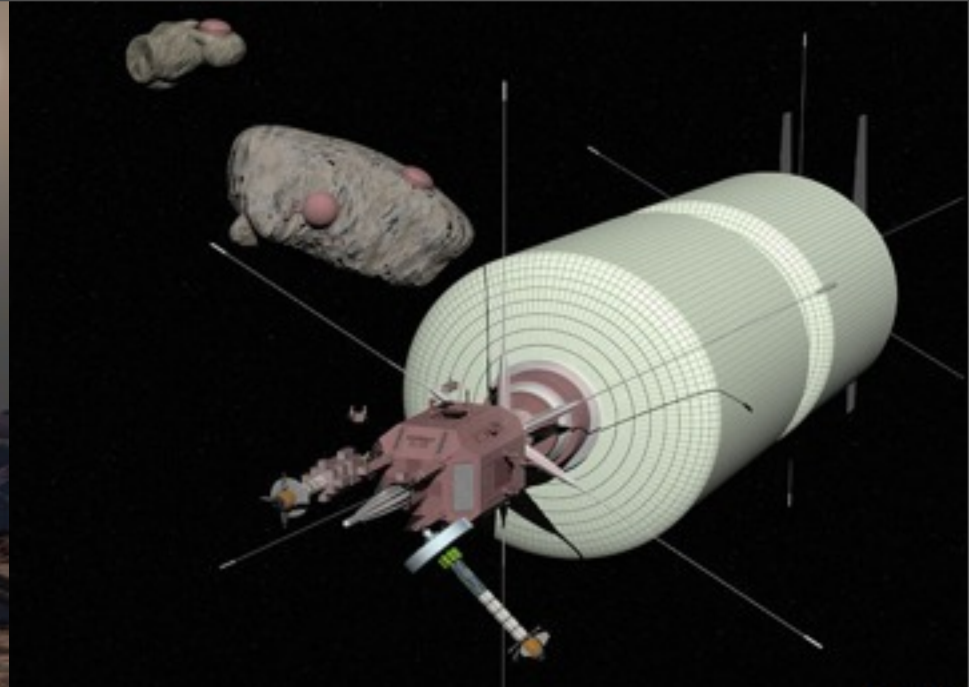
- Notional asteroid mining methods proposed in the literature can be abstracted into various categories
  - Bag & Boil => volatile extraction
  - Magnetic Rake => collect high grade ore
  - Divide & Deliver => take a smaller piece home
  - New Moon => put into earth orbit
  - Hot Knife => cut up a comet core with nuclear heat
  - Inside-out => remake it in your own image
  - Mosquito => remove the good stuff from under the shell
  - Laser torch => divide & conquer
  - Etc.

- Operational experience will determine which methods work (all of the above are theoretical at best)

- Note: There is a strong dependence between mining method and ore type / geomechanical properties…







Unit Operations

- The concept of “unit operations” is used in the mining industry to describe elements in the process that connects a pristine mineral occurrence to a deliverable commodity
- Elements of mining Unit Operations include
  - Resource Assessment – Determines what is available, where it is, what form it is in, and how it can best be extracted
  - Resource Extraction – provides raw materials from the local environment by removing them, concentrating them, and preparing them for further processing, manufacturing, or direct use
  - Resource Acquisition – Separates and removes the target raw material -- gas, liquid, and/or solid -- from its original location to Resource Beneficiation
  - Resource Beneficiation – Converts the raw material into a form suitable for direct use, manufacturing, or further processing
  - Site Management – Comprises supplemental capabilities needed for

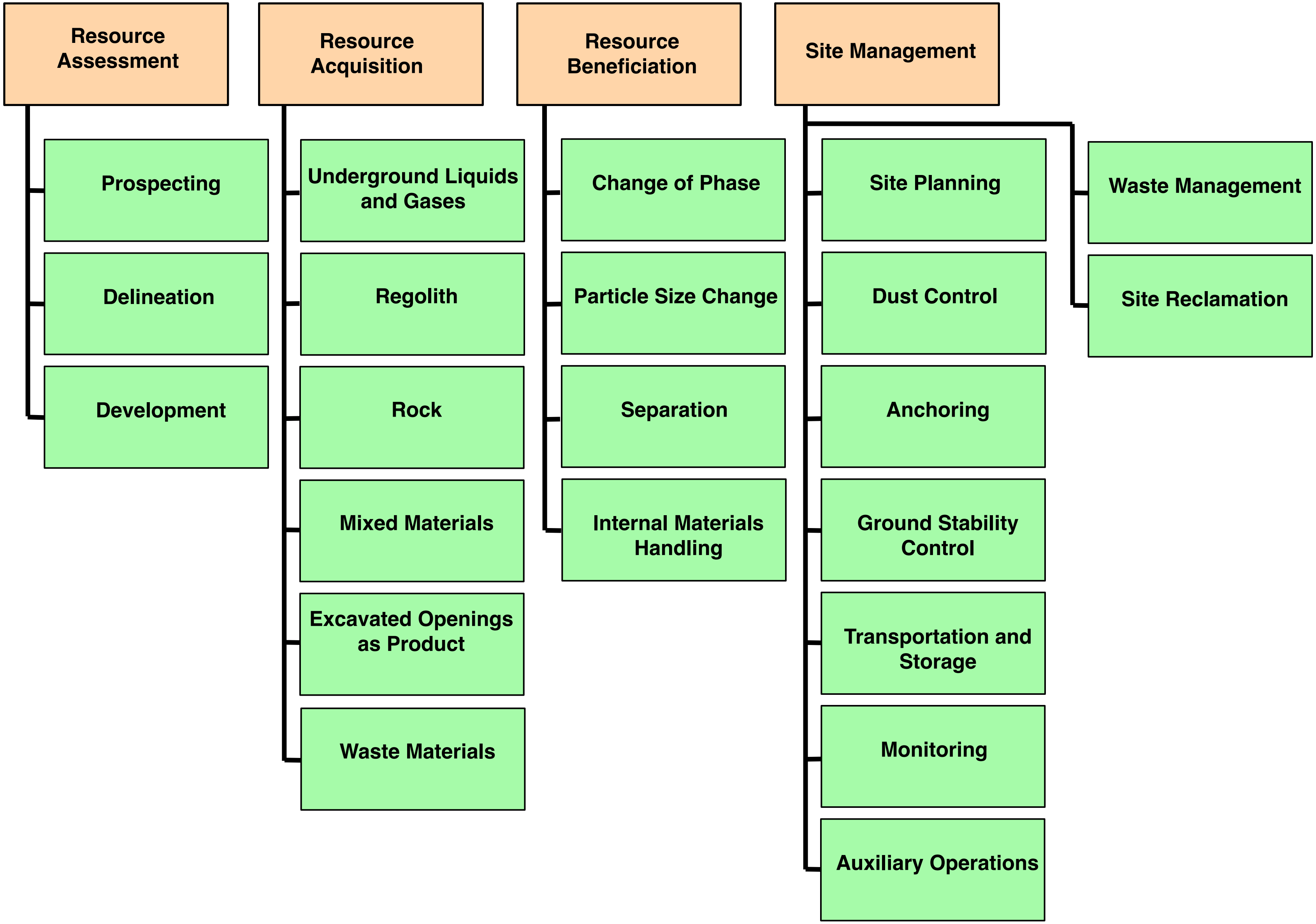
Capability analysis

- Several **technologies** usually can be applied to achieve the same ***capability***
- Drilling example (all create access to rock at depth)
  - mechanical excavation
    - down-the-hole hammer drilling
    - top-hammer drilling
  - chemical drilling
  - laser drilling
  - nuclear drilling
  - gnomes with picks and shovels…

Current Mining Capabilities

- Some **in-space capabilities** have already been demonstrated:
  - Scooping of regolith samples on the Moon and Mars.
  - Coring & drilling of regolith samples on the Moon.
  - Grinding and analysis of rock samples on the Moon and Mars.
  - Mars atmosphere capture and separation
  - Cryo-coolers demonstrated on satellites for long duration (Mars conditions).
- Present capabilities of **terrestrial resource extraction** include:
  - Semi-automated drilling/boring, fragmentation, excavation, and transportation of rock, both underground and on the surface.
  - Semi-automated pre-processing of gases, liquids, and solids into forms suitable for further processing, manufacturing, or direct use.
  - Production rates from a few liters/day to 200,000+ tonnes/day.
  - Successful operations:
    - from 4,600 m elevation to 3,800 m depth in the crust, and on the sea bottom;
    - in locations accessible only when the ground freezes, when it thaws, or

Required Asteroid Mining Capabilities



Asteroid Mining Gaps and Risks

- Gaps:
  - Products and target materials – better definition required
  - Extraction method depends on detailed resource information
  - Extraction and beneficiation also depend on detailed product specifications
  - Current data useful only for prospecting – better resolution required
  - Unknown mass/mission constraints – precise architecture required
  - Lunar and martian granular materials behavior poorly understood
  - Effects of lunar and martian environments on equipment technologies
  - Required capabilities are common to all environments
  - Only the technologies needed to achieve these capabilities vary
- Risks:
  - Prospecting uncertainty
  - Economic uncertainty (no current customers exist)
  - Systems reliability and costs
  - Effects asteroidal environmental conditions
  - Political and legal uncertain (e.g., property rights)
  - Terrestrial experience in resource extraction is broad and deep, but translating

Planetary Defense Synergies

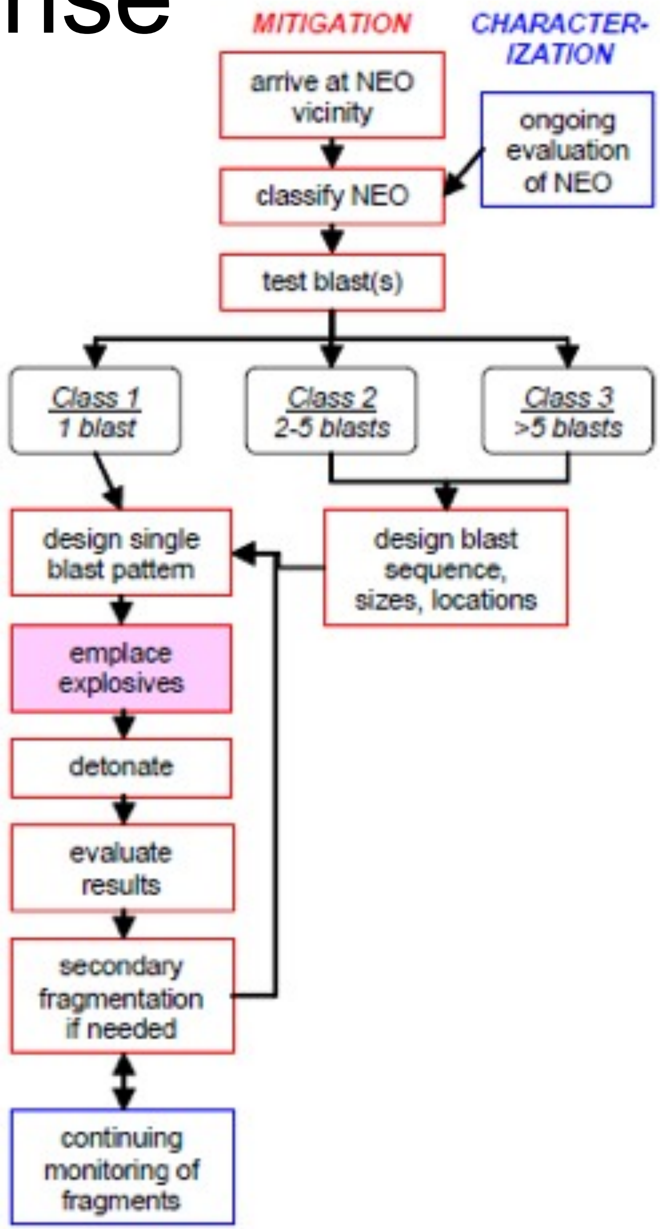
- Flood control analogy
  - Dams are built by USACE to avert floods
  - Power-generation and recreational facilities created by the impoundments provide benefits
  - Example of converting a hazard into a resource
- Asteroid mining could simultaneously de-threaten a PHA orbit while providing resources for space exploration
  - Public / private partnerships could leverage government resources with private capital
  - Partnership could extend limited liability to the private party and return valuable civil engineering data (dynamics of moving an asteroid)
  - Could help initiate a ‘space gold rush’

Mining for Planetary Defense

- Example asteroids classified:

	Class 1	Class 2	Class 3
Group 0			*Wild2*
Group 1		*Itokawa*	
Group 2			*Eros*
Group 3a			*1986 DA*
Group 3b			

- Controlled fragmentation process →
  - explosives emplacement needs R&D
  - resource extraction possible concurrently but is not the main focus



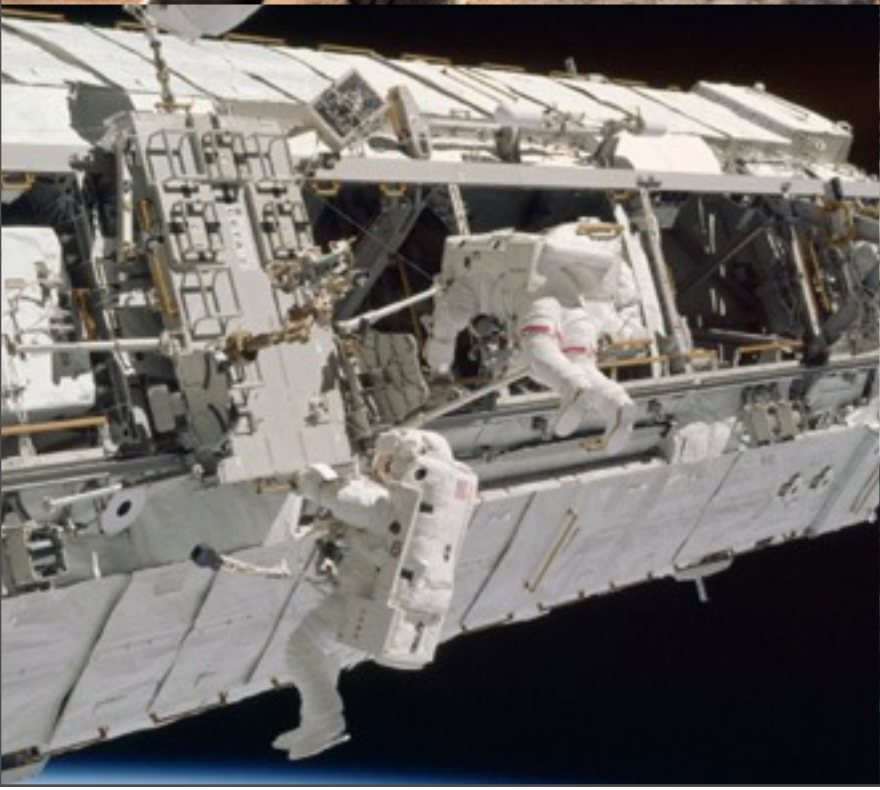
Physical Classification of Asteroids for Mining & Planetary Defense

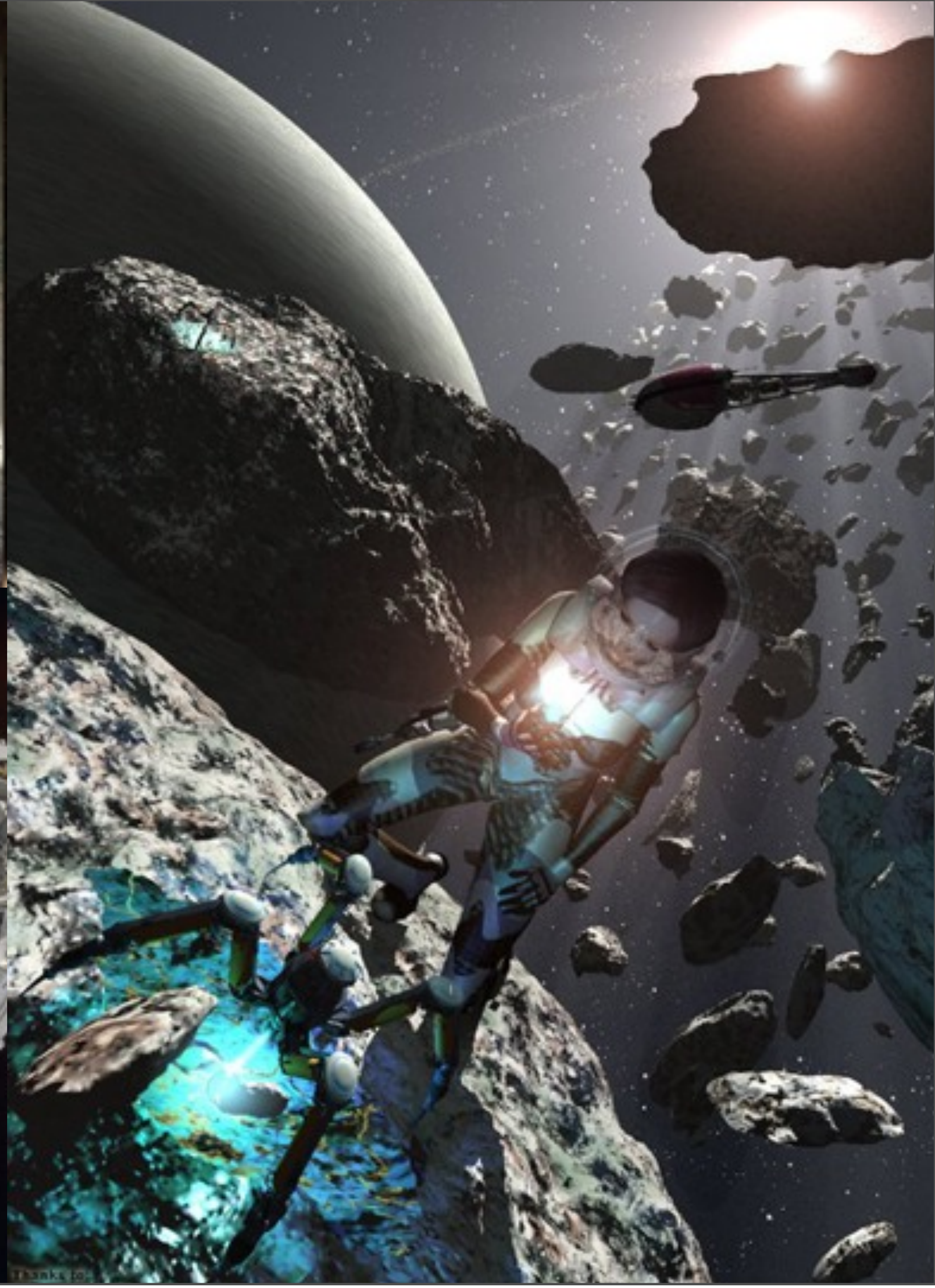
- Size Axis:
  - Class 1. Requires only one blast of a few to several hundred charges. A single human-robotic team is needed for blast design and construction.
  - Class 2. Requires between two and 20 simply layered blasts. One to several teams are needed, depending on the mitigation speed required.
  - Class 3. Requires more than 20 blasts, with significant complexity, including multiple layers of blasts. Many human-robotic teams needed.
- Composition Axis:
  - Group 0. Ice composites – very weak, containing ices with or without organic compounds.
  - Group 1. Friable rock – similar to Group 0, but with no volatile components. Also weak.
  - Group 2. Hard rock – strong and brittle, the most similar to materials encountered in terrestrial mining and excavation practice.
  - Group 3. Metallic:
    - 3a. Massive metal – may be ductile.
    - 3b. Rock-metal composites – would fracture mainly at rock-metal interfaces.

Conclusions

- Partner planetary defense with asteroid ISRU
  - Begin a comprehensive, ongoing missions program to characterize PHAs:
    - Measure properties pertinent to mining and defense
      - destruction and deflection can be designed for simultaneously
    - Return samples for detailed analysis
    - Build and maintain robust database of PHA traits
      - follow and improve on the USGS model with modern information technology

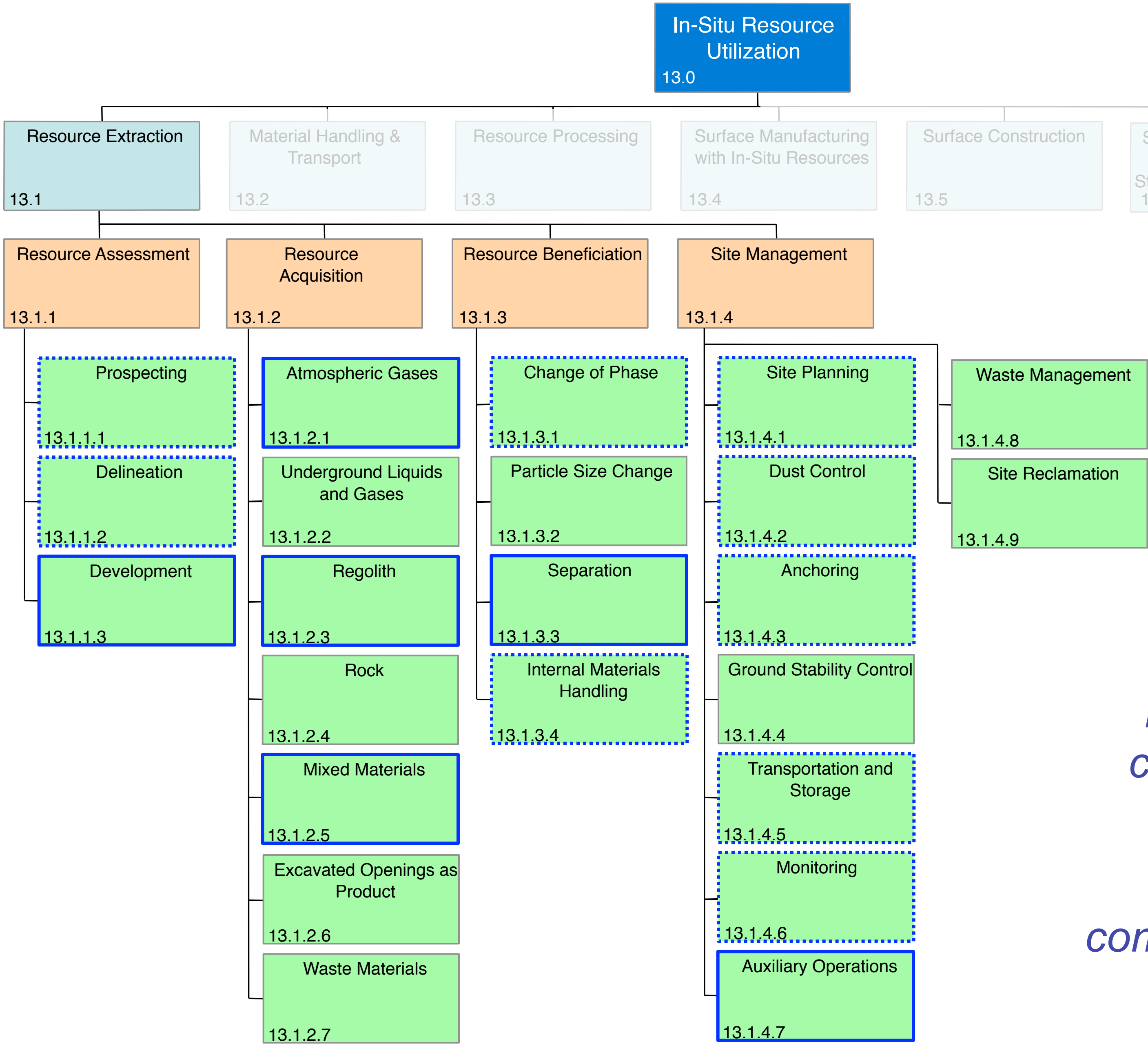
- A partnership between planetary defense and asteroid mining would be enabling for both
  - Certain PHAs may be excellent resource choices
  - Many common knowledge requirements exist
  - Many common technologies and capabilities apply
  - Detailed engineering analysis and design is warranted
    - Knowledge should include mining, aerospace and astrodynamics
    - Trade studies should include detailed analysis of technical requirements and constraints as well as economic forecasting





Backup Charts

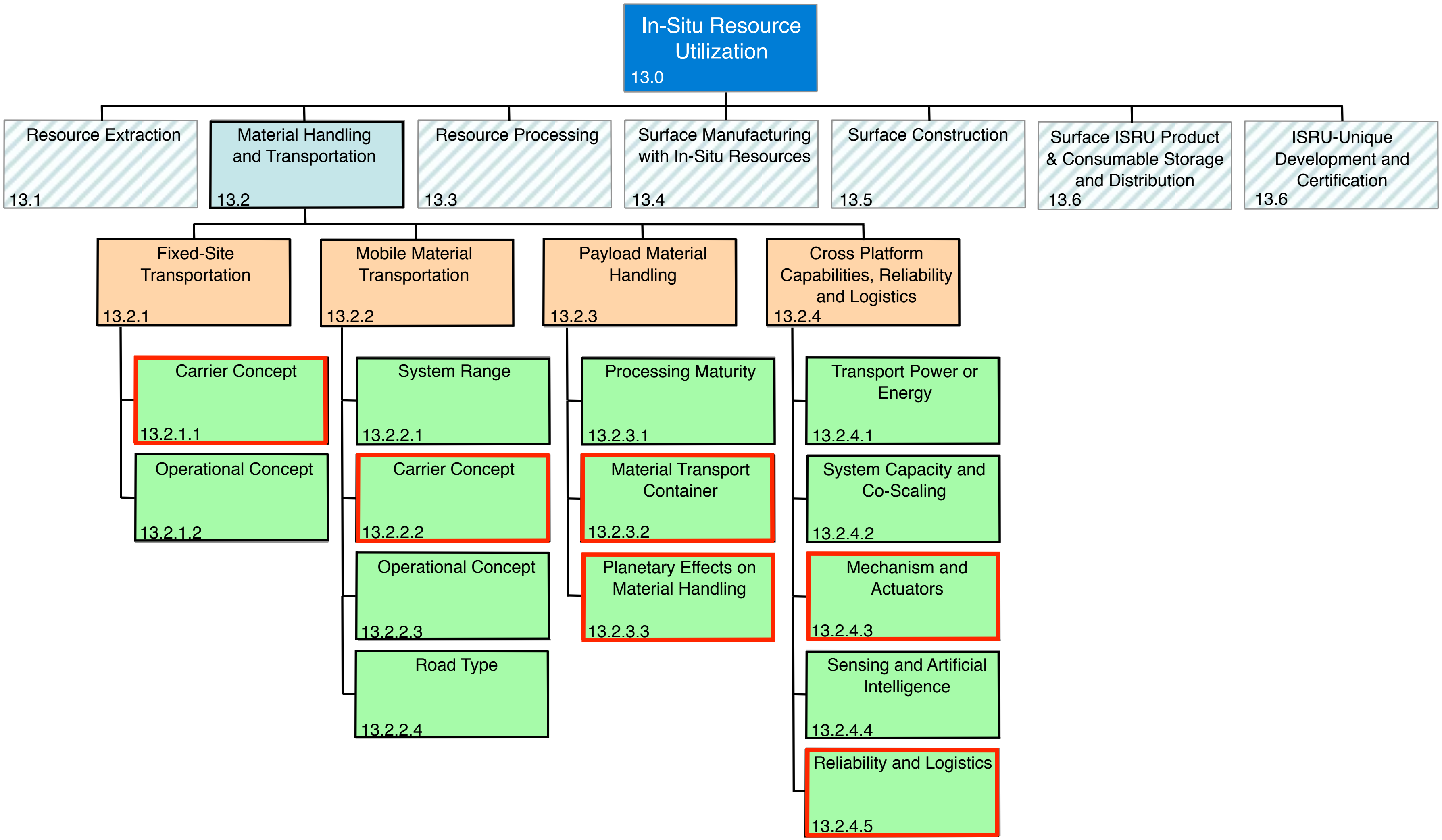
Resource Extraction



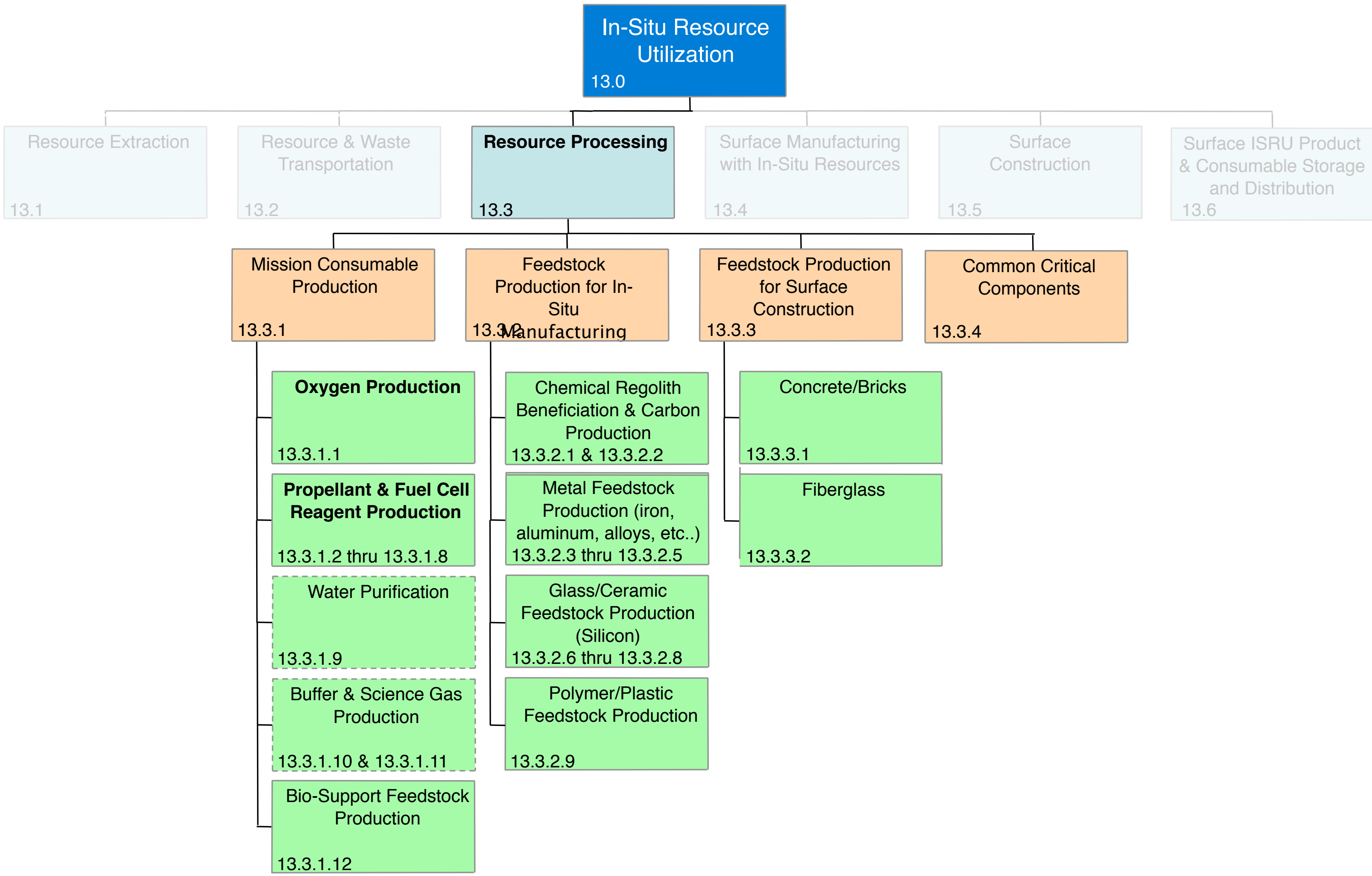
Blue outline = major capability needed for 2005-2035

Dashed outline = commonality with other capability(ies)

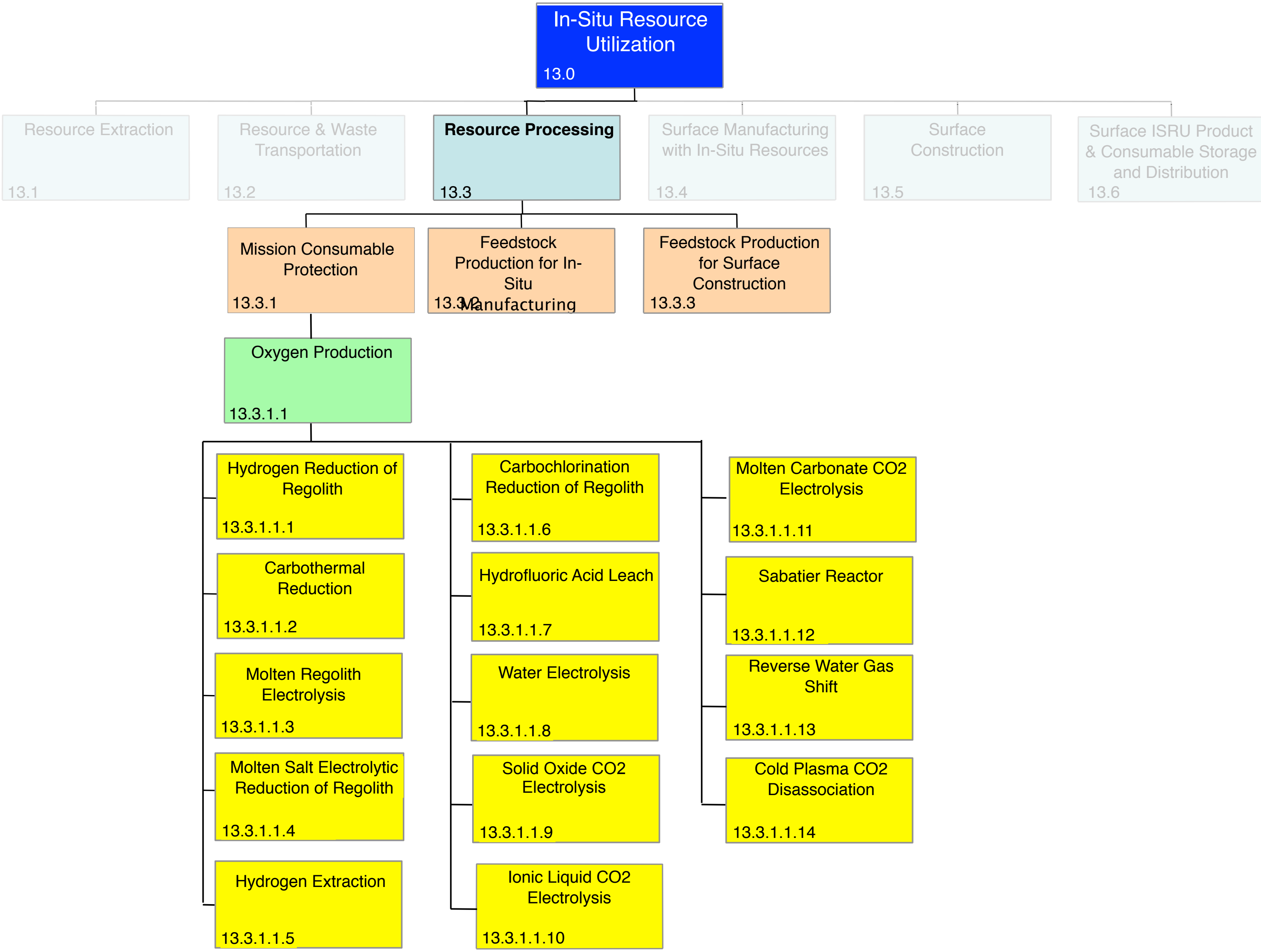
Material Handling and Transportation



Resource Processing



Resource Processing, cont'd



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Technology Concepts for Some Asteroid Mining Capabilities

- Fragmentation
  - Nuclear explosives
  - Cycling fatigue
  - Impact
- Drilling and excavation
  - Mechanical systems
    - Heat build up on cutting tools is limiting factor
    - Reaction mass is a major issue
  - Lasers
  - Kinetic drilling
  - Chemical drilling
- Beneficiation and processing
  - Synthetic biology
  - Electrostatic / electrodynamic separation systems

Note: for more detail see 1997 paper “Near-Earth Resources” in reference list

Technologies Needed

Capability	Key Technologies or Sub-Capabilities
Prospecting and Delineation	Field Sampling Technologies Mapping Technologies Remote Geophysical Surveying Technologies *In Situ* Geophysical Survey Technologies Sample Analysis Technologies
Prospecting, Delineation, and Development	Drilling Technologies Human & Pit and Tr
Development	Tunnel/Sh Atmosphe Borehole Surface E Undergrou *In Situ* Ex Gas Colle Dust Mitig
all Resource Acquisition capabilit	
Atmospheric Gases Resource Acqu	
Atmospheric Gases, Underground Liquids Resource Acquisition	
Underground Liquids and Gases Resourc	
Underground Liquids and Gases, Regolit	
Regolith and Rock Resource Acquisition	Surface E Undergrou
Regolith and Rock Resource Acquisition, and Excavated Openings as Product	Regolith & Regolith a Regolith a Pit and Tr Granular
Mixed Materials Resource Acquisition	*In situ* Ex

Capability	Key Technologies or Sub-Capabilities
Excavated Openings as Product	Tunnel/Shaft Excavation Technologies Pit and Trench Excavation Technologies
all Resource Beneficiation capabilities	Sample Analysis Technologies Process Monitoring Technologies Dust Mitigation/ Control Technologies
Beneficiation Change of Phase	Gas-Liquid Phase Change Technologies Solid-Plasma Phase Change Technologies Solid-Gas Phase Change Technologies Solid-Liquid Phase Change Technologies
	Solids Comminution Technologies Solids Agglomeration Technologies
	Gaseous Separation Technologies Liquid Separation Technologies Granular Solids Physical Separation Technologies Granular Solids Chemical Separation Technologies
ing	Granular materials performance models
	Liquid and Gas Containment Technologies Continuous Materials Handling Technologies Cyclic Materials Handling Technologies
Site Planning, Monitoring	Mapping Technologies Remote Geophysical Surveying Technologies *In Situ* Geophysical Survey Technologies Sample Analysis Technologies
Site Planning, Monitoring, Site Reclamation Transportation and Storage	Field Sampling Technologies Human&Robotic Transportation Technologies
Anchoring	Soil Anchoring Technologies Rock Anchoring Technologies
Anchoring, Ground Stability Control, Site Reclamation	Granular materials performance models
Ground Stability Control Ground Stability Control, Monitoring	Ground Stability Control Technologies Ground Stability Monitoring
Waste Management, Site Reclamation	Pit and Trench Excavation Technologies
Monitoring Monitoring, Site Reclamation	Process Monitoring Technologies Drilling Technologies

The lists that follow are derived from lunar ISRU technology roadmapping and needs modification to incorporate unique asteroid environmental effects – see Sanders et. al. reference

Technologies Needed

Technology	Capability Applications
Mapping Technologies Remote Geophysical Survey Technologies	Prospecting and Delineation, Site Planning, Monitoring
Human & Robotic Transportation Technologies	all Resource Assessment capabilities, all Resource Acquisition capabilities, Transportation and Storage
Pit and Trench Excavation Technologies	all Resource Assessment capabilities, Waste Management, Site Reclamation
Drilling Technologies	all Resource Assessment capabilities; Underground Liquids and Gases, Regolith, and Rock Resource Acquisition; Monitoring and Site Reclamation
In Situ Geophysical Survey Technologies	Prospecting, Delineation, Site Planning, Monitoring
Field Sampling Technologies	Prospecting, Delineation, Site Planning, Monitoring, Site Reclamation
Sample Analysis Technologies	Prospecting and Delineation, all Resource Beneficiation capabilities, Site Planning and Monitoring
Dust Mitigation/ Control Technologies	Development, all Resource Acquisition capabilities, all Beneficiation capabilities, and Dust Control
Atmospheric Extraction Methods	Development, Atmospheric Gases Resource Acquisition
Borehole Liquid & Gas Extraction Methods	Development, Underground Liquids and Gases Resource Acquisition
Surface Extraction (Mining) Methods Underground Extraction (Mining) Methods	Development, Regolith and Rock Resource Acquisition
In Situ Extraction Methods	Development, Mixed Materials Resource Acquisition
Tunnel/Shaft Excavation Technologies	Development, Rock Resource Acquisition, Excavated Openings
Gas Collection Technologies	Development; Atmospheric Gases, Underground Liquids and Gases Resource Acquisition
Granular materials performance models	Development; Regolith and Rock Resource Acquisition, and Excavated Openings as Product; Beneficiation Separation and Internal Materials Handling; Site Management, Anchoring, Ground Stability Control, Site Reclamation
Process Monitoring Technologies	all Resource Acquisition and Beneficiation capabilities
Continuous Materials Handling Technologies Cyclic Materials Handling Technologies	all Resource Acquisition capabilities, and Beneficiation Internal Materials Handling
Liquid and Gas Containment Technologies	Atmospheric Gases, Underground Liquids and Gases Resource Acquisition, Internal Materials Handling
Regolith & Rock Fragmentation Technologies Regolith & Rock Excavation Technologies Regolith & Rock Transport Technologies	Regolith and Rock Resource Acquisition, and Excavated Openings as Product
Gas-Liquid Phase Change Technologies Solid-Gas Phase Change Technologies Solid-Liquid Phase Change Technologies Solid-Plasma Phase Change Technologies	Beneficiation Change of Phase
Solids Comminution Technologies Solids Agglomeration Technologies	Beneficiation Particle Size Change
Gaseous Separation Technologies Granular Solids Chemical Separation Technologies Granular Solids Physical Separation Liquid Separation Technologies	Beneficiation Separation
Ground Stability Control Technologies Ground Stability Monitoring	Ground Stability Control Ground Stability Control, Monitoring
Soil & Rock Anchoring Technologies	Anchoring