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Lunar Site Characterization and Mining

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Before resources are committed to lunar mining, a significant amount of information will be needed. I hope that our workshop group will illuminate some of the more obscure areas, such as the specific requirements of an ore processing facility. Other important information can be acquired only through onsite exploration and testing.

Potential lunar mining sites can be divided into two general groups—generic sites and Apollo sites. Geologic data for both types of site are sparse and of poor spatial resolution.

Generic sites have not been visited. They are potential mine sites only because they are in lunar regions with mineralogic properties that are generally understood by comparison of remotely sensed data with data from analysis of Apollo site samples; e.g., mare sites, highland sites, or transition sites. See figure 15. Generic sites will require exploration at a variety of scales.

Initial exploration using a satellite in lunar orbit will allow regional exploration of many generic sites. Polar sites, if suitable ones can be identified, have several advantages for a mining operation. First, the continuous solar radiation at the poles would enable continuous mining operations under stable temperature and lighting conditions. (See figure 16.) Such an environment would eliminate the stress on mining equipment and personnel caused by the alternation of 2-week lunar nights and days at other sites. Second, the high thermal gradients encountered at the poles due to low Sun angles could help provide cryogenic storage for processing gases and product gases. Third, the potential occurrence of water frozen in the perpetually shadowed areas of the poles is an incentive for exploring polar sites.

Exploration of generic sites at intermediate scales is required to bridge the gap between the low-resolution remote sensing data and the more intensive measurements made by human beings. This intermediate-scale exploration could be done by automated rovers, which should be able to cover relatively large areas rather rapidly.

The automated nature of lunar exploration will demand advances in high-resolution sensing and in computer processing and integration of data acquired by different instruments on the same roving vehicle. Knowledge gained from terrestrial mineral exploration can be used for preliminary training of automated interpretation systems, but the unique conditions of the lunar environment will likely require an intelligent computer-vision system capable of "learning" and adjusting as new data become available.

Figure 15

a. Mare Site

While generic sites may be like Apollo sites in overall characteristics, important details of any site cannot be predicted. Here, Buzz Aldrin is carrying a laser ranging retroreflector (LRRR) and a passive seismic experiment package (PSEP). Note the smooth, relatively flat surface. Note the deeper footprints near the rim of the small crater in the foreground. These differences in footprint depth are related to differences in local bearing strength. Local variations in bearing strength should be expected at any site and cannot be documented without onsite surveys. Consequently, site surveys may be necessary before selecting the best location for buildings, mines, landing pads, and roadways.

b. Highland Site

Here, Charlie Duke is walking across the lunar surface in the vicinity of Plum Crater at Apollo 16, a highland site. This area has far fewer small rocks on the surface than does the mare area shown in figure 15a. However, the terrain is more rolling and generally less flat. It is difficult to characterize a generic highland site. Other parts of this same Apollo 16 site are much rougher, with numerous boulders. As with the mare site, detailed site characterization would be necessary before construction of facilities could be undertaken.

c. Transition Site

Here, we see the Lunar Module at the Apollo 15 site. This site is transitional between mare and highland. It contains mare terrain in the foreground and highland terrain in the background. Generic transition sites may have features of both, including smooth flat terrain and hilly terrain. The likely complexity of such transition sites may make detailed onsite surveys even more necessary for them than for mare or highland sites.

Figure 16

Polar Solar Power System

At a base near a lunar pole, a solar reflector (the large tower in the background) directs sunlight to a heat collector, where it heats a working fluid which is used to run a turbine generator buried beneath the surface. At such a location the solar power tower can track the Sun simply by rotating around its vertical axis. Power is thus provided continuously without the 2-week nighttime period which is characteristic of nonpolar locations. This continuous power would allow continuous mining and processing operations at the pole.

Note the sharp contrasts between light and shadow in this picture. The contrasting shadows offer another advantage and might afford a third. A polar site would have a number of zones that remain in perpetual shadow, such as inside craters. These zones would be ideal locations for cryogenic storage depots; the depots would not require active cooling to maintain oxygen at liquid temperatures. And these permanently shadowed zones might have served as cold traps for collecting water released from the lunar interior or from impacts of comets or water-bearing asteroids. Such water, preserved as ice, might be minable for use in life support or processing into rocket fuel.

The triangle in the background is a mining pit. In the foreground, two scientists collect rock samples for analysis at the base.

Artist: Maralyn Vicary

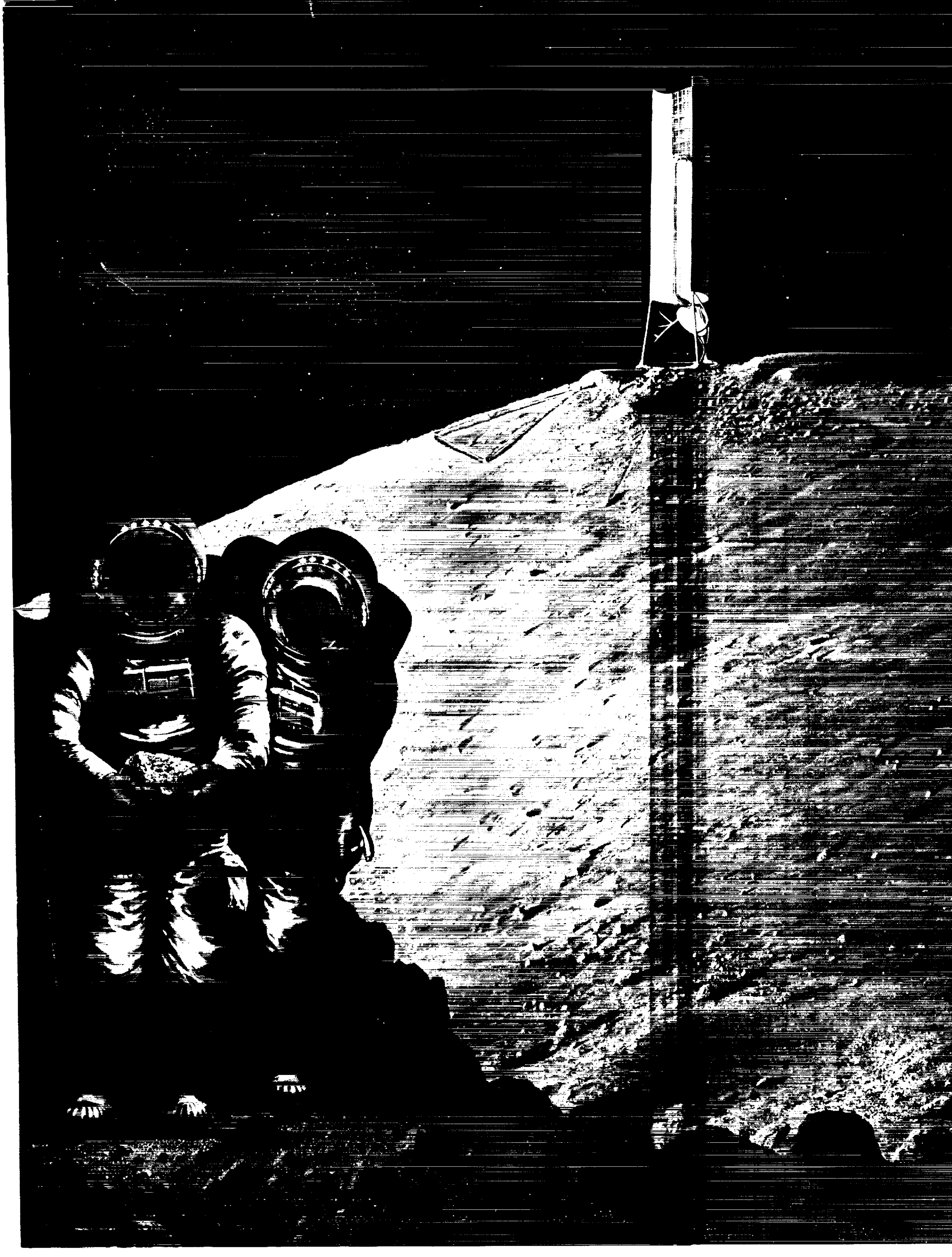
Completion of these exploration programs should bring our knowledge of generic sites up to that of the Apollo sites, the second general category. Regional exploration is not deemed necessary for the Apollo sites because of the relatively extensive body of knowledge already assembled. However, detailed site investigations to obtain specific parameters for mine design will be required for the first mining attempt.

In outlining these exploration requirements, our workshop group made several assumptions. First, we assumed that the prototype lunar mining venture should be an unqualified success. Second, we assumed that the startup product would be liquid oxygen, with the subsequent addition of such byproducts as metals for structural use, ceramics, and bulk materials for shielding. Third, we assumed that the mining operation would excavate lunar regolith and deliver a well-graded feedstock to the processing facility. (No crushing is required, with oversized material being removed mechanically.)

Specific Parameters for Mine Design

The final stage of the exploration program—to acquire specific parameters for mine design—will begin only after a chosen site has been as thoroughly explored as an Apollo site. Even for the Apollo sites, information is insufficient to assure the success of our first lunar mine. Factors that affect mining include mineralogy, grain size distribution, abrasiveness, depth of loosely compacted regolith, and surface topography. How these factors vary from place to place is not well understood. The Apollo missions were never intended to be resource appraisals. Nevertheless, a restudy of Apollo samples and survey data with an eye toward resource appraisal would be a promising first step toward obtaining the needed site detail.

Published information on Apollo 17 samples suggests a high degree of variability from place to place in mineralogy and in grain size distribution in soils. That variability is seen in samples numbering only in the tens taken over a 25-km^2



area. The density of sampling should be increased to intervals of 1 to tens of meters, depending on the scale of the anticipated operation. Not only the sample density, but also the sampling technique is inadequate to characterize a site for potential resource extraction.

The sampling program should permit assessment of

1. Mineralogy
2. Grain size distribution
3. Mechanical properties, including shear strength, hardness, compressive strength, friction angle, and elastic moduli*
4. Depth of regolith
5. Surface topography
6. Geochemical and geophysical information on the site such as resistivity, gravity, porosity, and the results of seismic and electromagnetic surveys
7. Abrasiveness

Analysis of all these types of data should involve techniques to help quantify the spatial characteristics of the lunar regolith at mining scales. These techniques will be used at the mine site to guide subsequent sampling both before and during production. Modeling should create 3-dimensional representations of the ore body to guide mine layout and design. These models should describe the distribution of material properties, such as ore grade and particle size. Such information is particularly important during the startup and early operations of the processing facility. Variations in the mill feed will be a critical design factor for both the mine and the mill. Blending at the mine will improve mill productivity. Modeling should simulate the entire mine life to permit optimal mining operations that are coordinated with processing operations.

Grain size distribution data will provide guidelines for excavation planning, crusher design, in-pit

*By "elastic moduli" I mean to embrace those conventionally measured; namely,
Young modulus (E)
Shear modulus (G)
Bulk modulus (K)
Poisson's ratio (v)
Further definitions can be found in L. Obert and W. I. Duvall, 1967, *Rock Mechanics and the Design of Structures in Rock* (New York: John Wiley & Sons), p. 53.

screening procedures, and plant feed simulations.

Mechanical property testing will provide parameters to assess mine stability and foundation design under both static and operational dynamic loads. It may be important, for example, to isolate the processing plant from mining and crushing vibrations either through foundation design or through physical site separation.

Measurements of the depth of the loosely compacted lunar regolith or soil will be used to design the mine, decide on the scope of the operation, and predict the volume. The depth to which one can mine without high-energy rock breakage (blasting, etc.) is important for design and planning. An unexpected change in the depth, geometry, or mineral character of the regolith could require that the mine and mill be relocated. And the fewer the equipment relocations, the lower the costs.

Surface topography will determine the general layout of the mine and processing plant. Some topographic features may be advantageous for maximizing gravity feed; others may help minimize excavation.

Requirements of the Lunar Mining System

The prototype lunar mining system should perform economically and dependably from startup to decommission. The system should meet the following requirements. However, some of these requirements may prove to be conflicting, in which case compromises and tradeoffs will have to be made.

1. It must accept and produce the volume specified.
2. The equipment should be rugged.
3. The equipment should be simple in design, simple to operate, and simple to repair.
4. The equipment should be versatile.
5. The system should be amenable to automation and later robotization.
6. Work force requirements should be low.
7. Weight and cost should be minimized.
8. The system should be testable at full scale on Earth before being put into service on the Moon.

Throughput Requirements

Because of the profit incentive, terrestrial surface mining techniques used in this country demand a significantly larger throughput than the 40 000 metric tons per year (or 10 metric tons per hour for a 4000-hour operating year) envisioned for the first lunar mine. Mining this quantity of material does not require advances in the state of the art of mining technology. Quite to the contrary, it requires scaling down the mining operation to maintain continuity in operations. For example, it may be advantageous to reduce the quantity of material excavated per unit load and increase the number of unit loads excavated per hour. The modest throughput requirements should result in increased flexibility in choosing the prototype lunar mining system.

Ruggedness of Equipment

The lunar mining equipment should be robust. It must withstand the rigors of normal mining operations, such as excavating and transporting abrasive dust, cobbles, and boulders; operating in a dusty environment; and operating continuously. In addition, it must operate in the hostile lunar environment with its severe temperature swings (except at polar sites).

Design Simplicity

The low throughput requirements encourage design simplicity, which will result in failure-resistant equipment. This design simplicity should extend to ease of repair, so as to minimize downtime. Thus, the prototype system should have few moving parts, be constrained in degrees of freedom, and be automated with exceeding care. To conserve energy, the mining and processing should take place as close together as possible.

Versatility

The unexpected is usually the most dependable occurrence in mining operations. Despite the care and thoroughness with which site characterization is performed, unexpected problems are inevitable once mining operations begin. For this reason the mining operation should be flexible and versatile enough to permit relatively easy relocation, reorientation, alteration in distribution network, and other changes during the operation cycle.

Automation

The mining system should be capable of automation to the level of sophistication of advanced automated systems at the time of implementation (see fig. 17). The system should also be flexible enough to incorporate the products of future robotics research. Full automation of routine mining operations should be incorporated within the prototype system.

The mining system should be instrumented and computer monitored to provide such operational information as power use, breakout force, and cable tension, so that stress and failure can be anticipated. In addition, mining systems having few degrees of freedom should be sought for early systems. Although laboratory automations have been demonstrated with numerous degrees of freedom and rudimentary tactile and visual sensors, it is not clear that these new advances will be sufficiently developed at the time of lunar resource exploitation.

Figure 17

Coal Mine Automation

Probably the most automated mining systems in use today are in coal mines. Here in a longwall mining system is a drum shear used to fragment a large coal seam. Such systems can operate unattended for relatively long periods of time.

Photo provided by the U.S. Bureau of Mines and the Colorado School of Mines.

Work Force Requirements

Lunar mining should be capital-intensive rather than labor-intensive. Human participation will rapidly increase cost and decrease the margin of profit. Human tending should be restricted to periodic maintenance, repair, and relocation. Routine mining operations should not require human operators.

Low Weight and Cost

It will be an asset if the mining equipment chosen for lunar resource extraction is not of the scale, in mass or dollars, common to current open-pit vehicles, such as power shovels and haulage trucks. Because of the modest soil-moving requirements, the equipment transported to the Moon need not be excessively massive or costly. There are, however, several good reasons for making excavation equipment heavy. Among these are traction, stability, and digging force. It may well be possible and desirable to design equipment so that weight can be *added* on the Moon (using lunar soil or rock, for instance). This may represent an unusual (and interesting) equipment design problem.

Equipment Testing

Rapid deployment of a lunar mining system will require that the entire system be thoroughly tested at full scale on Earth before it is launched to the Moon. All aspects of the system from software to hardware should be tested in a simulated lunar environment. Good understanding of the effects of reduced gravity and hard vacuum on the system is essential. Changes to the system during development and testing must be coordinated to ensure processing plant compatibility.

Conclusions

Lunar mining requirements do not appear to be excessively demanding in terms of volume of material processed. It seems clear, however, that the labor-intensive practices that characterize terrestrial mining will not suffice at the low-gravity, hard-vacuum, and inaccessible sites on the Moon. New research efforts are needed in three important areas. First, to develop high-speed, high-resolution through-rock vision systems that will permit more detailed and efficient mine site investigation and characterization. Second, to investigate the impact of lunar conditions on our ability to convert conventional mining and exploration equipment to lunar prototypes. Third, to develop telerobotic or fully robotic mining systems for operations on the Moon and other bodies in the inner solar system.