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To Build a Mine: Prospect to Product

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Developing Mineral Resources on Earth

The terrestrial definition of *ore* is "a quantity of earth materials containing a mineral that can be extracted at a profit." While a space-based resource-gathering operation may well be driven by other motives, such an operation should have the most favorable cost-benefit ratio possible. To this end, principles and procedures already tested by the stringent requirements of the profit motive should guide the selection, design, construction, and operation of a space-based mine. Proceeding from project initiation to a fully operational mine requires several interacting and overlapping steps, which are designed to facilitate the decision process and ensure economic viability (Baxter and Parks 1957, Pfleider 1972, Kuzvart and Bohmer 1978, Crawford and Hustrulid 1979, Church 1981).

Market Identification: Formulating the Project

All mineral extraction projects are market driven. The market determines product, project size, location, and extraction technology. The market will eventually determine all manner of project detail, such as distinguishing ore from waste. Questions such as possible products, product price, and infrastructure cost (e.g., power, labor, and transportation) must be answered. These answers provide an estimate of the scope of the projected mining operation and indicate reasonable geographic regions to explore. At this point, a regional exploration program can begin. Usually several regions to explore are identified and plans for the exploration of each region formulated.

Exploration: Finding Prospects

Regional exploration identifies specific mineral prospects within each region, which are then investigated in more detail. Large-scale regional exploration begins with historical studies. All references relating to the area, geology, markets, past production, etc., are researched. Concurrently or soon after, field work begins. Regional exploration tools include geochemical and geophysical remote sensing, aerial and satellite photography, stream sediment studies, studies of outcrops, and limited core drilling. In addition to the obvious geologic and mineralogic questions, many other factors enter into the picture: transportation needs, water supply, local labor force, local power supplies, equipment availability. Location of one or more properties that have passed the initial screening signals the end of regional exploration and the beginning of detailed site evaluation.

Site Evaluation: The Sampling Program

Even though local information on power, water, work force, roads, transportation, topographic relief, geologic factors, etc., continues to be collected and evaluated, the cornerstone of site investigation is the sampling program. While the immediate purpose of the sampling program is to delineate enough ore reserves to guarantee an economic mine, the quality of the program affects decisions made during the entire life of the mine. Geologic sampling takes many forms, but the most common tool by far is the core drill. Cores are taken at an interval small enough to sample accurately both ore reserves and any geologic formations that can affect mining operations. The depth and area of the core sampling program must represent the volume to be mined. While a minimum number of samples is required for a decision to start operations, sampling continues throughout the life of the mine.

Site Evaluation: The Ore Body Model

Ore body models are by far the major analytical tool used in the evaluation, design, and planning process. The importance of building as accurate a model as possible cannot be overstressed. The model itself is a mathematical representation of relevant subsurface and surface features: ore grades, amount of waste, geologic formations affecting mining, etc. This math model is derived from the data collected during the sampling program. Thus, sampling and modeling are related and concurrent processes. The model can be constructed in a variety of ways, from simple linear interpolation between samples (called "data points") to sophisticated variance-reduction geostatistical models. A modeling method may be selected because it worked well in the past. More than one model may be constructed, using one model to check the other. Regardless of the modeling method chosen, the influential factor in generating an accurate model is sampling interval and procedure.

The model allows the mine designer to plan the optimal mine, determine its profitability, and compare it to another property. The entire mining and milling operation is computer simulated over the life of the mine: different mining methods are tried; mill feed variation is calculated; production schedules are determined; sensitivity analyses are performed to determine the most important parameters for cost-effective operation. Over the life of the operation, data are collected and added to the model, and the model is continually updated and reanalyzed.

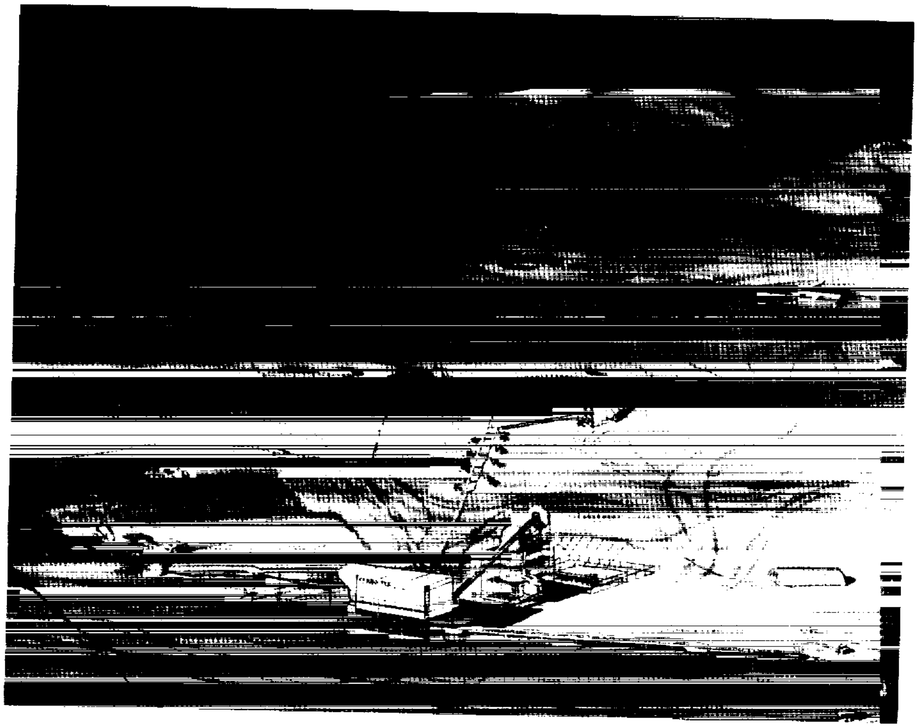
Design and Construction

The final model is no longer just a model of the ore body but a model of the entire project. Since the model determined economic viability, it is also the basis for mine design and production planning. The many design details are added, and the design is finished. As the design is completed, equipment and materials are ordered and construction begins. Design and planning continue throughout the entire mine life.

Implications for Nonterrestrial Resources

Presuming that the approach to developing nonterrestrial resources will parallel that for developing mineral resources on Earth, we can speculate on some of the problems associated with developing lunar and asteroidal resources. Even in the terrestrial case, the mine design and construction process is very complex. Much of the complexity results from the many unknowns in the process, which must be estimated from the data or in some cases guessed. As mineral sources, the Moon and the asteroids increase these unknowns by an order of magnitude.

The baseline for our study group was a small lunar mine and oxygen extraction facility. The facility would produce liquid oxygen (LOX) by electrostatically separating ilmenite from mined lunar soil and then reducing it to oxygen, iron, and titanium dioxide by a hydrogen reduction process. The production of 100 metric tons of lunar oxygen for delivery to low Earth orbit (LEO) implies production of an additional 300 metric tons for use in the Moon-LEO leg of the transportation system (200 to take 200 from the Moon to LEO; 100 of that 200 to bring hydrogen back to the Moon). This production requires that 40 000 metric tons of material be mined to supply the LOX feedstock. The mine and extraction facility would operate only during the lunar day (that is, 14 Earth days in operation, 14 off) throughout the year. Our study group considered only the problems that would be encountered in identifying the mining site, delineating the ore at the site, and building and operating the lunar mine, not those associated with the extraction facility or the technology.



Lunar Oxygen Plant

This plant is scaled to produce about 1000 metric tons of oxygen per year by extracting it from lunar ilmenite using hydrogen reduction. This figure is based on a design developed by Carbotek, Inc. In this conception, a front-end loader scoops up lunar soil from an open pit mine. The soil is carried by conveyor flights to a beneficiation plant, where the ilmenite is magnetically concentrated. The concentrated ilmenite is fed into a fluidized bed reactor, where the hydrogen extracts some of its oxygen as water. The water is then broken down by electrolysis, the oxygen is captured and stored cryogenically, and the hydrogen is recycled into the reactor. The unused portion of the lunar soil and the slag waste from the reduction process is finally transported to an old pit and used to fill it again.

To minimize the mining operation, the regolith should contain as much ilmenite as possible and the ilmenite should also be in a form (grain size and shape) which will allow concentration. Consequently, detailed evaluation of the potential mine site may be necessary before mining operations begin.

Artist: Pat Rawlings

Courtesy of Carbotek, Inc.

Most operating terrestrial mines have a very high rate of return (some on the order of 100 percent) merely to pay for finding and operating the ones that failed. Mining is a high risk business. Exploiting nonterrestrial resources will be even riskier; however, the returns in the long run may be much larger than for any single terrestrial mineral deposit.

The Market

While reasonable investigators have estimated nonterrestrial resource needs, so far no firm market, either product or quantity, has been identified. Meaningful detailed mine design and engineering work cannot begin until the market is better understood; however, the scenario presented by the LOX-to-LEO concept is useful in scoping a project. To produce and deliver to LEO the required 100 metric tons per year requires that 400 metric tons per year be produced on the Moon. There is also the possibility of producing bulk material and iron as byproducts for use on the Moon or in cislunar space. At this market size (which is a reasonable anticipation of the space transportation system requirements of a "business as usual" space program—see figure 1), the supply of lunar oxygen would offset transportation costs of approximately $600 000 000 per year for transporting oxygen from Earth to a space station using the Space Shuttle.

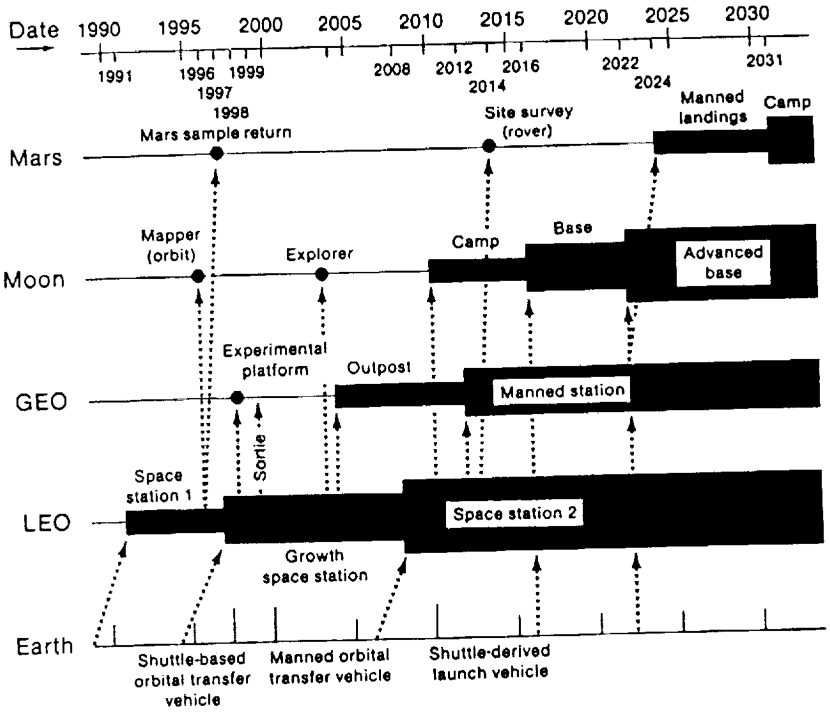


Figure 1

Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

Exploration

Two classes of sites have been proposed for nonterrestrial resource development. For the LOX-to-LEO project, both the Moon and asteroids could be sources of oxygen; asteroids might provide different byproducts than the Moon would.

Apollo data show that ilmenite concentrations in basalts range from 3 to 20 percent at the investigated lunar mare sites. An Apollo site such as Apollo 11 or Apollo 17 is thus considered a prospect. The major problem with this statement is that the rest of the Moon might be ignored in favor of a few sites selected at the time of the Apollo Program. We don't know what we might be missing. One possible approach would be to build the Apollo-site mine and use it as a base to find prospects for other ilmenite mines or more ambitious mining projects. Another approach would be to complete a well-conceived exploration program before selecting a mine site. While far more expensive, this approach could yield better long-term results.

The asteroids are more problematical. No good compositional data have been obtained for appropriate Earth-approaching asteroids. While the probability is good that a favorable body exists, at present there is no asteroid "prospect" identifiable by terrestrial rules. Earth- or orbit-based asteroid watches may find promising bodies, but these bodies cannot be considered mining prospects until they have been physically sampled. Space mining is too risky and expensive to fly an asteroid retrieval mission solely on the basis of spectral and statistical data.

While we strongly support additional remote sensing missions such as the Lunar Observer* and asteroid watches as means to continue the exploration phase of nonterrestrial resource development, we doubt these programs will locate specific ore bodies. Terrestrial remote sensing programs rarely find mining prospects but have better success at locating areas of promise. Remote sensing from space has a relatively coarse resolution at mining scales and the interpretation of the resulting data consequently leaves many unknowns. It appears that these investigations will continue to be driven primarily by science considerations. But the instrument packages for space flights and the telescopes for asteroid search programs should be given close scrutiny as to data requirements and sensor resolution for mining purposes.

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* The Lunar Observer is to be a lunar polar orbiter equipped to obtain geochemical data.

Sampling Program

Even before a sampling program that will support detailed mine modeling begins, a site may have enough supporting data to be considered a mining prospect. The best explored Apollo sites are characterized well enough to be considered mining prospects, particularly Apollo 17 for LOX-to-LEO. Assumptions may be made about the nature of the resources at these sites, and feasibility studies can begin. Such feasibility studies are a common and powerful tool in the mining industry, but they indicate that the major work on the prospect has just begun.

As a mining site, even Apollo 17 does not have nearly enough information to support mining operations. Questions such as grade variability, minable depth variability, and distribution of grain size (particularly oversized material) must be answered before mine and mill design can begin in earnest. The tool to answer these questions is the sampling program and ore body model. The Apollo sites were not sampled for the purpose of mining but for scientific inquiry. While it seems likely that the Moon is a fairly homogeneous body, there are not enough data even to predict the necessary sampling interval to build an accurate ore

Apollo 15 Astronaut Taking a Core Sample of the Lunar Regolith

Apollo astronauts collected most samples by picking them up with tongs, a scoop, or a rake and bagging them for return to Earth. All rock samples were found as fragments or boulders in the lunar regolith (rock ground up by meteoroid impacts). A few cores were obtained. The longest, approximately 3 meters in length, were collected using a power drill. This one was obtained with a drive tube which was pushed or hammered into the regolith. Effective sampling for lunar resources will require more sophisticated drilling devices.

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body model. Since the lunar samples cannot be adequately correlated with underlying bedrock, additional investigations will be required that can define the extent and thickness of the regolith to be mined.

Mine and mill operations must be designed to handle such variables as soil mineralization, grain size, and mining depth. For example, constant feed simplifies mill operation, making it more efficient. Oversized material must be rejected, preferably in the mining operation before it reaches the mill. The many factors affecting operations must be determined and characterized. Since the scale of these soil variables is unknown, the sample interval itself must be determined before the program is implemented.

Rejection of Oversized Material

A number of methods exist for sorting larger rocks and boulders from mined material. The device shown here (Side-Kick by General Industries, Inc., Marietta, GA) automatically removes the larger rocks from a conveyor belt and collects them in a stockpile. The motion of the conveyor belt forces the rocks into several spoked wheels, placed at a predetermined angle to and a preset level above the oncoming conveyed materials. The rocks spin these wheels, causing the spokes of the wheels to kick these rocks over the side of the belt. Thus, the device works much like a diverting waterwheel in a stream. The kicked out rocks can be collected in a pile or a bin. A lunar version of this device could provide a selection of different sizes of rocks for use as paving and building stones as well as eliminating the larger rocks from the feedstock to be processed for oxygen or hydrogen.

For terrestrial mines, the cost of sampling is usually much lower than the cost of unexpected operational problems caused by failure to sample adequately. On the Moon even the best explored sites have far too little data to support operations. Thus, the quality of the lunar sampling program will directly reduce operational problems.

Mine Design and Construction

Even with limited data on prospective lunar mining sites, basic site characterization supplied by Apollo allows some generalized design work to begin. Integrating limited data with a few assumptions can yield a reasonable baseline lunar mining and milling operation.

The high cost of space transportation, especially of people, suggests that a lunar or asteroidal mine should be highly automated. But terrestrial mining industry experience with automation has been bleak. Mining operations, because they are complex, difficult, hard on equipment, and have many degrees of freedom, are poor candidates for automation. While systems like ventilation control, haulage trains, and equipment monitoring have been automated, no mine production system has ever been completely automated. Even though removing workers from a relatively dangerous environment seemed sufficient justification, production automation was too complex and unreliable to be economic. Present industry practice is driven solely by economics: Can money be saved by automating? The strategy is to automate a small, well-defined task and then do extensive debugging before automating another task. Given this poor record, automatic systems should be used with caution, have plenty of redundancy, and, if possible, have people present to solve the inevitable unexpected problems.

The automation trend does appear to be accelerating, however. The latest attempts are far more sophisticated and complex. For example, a Swedish firm has been experimenting with an automatic underground blast hole drilling rig. Underground blast hole drilling is a complex operation with many degrees of freedom and multilevel decision-making.

Our study group advises caution in automating lunar or asteroidal mining operations. Although it is possible that a completely automated mine would be less expensive than a similar manned operation, the issue is still in doubt and needs further study. We further note that a completely unmanned system is highly unlikely; no matter how well designed they are, automatic systems will eventually require human intervention. The basic tradeoff question is, "Would it be less expensive to develop an automated system or to accept the higher operating costs of a manned operation?" One more, important point should be made: The development of reliable automated mining systems would find a lucrative terrestrial market.

Recommendations

We recommend that several steps be taken to clarify the questions of lunar and asteroidal mining:

1. Determination of realistic markets for products from nonterrestrial resources is of major importance, because market income determines mine size, location, and mining and milling method—in short, the project.

2. Additional remote sensing by satellite for the Moon and by telescope and later spacecraft for asteroids should be done to provide a more robust data base on which to evaluate nonterrestrial resources.

3. Any remote sensing or onsite data-gathering projects must be evaluated for specific support of mining activities. Site information lowers costs.

4. Local sampling programs to determine the extent and minability of the deposits will still be necessary even after reconnaissance data have been gathered. These programs may combine surface sampling and sample return missions.

5. Technology for nonterrestrial mining must be studied in detail. Mining operations are notably difficult to automate and may ultimately require significant human intervention in the nonterrestrial case. The tradeoffs between manned and automated mining methods must be analyzed in detail and the best strategy selected. Error in either direction could result in the failure of the project.

6. Simplicity of equipment and mining method is a must for the first project gathering nonterrestrial materials. Reducing complexity will reduce development, capital, and operating costs.

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