LUNAR MINING: KNOWNS, UNKNOWNS, CHALLENGES, AND TECHNOLOGIES. L. S. Gertsch[1], [1]Missouri University of Science and Technology (Rock Mechanics and Explosives Research Center, 1006 Kingshighway, Rolla, MO, 65409-0660, United States, GertschL@mst.edu).

Introduction: Humans have mined rock and soil for more than 300,000 years [1]. The first mining technology was digging tools shaped from antler, bone, wood, and rock [2],[3]. Today's mines rely on global positioning satellites, semi-automated machines, and explosives. Lunar and planetary mines will use technology derived from this background and adapted for new environments. All, however, use their technologies for the same purpose: to access the desired material, and separate it from the unwanted material with which it is mixed, using the least energy or economic expenditure possible.

The mining cycle. The mining cycle includes:

- Resource assessment.
- Resource extraction.
- Resource beneficiation.
- Mine closure

Mining unit operations. Every mining method must achieve these unit operations. How they are achieved, and their difficulty, depend on the material of interest, its surroundings, and numerous other environmental characteristics. The unit operations are:

- Fragmentation - breaking material from its *in situ* surroundings.
- Excavation - picking up and loading the fragmented pieces.
- Material handling - hauling as needed.
- Beneficiation - onsite preparation of the mined material for further processing or for use.

Technologies: The technologies used in mining and excavation consist of all the methods by which the fundamental laws of physics can be harnessed in the specific locale of interest to achieve the goals of the project. Even on Earth, there is enough of a range of operational constraints that a correspondingly wide range of technologies has evolved. Expansion to a nonterrestrial location with its significantly different constraints will involve re-examination of the motives for the means, and re-engineering for effective operation there. It will also offer new opportunities for technology development, as well as new difficulties. Many of both are presently unforeseen.

Mining technologies evolved to achieve the unit operations as needed in the various stages of the mining cycle in various types of locations. Workable systems of these are termed "mining methods," which are in turn classified in a variety of ways. This review follows the classification of mining methods on the basis of access: surface methods and underground methods. The choice between approaches is ordinarily made on economic grounds. For lunar operations, the choice will be recast in terms of launch mass and energy in the early stages, and probably in terms of energy alone for later stages.

Surface mining methods. These are operations where personnel are not required to go underground; usually (but not necessarily) all material from the original ground surface to the bottom of the mine is removed. Those that appear most applicable to the Moon consist of open pit mining, area (strip, or opencast) mining, auger (highwall) mining, and dry dredging.

Open pit mining is best applied to thick, irregular deposits expressed on the surface or occurring at shallow depths. It removes all material to create one or more horizontal benches, each successively deeper and covering less area than the preceding one. The unwanted material is stored or disposed of in surface stockpiles nearby.

Area mining is similar except that the unwanted material is piled within previously mined areas. Over time the pit, usually a trench, remains a constant size and area, and appears to march across the landscape. (Open pit mines, on the other hand, grow deeper and/or larger over time.) Area mining is used in horizontally bedded deposits such as coal.

Modern auger mining occurs underground, but is run entirely from the surface. Single or double augers (or other types of excavators) bore into the otherwise unavailable highwalls left when coal seams are mined in mountainous terrain.

Dry dredging, in the form most applicable to lunar operations, is similar to surface versions of the slusher mining methods previously used in some underground mines. A slusher is a drag scraper. Here is an example of the close relationship between methodology and technology.

Underground mining methods. Underground mines are accessed by passages through undesired material to an orebody; mining occurs beneath the cover of overlying formations. The major types are unsupported, supported, and caving. Several methods have been used for underground extraction of near-surface, unconsolidated deposits and thus may be useful initiation points for lunar regolith mining. More mining methods can be found in [4], with more detailed descriptions in [5].

Top-slicing was used to mine placer gold from thick stream gravel deposits before the equipment for modern high-volume methods was available and where contemporary methods such as hydraulic mining could not be used. Similar deposits are mined today either by surface methods (above) or, if in permafrost, by adaptations of methods developed for rock. The most common of the latter approaches is room-and-pillar (below). In the form most suitable for regolith mining, top-slicing consists of

Room-and-pillar mines require the ore to be strong enough to support openings wide enough for the equipment to operate. This method leaves areas of ore (pillars) to support the overlying material, which itself must be strong enough to bridge the gaps between the pillars.

Longwall and shortwall are mechanized adaptations of top-slicing that also permit / require the overlying material to fail and fill the void created by removal of the ore. The main difference between these and top-slicing is that, to date, the ore has had to be strong enough to support excavations without the significant artificial support requirements of top-slicing.

Knowns: The first target of lunar mining and construction will be the regolith. That will expand to include intact rock when operation depths exceed the thickness of the regolith covering.

Many aspects of regolith behavior have been measured from the perspective of soil mechanics, summarized by [6]. The low number of sample sites, and their bias toward mare locations, will be ameliorated by the much greater coverage and resolution of the LRO mission.

Feedstocks for the production of propellants, life-support gases, and basic structural materials probably will require only minimal beneficiation of excavated regolith prior to processing.

Unknowns: The variability and spatial scale of variability, of the regolith properties that affect mining and excavation are not well-characterized in three dimensions. Regolith variability is controlled by its formation mechanisms, which are due primarily to impact processes. Understanding the effects of these processes will enhance understanding of the spatial distribution of material targets, and *vice versa*. It also will improve the development of effective excavation techniques and equipment.

The fourth dimension -- time -- may be of some importance to the determination of potential orebodies and is being studied (*e.g.*, [7], [8]).

Political and legal uncertainty are two unknowns unrelated to science or engineering that nevertheless affect the probability of success. The former speaks directly to government support. The latter controls the willingness of the mining industry to commit.

Challenges: The unknowns listed above lead to engineering challenges expected during lunar mining and excavating.

Regolith *in situ* is tightly compacted and contains varying densities of pebbles, rocks, and boulders. Even without the cementing effect of intergranular ice, undisturbed regolith deposits require some force to fragment and excavate [9]. Mass usually provides the reaction force for surface mining, yet launched mass will be at a premium. Can the materials needed for the pre-manufacturing stage of lunar presence be obtained from the more easily excavated upper layers?

Digging becomes more difficult with depth, possibly plateauing below some critical depth. This, in addition to the presence of oversized particles, will require development of techniques for real-time ahead-of-the-face sensing and machine control. This is part of the challenge of sufficient characterization of the target material, which needs to be more complete than on Earth to offset the difficulty of the additional challenges of remote operation, maintenance, and repair.

Mining and excavation equipment is built to be robust, because it must deal with significant -- and difficult-to-characterize -- ranges of material behavior. This is true in any natural geologic material. Long-term operation of such equipment in the unfamiliar and extreme environment of the Moon adds the difficulties referred to above.

Any prototype technology, or old technology used in a new way or a new place, requires significant development and testing. NASA is familiar with this, but the greatest challenge will be whether humanity yet has the political and financial will to carry the process through well enough to encourage success.

References:

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