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VOLUME 3

SPACE RESOURCES

Materials

Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

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Space Resources

Materials

Editors

Mary Fae McKay, David S. McKay, and Michael B. Duke

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

This volume—Materials—covers a number of technical and policy issues regarding the materials in space (mainly lunar and asteroidal) which can be used to support space operations. The first of the three parts of this volume discusses the nature and location

of these materials, exploration strategy, evaluation criteria, and the technical means to collect or mine these materials. A baseline lunar mine and the basics of asteroid mining are presented and critiqued. The second part discusses the beneficiation of ores and the extraction of such materials as oxygen, metals, and the makings of concrete. The final part of the volume discusses the manufacturing and fabrication of nonterrestrial products. Considered are the economic tradeoffs between bringing needed products from Earth and making these products on location in space.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier,* and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space,* also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom,* our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources,* offers substantiation for NASA's bid to carry out that new initiative.

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PART 1—Exploring, Evaluating, and Mining Nonterrestrial Resources

Richard E. Gertsch

The earliest writings on space industrialization recognized the need for materials to feed factories in orbit (O'Neill 1974; Johnson and Holbrow 1977; Billingham, Gilbreath, and O'Leary 1979). Transportation economics dictated (and still dictate) that the Earth cannot be the source of these materials. Recent writings (such as O'Leary 1983) have backed away from the concept of many large factories in orbit and concentrated instead on small, specific projects involving nonterrestrial materials.

Early large-scale thinking indicated that space manufacturing was economically favorable and could be a source of exciting new technologies. Space as a source of new wealth inspired dreams of capturing large asteroids, building Lagrangian industrial parks, and supplying cheap, plentiful products to a needy Earth. But industrial space parks represent a mature system and beg the question of how we get there. Given the expense of current space missions and our lack of deep space experience, moving directly to a mature system is not practical. A more circumspect scenario is needed. The early writers were not wrong, just premature; the question is, "What can we do tomorrow?"

While that question has not yet been answered, it has at least been formulated. One approach that has been suggested is to extract liquid oxygen from lunar materials and supply it to low Earth orbit (LOX to LEO) for use as spacecraft propellant (Davis 1983). Even if the idea never matures, it is an excellent starting point. In its mining and manufacturing activities, the project is modest, although it requires a significant jump in space transportation capability. It's specific, and it promises a return on investment. Much of this workshop's attention was focused on the LOX-to-LEO idea, although participants also recommended beginning an asteroid exploration program. The authors of the papers that follow concentrate on key practical problems in finding and exploiting the necessary raw materials, and they recommend solutions to these problems.

The members of our workshop group also considered some more advanced projects, such as a larger scale lunar base, capable of providing additional products. But, in the advanced scenarios, the group felt hampered by lack of problem definition. There was simply too little direction on types of products and project size. Terrestrial mining operations are driven by the market price of the product. Without such basic definitions, the group decided to concentrate on the LOX-to-LEO plan.

We discussed missions to retrieve material from asteroids that pass close to or cross the Earth's orbit. Although the difficulties in an

mission, we recommend that asteroid resource research be continued. Lunar exploitation may lead to exploitation of the asteroids from a cislunar staging area, using space manufacturing equipment and methods developed on the Moon. The Moon would then become a learning ground as well as a materials source. Or subsequent study of the lunar mining plan may show that asteroid retrieval is a superior mission, because particular resources are needed or a very favorable asteroid is found. In any case, projects like Earth-based asteroid watches and sample retrieval missions are justifiable on scientific grounds and are being included in NASA advanced planning scenarios. The data to be collected from these projects must be reviewed to ensure that they are appropriate to support mining enterprises.

To Build a Mine: Prospect to Product

Richard E. Gertsch

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.

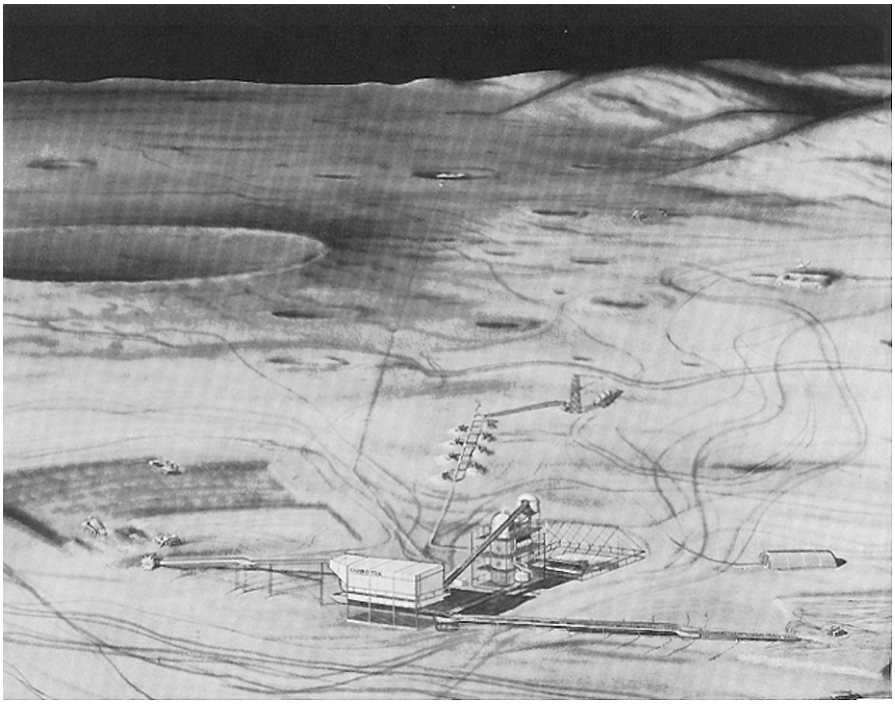
Design and Construction

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 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.

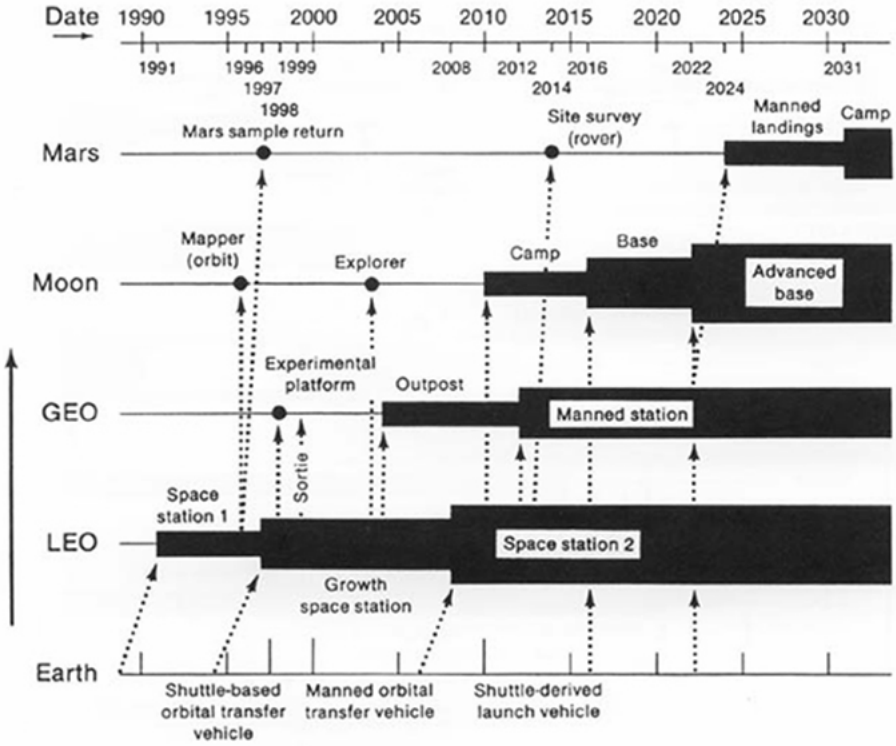


Figure 1

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.

* 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.

NASA photo: AS15-92-12424

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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Lunar Exploration for Resource Utilization

Michael B. Duke

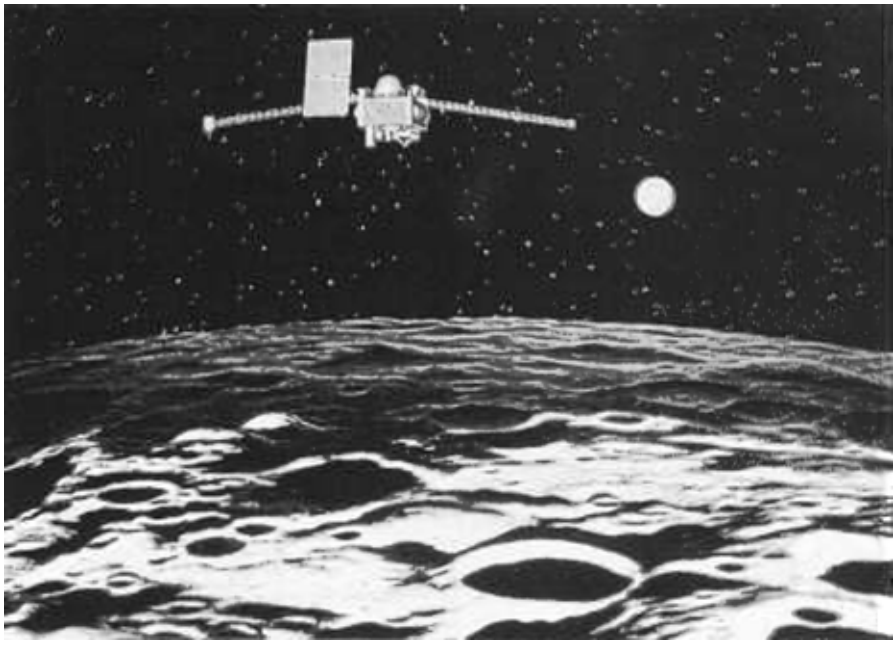
The strategy for developing resources on the Moon depends on the stage of space industrialization. A case is made, in part 3 of this volume, for first developing the resources needed to provide simple materials required in large quantities for space operations. Propellants, shielding, and structural materials fall into this category. As the enterprise grows, it will be feasible to develop additional resources—those more difficult to obtain or required in smaller quantities. Thus, the first materials processing on the Moon will probably take the abundant lunar regolith, extract from it major mineral or glass species, and do relatively simple chemical processing.

Little additional information on ore availability, beyond what was learned in the Apollo Program, is necessary to plan these early steps. Nevertheless, there are classes of information that need to be obtained before we actually develop lunar resources and a lunar base. We need to conduct a lunar remote sensing mission to determine the global distribution of features, geophysical properties, and composition of the Moon, information which will serve as the basis for detailed models of and engineering decisions about a lunar mine.

A satellite placed in low lunar polar orbit for a year or more can completely map the Moon in several ways. Such a mission, a lunar polar orbiter, has been proposed for 15 years, and the desirable complement of instruments for it is relatively well defined. See figure 2.

The combined data set from a lunar polar orbiter would serve to upgrade our understanding of the Moon and its geological evolution. The better we understand that evolution, the better we will be able to predict where to look for valuable resources.

The first contribution of such a mission would be to obtain additional images of the Moon, a process which was left incomplete by the Apollo Program. Past plans for lunar orbiters have not stressed high-resolution image data; however, such imagers have been proposed in more recent concepts of this mission. The instrument will probably be a charge-coupled device (CCD) imager.



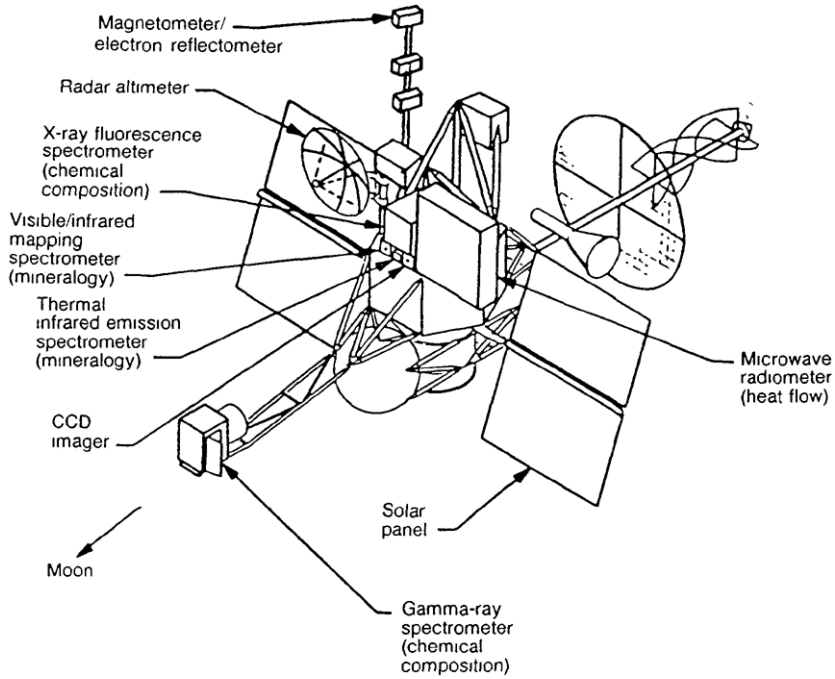


Figure 2

Lunar Observer

A spacecraft orbiting the Moon around its poles, the Lunar Observer, would map the chemical composition of the entire Moon, at a resolution of a few hundred meters. At that resolution, it will be possible to locate areas that are rich in particular lunar minerals, like ilmenite ($FeTiO_3$), and to check the idea that water ice may be trapped in polar cold spots. The Lunar Observer will improve general geological modeling of lunar resource distribution, but the presence of the lunar regolith, which has somewhat homogenized the uppermost surface, will make difficult the detection of specific ore bodies from lunar orbit. Besides such mining information, the Lunar Observer would also gather a broad range of useful scientific information.

Several geophysical instruments—a combination magnetometer and electron reflectometer, a radar (or laser) altimeter, and possibly a microwave radiometer—would gather important geophysical data.

Using x-ray and gamma-ray spectrometers, at a resolution of 1 to a few kilometers, this mission would provide a map of the chemical constituents of the lunar surface. If, as has been speculated, there are concentrations of water in permanently shadowed regions near the lunar poles, the gamma-ray device should be able to detect them. These data will provide information on the global distribution of rock and soil compositions but will not pinpoint small ore deposits, because the lunar regolith has been thoroughly mixed by eons of meteoroid bombardment.

A visible and infrared mapping spectrometer would take spectra of known points on the surface to provide mineralogical data at a finer scale. The results would be low-resolution spectral images of the surface. A thermal infrared emission spectrometer would gather spectra of a longer wavelength, which can be interpreted in terms of surface mineralogy of targeted points, but it would not produce images, This instrument might be upgraded to an imaging spectrometer if technology and costs allow its development.

Although the resolution of chemical mapping by a lunar orbiter may not be high, there are questions of site selection for a processing facility that can be addressed with orbiter data. For example, we know that there are titanium-rich basalts and soils and that there are likewise aluminum-rich anorthosites and soils. Our knowledge of where both types of materials can be accessed readily is less certain. If we plan to develop a lunar facility that depends on the availability of both titanium and aluminum, the lunar orbiter may be able to discover optimum locations.

Geochemical anomalies (ore bodies) may be difficult to locate directly with a lunar polar orbiter. However, some ore deposits may be related to geophysical irregularities. For example, there is a significant magnetic anomaly in the vicinity of the crater Reiner Gamma. The explanation of the anomaly is not in hand, but further exploration of it and similar anomalies, if they are found, may lead to the discovery of new resources. In general, the correlation of chemical and geophysical data should be pursued.

There are a number of issues related to the operation of a lunar base and its resource extraction facilities for which additional image information would be desirable. These include questions of engineering feasibility, surface trafficability, safety, ease of working with the regolith, availability of slopes, and soil cohesiveness. As part of a lunar polar orbiter mission, images with resolution of a few meters should be obtained for areas under consideration as sites for lunar bases.

A lunar orbiter can provide information to establish the surface characteristics of the Moon before extensive human activities there. Because of the static nature of the lunar surface under natural conditions, human activity on the Moon will inevitably change the environment. It will be important to obtain global maps before that stage of development, both to serve as a baseline for further survey work and to record a state that will be changed irreversibly.

Lunar Material Resources: An Overview*

James L. Carter

Abstract

The analysis of returned lunar samples and a comparison of the physical and chemical processes operating on the Moon and on the Earth provide a basis for predicting both the possible types of material resources (especially minerals and rocks) and the physical characteristics of ore deposits potentially available on the Moon. The lack of free water on the Moon eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, (b) secondary mobilization and enrichment, (c) precipitation from a body of water, and (d) placer.

The types of lunar materials available for exploitation are whole rocks and their contained minerals, regolith, fumarolic and vapor deposits, and nonlunar materials, including solar wind implantations. Early exploitation of lunar material resources will be primarily the use of regolith materials for bulk shielding; the extraction from regolith fines of igneous minerals such as plagioclase feldspars and ilmenite for the production of oxygen, structural metals, and water; and possibly the separation from regolith fines of solar-wind-implanted volatiles. The only element, compound, or mineral that by itself has been identified as having the economic potential for mining, processing, and return to Earth is helium-3.

Introduction

To be economical, a lunar base operation requires the identification, characterization, development, and utilization of local resources (Flawn 1966, Dalton and Hohmann 1972, Criswell 1980, Haskin 1983, Carter 1985). Even though it is romantic to dream about exotic and fabulously rich mineral deposits, history has shown us repeatedly that in any area the natural resources that are exploited first are those that (a) are needed for basic survival, (b) are readily available, and (c) can be used with the least modification.
Ore deposits that are remote, mineralogically complex, or low grade (and therefore must be dealt with in large volume) are not exploited until after the infrastructure necessary for their exploitation can be constructed. Meeting the criteria for early exploitation is material from the lunar regolith, the layer of debris that covers the surface of the lunar bedrock. Such material can be used as is for bulk shielding to reduce cosmic ray exposure. And from the lunar regolith such desirable elements as oxygen and iron can be extracted without extensive processing such as crushing. The ideal situation ultimately will be to use the lunar regolith material as a feedstock and to separate from it numerous

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elements and products (Lindstrom and Haskin 1979), but this requires an extensive infrastructure of sophisticated and elaborate processing equipment (Williams et al. 1979).

In this paper I develop a general overview of what can be inferred from theoretical considerations of the physical and chemical processes operating on the Moon and what is known about possibly available types of lunar materials from analysis of samples returned by the Apollo and Luna missions. My overview will include an evaluation of lunar regolith fines (the less-than-1-mm fraction) as a source of volatile elements.

Physical and Chemical Processes

Comparison of physical and chemical processes operating on the Earth and on the Moon provides a basis for predicting both the possible types of material resources, especially minerals, and the physical characteristics of ore deposits potentially available for exploitation on the Moon.

Active Surface Agents

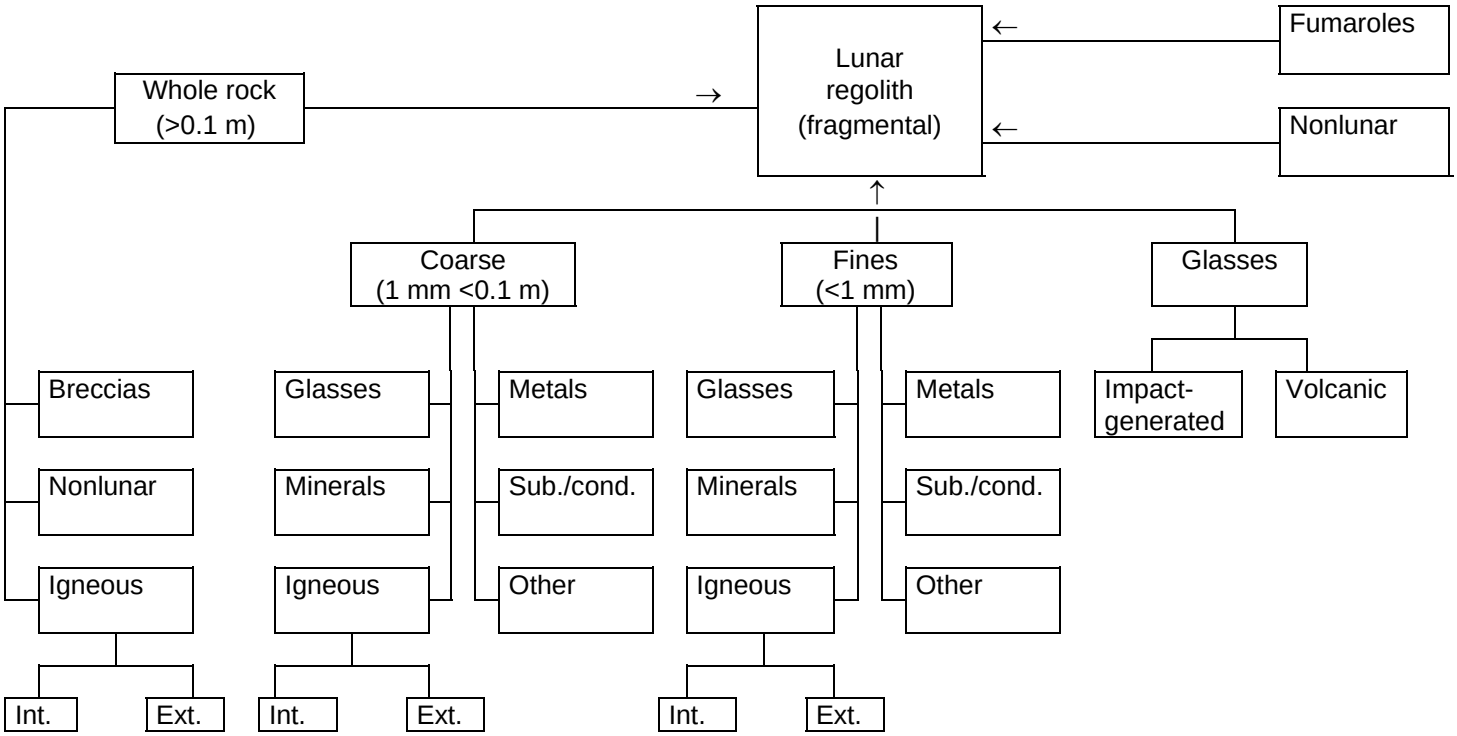
One approach to evaluating possible lunar material resources is to compare the active surface agents that affect the Earth and the Moon. These are listed in table 1. The most striking feature described in table 1 is that the Moon has no atmosphere. Therefore, it has (a) no free water (and thus no freeze/thaw cycles and few, if any, water-bearing minerals such as clays), (b) no free oxygen (and thus no oxidation), and, most importantly, (c) no biological activity. The major physical (erosional) and chemical (weathering) agents—water and oxygen, respectively—and the resulting products we are familiar with on Earth play no role in shaping the surface of the Moon and thus they play no role in the formation of potential lunar ore deposits. The only indigenous lunar erosional agent is volcanic, especially basaltic, lava flows (Hulme 1973). The extremely low viscosities and thus the high extrusion rates of lunar basaltic lava flows (Moore and Schaber 1975) are conditions favorable for the formation of lava channels and tubes, which are very abundant on the lunar surface (Oberbeck et al. 1971). It may be possible to use the naturally sheltered environment of a large lava tube as housing for a lunar base (Hörz 1985). Moreover, some lava tubes may contain accumulations of volatiles.

TABLE 1. *Comparison of Active Surface Agents on the Earth and on the Moon*

Process		Agents	Type	Earth	Moon
ENDOGENIC	Atmosphere	H_2O	Free	Yes (major)	No? (transient)
		O_2	"	Yes (major)	No? (transient)
		CO_2	"	Yes	Yes? (transient)
		H_2	"	Yes (v. minor)	Yes (v. minor) (transient)
		S	"	Yes?	Yes (v. minor) (transient)
		Others	"	Yes	Yes? (transient)
	Liquid water			Yes (major)	No
	Volcanic	Solids		Yes (major)	Yes (minor?)
		Liquids		Yes (major)	Yes (major)
		Gases		Yes (minor)	Yes (v. minor)
	Thermal	Freeze/thaw		Yes (major)	No
		No water		Yes? (v, minor)	Yes (v. minor?)
	Biological			Yes (major)	No
	Gravity			Yes (major)	Yes (minor)
EXOGENIC	Solar wind			No	Yes (major)
	Impact-produced	Solids: Micro. met.		No?	Yes (major)
		Solids: Macro. met		Yes (v. minor)	Yes (major)
		Liquids: Micro. met.		No	Yes (major)
		Liquids: Macro. met		Yes (v, minor)	Yes (major)
		Gases: Micro. met.		No?	Yes (minor)
		Gases: Macro. met		Yes (v. minor)	Yes (major)

The lack of an atmosphere on the Moon allows meteorites, comets, micrometeorites, and the solar wind to bombard the lunar surface unimpeded. These are the most important agents shaping the lunar surface. They also contribute to its material resources (table 2; see also Williams and Jadwick 1980).

TABLE 2. *Types of Lunar (Mare, Highland, Other) Materials Resources*



Cond. = condensates
Ext. = extrusive
Int. = intrusive
Sub. = sublimates

The various types of materials that contribute to the lunar regolith are diagrammatically displayed in table 2. To reveal the exploitation potential of the contents of any box requires much additional information. Also of importance is the distribution of the various types of lunar materials. From the simplest point of view, the Moon has two basic types of physiographic provinces: light-colored lunar highlands and dark-colored lunar maria. The highlands are old crust (more than four billion years). The maria are relatively young (less than four billion years) and are large impact-produced craters that are flooded with basaltic rock types (Taylor 1975).

The chemistry of these two basic physiographic provinces is similar, except in aluminum, iron, calcium, and titanium (table 3), but their mineralogy is quite different. The highlands consist of rocks very rich in plagioclase and thus rich in aluminum and calcium; whereas, the maria consist of ilmenite-bearing basaltic rocks and thus are titanium- and iron-rich. The ideal early exploitation target would be situated where both types of materials are juxtaposed, such as near the margins of some mare (McKay and Williams 1979) or on a ray from a major impact that extends from the lunar highlands into a mare.

TABLE 3. *Average Major Element Chemistry for Mare and Highland Soil*
[From Turkevich 1973]

Element	Percent of atoms			Weight percent of oxides		
	Mare	Highland	Average surface	Mare	Highland	Average surface
O	60.3 ± 0.4	61.1 ± 0.9	60.9			
Na	0.4 ± 0.1	0.4 ± 0.1	0.4	0.6	0.6	0.6
Mg	5.1 ± 1.1	4.0 ± 0.8	4.2	9.2	7.5	7.8
Al	6.5 ± 0.6	10.1 ± 0.9	9.4	14.9	24.0	22.2
Si	16.9 ± 1.0	16.3 ± 1.0	16.4	45.4	45.5	45.5
Ca	4.7 ± 0.4	6.1 ± 0.6	5.8	11.8	15.9	15.0
Ti	1.1 ± 0.6	0.15 ± 0.08	0.3	3.9	0.6	1.3
Fe	4.4 ± 0.7	1.8 ± 0.3	2.3	14.1	5.9	7.5

Rock Cycle

Another approach to evaluating possible lunar material resources is to compare the rock cycle of the Moon (fig. 3) to that of the Earth (fig. 4). A rock cycle is a sequence of events leading to the formation, alteration, destruction, and reformation of rocks as a result of various physical and chemical processes. Thus, it is a pictorial way of viewing the different processes that lead to natural material resources such as ore deposits and of predicting the types of deposits that result from the various physical and chemical processes. A comparison of the Moon's rock cycle with the Earth's (shown in figures 3 and 4, respectively) reveals the

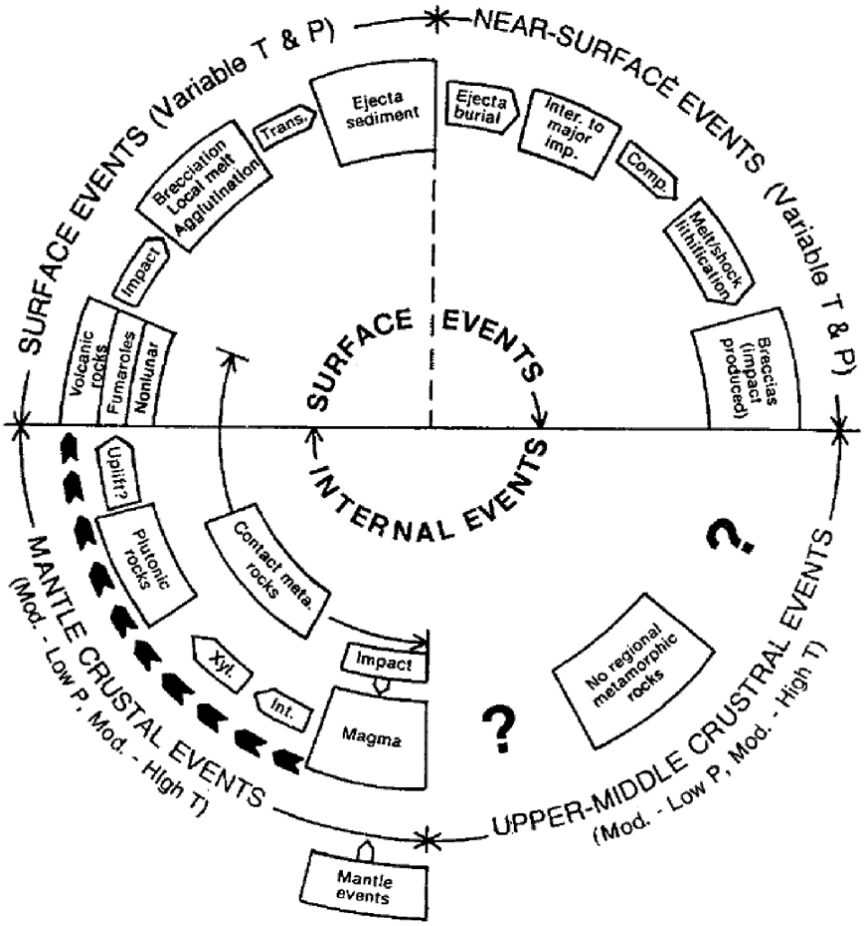


Figure 3

Moon Rock Cycle

Comp. = compression
Imp. = impact
Int. = intrusion
Inter. = intermediate
Meta. = metamorphic
Mod. = moderate
Trans. = transport
Xyl. = crystallization

fundamental differences resulting from the lack of free water and oxygen on the Moon. The comparison also shows that, while the Moon has been dominated by external processes, the Earth has been dominated by internal processes. The various types of physical and chemical processes represented by the rock cycles, the resulting commercial types of mineral deposits on Earth, and the probable types of lunar deposits are shown in table 4.

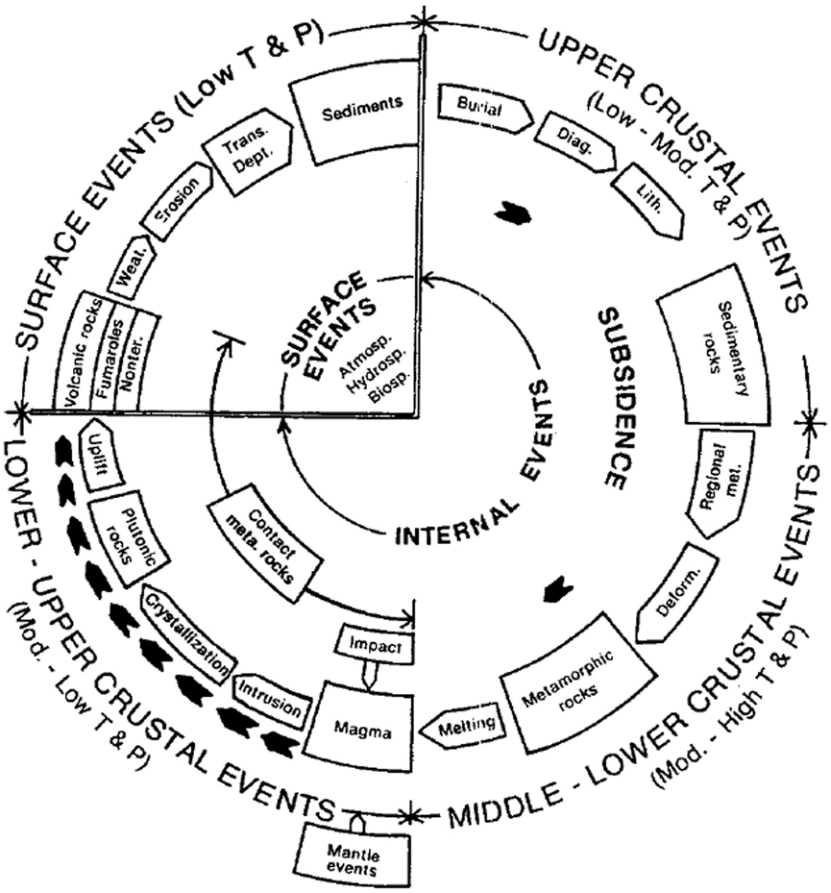


Figure 4

Earth Rock Cycle

Atmosp. = atmospheric
Biosp. = biospheric
Deform. = deformation
Dept. = deposition
Diag. = diagenesis
Hydrosp. = hydrospheric
Lith. = lithification
Met. = metamorphism
Meta. = metamorphic
Nonter. = nonterrestrial
Trans. = transport
Weat. = weathering

TABLE 4. *Various Processes in Mineral Deposit Formation*

Type	Probably occur on Moon	Commercial type Earth deposit	Probable type lunar deposit
I. Igneous			
A. Intrusive magmatic			
1. Early			
a. Dissemination	Yes	Diamonds, apatite, corundum	Ilmenite
b. Segregation	Yes	Chromite, Pt, anorthite, ilmenite, titanomagnetite	Ilmenite, anorthite, chromite?
c. Injection	Yes?	Magnetite	Oxides?
2. Late			
a. Gravitative liquid accumulation			
i. Seg.	Yes	Chromite, Pt, titanomagnetite	Ilmenite, titanomagnetite?
ii. Inject.	Yes?	Magnetite, apatite	Oxides?
b. Immiscible liquid			
i. Seg.	Yes	(Ni,Cu)S, Pt, Au	(Ni,Cu,Fe)S, Pt, Au?
ii. Inject.	Yes	(Ni,Cu)S, Pt	(Ni,Cu,Fe)S, Pt
c. Carbonatite	No?	Rare earths	?
d. Felsic pegmatite	No?	Feldspar, mica, rare earths, quartz, gemstones	?
B. Volcanic			
1. Glass	Yes	Perlite, pumice	Ti-, Al-rich
2. Submarine exhalative	No	Base metal	None
3. Sublimates; condensates	Yes	S, NaCl	S?, chlorides
II. Metamorphic/metasomatic			
A. Contact	Yes	W, Cu, Pb, Zn	?
B. Regional	No?	Abrasives, aluminosilicates	None?
C. Thick ejecta blanket	Yes	Meteoritic material	Phosphates, volatiles?
III. Surficial (sedimentation)			
A. Sedimentation	Yes	Sand, gravel, limestone	Regolith
B. Biochemical processes; organic accumulations	No	Petroleum	None
C. Oxidation; supergene enrichment	No	Base metal, Au, Ag, U	None
D. Residual/mechanical concentration	No?	Au, rare earths, Al, Fe, diamonds	None?
E. Evaporation	No?	Salts	None?
F. Groundwater	No?	U, Cu	None?
IV. Asteroid/comet impact	Yes	Ni, Fe, Pt?	Ni, Fe, Pt, C, H_2O, chlorides

The apparent lack of plate tectonics operating on the Moon (Taylor 1975) is also of importance in evaluating possible lunar material resources. Plate tectonics, which is characterized on Earth by a small number of large, broad crustal plates, each of which "floats" on a viscous underlayer (mantle) and moves more or less independently of the others, is fundamental to the development of most commercial type ore deposits and even petroleum deposits on Earth (Mitchell and Garson 1981, Hutchison 1983). One important aspect of plate tectonics on the Earth is the recycling and partial fusion of crustal materials to form granites and their related ore deposits and pegmatites (Mitchell and Garson 1981, Hutchison 1983). Even though a granite-like residual phase (mesostasis and "veinlets") and very small granitic clasts in breccias occur in rocks on the Moon (Rutherford et al. 1976, Warren et al. 1983a), there is no evidence that large-scale granitic bodies occur on the Moon (Taylor 1975). Moreover, unlike the majority of similar Earth rocks, the granite-like Moon rocks are completely devoid of hydrous phases (Warren et al. 1983a).

Lunar Material Resources

The types of lunar materials available for exploitation (table 2) can be grouped into four basic categories: whole rocks and minerals, regolith, fumarolic and vapor deposits, and nonlunar materials. We have very little direct knowledge of whole rocks in situ, and we know virtually nothing about possible fumarolic deposits. The Apollo and Luna missions were designed to study the lunar regolith, with cores taken a maximum of 3 meters deep (Carrier 1974, Taylor 1975). Thus, in the subsequent sections, I will mainly discuss the potential of the near-surface lunar regolith as a source of materials, especially as a source of volatile elements.

Rocks and Minerals

Rocks: The major rock types in the maria are basalts, gabbros, pyroxene-rich peridotites, and breccias (Mason and Melson 1970, Levinson and Taylor 1971, Taylor 1975, Gillett 1983, Taylor 1984). The major rock types in the highlands are various types of anorthosites; anorthositic gabbros;

KREEP basalt enriched in potassium, rare earths, and associated elements; low-potassium basalt; norite; dunite; and breccias (Taylor 1975, Gillett 1983).

The mare rock types are composed primarily of plagioclase feldspars, clinopyroxenes, and ilmenite, with minor olivine, chromite/ulvöspinel, and tridymite/cristobalite (Taylor 1975). The highland rock types are composed primarily of plagioclase feldspars, orthopyroxenes, and olivine, along with minor ilmenite (Taylor 1975). The whole rocks represent a potential source of these minerals and someday may be used as a feedstock because they would supply material of relatively uniform physical characteristics, but their use would require an extensive infrastructure for mining and processing. The regolith fines will probably be exploited first because they have already been pulverized by meteoritic and cometary bombardment. The ranges of modal abundances for the major lunar minerals in various rock types are shown in table 5. The ranges of chemical compositions for the major lunar minerals in various rock types are shown in table 6.

TABLE 5. *Ranges of Modal Abundances (Volume %) for the Major Lunar Minerals in Various Rock Types*
[Modified from Waldron, Erstfeld, and Criswell 1979]

	High-Ti mare basalts	Low-Ti mare basalts	Highland rocks
Pyroxene	42 – 60	42 – 60	5 – 35
Olivine	0 – 10	0 – 36	0 – 35
Plagioclase	15 – 33	17 – 33	45 – 95
Opaques (mostly ilmenite)	10 – 34	1 – 11	0 – 5

TABLE 6. *Ranges of Chemical Compositions for the Major Lunar Minerals in Various Rock Types*
[Modified from Waldron, Erstfeld, and Criswell 1979]

Components (wt. %)	Pyroxene	Olivine	Plagioclase	Opaques (mostly ilmenite)
a. High-titanium mare basalts				
SiO_2	44.1 – 53.8	29.2 – 38.6	46.9 – 53.3	<1.0
Al_2O_3	0.6 – 6.0		28.9 – 34.5	<2.0
TiO_2	0.7 – 6.0			52.1 – 74.0
Cr_2O_3	<0.7	0.1 – 0.2		0.4 – 2.2
FeO	8.1 – 45.8	25.4 – 28.8	0.3 – 1.4	14.9 – 45.7
MnO	<0.7	0.2 – 0.3		<1.0
MgO	1.7 – 22.8	33.5 – 36.5	<0.3	0.7 – 8.6
CaO	3.7 – 20.7	0.2 – 0.3	14.3 – 18.6	<1.0
Na_2O	<0.2		0.7 – 2.7	
K_2O			<0.4	
b. Low-titanium mare basalts				
SiO_2	41.2 – 54.0	33.5 – 38.1	44.4 – 48.2	< 1.0
Al_2O_3	0.6 – 11.9		32.0 – 35.2	0.1 – 1.2
TiO_2	0.2 – 3.0			50.7 – 53.9
Cr_2O_3	<1.5	0.3- 0.7		0.2 – 0.8
FeO	13.1 – 45.5	21.1 – 47.2	0.4 – 2.6	44.1 – 46.8
MnO	<0.6	0.1 – 0.4		0.3 – 0.5
MgO	0.3 – 26.3	18.5 – 39.2	0.1 – 1.2	0.1 – 2.3
CaO	2.0 – 16.9	<0.3	16.9 – 19.2	<1.0
Na_2O	<0.1		0.1 – t.3	
K_2O			< 0.3	
c. Highland rocks				
SiO_2	51.10 – 55.4	37.70 – 39.9	44.00 – 48.0	<0.1
Al_2O_3	1.00 – 2.5	<0.1	32.00 – 36.0	0.80 – 65.0
TiO_2	0.45 – 1.3	<0.1	0.02 – 0.03	0.40 – 53.0
Cr_2O_3	0.30 – 0.7	<0.1	<0.02	0.40 – 4.0
FeO	8.20 – 24.0	13.40 – 27.3	0.18 – 0.34	11.60 – 36.0
MgO	16.70 – 30.9	33.40 – 45.5	<0.18	7.70 – 20.0
CaO	1.90 – 16.7	0.20 – 0.3	19.00 – 20.0	<0.6
Na_2O			0.20 – 0.6	
K_2O			0.03 – 0.15	

Minerals: The number of mineral species positively identified on the Moon is 70, with 14 others tentatively identified (table 7) (Levinson and Taylor 1971, Frondel 1975, Warren et al. 1983b, Meyer and Yang 1988), which is less than 2 percent of the mineral species known on Earth (Fleischer 1987). However, less than 2 percent of the 3800 mineral species known on Earth makes up more than 95 percent of the commercially exploitable mineral deposits on Earth. These may be divided into those that can be used in their natural state, either singularly or combined with others to form a rock, and those that must be refined. Of the known lunar minerals, a maximum of one-sixth have "early" exploitation potential. These are apatite, armalcolite, chromite, "goethite," ilmenite, iron-nickel, olivine, plagioclase feldspars, potassium feldspars, and whitlockite (table 7). But of these only ilmenite, plagioclase feldspars,

TABLE 7. *Lunar Minerals*

Common and abundant minerals		**Important accessory minerals**	
Clinopyroxenes	$(Ca,Mg,Fe)_2Si_2O_6$	Apatite	$Ca_5(PO_4)_3(F,Cl)$
Augite		Armalcolite	$(Fe,Mg)Ti_2O_5$
Ferroaugite		Baddeleyite	ZrO_2
Ferrohedenbergite		Cristobalite	SiO_2
Ferropigeonite		Iron-nickel	FeNi
Pigeonite		Kamacite	
Salite		Taenite	
Subcalcic augite		Potassium feldspars	$KAlSi_3O_8$
Titanaugite		Hyalophane	
Ilmenite	$FeTiO_3$	Orthoclase	
Olivine	$(Mg,Fe)_2SiO_4$	Sanadine	
Chrysolite		Pyroxferroite	$CaFe_6(SiO_3)_7$
Fayalite		Quartz	SiO_2
Forsterite		Spinels	$(Fe,Mg,Ti)(Al,Cr,Ti)_2O_4$
Orthopyoxenes	$(Mg,Fe)SiO_3$	Chromite	
Bronzite		Picotite	
Enstatite		Pleonaste	
Hypersthene		Hercynite	
Plagioclase feldspars	$(Ca,Na)Al_2Si_2O_8$	Spinel	
Andesine		Titanian chromite	
Anorthite		Tranquillityite	$Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$
Bytownite		Tridymite	SiO_2
Labradorite		Troilite	FeS
		Ulvöspinel	Fe_2TiO_4
		Whitlockite	$Ca_9MgH(PO_4)_7$
		Zirkelite	$(Ca,Fe)(Zr,Ti)_2O_7$

TABLE 7 *(concluded).*

Rare minerals	
Aluminum carbide	Al_4C_3
Amphibole	
Hornblende	
$(Ca,Na,K)_{2–3}(Mg,Fe,Al)_5$ $([OH]?,F,Cl)_2Al_2Si_6O_{22}$	
Magnesioarfvedsonite	
$(Na,K,Ca)_3(Mg,Mn,Fe)_5$ $([OH]?,F)_2(Si,Al,Ti)_8O_{22}$	
Bomite	Cu_5FeS_4
Brass	CuZn
Calcite (?)	$CaCO_3$
Chalcopyrite	$CuFeS_2$
Cohenite	$(Fe,Ni)_3C$
Copper	Cu
Corundum	Al_2O_3
Cubanite	$CuFe_2S_3$
Garnet	
Almandine	$Fe_3Al_2(SiO_4)_3$
"Goethite"	FeOOH
Akaganeite	
Lepidochrosite	
Lawrencite	$FeCl_2$
Mackinawite	FeS
Mica	
Biotite	
K_2 $([OH]?,F)_4(Mg,Fe,Al)_6(Si,Al)_8O_{20}$	
Muscovite (?)	
$KAl_2(AlSi_3)O_{10}$ $([OH]?,F)_2$	
Monazite	$(Ca,La,Y,Th)PO_4$
Niningerite	MgS
Pyrochlore	
Yttrobetafite	
$(Ca,Y,REE,Fe,Pb,Th,U)_2(Ti,Nb,Fe)_2O_7$	
Rutile	TiO_2
Schreibersite	$(Fe,Ni,Co)_3P$
Sphalerite	ZnS
Thorite	$ThSiO_4$
Tin	Sn
Titanite	$CaTiSiO_5$
Zircon	$ZrSiO_4$
Tentative minerals	
Aragonite	$CaCO_3$
Farringtonite	$(Mg,Fe)_3(PO_4)_2$
Garnet	
Spessartite	$Mn_3Al_2(SiO_4)_3$
Hematite	Fe_2O_3
Magnetite	Fe_3O_4
Melilite	
$(Ca,Na)_2(Mg,Fe)(Al,Si)_2O_7$	
Moissanite	SiC
Nickel	Ni
"Nickel silver"	CuNiZnFe
Pentlandite	$(Fe,Ni)_9S_8$
Perovskite	$CaTiO_3$
Sillimanite (or mullite)	Al_2SiO_5
Tainakhite	$Cu_9(Fe,Ni)_9S_{16}$
Wüstite	FeO

and possibly "goethite" are very likely to be exploited early (McKay and Williams 1979). These minerals could be used to produce oxygen, structural metals (aluminum, iron, and titanium), and water, and they seem to occur in concentrations high enough to warrant exploitation. Apatite, potassium feldspars, and whitlockite are important raw materials in the production of fertilizers for growing plants on the Moon, but they may not be present in high enough concentrations to be easily exploited.

Regolith

The lunar regolith, especially the fraction called “fines” (the particles that are less than 1 mm in diameter), offers the opportunity to take advantage of two different physical processes operating on the lunar surface: (1) brecciation, including pulverization through meteoritic and cometary impact, and (2) solar wind implantation of volatile species. The longer the lunar regolith is exposed to bombardment, the greater the extent of pulverization and implantation of volatile species, However, two counterproductive processes are in operation. First, major impacts result in throw-out of large volumes of material that cover up older regolith. Second, micrometeorite bombardment results in production of agglutinates, which are lunar fines welded together with liquid silicate (glass) (McKay et al. 1971). Thus, there are both destructive and constructive processes operating on the lunar surface.

The heating of the fines associated with micrometeoritic events liberates some of the solar-wind-implanted volatile species (Carter 1985) and plays an important role in the distribution and redistribution of volatiles on the Moon (Wegmüller et al. 1980).

The formation of agglutinates also decreases the availability of minerals, such as plagioclase feldspars and to a lesser extent ilmenite, for concentration from lunar fines (tables 8 and 9; figure 5). But agglutination does produce a small amount of metallic iron (Morris 1980), which should be concentratable by magnetic means. There is, in any case, an upper limit for production of agglutinates (McKay and Basu 1983). The ideal situation would be to have lunar regolith old enough to allow maximum solar wind implantation but not so old as to allow extensive production of agglutinates.

TABLE 8. *Grain Populations in Percent for Selected Particle Types of the 90–150 Micrometer Size Fraction in Some Apollo 16 Soils*
[From McKay and Williams 1979]

	Sample	Plagioclase	Anorthosite	Light matrix breccia	Total	Normative anorthite	Agglutinates
Core	60009,455	47.0	6.8	3.8	57.6	82	12.5
	60009,457	76.2	3.8	0.8	80.8	---	2.2
	61161	14.7	4.7	13.6	33.0	72	37.0
STA 1	61181	5.3	4.3	7.3	16.9	74	59.6
	61221	17.0	13.6	10.0	40.6	77	6.3
	61241	12.3	5.0	18.3	35.6	74	27.1
STA 2	62281	16.0	5.6	11.3	32.9	73	40.0
	63321	9.6	11.2	14.0	34.8	79	32.6
STA 3	63341	12.6	5.9	14.9	33.4	79	40.0
	63501	10.3	3.0	16.7	30.0	76	44.6
STA 4	64501	20.3	3.0	6.6	29.9	75	51.6
STA 8	68501	12.3	1.9	29.3	43.5	73	38.6
	67481	15.0	10.9	20.3	45.2	79	23.0
	67601	14.0	3.6	24.0	41.6	79	36.0
STA 11	67701	21.0	3.3	34.0	58.3	78	15.6
	67711	41.0	4.6	36.6	82.2	80	1.6

TABLE 9. Modal and Normative Ilmenite in Mare Basalts From the Apollo Missions
[From McKay and Williams 1979]

Sample	Modal ilmenite content, %	Normative ilmenite content, %
10003	14–18	21.5
10017	14–24	22.4
10044	6–12	17.1
10045	7–11	21.3
10049	16–17	21.5
10072	13–22	22.8
Apollo 11 mean	**14.5**	**21.1**
12202	8–11	4.9
12012	5–12	6.6
12022	9–23	9.3
12039	8–10	5.7
12051	8–11	8.9
12063	8–10	9.5
Apollo 12 mean	**10**	**7.5**
15016	6	4.4
15076	0.5	3.6
15475	1.0	3.4
15555	1–5	4.0
15556	2	5.1
Apollo 15 mean	**2.6**	**4.1**
75055	12–20	20.5
70215	13–37	24.7
70035	15–24	24,7
70017	19–23	24.7
Apollo 17 mean	**20.4**	**23.7**

Minerals: The constant meteoritic and cometary bombardment of the lunar surface results in comminution of whole rocks, with liberation of the mineral constituents. Most of the minerals listed in table 7 have been found as isolated grains or as composite particles in the lunar regolith fines. The available anorthite content in the Apollo 16 lunar highland regolith samples (90- to 150-micrometer size fraction) varies from just under 17 percent to just over 82 percent (see table 8) and averages 43.5 percent. The lower values result from the inverse relationship between available anorthite content and agglutinate content (see figure 5). The ilmenite content of mare basalts from all Apollo missions varies from 0.5 percent to 37 percent (see table 9) and averages 11.5 percent. If the significantly lower Apollo 15 samples are omitted, the average is 14.4 percent. Electrostatic separation experiments in vacuum by Agosto (1985) suggest that grade and recovery percentages should be between the high 70s and the low 90s.

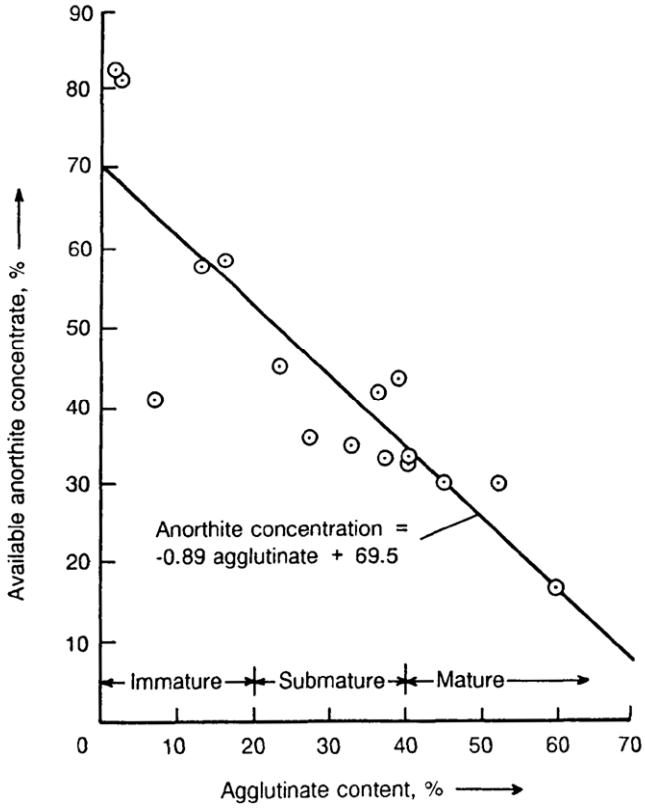


Figure 5

Relationship Between Available Anorthite and Maturity of Soil

From McKay and Williams 1979.

Glasses: There are two main types of glasses found in the lunar regolith—homogeneous and heterogeneous (Taylor 1975). The homogeneous glasses are "volcanic" in origin or produced by major impacts, and the heterogeneous glasses are produced by more minor impacts. Two chemically distinct homogeneous glasses have been found to be abundant in spots: green and orange (Taylor 1975). The green glasses are of the most primitive lunar composition yet found and are a possible source of aluminum. The orange glasses are a possible source of titanium. In addition, both have surface coatings that may offer chlorine, copper, lead, zinc, and other volatile elements and compounds (Jovanovic and Reed 1973, Rhodes 1973, Chou et al. 1975, Meyer et al. 1975). However, in order to utilize this material, we would have to undertake extensive chemical processing. The heterogeneous glasses have a wide range of chemistries (Taylor 1975), and thus it would be difficult to separate them from the rest of the regolith.

Volatile species: Because the Moon has no atmosphere, the lunar regolith fines are a potential source of solar-wind-implanted ions such as H, N, C (table 10; see also, for example, Eberhardt et al. 1972 and Gibson, Bustin, and McKay 1988), and ^{3}He. Wittenberg, Santarius, and Kulcinski (1986) calculated that the Moon's surface materials contain approximately 10^{9} kg of ^{3}He. If ^{3}He can be developed as an energy source, the energy payback for extracting and transporting ^{3}He to Earth is approximately 250, which is better than 10 times the payback for conventional energy sources on Earth.

TABLE 10. *Concentration of H, C, and N in Lunar Regolith Fines*
[Modified from Taylor 1975]

Site	Concentration, ppm		
	H	C	N
Apollo 11	46– 54	142– 226	102– 153
Apollo 12	38– 80	23– 180	40– 130
Apollo 14	36– 70	42– 186	80– 164
Apollo15	13– 120	21– 186	25– 113
Apollo 16	8– 79	31– 280	30– 155
Apollo 17	42– 211	4– 200	7– 130
Luna 16			134– 2100
Luna 20			80– 800

Wittenberg, Santarius, and Kulcinski (1986) further calculated that, even if the U.S. electrical demand doubled every 25 years until the 22nd century and deuterium/helium-3 fusion provided all the electrical energy required after the year 2020, only 3 percent of the Moon's ^{3}He resources would be used. In addition, they concluded that "It should also be possible to use the lunar surface as a source of fuel for power plants in earth orbit, on the moon or on other planets. This lunar source of ^{3}He is sufficiently large to provide for a century or more of space research to exploit the extremely large ^{3}He reserves on Jupiter. Thus, the lunar ^{3}He can help deliver the 'clean' energy source that fusion scientists have been promising for over 30 years."

Fumaroles and Vapor Deposits

As I have stated previously, there is little direct evidence that fumaroles exist or ever existed on the lunar surface. The observation of gaseous emanations from the crater Alphonsus by Kozyrev (1962) and the probable fire-fountaining origin of the orange glass spheres (McKay and Heiken 1973) suggest that volcanic gases occur on the Moon. The crystallization of subsurface magma should release dissolved volatiles and, if these volatiles accumulate, then fumarolic activity should occur (Sato 1979), with possible deposition of volatile species. Another source of volatiles is emanations from the lunar interior (Gorenstein, Golub, and Bjorkholm 1974; Hodges and Hoffman 1974; Geake and Mills 1977; Middlehurst 1977; Runcorn 1977). Fumarolic-like activity may also occur through the remobilization of material from the heating associated with major meteoritic or cometary impacts (McKay et al. 1972, Jovanovic and Reed 1975, Cirlin and Housley 1980). The discovery by McKay et al. (1972) of vapor-deposited apatite, ilmenite, metallic iron, plagioclase, pyroxene, and troilite in recrystallized Apollo 14 breccias is an example of remobilization of elements by a major impact event.

The permanently dark and cold areas of the lunar polar regions may be a source of cryotrapped volatiles (Watson, Murray, and Brown 1961; Arnold 1979; Lanzerotti, Brown, and Johnson 1981). Temperatures possibly as low as 40 K suggest the possibility of both surface and subsurface ices that could survive for billions of years. However, until exploration of the polar regions occurs, we can only speculate as to the possible presence and nature of ices (Staehle 1983). If they occur in useful quantities, they will provide an overwhelming reason for locating at least some part of a base complex near a pole (Burke 1985).

Nonlunar Materials

There are two basic types of nonlunar inputs: (1) meteoritic, including cometary, and (2) solar wind. The rocks from which the lunar regolith is formed are fragmented by meteoritic and cometary impacts. This process results in the input of material of nonlunar sources (Ganapathy et al. 1970, Baedecker, Chou, and Wasson 1972; Zook 1975). The fragmented material, with its included nonlunar material, is a potential resource. For example, if large masses or concentratable fragments of chondritic materials can be located, they will be a source of volatile elements (Taylor 1975). Meteoritic debris is also a source of metallic iron, nickel, and cobalt (Dalton and Hohmann 1972; Goldstein and Axon 1973; Goldstein, Hewins, and Axon 1974; Wänke, Dreibus, and Palme 1978; Mehta and Goldstein 1980) and a potential source of the platinum group elements and gold (Ganapathy et al. 1970, Wlotzka et al. 1972, Hertogen et at. 1977).

Discussion

The surface of the Earth is dominated by water-related erosional processes, oxidation, and biological activity, whereas the surface of the Moon is dominated by bombardment processes (table 1). Internal crustal processes for both the Earth and the Moon are dominated by metamorphic reactions in which water plays an important role on Earth (figs. 3 and 4). There is no evidence of free water on the Moon. The lack of free water on the Moon significantly affects the nature of possible ore deposits on the Moon and eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, which includes all base metal sulfide and precious metal vein deposits; (b) secondary mobilization and enrichment, which includes all ground-water-related ore deposits; (c) direct precipitation from a body of water, which includes evaporite deposits such as gypsum and salt; and (d) placer, which includes heavy mineral deposits such as diamond, gold, ilmenite, monazite, rutile, and zircon. These types of ore deposits have made up a significant percentage of the ores mined on Earth, because these processes concentrate the elements and the heavy minerals into exploitable deposits.

The data in tables 1 and 2 and the evaluation of figures 3 and 4 offer no evidence, direct or theoretical, for significant base metal sulfide or precious metal vein deposits on the Moon. However, we must be somewhat cautious about making categorical statements, because only nine lunar landing sites (six manned Apollo and three unmanned Luna) have been sampled and these were not chosen at random. Even though

meteoritic processes result in throw-out of materials and thus a potentially wide distribution of fragmented rock types, there could be small, localized, but very concentrated sources of desirable elements or compounds that would go unrecognized in studies of particles among the returned lunar regolith fines. If concentrations of desirable elements or compounds do occur, they should be found in igneous rocks, meteoritic and cometary debris, and regolith fines that have been affected by solar wind implantation (table 2; figure 3).

In 1985 I made a pioneering effort to evaluate quantitatively the lunar regolith fines as a primary source of hydrogen. The theoretical foundation laid in that paper can be used to evaluate quantitatively any solar-wind-implanted species or any species found on or near the surface of a particle, no matter what its origin.

The known concentration range of hydrogen, nitrogen, and carbon in the lunar regolith fines is shown in table 10. Such values are often used as evidence that the Moon is devoid of water, even though 100 ppm of hydrogen is equivalent to 0.09 percent by weight of water, In addition to water, other elements necessary for the growth of plants—nitrogen and carbon (carbon dioxide)—are also present on the Moon. However, because these three elements together total less than 0.3 percent of the lunar regolith (table 10), they must be beneficiated (concentrated) before they can be economically extracted. Beneficiation of lunar regolith fines can only occur under the following conditions: (1) A relatively small portion of the fine material must contain a significant amount of the element sought. (2) That material must be separable; that is, it must have unique physical and chemical properties. (3) The separation process must be economical; that is, not labor intensive or technically complex.

In my 1985 paper I demonstrated that the lunar regolith fines meet the basic requirement for beneficiation because a major portion (a minimum of two-thirds) of the hydrogen, and probably other solar-wind-implanted elements, occurs in the less-than-20-micrometer size fraction—a relatively small part of the fines. A comparison of the lunar data of Bustin et al. (1984) with the results of my theoretical calculations (table 11) reveals excellent similarity, except for a slight but significant increase of hydrogen in the size fractions that are greater than 120 micrometers. This enrichment of the lunar samples is due to the presence of constructional particles (McKay et al. 1971, Carter 1971); namely, agglutinates (DesMarais, Hayes, and Meinschien 1974) and other types of dust-welded particles.

One aspect of the question of economics is how difficult and expensive it is to extract the solar-wind-implanted elements from the beneficiated lunar regolith fines. In 1985 I recalculated the hydrogen thermal release pattern for a sample of Apollo 11 regolith fines (10086) (Gibson and Johnson 1971) and found that approximately 81 percent of the hydrogen is released below 600 °C. This calculation means that only a moderate amount of thermal energy should be required to extract a significant portion of the hydrogen, especially if advantage can be taken of daytime temperature on the lunar surface and if heat can be recycled to preheat the beneficiated fines. However, I also demonstrated that the amount of material that would have to be processed to supply 1 metric ton of hydrogen is significant, even when all efforts have been made to enhance the production. I found that, for the 63 percent of the hydrogen that occurs in the less-than-20-micrometer size fraction of Apollo 15 sample 15021 (Bustin et al. 1984), a minimum of 19 596 metric tons of lunar regolith fines would have to be processed, with 4507 metric tons of concentrate heated, yielding a recovery of 51 percent of the

TABLE 11. *Comparison of Calculated Percentages (by Volume) of Coatings (200 Å Thick) on Particles of Various Size Fractions With Measured Percentages (by Volume) of Hydrogen in Such Particles*
[From Carter 1985]

Average particle diameter, µm	Percentage of total volume of fraction that is coating	Percentage of total coating in fraction	Percentage of total hydrogen in fraction*
10.0	1.195	56.46	51.34
32.5	0.369	17.42	17.11
60.0	0.200	9.44	9.73
82.5	0.145	6.87	6.38
120.0	0.100	4.72	5.03
200.0	0.060	2.83	4.36
375.5	0.032	1.51	4.03
750.0	0.016	0.76	2.01
Total	**2.117**	**100.01**	**99.99**

*Calculated from g/g data by Bustin et al. (1984) for Apollo regolith fines sample 15021.

hydrogen. Although these tonnages are not high by terrestrial standards, they will probably limit production of hydrogen in the early exploitation of the lunar regolith fines to that obtained as a byproduct or coproduct from the mining and processing of other materials. The production of two or more products at the same time may be the best way to reduce costs to economical levels (Criswell 1980, Simon 1985).

It is also interesting to speculate on bringing back to Earth valuable elements, compounds, or minerals. However, the only element, compound, or mineral that by itself has economic potential for mining, processing, and return to Earth is ^{3}He (Wittenberg, Santarius, and Kulcinski 1986). It is very expensive to transport materials from Earth and put together an infrastructure on the lunar surface (Simon 1985). It takes at least $25 000 in 1987 dollars to deliver a pound of material to the lunar surface, which is approximately 5 times the value of a pound of gold on Earth!

In 1966, before a man walked on the Moon, Peter Flawn was insightful when he wrote,

> Because of the acceleration of change in the last half-century, this writer is not inclined to state categorically that mineral materials will never be transported through space from an extra-terrestrial source to earth. It is, however, difficult to conceive of the system under which such an enterprise could take place. Mining of local materials around extra-terrestrial bases, however, is something entirely different and makes good sense. The pioneers on earth found that where transportation facilities were nonexistent or where they were prohibitively expensive, they had to make do with local materials. Space pioneers will be in the same situation. Use of local minerals for sources of oxygen, for energy, and for materials will undoubtedly be more economical than large-scale transport from earth. Thus although extra-terrestrial minerals are not likely to be a source for augmenting earth supplies, they are a source which will reduce by minute amounts the export of earth minerals.

These thoughts still apply. Moreover, the comments on transportation of nonterrestrial mineral materials to Earth should remain valid at least until a significant infrastructure is in place on the lunar surface.

Conclusions

1. The type and range of lunar material resources are defined to a first approximation on the basis of analysis of samples returned, remote sensing, and theoretical considerations. Major uncertainties remain as to the presence of cryotrapped volatiles in the permanently dark and thus cold areas of the lunar polar regions and the presence of fumarolic deposits containing material rich in volatile elements or compounds.

2. Early exploitation of lunar material resources will be for shielding purposes and for local use of phases or elements that do not require extensive processing. Present knowledge suggests that this activity will be confined primarily to the minerals (plagioclase feldspars and ilmenite) and rock types that result from igneous processes, to meteoritic and cometary debris, and to regolith fines that are significantly affected by solar wind implantation.

3. Lunar regolith fines are an important source of (a) silicate minerals such as plagioclase feldspars, olivines, and pyroxenes; (b) oxide minerals such as ilmenite and spinels; (c) metallic iron-nickel-cobalt alloys; and (d) solar-wind-implanted elements such as H, N, C, and ^{3}He.

4. Lunar regolith fines meet the basic requirement for beneficiation because a major portion of the elements implanted by the solar wind occurs in the less-than-20-micrometer size fraction, which is a relatively small part of the lunar regolith fines.

5. Early exploitation of the lunar regolith fines for hydrogen probably will be limited to hydrogen obtained as a byproduct or coproduct from the mining and processing of other materials, because it takes at least 20 000 metric tons of typical lunar regolith fines to produce 1 metric ton of hydrogen.

6. There is no evidence, direct or theoretical, for significant base metal sulfide or precious metal vein deposits on the Moon.

7. Lack of free water on the Moon eliminates the classes of ore deposits that are most exploitable on Earth; namely, (a) hydrothermal, (b) secondary mobilization and enrichment, (c) direct precipitation from a body of water, and (d) placer.

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Ground-Based Observation of Near-Earth Asteroids

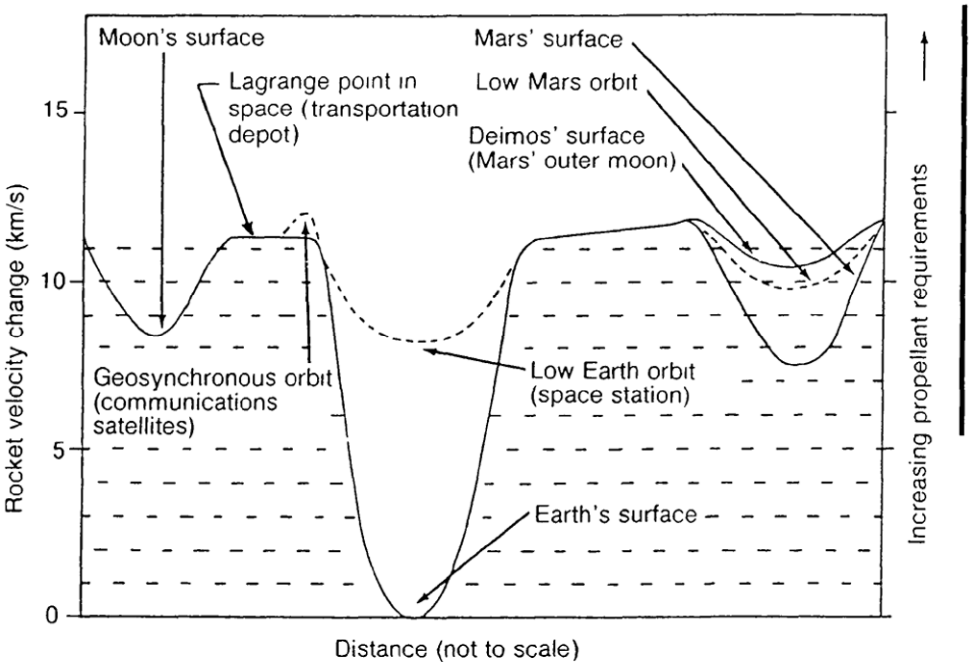
Michael J. Gaffey

An increased ground-based observation program is an essential component of any serious attempt to assess the resource potential of the near-Earth asteroids. A vigorous search and characterization program could lead to the discovery and description of about 400 to 500 near-Earth asteroids in the next 20 years. This program, in conjunction with meteorite studies, would provide the data base to ensure that the results of a small number of asteroid-rendezvous and sample-return missions could be extrapolated with confidence into a "geological base map" of the Aten, Apollo, and Amor* asteroids.

Ground-based spectral studies of nearly 30 members of the Aten/Apollo/Amor population provide good evidence that this class includes bodies composed of silicates, metal-silicates, and carbonaceous assemblages similar to those found in meteorites. It is probable that the full range of known meteoritic materials (if not an even greater diversity) is represented in the near-Earth population. These include water- and carbon-bearing C1 and C2 types and metal-silicate bodies that are 5- to 50-percent metal.

Among the relatively few known members of this large near-Earth population are objects in orbits that require less (sometimes much less) energy to reach from low Earth orbit (LEO) than the lunar surface requires. Their orbits are similar to the orbit of the Earth, though many are inclined to it. And, because they are much smaller than the Moon, they have little gravitational attraction. Thus, only a small amount of propulsive energy is required to approach or leave those whose orbits are both close and in nearly the same plane. Using current propulsion technologies, the vast majority of near-Earth asteroids are practically inaccessible. However, if there are as many near-Earth asteroids as we think there are, many more seem likely to be found that are in favorable orbits.

*The Aten asteroids are those whose orbits lie mostly within the Earth's orbit; that is, between Earth and Venus. The Apollo asteroids have orbits that cross the Earth's orbit. The Amor asteroids approach Earth on the Mars side but do not cross the Earth's orbit. These definitions were supplied by Lucy-Ann McFadden, David J. Tholen, and Glenn J. Veeder in their chapter "Physical Properties of Aten, Apollo and Amor Asteroids" in the 1989 book *Asteroids II,* ed. Richard P. Binzel, Tom Gehrels, and Mildred S. Matthews (Tucson: University of Arizona Press).



Velocity Changes (ΔV's) Required To Get to Various Places

Distance to objects in the inner solar system is, in many cases, not as important as the velocity that must be imparted to a spacecraft to enable it to escape the Earth's gravity, reach the object, change direction at the target object, return to Earth, and land softly. The higher the velocity required, the more rocket propellant is necessary to achieve it, and the propellant requirement increases as the square of the velocity change.

The velocity change is dominated by the velocity required to leave a planet's gravitational field. This figure illustrates the effect of "gravity wells" in the inner solar system. Getting off the Earth is the biggest effort, and most models assume that transportation in space starts from low Earth orbit. The Lagrange points and lunar orbit represent the limits of the Earth's gravity well. (Getting to geosynchronous orbit takes a little more energy than getting to lunar orbit.)

The velocity change to get from low Earth orbit to the surface of the Moon is similar to that required to reach orbit around Mars. Some near-Earth asteroids require about the same velocity change as that required to get to martian orbit. The Moon and Mars have significant gravity wells of their own, however; whereas asteroids, being so small, have no significant gravity well. To return to the Earth from the lunar or martian surface requires that the velocity change be reversed.

It is the lack of a gravity well that makes asteroid missions (or missions to Mars' moons, Phobos and Deimos) attractive from an energy standpoint. To return to Earth from an asteroid or Deimos can take as little propellant as that required to go between their orbits and the edge of Earth's gravity well (the Lagrange "plateau" in the figure). From there, aerobraking can take the spacecraft to the orbit of a space station or to the surface of the Earth.

Falling into the gravity well of Mars or the Earth need not take as much propellant as getting out, because the atmosphere can be used to slow down the spacecraft. That was the function of the Apollo heat shield and is the function of the Space Shuttle's thermal protection tiles. Providing such an "aerobrake" to disperse the frictional energy of reentry can reduce the propellant requirement significantly.

Aerobrakes are not "free," as they add mass to the spacecraft going to and returning from the target object. Improving thermal control systems and aerobrake materials will have important consequences for round-trip missions to asteroids.

Figure provided by Paul W. Keaton, Los Alamos National Laboratories.

Table 12 lists the instruments that are being used or could be used to search for near-Earth asteroids. Currently, only a few near-Earth asteroids per year are being found. (See figure 6.) Table 13 lists techniques useful in characterizing asteroids and the types of information obtainable using these techniques. To be confident that usable materials could be recovered from asteroids, we need more specific characterization of their composition. A small commitment of resources (a few million dollars per year) to continue and modestly expand the efforts to find and characterize near-Earth asteroids would enable much greater progress to be made.

TABLE 12. *Near-Earth Asteroid Search Instruments*

Instrument	Detector	Status	Discovery rate per year, current full-time
Large, wide-field telescope (e.g., 48-in. or 120-cm Schmidt) [ground-based]	Photographic with daily plate survey	3-4 days/ month at 1 site	5 / 10s
Large, conventional telescope (e.g., 70-in. or 180-cm Cassegrainian) [ground-based]	CCD with real-time discrimination of fast-moving objects	Half-time operation	1 / 10s?
Infrared satellite (IRAS-type) survey [in LEO]	Liquid-helium-cooled mirror array detector for real-time detection of fast moving objects	Infrared Astronomical Satellite was flown successfully for other purposes	NA / > 10s

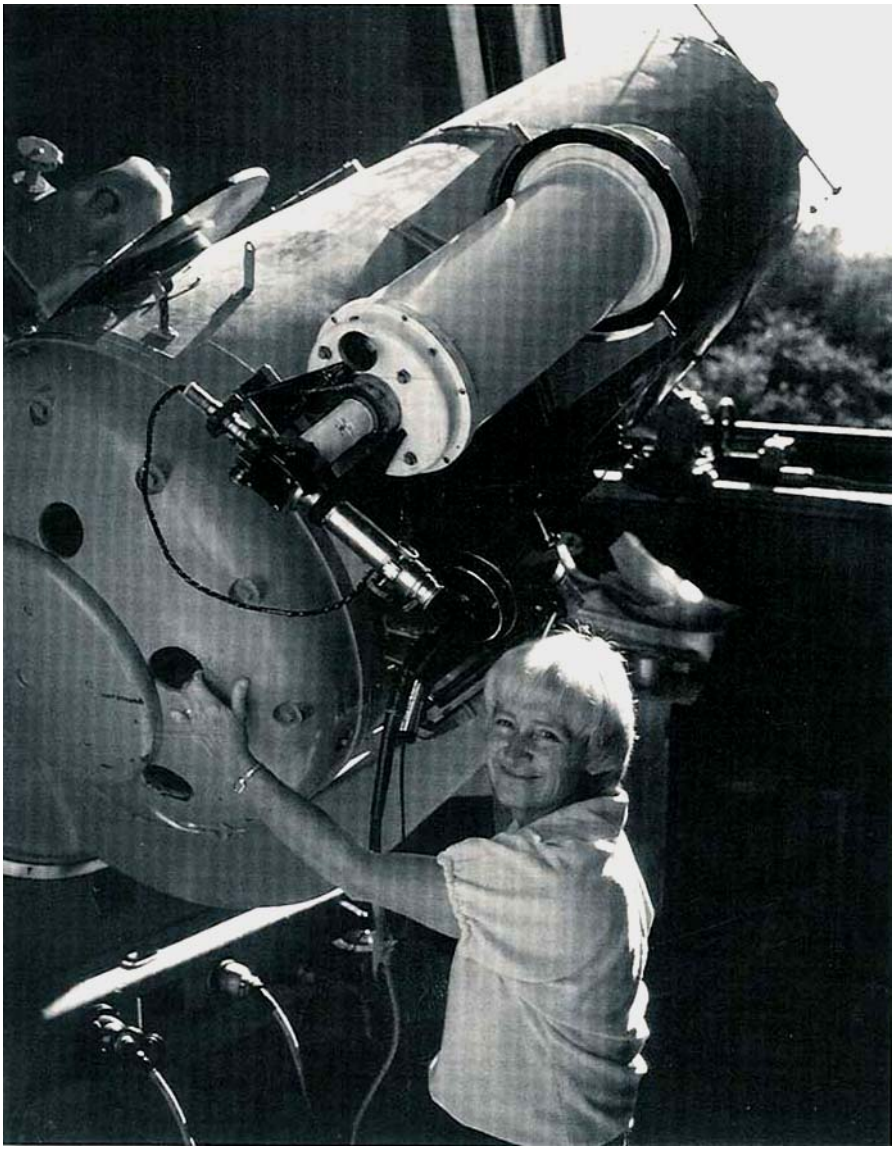


Figure 6

Schmidt Telescope

The search for asteroids is conducted with wide-field telescopes known as Schmidt telescopes. A few near-Earth asteroids are being found each year by a team including Eugene Shoemaker, Carolyn Shoemaker (shown here with the Schmidt instrument at the Palomar Observatory), and Eleanor Helin. The telescopes are scanned at the same rate as the Earth turns, so that on photographic plates the stars remain fixed points. Under these conditions, asteroids which are moving across the star field appear as streaks on the plates. The small size and scarcity of near-Earth asteroids makes their discovery a particularly tedious task.

TABLE 13. *Asteroid Characterization Techniques and Information Derived*

Technique	Information derived [Requirements and limitations]
Reflectance spectroscopy and multicolor photometry[a]	Asteroid class[1] [Not a determination of specific composition] Surface mineralogy[2] [Requires broad spectral coverage, high resolution, and high signal-to-noise ratio; knowledge of albedo improves characterization] Detection of water-bearing materials[3] [Data in the 3-m spectral region required]
Visible photometry and lightcurve photometry[a]	Size[4] [Requires knowledge of albedo] Albedo[4] [Requires knowledge of size] Rotation period[5] [Requires a sequence of closely spaced observations over several nights] Approximate shape[6] [From analysis of lightcurves] Orientation of spin axis[6] [From variation of lightcurve form with viewing geometry]
Visible polarization[a]	Albedo[7] [Requires observations over a range of phase angles]
Infrared photometry[a]	Size[8] [Knowledge of albedo improves determination] Albedo[8] [Derived in combination with visible photometry] Relative emissivity[9] [Model-dependent indication of metal abundance or surface texture]
Radar[b]	Surface conductivity or metal abundance[10] [Model depends on assumptions of surface porosity] Diameter[10] [From duration of returned signal] Rotation rate[10] [From frequency spread and delay in signal] Shape[10] [From temporal variation of frequency spread and time delay]

TABLE 13 *(concluded).*

Technique	Information derived [Requirements and limitations]
Passive microwave radiometry and spectroscopy[a]	Near-surface temperatures[11] Temperature gradients, conductivities, and thermal inertias
Occultations	Diameter[12] [Dependent on obtaining accurate durations from several sites] Shape[12] [Profile for moment of occultation]
Space telescope images	Moderate resolution images[13] [Approximately 30-km resolution in middle of asteroid belt]

[a] The spectral coverage and the spectral resolution of observations depend on the specific instrument and telescope being used. For any particular system, the quality (signal-to-noise ratio)of the resultant data depends on the brightness of the asteroid, which is proportional to the square of its radius and the inverse square of its distance from the Earth and from the Sun. At visible wavelengths the signal is also proportional to the surface albedo, and at infrared and microwave wavelengths it is proportional to 1 minus the albedo.

[b] The strength of the returned radar signal is proportional to the strength of the transmitted signal, proportional to the square of the diameter of the target asteroid, and proportional to the inverse fourth power of the distance to the asteroid. Asteroid distance is the major factor in data quality.

The following references provide detailed reviews of the various techniques listed in this table:

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[2]Gaffey, Michael J.; Jeffrey F. Bell; and Dale P. Cruikshank. 1989. Reflectance Spectroscopy and Asteroid Surface Mineralogy. In Asteroids II, 98–127.

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[4]Bowell, Edward, and Kari Lumme. 1979. Calorimetry and Magnitudes of Asteroids. in Asteroids, ed. Tom Gehrels, 132–169. Tucson: Univ.of Arizona Press.

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[9]Gaffey, M. J. 1989. Asteroid Surface Metal Abundances. Bull. American Astron. Soc. **21**:963.

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[13]Zellner, B.; Eddie N. Wells; Clark R. Chapman; and D. P. Cruikshank. 1989. Asteroid Observations with the Hubble Space Telescope and the Space Infrared Telescope Facility. In Asteroids II, 949–969.

A coordinated effort should include the following:

1. An increase in the level of effort, presently that of about 1 person per year to that of 5–10 persons per year. All available time on Schmidt telescopes with apertures 60 cm and larger would be used. Smaller telescopes would not detect enough asteroids to make efficient use of the observers' search time.

2. Construction of a 60-cm Schmidt telescope dedicated to the search for near-Earth asteroids. This facility could be built in 1 year, would cost from $200 000 to $300 000, and should allow investigators to discover 5 to 10 near-Earth asteroids per year. At this rate of discovery, the number of candidate asteroids for near-Earth rendezvous missions would be adequate within just a few years.

3. Construction of a 120-cm Schmidt telescope dedicated to the search for near-Earth asteroids. Such an instrument could photograph approximately 700 fields each year. The development of automatic scanning systems has eliminated the immense task of visually scanning these plates for trailed images. This next-generation search instrument is needed to achieve the goal of discovering 400 to 500 near-Earth asteroids in the next 20 years. The survey would allow the choice of an asteroid for detailed investigation possibly leading to mining operations. This telescope would take about

3 years to complete and cost from $3 million to $4 million. The search program would require the work of about 6 persons per year. Discovery rates with this facility should be from 20 to 30 near-Earth asteroids per year.

4. Assembly and monthly update of a central index of wide-field plates. This cooperative effort would allow rapid access to all images containing the asteroid, including those recorded before the asteroid was recognized, and would thus contribute to the precise determination of its orbit. This effort would require the equivalent of about 1 person's work per year.

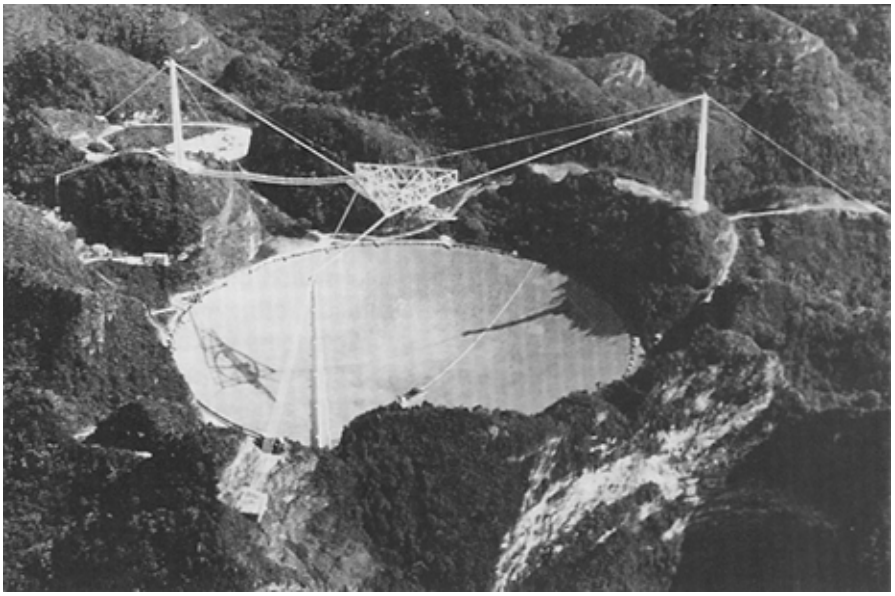
5. Application of radar to the study of near-Earth asteroids. Radar has only recently been successfully applied to asteroid studies, primarily from the Arecibo facility (see fig. 7). Because signal strength is related to the inverse fourth power of the distance to the target and because the target asteroids are relatively near, radar promises to be a very powerful technique for studying them. Radar can provide information on size, shape, and rotation rate. And radar wavelengths will be responsive to composition (e.g., metal content) and surface structure.

Without an accelerated discovery program, we will probably continue to discover only a few near-Earth asteroids each year. Only a small number of these are easily accessible to spacecraft. Therefore, in order to utilize asteroidal resources within the next 20 to 30 years, we need an expanded search program to find near-Earth asteroids and we need measurements of their physical properties to evaluate their usefulness.

Figure 7

Arecibo Observatory

The Arecibo Observatory, in Puerto Rico, is the premier radio telescope instrument used in the Earth-based study of the planets and small bodies in the solar system. It is capable of beaming a powerful signal into space and receiving the radio waves reflected from the source. The telescope has been used to map the surface characteristics of the Moon, Venus, and Mars, and recently has started to provide data on the physical properties of near-Earth asteroids. The radio wave reflection properties are affected strongly by the surface roughness and by the granularity of surface materials, and to a more limited extent by the composition of the asteroids.



Asteroid Resources*

John S. Lewis

There are three types of possible asteroidal materials that appear to be attractive for exploitation:

1. Volatiles
2. Free metals
3. Bulk dirt

Because some of the near-Earth asteroids are energetically more accessible than the Moon [require a round-trip total change in velocity (ΔV) less than 9 km/sec (though the trip time would be measured in years, not days)], such an asteroid might be chosen as the source of any useful material, even if that material was also available on the Moon. Provided that the asteroid was minable, it might therefore be chosen as the source of bulk dirt needed for shielding in low Earth orbit (LEO) or elsewhere in near-Earth space.

And the near-Earth asteroids may offer materials that are rare or absent on the surface of the Moon. Some of them are spectrally similar to ordinary and carbonaceous chondrites. These meteorites contain free metals and volatiles at a concentration about 100 times that in the lunar soil. Thus, if an asteroid was found to have one of these compositions and to be accessible and minable as well, it would be a very attractive source of such needed materials.

An asteroid of the composition of an ordinary chondrite could be processed to provide very pure iron and nickel for use in structures in LEO. The principal byproducts would be cobalt, the platinum group metals, and other useful elements such as gallium, germanium, and arsenic. These are all materials of high value and utility in an industrial economy. Some might even be valuable and useful enough to merit being returned to the surface of the Earth (though the high cost of space transportation has ruled out economical return of gold and even diamonds, thus far).

* The editor acknowledges the critical help of John Wasson, for figure 11 and its interpretation; Lucy McFadden, for the spectral classifications of the near-Earth asteroids and other clarifications; and Michael Lipschutz, for the relationship between meteorites and asteroids and other information. Wasson's figure comes from his book *Meteorites: Their Record of Early Solar-System History* (New York: W. H. Freeman and Co., 1985), p. 29. McFadden and Lipschutz are the lead authors of two chapters in the 1989 book *Asteroids II,* ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: Univ. of Arizona Press). McFadden's "Physical Properties of Aten, Apollo and Amor Asteroids" is coauthored by David J. Tholen and Glenn J. Veeder. Lipschutz's "Meteoritic Parent Bodies: Nature, Number, Size and Relation to Present-Day Asteroids" is coauthored by Michael J. Gaffey and Paul Pellas.

Volatiles, such as water and carbon dioxide, obviously useful in any space settlement, could be found in an asteroid that resembles a carbonaceous chondrite or one that consists of the nucleus of a former comet. Water content by weight for these materials may range from 5 percent for C2 chondrites through 10 percent in C1s to about 60 percent in typical cometary nucleus material. The abundance of organic matter in C1s is about 6 percent by weight, and nitrogen, sulfur, and chlorine are readily available. Attractive bonuses from C1s are that on the order of 10 percent of their weight may be magnetite* and about 2 percent is nickel-rich sulfides. As an alternative to returning asteroidal volatiles to LEO, the in situ extraction of water on an asteroid may be justifiable.

The Asteroid-Meteorite Relationship

Spectroscopic comparisons of asteroids with laboratory samples of meteorites show that the dominant minerals in meteorites are also the principal components of asteroid surfaces. Indeed, many asteroids have reflectance spectra that are identical with those of known classes of meteorites. See table 14. However, many asteroids appear not to belong to known classes of meteorites (although they are made of the same major minerals). Further, there is little relation between the abundance of meteorites of a given type and the abundance of asteroids of the corresponding spectral class. Of course, the large majority of the asteroids studied are in the asteroid belt, beyond the orbit of Mars, while the objects that fall on Earth must have very different orbits. It is instructive to note that the commonest class of meteorites falling on Earth, the ordinary chondrites, is apparently absent in the asteroid belt, but at least one spectroscopic match for ordinary chondrites can be found among the small, poorly studied near-Earth asteroids.

We have known for many years that the Earth receives in the meteorites a biased sampling of the asteroid types as spectral reflectance classifies them. The main problem is that the most

* M. Hyman and M. W. Rowe, 1983, “The Origin of Magnetite in Carbonaceous Chondrites,” abstract in Lunar & Planetary Sci. XIV (Houston: Lunar & Planetary Inst.), pp. 341–342.

TABLE 14. *Asteroid Types: Surface Mineralogy and Meteoritic Analogs from Reflectance Spectroscopy*[a]

Type	(No.)[b]	Inferred surface mineralogy	Possible meteoritic analogs
A	(4)	Olivine or olivine-metal	Olivine achondrites or pallasites
B C F G	(6) (88) (13) (5)	Hydrated silicates + carbon/organics/opaques	CI1-CM2 assemblages and assemblages produced by aqueous alteration and/or metamorphism of CI/CM precursor materials
D P	(26) (23)	Carbon/organic-rich silicates?	Organic-rich cosmic dust grains? CI1-CM2 plus organics?
E	(8)	Enstatite or possibly other iron-free silicates	Enstatite achondrites
M	(21)	Metal (possibly trace silicates) Metal + enstatite?	Irons (possibly with silicate inclusions) Enstatite chondrites?
Q	(1)	Olivine + pyroxene + metal	Ordinary chondrites
R	(1)	Pyroxene + olivine	Pyroxene-olivine achondrites
S	(144)	Metal +/- olivine +/- pyroxene	Pallasites with accessory pyroxene Olivine-dominated stony-irons Ureilites and primitive achondrites CV3/CO3 chondrites
V	(1)	Pyroxene +/- feldspar	Basaltic achondrites
T	(4)	Possibly similar to types P/D	

[a]Table taken from Michael J. Gaffey, Jeffrey F. Bell, and Dale P. Cruikshank, 1989, "Reflectance Spectroscopy and Asteroid Surface Mineralogy," in *Asteroids II,* ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: Univ. of Arizona Press), p. 114.

[b]Number of asteroids classified as this type by David J. Tholen in his Ph.D. thesis, Asteroid Taxonomy from Cluster Analysis of Photometry, Univ. of Arizona, 1984.

abundant meteorites (the ordinary chondrites, which comprise almost 3/4 of the meteorites we have found on Earth) have rare asteroidal analogs and the most abundant asteroids (spectral type S, which comprises about 1/3 of all the asteroids that have been classified and over 1/2 of the near-Earth asteroids that have been classified) have rare meteoritic analogs. (See figure 8 for the type distribution of the near-Earth asteroids.) The explanation for this mismatch is among the most intriguing subjects being addressed by meteoriticists and asteroid spectroscopists.

We know that asteroid discoveries are biased in favor of the brighter objects; that is, those that are large or close (in the inner as opposed to the outer belt) or have a high albedo. We know that meteorite finds are biased in favor of those that can survive atmospheric entry. There may be an accidental bias in the meteorite population: that is, they could be the products of the fragmentation of only a few, unrepresentative parent asteroids. The ordinary chondrites could come from only parts of larger asteroids. These meteorites could come from somewhere other than the asteroid belt. There may be a

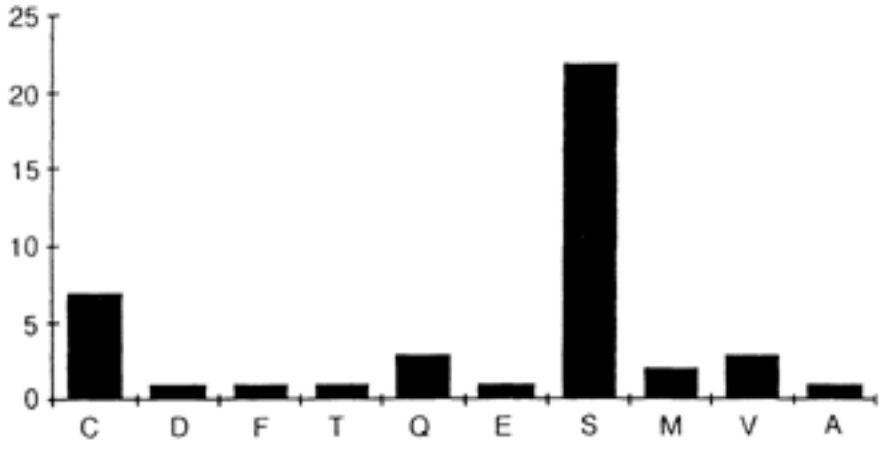


Figure 8

Spectral Type Distribution of Observed Near-Earth Asteroids

This distribution, as determined by David J. Tholen using the Eight-Color Asteroid System, has not been corrected for observational bias. The asteroid types are defined in table 14.

From Lucy-Ann McFadden, David J. Tholen, and Glenn J. Veeder, 1989, "Physical Properties of Aten, Apollo and Amor Asteroids," in Asteroids II, *ed. Richard P. Binzel, Tom Gehrels, and Mildred Shapley Matthews (Tucson: University of Arizona Press), p. 448.*

time bias; comparison of the well-preserved meteorites found in the Antarctic with the more weathered meteorites found elsewhere (which presumably fell within the last 200 years) suggests that Antarctica may have sampled a different meteoroid population in the past than is being sampled by contemporary, non-Antarctic falls and finds.

Thus, although we must be aware that, as Lipschutz says, “the meteorites are an incomplete and unrepresentative sample of the asteroid belt” (and of intermediate parent bodies such as the near-Earth asteroids), the volume of data on the meteorites so far exceeds the volume of data on the near-Earth asteroids that we are compelled to assume for the time being that the meteorites are adequate representations of the near-Earth asteroid population.

In this paper, I will present a brief overview of the entire range of meteorite compositions, with emphasis on the occurrence of interesting resources. I will focus on materials useful in space, especially volatiles, metals, and raw “dirt.” Those few materials that may have sufficiently high market value to be worth returning to Earth will also be mentioned.

Meteorite Classes

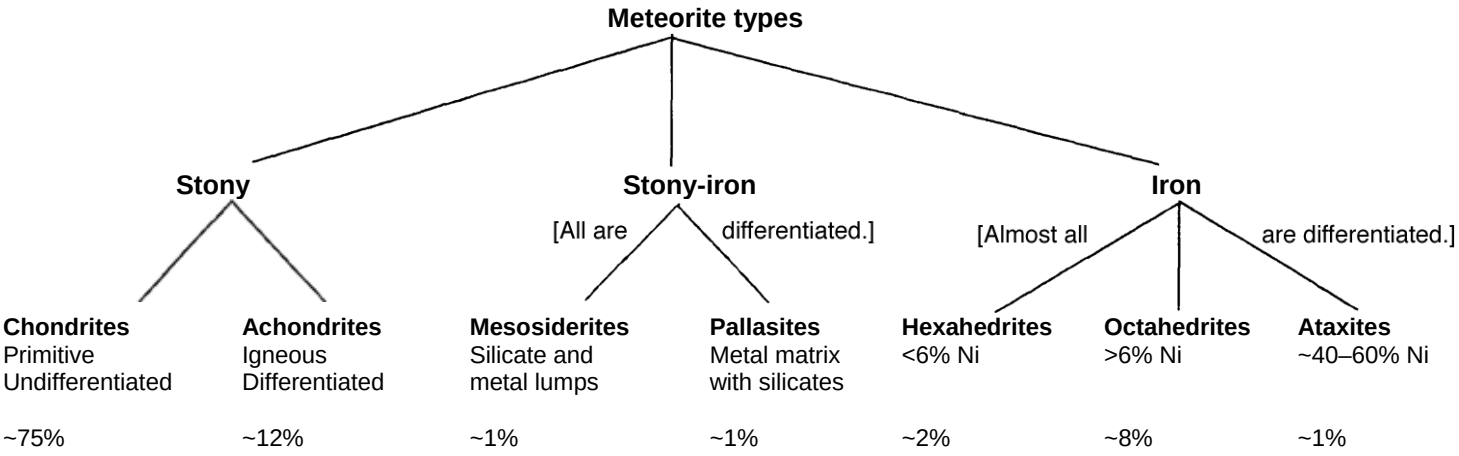
Figure 9 shows the general scheme for classification of meteorites. This scheme unifies the more than 30 known classes under the three principal headings of *stones, stony-irons,* and *irons.* Primitive solid material, in which the major rock-forming elements have about the same relative abundances as in the Sun, accounts for the subset of stony meteorites called *chondrites.* All other classes of meteorites are the results of melting and density-dependent geochemical differentiation of primitive material. Chondrites fall on Earth far more often than all these other meteorite types combined.

The prospect of mining differentiated asteroids is not encouraging. Volatiles are probably rare or absent, and free metals will probably have drained into a massive monolithic core. Conversely, chondritic asteroids, both those with high volatile content and those with high free-metal content, are attractive targets.

The various classes of chondrites differ greatly in mineralogy, oxidation state, and volatile content (fig. 10) as a consequence of having formed at different temperatures. The content (by weight) of volatile-rich, low-temperature carbonaceous (C1) chondrites is up to 20 percent water chemically bound in clay minerals, up to 6 percent organic matter, and up to 11 percent magnetite. Nitrogen is present in the organic matter, and sulfur may be found as sulfides, elemental sulfur, and water-soluble sulfates. Carbonates and halides are abundant. All members of the C1 subtype of carbonaceous chondrites are very easily crushed; so are the members of the C2 subtype. But the crushing

Figure 9

Meteorite Types *(and Presumably Types of Near-Earth Asteroids)*



strength of all other meteorite classes, including the C3 subtype, varies.* Carbonaceous chondrites make up on the order of 1 percent of all meteorite falls.

Equally rare, the enstatite (E) chondrites display markedly different compositions. All the E chondrites are in a state of extraordinary chemical reduction. Iron oxides are wholly absent and iron is found only as the sulfide troilite (FeS) and in iron-nickel-cobalt alloys. The dominant mineral is enstatite, the very pure magnesium orthosilicate. These meteorites are so strongly reduced that as much as 1 percent by weight of the metal phase in enstatite chondrites is elemental silicon in solid solution with the iron and nickel. Accessory materials such as calcium sulfide (the mineral oldhamite), magnesium sulfide (niningerite), titanium nitride (osbornite), manganese sulfide (alabandite), silicon oxynitride (sinoite), and even potassium- and titanium-bearing sulfides are found in the E chondrites or in their differentiated counterparts, the E achondrites.

However, more than 95 percent of the chondrites that fall on Earth (about 3/4 of all known meteorites) lie between the extremes represented by the E and C chondrites. These intermediate "ordinary" chondrites are subdivided into three groups according to the total amount of iron they contain and the proportion of that iron (and of the siderophilic elements) that is found as free metal: the H group with high iron content (much of it metallic), the L group with low iron content (less of it metallic), and the LL group with low iron and low free metal content. Table 15 and figure 11 show the compositional relationships among the five major classes of chondrites.

*Michael Lipschutz, personal communication with the editor

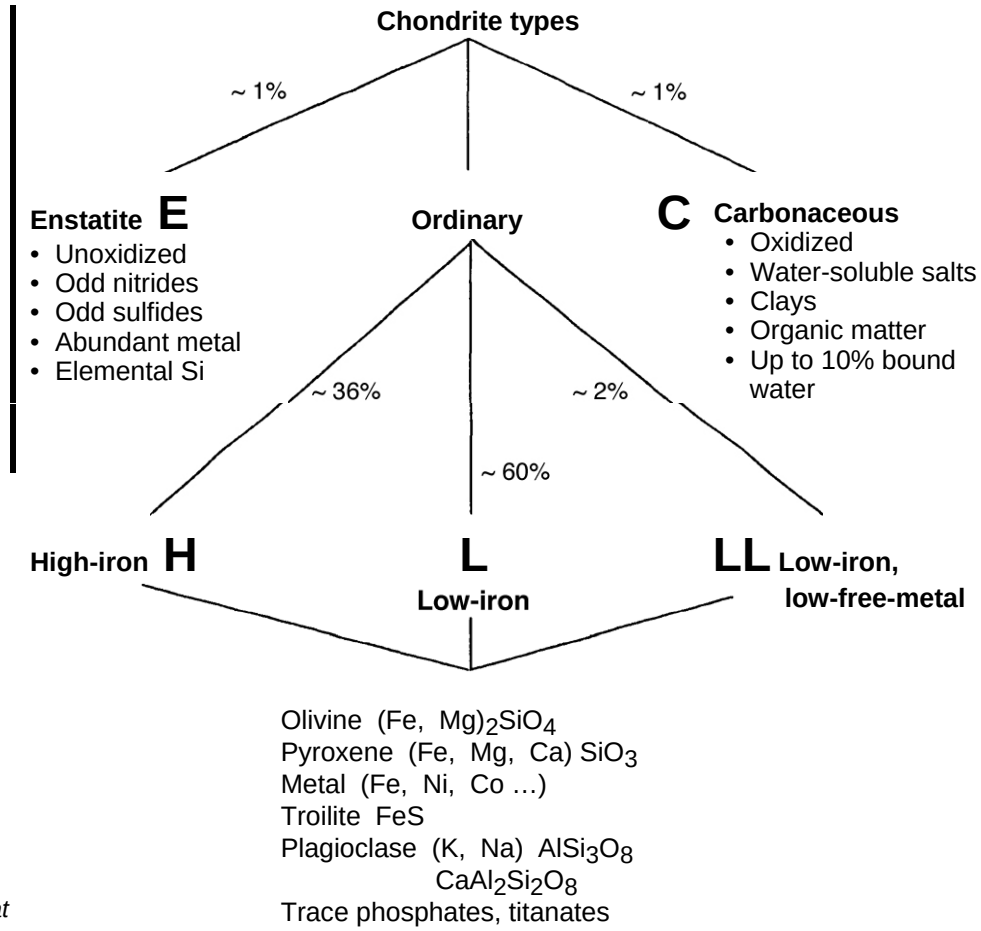


Figure 10

Classes of Chondritic Meteorites

(With Percentages of All Chondrites That Belong to Each Type)

TABLE 15. *Chemical Compositions (Weight %) of Two Enstatite Chondrites and of the Other Chondrite Groups*[a]

Class	Enstatite (E)		Ordinary		Carbonaceous (C)		
Group			H	L (& LL)[b]	C1	C2	C3
Component (wt. %)							
Si	16.47	20.48	17.08	18.67	10.40	12.96	15.58[c]
Ti	0.03	0.04	0.06	0.07	0.04	0.06	0.09
Al	0.77	1.06	1.22	1.27	0.84	1.17	1.43
Cr	0.24	0.23	0.29	0.31	0.23	0.29	0.35
Fe	33.15	22.17	27.81	21.64	18.67	21.56	24.92
Mn	0.19	0.12	0.26	0.27	0.17	0.16	0.16
Mg	10.40	13.84	14.10	15.01	9.60	11.72	14.29
Ca	1.19	0.96	1.26	1.36	1.01	1.32	1.57
Na	0.75	0.67	0.64	0.70	0.55	0.42	0.41
K	0.09	0.05	0.08	0.09	0.05	0.06	0.06
P	0.30	0.15	0.15	0.15	0.14	0.13	0.12
Ni	1.83	1.29	1.64	1.10	1.03	1.25	1.36
Co	0.08	0.09	0.09	0.06	0.05	0.06	0.08
S	5.78	3.19	1.91	2.19	5.92	3.38	2.09
H	0.13	trace	trace	trace	2.08	1.42	0.26
C	0.43	0.84	trace	trace	3.61	2.30	0.76
Fe^0/Fe_{tot}	0.70	0.75	0.60	0.29	0.00	0.00	0.10
Samples	1	1	36	68	3	10	12

The Fe entry in this table includes iron in metal, silicate, oxide, and sulfide phases.
The amount of metallic iron can be determined from that number and the ratio Fe^0/Fe_{tot}.
The amount of oxygen is not shown but is the remainder to make up 100 percent.

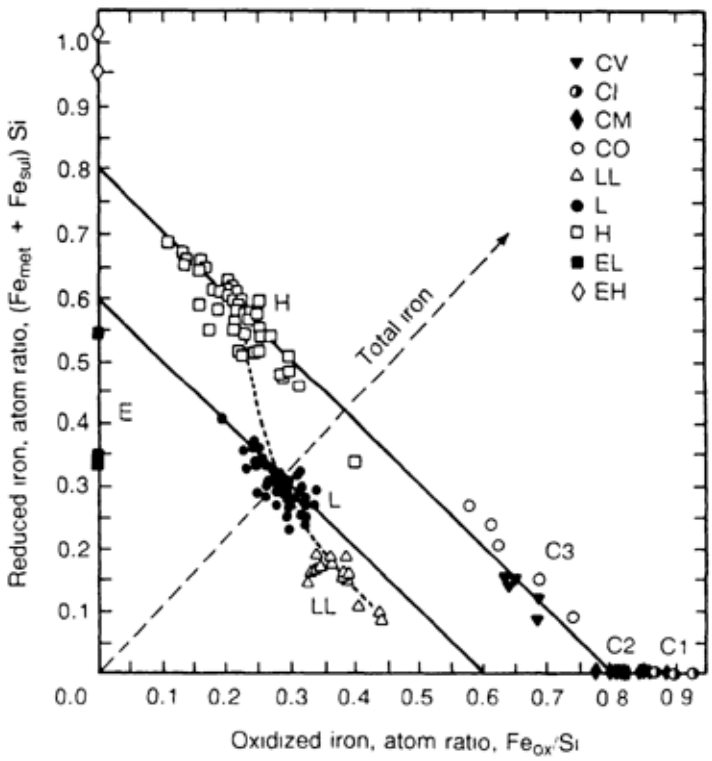
[a]Table modified from Robert T. Dodd, 1981, *Meteorites: Petrological-Chemical Synthesis* (Cambridge University Press), p. 19.
[b]Dodd grouped the low-iron (L) and low-iron, low-metal (LL) chondrites in his analysis.
[c]Weighted average for Dodd's five CO chondrites and seven CV chondrites.

Figure 11

Reduced vs. Oxidized Iron in the Five Classes of Chondritic Meteorites

Reduced iron (metallic iron and that present as FeS) in chondritic meteorites is plotted against oxidized iron (that present in silicates and, in CM and CI, as Fe_3O_4). Lines having slopes of -1 correspond to constant total Fe/Si ratios; two are shown for reference purposes. The highly reduced enstatite (EH and EL) chondrites plot along the left axis; the highly oxidized CM (C2) and CI (C1) chondrites, along the bottom axis.

Modified from John T. Wasson, 1985, Meteorites: Their Record of Early Solar-System History *(New York: W. H. Freeman and Co.), p. 29.*



The most highly oxidized ordinary chondrites (LL) and the most volatile-poor and unoxidized of the carbonaceous chondrites (C3) contain by weight only 16 percent free metal. But, because the less abundant components of the metal (nickel, cobalt, and the platinum group metals) are harder to oxidize than iron, they have been concentrated in the metal grains. Thus, the metal grains in these more oxidized chondrites contain far greater concentrations of these metals than do the metal grains in, say, the E chondrites. Nickel ranges from about 6 percent of the metal in E chondrites to 60 percent in the C3 chondrites, and cobalt and the platinum group follow suit. In each class of chondrites, the concentration of the more valuable elements in the metal phase is highest in the smallest grains.

Table 16 shows the concentrations of a number of elements in the magnetically separable (metallic) component of chondritic meteorites. It can be seen that the fourfold overall depletion of the metallic elements in the LL chondrites relative to H chondrites is accompanied by only a twofold depletion in their platinum group content. It is thus not terribly important which class of ordinary chondrites is exploited for these elements. Magnetic extraction of iron-rich phases (magnetite, FeS, etc.) might be applied to a C1 chondrite, which is lacking in free metal, since C1 chondrites contain by weight up to 11 percent magnetite and about 2 percent nickel-rich sulfides. However, it has not yet been shown that such a separation process is practical.

TABLE 16. *Concentrations of Components of the Metal Phases of Ordinary Chondrites*

	Class					
	LL		L		H	
Concentration (% by wt.) of total metal in meteorite:	4	(±1)	9	(±2)	16	(±3)
Nickel conc. (% by wt.) in metal	25	(±5)	15	(±3)	10	(±2)
Cobalt conc. (% by wt.) in metal	1.2	(±0.2)	0.7	(±0.1)	0.5	(±0.1)
Concentration (ppm) in metal:						
Platinum group metals						
Platinum	21	(±5)	13	(±1)	11	(±2)
Ruthenium	12	(±1)	8	(±1)	5.7	(±0.6)
Osmium	10	(±2)	6	(±1)	4.7	(±0.4)
Iridium	10	(±2)	5	(±1)	4.8	(±1.2)
Rhodium	1.0	(±0.2)	0.6	(±0.1)	0.5	(±0.1)
Other elements of interest						
Gallium	1 to 15		6 to 30			?
Germanium	200	(±30)	110	(±30)		?
Arsenic	1.2	(±0.2)	1.7	(±0.2)	2.1	(±0.2)

Meteorites as Sources of Volatiles and Metals

If the resources of primary interest are volatiles, then, among meteorites, the carbonaceous chondrites are the target of choice. The concentrations of hydrogen, carbon, nitrogen, and sulfur in C1 chondrites are more than 100 times those in the lunar regolith: the C1s contain (by weight) 4 to 6 percent carbon, about 0.3 percent nitrogen, 6 percent sulfur, and 10 to 20 percent water (1 to 2 percent hydrogen). Most of the carbon, nitrogen, and sulfur is, like the hydrogen, compounded, though there may be some pure carbon.

If metals are the principal resource desired, then all classes of chondritic meteorites are of great interest. The abundance of free iron in a typical chondrite is much higher than on the lunar surface, where only meteoritic fragments can be found. And the amount of metallic nickel in a typical chondrite is about 100 times the nickel content of lunar regolith. As figure 11 shows, there is real variation in the Fe_{total}:Si atomic ratio [from about 0.4 in LL and some E chondrites (the EL subtype, including Indarch) to about 1.0 in C1 and some other E chondrites (the EH subtype, including Khairpur)], but the large majority of the chondrites landing on Earth (the L and H groups) have Fe_{total}:Si atomic ratios of 0.6–0.8. As shown in figure 11, the C3 chondrites and C2 chondrites contain fully as much total iron (relative to silicon) as the H chondrites; the amount of free metal in the chondrite, however, varies from about 1 percent in the C3s to about 20 percent in the H group.

Figure 12 shows the total concentrations of water and free metal in the major classes of chondrites.

Mechanical Properties of Meteorites

Meteorites have seldom been subjected to tests of bulk physical properties. There is a great variation in crushing strength and porosity, with C1 chondrites apparently most porous (more than 10 percent of their volume is pores) and weakest (crushing strengths of only a few bars). The ordinary chondrites have measured strengths ranging from 60 to 2600 bars (1 bar = 10^5 N/m^2). Iron meteorites range in strength up to 3600 bars at room temperature. At low temperature and in the presence of hydrogen, these are subject to embrittlement and should be much easier to crush. However, iron asteroids, if found, would present significant processing challenges.

Meteorites are the subset of nonterrestrial projectiles that survive entry into the atmosphere. Thus, they have been selected for strength. Stony fireballs often break up at high altitudes and yield no meteorites. Typical strengths for such fireballs are about 40 bars. The famous Tunguska object

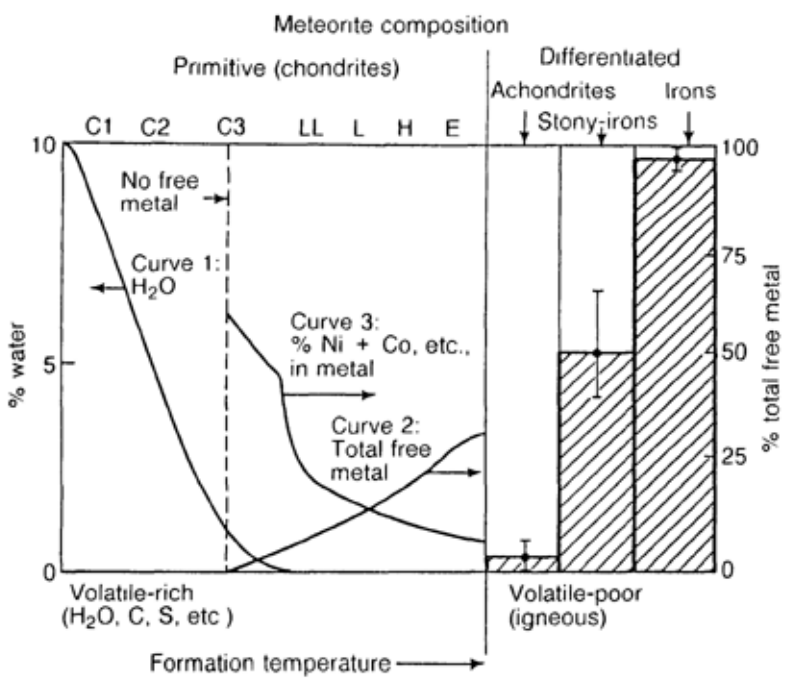


Figure 12

Volatile and Metal Variations in Meteorites

Curve 1, as measured on the left scale, shows the concentration of water in different types of chondritic meteorites. The carbonaceous chondrites contain the most water and become progressively less hydrous in going from type C1 to type C3. The ordinary chondrites (LL, L, and H) contain even less water. Most of the other common volatile species (carbon as CO_2, sulfur, etc.) are also present in significant amounts only in the meteorites that contain significant water.

Curve 2, as measured on the right scale, shows the total free metal in these same meteorite types. The total free metal (that is, the metallic elements that are not combined as oxides, silicates, etc.) generally increases as water decreases. As curve 3 (measured on the right scale) shows, the concentration of nickel, cobalt, and the platinum group elements within the metal phase is generally highest in meteorites having the lowest amounts of free metal.

The amount of free metal in differentiated meteorites is shown by the shaded areas as measured on the right scale.

that detonated over Siberia in 1908 completely ruptured under an aerodynamic pressure estimated at 200 bars. Fireballs associated with the orbits of known comets break up at loadings of 0.1 to 1 bar. This may be a very important and relevant datum, since some near-Earth asteroids are thought to be extinct comet nuclei. Beneath surface dust mantles, such asteroids may be 60 percent or more ice.

The available data on the crushing strengths of Earth-crossing bodies are summarized in table 17.

TABLE 17. *Crushing Strengths of Lunar Materials and Various Types of Meteors*

		Crushing strength, bars (1 bar = 10^5 N/m^2)
Moon		
	Regolith—precrushed	0
	Rocks (anorthosite, basalt)	~2500
Meteors		
	Irons—room temperature	3600
	—low temperature (Brecher)	< 1000
	Stones—measured (L)	> 60
		< 2600
	Fireballs that yield stones (Lost City, Innisfree)	> 200
	Tunguska explosion	200
	Fireballs	
	PN40503	30
	EN160166	50
	Cometary fireballs	> 0.1
		<1

Asteroid Orbits

Eleanor Helin has recently summarized for the Spacewatch Report the orbital data on the asteroids crossing the Earth's orbit and closely approaching the Earth. An updated version of this list (through 1984)* is given in table 18. The orbital eccentricities of these asteroids range from 0.182 to 0.894, with an average (and most probable) value of 0.55. Inclinations range from a low of 1.4 degrees for 1982 DB up to over 68 degrees. Those asteroids which take the least energy to reach from Earth must have low inclinations *(i)* and eccentricities *(e)* and should have semimajor axes not too different from Earth's. Asteroids with orbital periods greater than 1 year are usually easiest to reach if their perihelion distance is near 1 astronomical unit (AU), the mean Earth-Sun distance. A simple but useful approximation rule is that an asteroid will be accessible with a round-trip total change in velocity (ΔV) of less than 6 km/sec if $20e + i$ is less than 14 and the perihelion distance is between 0.8 and 1.15 AU. The first criterion is met by 8 of the 63 known near-Earth asteroids, and 7 satisfy both criteria. Of these, five have round-trip ΔV's under 6 km/sec, and two are just over the limit. For comparison, the ΔV for ascent from low Earth orbit (LEO) to the lunar surface is 6 km/sec one-way and 9 km/sec round-trip. The most favorable asteroid, 1982 DB, requires less than 4.6 km/sec for a round trip.†

*A further updated list (through 1988) is available in the chapter by McFadden, Tholen, and Veeder in *Asteroids II.*

†It should be noted, however, that we do not have a spectral type for 1982 DB. Two (1982 XB and 1943 Anteros) of the other four asteroids listed in table 19 have been classified (as S). Only one other (3908 1980 PA) of the asteroids meeting these criteria for accessibility has been classified (as V).

TABLE 18. *Near-Earth Asteroids—Atens, Apollos, and Amors*
[After Eleanor Helin in Spacewatch Report]

Name/number[a]	Discovery year	Perihelion distance	Aphelion distance	Semimajor axis	Eccen-tricity	Incli-nation	Spectral type[b]
3200 Phaethon	1983	0.14	2.47	1.30	0.894	22.8	F
1566 Icarus	1949	0.19	1.97	1.08	.827	23.0	S
2212 Hephaistos	1978	0.36	3.97	2.16	.835	11.9	SG[c]
1974 MA	1974	0.42	3.13	1.78	.762	37.8	
2101 Adonis	1936	0.44	3.30	1.87	.764	1.4	
2340 Hathor	1976	0.46	1.22	0.84	.450	5.9	CSU[d]
2100 Ra-Shalom	1978	0.47	1.20	0.83	.437	15.8	C
1954 XA	1954	0.51	1.05	0.78	.345	3.9	
1984 KB	1984	0.53	3.88	2.21	.760	4.6	S
3362 Khufu	1984	0.53	1.46	0.99	.469	9.9	
1982 TA	1982	0.53	4.07	2.30	.769	12.1	
1864 Daedalus	1971	0.56	2.36	1.46	.615	22.1	SQ
1865 Cerberus	1971	0.58	1.58	1.08	.467	16.1	S
Hermes (1937 UB)	1937	0.62	2.66	1.64	.624	6.2	
1981 Midas	1973	0.62	2.93	1.78	.650	39.8	
2201 Oljato	1947	0.63	3.72	2.17	.712	2.5	
1981 VA	1981	0.63	4.22	2.46	.744	22.0	
1862 Apollo	1932	0.65	2.29	1.47	.560	6.4	Q
1979 XB	1979	0.65	3.88	2.26	.713	24.9	
2063 Bacchus	1977	0.70	1.45	1.08	.349	9.4	
1685 Toro	1948	0.77	1.96	1.37	.436	9.4	S
1983 LC	1983	0.77	4.50	2.63	.711	1.5	
2062 Aten	1976	0.79	1.14	0.97	.182	18.9	S
2135 Aristaeus	1977	0.79	2.40	1.60	.503	23.0	
1983 VA	1983	0.81	3.67	2.24	.636	15.4	
3361 Orpheus	1982	0.82	1.60	1.21	.322	2.7	
6743 P-L	1960	0.82	2.42	1.62	.493	7.3	
1983 TF_2	1983	0.82	3.62	2.61	.387	7.8	
2329 Orthos	1976	0.82	3.99	2.40	.658	24.4	
1620 Geographos	1951	0.83	1.66	1.24	.335	13.3	S
1959 LM	1959	0.83	1.85	1.34	.379	3.3	
1950 DA	1950	0.84	2.53	1.68	.502	12.1	
1866 Sisyphus	1972	0.87	2.92	1.89	.540	41.1	
1978 CA	1978	0.88	1.37	1.12	.215	26.1	S
1973 NA	1973	0.88	4.04	2.46	.642	68.1	

TABLE 18 *(concluded)*.

Name/number[a]	Discovery year	Perihelion distance	Aphelion distance	Semimajor axis	Eccen-tricity	Incli-nation	Spectral type[b]
1863 Antinous	1948	0.89	3.63	2.26	0.606	18.4	SU
2102 Tantalus	1975	0.91	1.67	1.29	.298	64.0	
1982 BB	1982	0.91	1.91	1.41	.355	20.9	E
6344 P-L	1960	0.94	4.21	2.58	.635	4.6	
1982 DB	1982	0.95	2.02	1.49	.360	1.4	
1979 VA	1979	0.98	4.29	2.64	.627	2.8	CF
3671 Dionysius	1984	1.01	3.41	2.21	.544	13.7	
3757 1982 XB	1982	1.01	2.70	1.86	.454	3.9	S
3122 1981 ET_3	1981	1.02	2.52	1.77	.422	22.2	
2608 Seneca	1978	1.02	3.93	2.48	.587	15.6	S
3908 1980 PA	1980	1.04	2.82	1.93	.459	2.2	V
1980 AA	1980	1.05	2.73	1.89	.444	4.2	
2061 Anza	1960	1.05	3.48	2.26	.537	3.7	TCG
1915 Quetzalcoatl	1953	1.05	3.99	2.52	.583	20.5	S
1943 Anteros	1973	1.06	1.80	1.43	.256	8.7	S
1917 Cuyo	1968	1.06	3.23	2.15	.505	24.0	
3551 1983 RD	1983	1.07	3.12	2.10	.488	9.5	V
1221 Amor	1932	1.08	2.76	1.92	.436	11.9	
1980 WF	1980	1.08	3.38	2.23	.514	6.4	QU
1981 QB	1981	1.08	3.39	2.24	.518	37.1	
1983 RB	1983	1.09	3.35	2.22	.490	18.0	
3288 Seleucus	1982	1.10	2.96	2.03	.457	5.9	S
1982 YA	1982	1.11	5.09	3.10	.641	33.2	
1627 Ivar	1929	1.12	2.60	1.86	.397	8.4	S
1580 Betulia	1950	1.12	3.27	2.20	.490	52.0	C
2202 Pele	1972	1.12	3.46	2.29	.510	8.8	
433 Eros	1898	1.13	1.78	1.46	.223	10.8	S
887 Alinda	1918	1.15	3.88	2.52	.544	9.1	S

[a]When first discovered, asteroids are given a provisional designation which consists basically of the year and two letters. The first letter refers to the half-month interval in which it was discovered; the second, to the chronological order of its announcement within that particular half-month interval. So, for example,1982 DB was the second (B) asteroid discovered during the second half of February (D) in 1982. After the orbit of an asteroid has been well enough determined that it can be found again, it is given a sequential number and, when its discoverer can think of one, a name. Names seem to be needed for Amors 3757 1982 XB, 3122 1981 ET_3, 3908 1980 PA, and 3551 1983 RD, so readers with lovely ideas may submit them to the International Astronomical Union, Commission 20 (Positions and Motions of Minor Planets, Comets and Satellites).

[b]See table 14 for the definitions of these spectral types and possible meteoritic analogs of them.

[c]When more than one spectral type is listed, the indication is that the data are ambiguous or noisy.

[d]U = Unclassified.

The best possible target would be a body that can be reached simply by achieving escape velocity from Earth and which is about to collide with the Earth (so that no return propulsion is required). The round trip ΔV from LEO for this unattainably ideal case is about 3.4 km/sec. A reasonable estimate of the number of near-Earth asteroids with radii of 1 km or more yet to be discovered is 1000 to 4000. Estimating that 10 percent of them will be in accessible orbits (round-trip total $\Delta V < 6$ km/sec), some 100 to 400 1-kilometer-size bodies should be available for exploitation. The number of bodies with radii of 100 m to 1 km is probably several hundred times as large.

The martian satellites Phobos and Deimos are less attractive in terms of the energy needed to reach them than the near-Earth asteroids but still more accessible for exploitation than the surface of the Moon. Like the Moon, Phobos and Deimos apparently have a regolith and lack an atmosphere. Three independent sources of information—thermal inertia measurements and photographs made from Mariner 9 and Viking and ground-based radar measurements—indicate the presence of a lunar-like regolith that is tens of meters deep in some places. Measurements of the densities of Phobos and Deimos, their albedo (dark), and their spectral reflectance are similar to those for carbonaceous chondrite meteorites and the possibly organic-rich D- and P-type asteroids. However, ground-based photometry of Deimos made during the 1988 opposition of Mars shows no 3-micron water band in its spectrum, and data from the Soviet spacecraft Phobos 2 must be thermally modeled before these images and spectra can provide information on the presence of water on Phobos. Thus, to associate the composition of Phobos and Deimos with any meteorite type would require a mission capable of taking a chemical inventory of these satellites.*

*Lucy McFadden, 1989, in vol. VI of Exploration Studies Technical Report, published by the Office of Exploration, Johnson Space Center, NASA TM-4170, pp. 2-6 & 2-7.

The ΔV requirements for the outbound (LEO to surface of body) and inbound (surface of body to LEO) legs and the trip times for asteroidal, lunar, and martian trajectories are compared in table 19. Note that the Mars system is mainly useful for supplying resources to support Mars endeavors. However, return of martian satellite materials to LEO is somewhat more attractive energetically than return of lunar materials to LEO (return ΔV's about 40% lower).

TABLE 19. *DV's and Trip Times Between LEO and the Surfaces of the Moon, Selected Asteroids, Mars, and Phobos/Deimos**

Body	Outbound		Inbound	
	ΔV, LEO—→surface, km/sec	Time of flight, days	ΔV, surface—→LEO, km/sec	Time of flight, days
Asteroids:				
1982 DB	4.45	210	0.06	480
1982 XB	5.30	220	0.22	470
1982 HR	5.30	180	0.26	320
1980 AA	5.40	690	0.36	450
1943 Anteros	5.27	390	0.39	290
Moon	6.00	3	3.10	3
Mars	4.80	270	5.70	270
Phobos/Deimos	5.60	270	1.80	270

*All returns to LEO are via aerocapture. All arrivals in the Mars system are also via aerocapture in the martian atmosphere.

Asteroids as Targets for Resource Exploitation

Although both meteoriticists and asteroid spectroscopists are puzzled over the lack of correspondence between types of meteorites as analyzed in the laboratory and types of asteroids as measured by remote sensing of their surface mineralogy, there are indications in these spectral reflectance data that some of the near-Earth asteroids resemble the volatile-rich carbonaceous chondrites. So useful would volatiles, including water and carbon dioxide, be in space settlements that additional support for the effort to find and characterize more of these asteroids seems warranted. (See the preceding paper by Mike Gaffey.)

Though we have no spectral typing of the most accessible asteroid, 1982 DB, the fact that a round trip to it or one of several other near-Earth asteroids requires less energy than a round trip to the surface of the Moon is another reason to keep looking for an asteroid that is both accessible and of a desirable composition. Should such a candidate for resource exploitation be found, then we would want to send a reconnaissance mission to it to determine if it is really a mining prospect. (See Rich Gertsch's subsequent paper on asteroid mining.)

Lunar Resource Evaluation and Mine Site Selection

A. Edward Bence

I have considered two scenarios in this evaluation of lunar mineral resources and the selection of possible mining and processing sites. The first scenario assumes that no new surface or near-surface data will be available before site selection (presumably one of the Apollo sites). The second scenario assumes that additional surface geology data will have been obtained by a lunar orbiter mission, an unmanned sample return mission (or missions), and followup manned missions.

Regardless of the scenario, once a potentially favorable mine site has been identified, a minimum amount of fundamental data is needed to assess the resources at that site and to evaluate its suitability for mining and downstream processing. Since much of the required data depends on the target mineral(s), information on the resource, its beneficiation, and the refining, smelting, and fabricating processes must be factored into the evaluation. The annual capacity and producing lifetime of the mine and its associated processing plant must be estimated before the resource reserves can be assessed. The available market for the product largely determines the capacity and lifetime of the mine.

While realistic market determination is several years away, this study starts by assuming a 40 000-metric-ton-per-year lunar mining operation with a minimum lifetime of 10 years. This size would be sufficient to supply 100 metric tons of liquid oxygen (LOX) per year to low Earth orbit (LEO), assuming a 100-percent extraction efficiency and using an additional 300 metric tons of lunar oxygen to deliver the usable lunar oxygen to LEO and to bring tankers and hydrogen back to the Moon.

A 10-year operation requires processing of nearly 500 000 metric tons of ore. In the cases of iron-titanium mare basalts and of aluminous material from the lunar highlands, this amount of ore is insignificant compared to the potential reserves. And there should be no problem defining adequate reserves of oxygen, iron, titanium, silica, and bulk materials at any otherwise acceptable site.

How does one go about evaluating an ore body on the Moon? On Earth it is fairly straightforward. Data on ore grade, grade continuity, geometry and size of the ore body, grain size and grain size distribution, state of aggregation, accessibility, local relief, availability of power and water, and environmental issues must be collected, analyzed, and evaluated for economic impact. In the terrestrial case, the underlying constraint is profitability. In the lunar case, the only constraint is that the cost of placing the final product in LEO be less than the cost of bringing it from Earth.

Physical and chemical characterization of a potential ore body (prospect) on Earth is accomplished by a detailed sampling program that includes extensive core drilling. Terrestrial remote sensing rarely locates actual ore bodies, only prospects which are then explored in more detail on the ground. It is unlikely that such a sampling program would be carried out at a new landing site. Most of the exploration for lunar mining prospects would probably be done by remote sensing. The proposed resolution of the lunar resource mapper will not yield as much site information as is already known about the Apollo sites. For this reason an Apollo site, if it contains the appropriate materials, would be the most suitable site for a regolith mining operation. Since water has not yet been discovered on the Moon, it is not considered here. However, if water (ice) were discovered in the polar regions, its availability alone could strongly influence site selection.

William Snow, another participant in the summer study and the author of a paper in volume 2 entitled "Electromagnetic Launch of Lunar Material," has this to say about siting the lunar mine and oxygen production plant:

To obtain lunar oxygen at the earliest possible date, the electromagnetic launcher and liquid oxygen production plant should be deployed at one of the Apollo landing sites. Doing so would eliminate the need for a geochemical orbiter to survey the entire Moon first. To send a geochemical orbiter is good science, but it is not required for siting a lunar oxygen plant. Requiring a preliminary survey would be like having Sutter discover gold in California and then requiring a complete survey of the state before gold mining could begin. We know the mineralogy and chemistry sufficiently well at six locations on the Moon and could begin today designing and constructing a lunar oxygen processing plant on the basis of the samples brought back by the Apollo missions.

California "Forty-niners"

Soon after the news leaked out that gold had been discovered at Sutter's mill on January 24, 1848, the California gold rush began. No one waited for a government study to determine the most likely mine locations. Instead, in the following year, tens of thousands of prospectors—the "forty-niners"—streamed to California and began to look for a share of the 550 million dollars' worth of gold that was mined there in the next 10 years.

Return to an Apollo Site

Even with our current knowledge of the Apollo sites, we need additional information to assess their suitability for mining. For example, even at the best characterized site, Apollo 17 (fig. 13), small-to medium-scale (in meters) variability in composition and particle size is not sufficiently well known. Because such characteristics profoundly affect the success of a mining and ore processing venture, many more regolith cores would need to be collected before a mine was specifically located within the area where Apollo 17 landed. The coring locations would be chosen so as to define a grid over each prospect. Each block in the grid would be on the order of several meters square by 2 meters deep. Variations in grain size and mineralogy across the grid would be used to assess the suitability of a specific prospect.

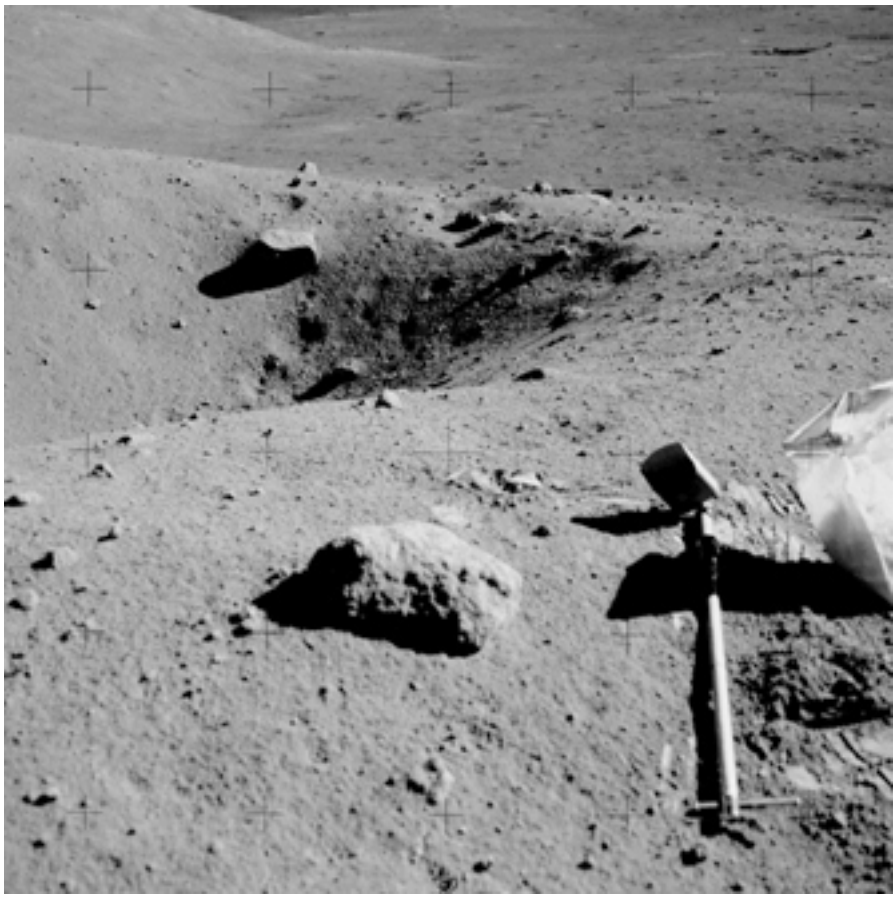


Figure 13

Typical Lunar Surface View at Apollo 17

The crater in the photograph (Ballet Crater) is about 30 meters in diameter. The rock in the foreground is about 40 centimeters across. We have good information over nearly all the surface of the Apollo 17 site on the sizes of craters and rocks on a submeter scale of resolution. However, we have very little information on variation in the third dimension, depth. We have only a single 3-meter core and a few drive tubes which penetrated less than 1 meter. Since mining would likely go to a depth of at least a few meters, knowledge of the regolith properties to that depth might be a requirement for resource evaluation.

NASA photo: AS17-138-21160

From the Apollo 17 site at Taurus Littrow, we have the largest suite of samples and we also have the onsite observations of geologist-astronaut Jack Schmitt. By designing flexibility into mining and processing equipment, we can eliminate the need for some of the data normally required.

The chief feedstock at the Apollo 17 site would be the iron- and titanium-rich mare basalts. This “ore” could be scraped from the surface and provided as bulk material; oxygen and metallic iron could be extracted from it; and ceramics could be made from it—all with relatively simple mining, beneficiation, extraction, and processing procedures. However, even the simplest resource operations present difficulties on the lunar surface and require the support of a sophisticated transportation system and the presence of human beings.

Oxygen Production

All of the major rock types we have found on the Moon offer the potential for oxygen production in large quantities. However, ilmenite-rich mare basalts, such as those at the Apollo 17 site, seem to offer the widest range of production methods, including ilmenite reduction. Adequate separation of the ilmenite from the silicates in these basalts could be a problem. Because the ilmenite-rich soils at this site derive from basalt flows, the ilmenite crystals are both fine-grained and intergrown with silicate crystals. An answer to this separation problem might be to use an oxygen production process (such as magma electrolysis or the carbothermal reduction of silicates) which does not require beneficiation (mineral concentration).

Metal Extraction

Iron seems to be the metal most easily obtained from lunar rocks. It can be obtained as a byproduct of the direct hydrogen reduction of ilmenite and possibly by other methods. Mare basalts, relatively rich in iron and titanium, provide the best large-scale source known on the lunar surface. The basalts at the Apollo 17 site are thus an adequate source of iron.

Bulk Material

While bulk material is available at virtually any lunar location, a site with a deep, relatively fine-grained regolith is preferred from the point of view of moving large amounts of material. The Apollo 17 site provides adequate access to this resource.

Other Site Considerations

Proximity to highlands: Although we anticipate that the first lunar resources used on the Moon will be obtained from mare soils, it may be that, in the long range, materials such as aluminum, lime, and certain ceramics may best be obtained from highland rocks. Thus, selection of an initial lunar mining and processing site close to lunar highlands seems prudent. This requirement would also be satisfied by the Apollo 17 site (see fig. 14).

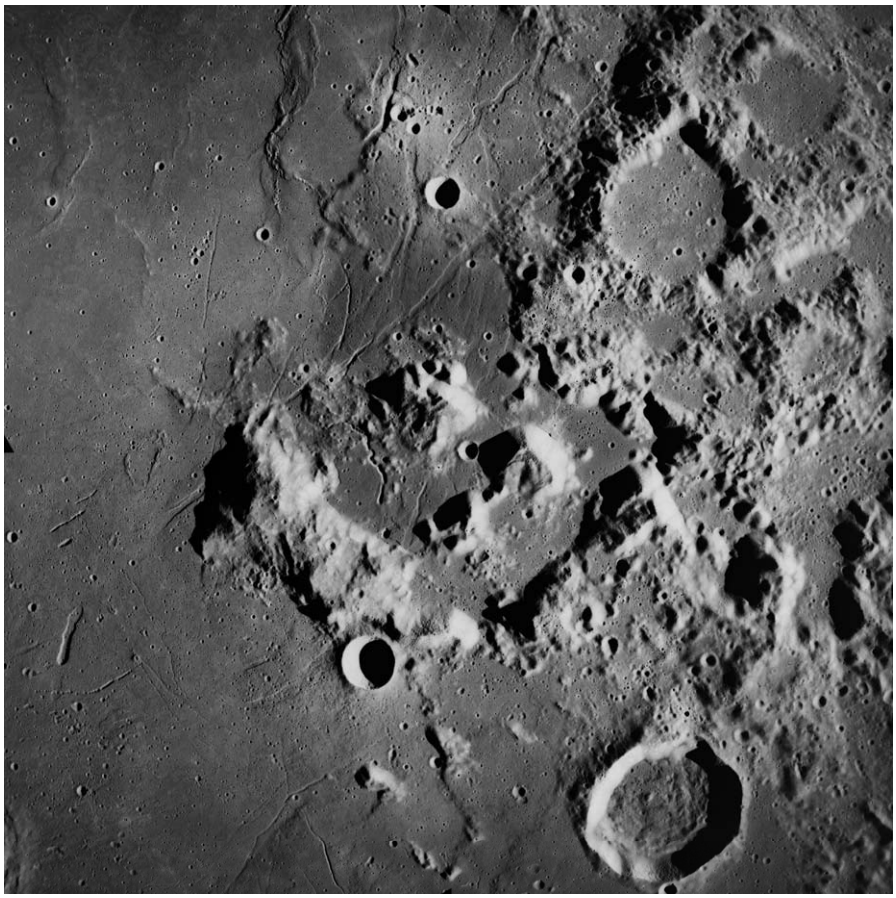


Figure 14

Orbital View of the Apollo 17 Site

Apollo 17 is an example of a site at a boundary between a mare and a highlands area. In this orbital view, Mare Serenitatis can be seen to the left and part of the "Western Highlands" to the right (east). Between these two features, to the right of center, is the Taurus Littrow Valley (note the landslide there). Such sites have a geological diversity that, besides being scientifically interesting, may offer many different types of usable materials.

NASA photo: AS17-0447

Specific siting of mine and plant: Optimum location of the first lunar mine and resource-processing plant will require additional site evaluation. Detailed characterization of the regolith is needed in order to construct an adequate ore body model. Further sampling to establish the necessary sampling grid would be a prime task for the next astronauts to occupy the Apollo 17 site. Their other chief concern will be to establish a base camp that can evolve into a permanent habitat.

New Sites

In terms of currently recognized lunar mineral resources, there is very little justification for developing a site other than an Apollo site. If, however, water were located in the polar regions, then a water-bearing site would have a higher priority than any other site. Evaluation of resources at a site or sites other than an Apollo site would require implementation of a regional exploration program. This program would include the discovery phase, presumably by an orbiter mission, in which a number of potentially favorable mining sites would be identified, each with multiple prospects. This phase would be followed by an unmanned surface mission or missions to several of the most favorable sites. Such a mission would include a Rover-type vehicle capable of obtaining regolith cores at least 2 meters deep and returning the samples to Earth. Followup manned missions would land at one or two places from which candidate mining sites are accessible.

The objectives of the earliest manned missions would be to set up an exploration base and, operating from that base, to carry out a rigorous sampling and evaluation program at a small number (no more than 5 or 6) of the most favorable prospects. From this evaluation, all the prospects found to be ore bodies would be ranked from most to least favorable on the basis of mining and milling criteria. Final site acceptance would factor in accessibility, potential hazards, power requirements, and the myriad of site details required by any mining operation.

Conclusion

Any otherwise acceptable mining site on the Moon should have adequate resources to support a 10-year, 40 000-metric-ton-per-year operation. Of the sites sampled, that of Apollo 17 is the best characterized and should require the least pre-development work. Only a site having frozen water would be more desirable. Even though the Apollo 17 site is the best characterized of the sites, pre-development work involving extensive coring of the regolith is required to assess its physical and compositional variability.

Lunar Site Characterization and Mining

Charles E. Glass

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.

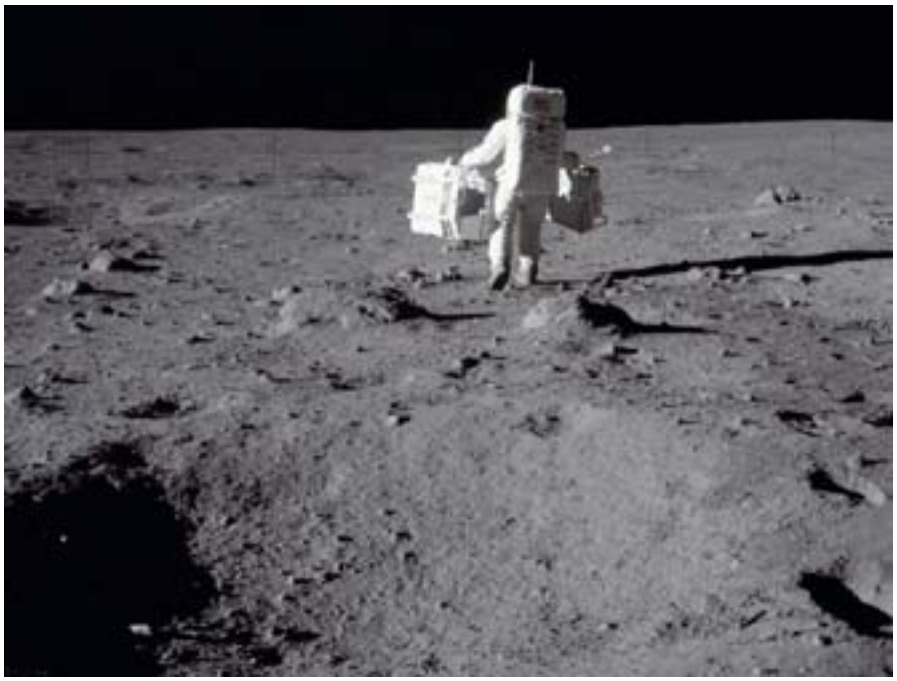
The automated nature of lunar exploration will demand advances in high-resolution sensing and in computer processing and integration of data acquired by different instruments on the same roving vehicle. Knowledge gained from terrestrial mineral exploration can be used for preliminary training of automated 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.

NASA photo: AS11-40-5944



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.

NASA photo: AS16-114-18427

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.

NASA photos: AS15-82-11055 & -11057

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 the 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 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.

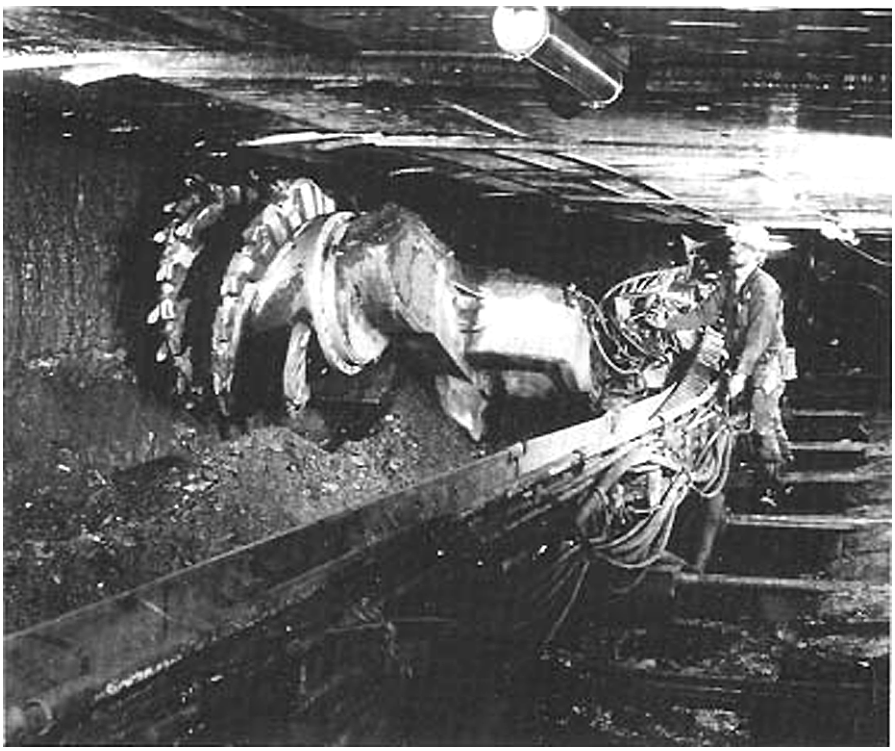


Figure 17

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.

A Baseline Lunar Mine

Richard E. Gertsch

In this section I propose a modest lunar mining method. It illustrates the problems to be expected in lunar mining and how they might be solved. While the method is quite feasible, it is, more importantly, a useful baseline system against which to test other, possibly better, methods. Our study group proposed the slusher to stimulate discussion of how a lunar mining operation might be successfully accomplished. Critics of the slusher system are invited to propose better methods. The group noted that while nonterrestrial mining has been a vital part of past space manufacturing proposals, no one has proposed a lunar mining system in any real detail (Carrier 1979, Williams et al. 1979). The group considered it essential that the design of actual, workable, and specific lunar mining methods begin immediately.

Based on an earlier proposal (Gertsch 1983), the method is a three-drum slusher, also known as a cable-operated drag scraper (Ingersoll-Rand Company 1939, Church 1981). Its terrestrial application is quite limited, as it is relatively inefficient and inflexible. The method usually finds use in underwater mining from the shore and in moving small amounts of ore underground. It uses the same material-moving principles as more efficient, high-volume draglines.

The slusher is proposed here because the LOX-to-LEO project is a very small operation by terrestrial standards and requires a method that minimizes risk. The three-drum slusher has already proven itself in this context. It has the advantages of simplicity, ruggedness, and a very low mass to be delivered to the Moon. When lunar mining scales up, the lunarized slusher will be replaced by more efficient, high-volume methods, as has already happened here on Earth.

The Machine and Duty Cycle

Before discussing the advantages of the machine in a small-scale startup lunar mining scenario, I will describe the slusher and its duty cycle. It consists of the following modules (see figs. 18 and 19):

1. A mobile power unit and loading station—including three drums around which the cables are wound, a mechanism to place anchors, a mechanism to change tools, an optional operator cab, a dozer blade, and a conveyor to load material into the electrostatic separator
2. Three lengths of cable to operate the scraper or other mining tools
3. Two anchored pulleys
4. Interchangeable working tools, including scrapers, rakes, plows, and rippers

Figure 18

The Mobile Lunar Slusher

Several features of a mobile slusher (cable-operated drag scraper) are shown in this perspective view. The scraper loading material in the center of the pit will continue to load material until it reaches the discharge point or loading station to the left. In the method proposed in the text, the slusher will load into a mobile mill module with the aid of a conveyor. (Neither the conveyor nor the mill module is shown here. The module behind the loading station is a transporter.) The mobile power unit loading station will be anchored (not shown) to counter the forces on it. The function of the two anchored pulleys should be clear from the illustration. The "box-type" slusher bucket has enclosed sides, which keep the very fine lunar material from spilling out while being loaded and transported.

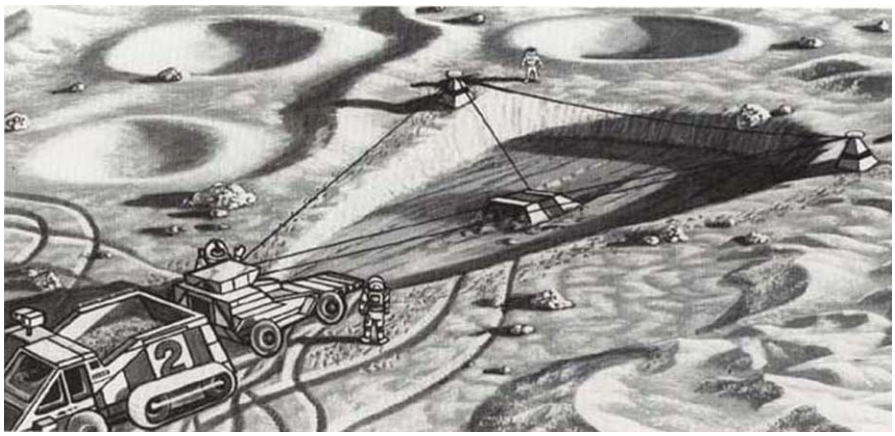
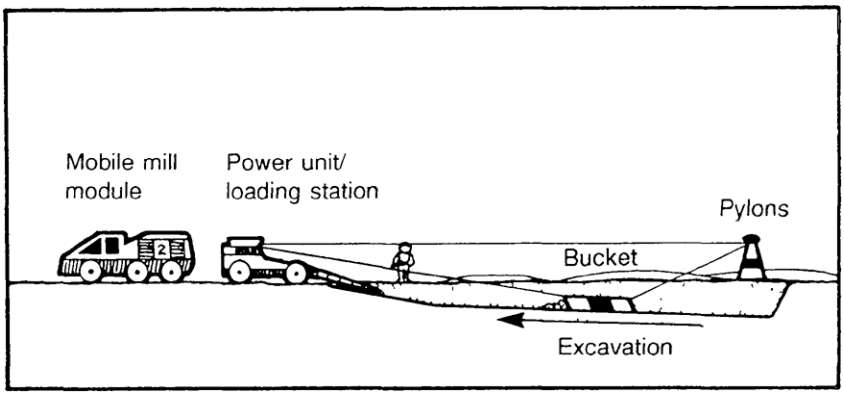


Figure 19

Side View of the Mobile Lunar Slusher

This side drawing of the slusher shows the mobile mill module behind the combination power unit and loading station. In this setup, the material from the slusher bucket is dumped directly into the mill module. The pylons holding the pulleys must be firmly anchored. They position the bucket when it is pulled out from the loading station into the mining area.



The duty cycle starts with machine setup. The mobile power/loader unit places two pulleys at appropriate locations at the mine site. They could be anchored by large augers in the firm regolith below the loose soil or by other methods. The preferred anchoring method depends on specific site characteristics. After the pulleys are anchored, the power unit similarly anchors itself. The two pulleys and the power unit form a V-shaped mining area. Because machine setup is done only infrequently, is a complex job, and requires firm anchoring, it could be left as a manual operation. For one reason, the anchoring augers might hit buried rocks before they are successfully emplaced. Further study may show that automated or teleoperated setup is also feasible and more desirable.

In this short paper, it is impossible to cover adequately all the alternatives and options, even within a well-defined system such as the slusher. However, I will mention one major alternative—a stationary power/loader unit (fig. 20), which is the terrestrial configuration. In this case, the

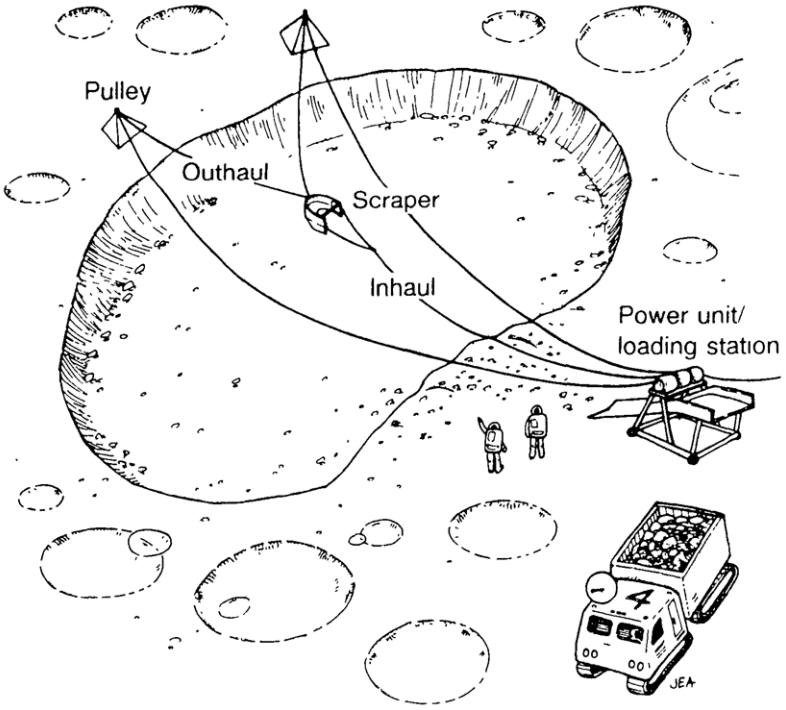


Figure 20

The Stationary Lunar Slusher

A stationary lunar slusher would have the same operational features as the mobile slusher. Because it is not self-propelled, it is much simpler and lighter; however, for the same reason, it requires another vehicle to move it from site to site.

From Gertsch 1983.

slusher itself would be far simpler, but such a system would require an auxiliary vehicle to transport the slusher from site to site and set it up. A stationary slusher would be less able to remove unexpected obstacles from the pit, as I will discuss. Either way, the excavation duty cycle is basically the same.

After setup, the excavation duty cycle begins with the scraper (or other tool) at the loading station. The scraper can be moved to any point within the V by a combination of tensions on the two outhaul cables. After reaching the desired position, usually as far into the pit as possible, the scraper is pulled back to the power/loader unit by the inhaul cable. During inhaul, a combination of inhaul force and scraper weight (fig. 21) causes the scraper to fill with loose regolith and carry it back to the power/loader unit. Here the material is pulled up the ramp, discharged from the scraper onto the conveyor, and loaded directly into the mill module.

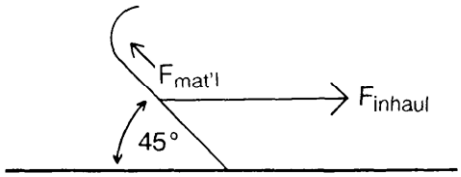


Figure 21

Forces on a Hoe Scraper

The 45-degree scraping angle is considered optimum. The angle has been determined by many years of terrestrial experience. It seems most likely that this angle will be the same for the Moon, but can we be sure? One missing force vector is the weight of the bucket. For proper operation, the weight of the bucket may need to be augmented with lunar rocks or other material.

The mill is the electrostatic separator described by Agosto in the section on beneficiation. The separator should be in direct contact with the slusher. This eliminates rehandling of the mined material, resulting in a significant energy saving, since 90 percent of the mined material will be rejected by the separator. The waste from the separator is dumped away from the production area by ballistic transport or another method. Waste transport need only be far enough to keep the separator and slusher from being buried in their own waste.

The box-like scraper will have closed sides to keep the very fine regolith from spilling out, as has been the terrestrial experience.

Because the machine defines its own mining area and machine motions are repetitive, the scraping operation is a reasonable candidate for automation. Feedback control for automatic loading of the scraper will be supplied through sensing the inhaul cable tension. Loading always requires complex motion control, but the problem is more easily resolved with a limited-motion machine such as the slusher than with fully mobile equipment, such as front-end loaders, which have unlimited freedom of motion.

After mining starts, the mobile power unit generally does not move. If an obstacle is uncovered in the pit, the mobile version of the power/loader unit can detach from its anchor and move into the pit. (The anchor is not removed from the soil unless the machine is moving to another site.) To facilitate pit work, the loading ramp is tilted up and a dozer blade extends to its working position. The blade can push boulders out of the pit or mine a small selected area. Because the power/loader unit is lightweight and consequently has poor traction characteristics, it must pull against the outhaul cables when it works a load in the pit. The complexity and uniqueness of this job argue against automating it, but automation is not impossible and teleoperation is a possibility. Both setup and power unit pit work can be done by teleoperation, except for handling severe unforeseen problems that require human intervention.

During normal operation, electric power is supplied to the power/loader unit by a stationary cable. When the power/loader unit works the pit, it gets its power through a cable reel located at the anchor. One advantage of stationary mining equipment such as the slusher (even the mobile version moves very little during excavation) is simplicity of power supply. Most mobile terrestrial equipment has diesel power, which is rugged, capable, efficient, and, most importantly, onboard. These loaders are very flexible and rugged earth-movers. The lunar alternatives are less satisfactory. Lunar loaders with onboard power would probably use electric motors driven by fuel cell or battery technology. Both are expensive options. Versions with external power must be fed electricity through a trailing cable. Terrestrial experience has shown that trailing cables are high maintenance items, but adaptation to the Moon is possible. Another possibility is a new-technology internal combustion engine, but developing the engine and finding lunar fuel sources are difficult problems.

The Lunar Environment and Machine Design Principles

The major reason for proposing the three-drum slusher is to illustrate problems to be expected in a lunar mining project.

Simplicity in Design and Operation

Compared to other mining machinery, the three-drum slusher is quite simple in design and operation. This simplicity yields several interrelated advantages.

1. Fewer moving parts, resulting in fewer failures per operating hour
2. Simpler repair, reducing downtime after a failure
3. Smaller inventory of repair parts, hence less weight to transport to the Moon
4. Simpler parts, with faster adaptability to lunar manufacture
5. Less redesign for lunar conditions, with consequently lower R&D costs
6. Fewer degrees of freedom than mobile equipment, and therefore relative ease of automation
7. Fewer project startup problems

Traction Independence

Mobile mining equipment depends on traction to generate sufficient loading forces on the blade or scraper. Most terrestrial mobile equipment loads near its traction limit. On the Moon, reduced gravity creates a less favorable inertia:traction ratio. Increases in traction are achieved by increases in mass, but increases in mass add inertia, which decreases control of a moving machine. To achieve the same traction as on the Earth, a mobile machine on the Moon would have to have six times as much mass. This greater mass would cause correspondingly higher inertial resistance to turning and slowing.

Slusher loading forces are supplied through the cable, thus almost eliminating traction problems. The scraper bucket will have to be more massive than on Earth, simply to cause the bucket to fill. To lower launch weight, the extra mass needed by the scraper bucket can be supplied by lunar rocks.

Since the slusher is a relatively low-production method, upscale lunar mining projects will eventually use mobile mining methods. It is necessary to address inertia-traction problems as early as possible. Further study may find that long-term considerations argue for using mobile equipment from the very beginning. As with the scraper bucket, the extra traction mass can be supplied by lunar materials. Perhaps traction could be improved by new tread or track designs.

Mining Flexibility and Selectivity

The lunar slusher differs from the terrestrial slusher by one major design addition: the power unit is mobile rather than stationary. This allows the machine to set itself up and eliminates the need for an auxiliary vehicle. Most important, by adding a dozer blade, the machine can doze undesirable rocks from the pit. Such large rocks would impede mining operations if the power unit were stationary.

The mobile power unit makes the machine more selective. By allowing the power/loader unit to reposition, the slusher has some ability to separate different soils during the mining process or to go into the pit and mine a small area of interest.

Mining Tools for Selecting Particle Size and Breaking Regolith

The ability to change from a scraper to a rake allows the machine to select different size fractions. For example, if fines are required, the area can be raked on the outhaul, so that oversized rocks are moved to the far side of the pit. Then the rake can be exchanged for a scraper to mine the remaining fines. If larger sizes are desired, they can be raked in on the inhaul.

Other tools, such as rippers or plows, are used to break difficult ground. Lower levels of lunar regolith appear to have a high degree of compaction (Carrier 1972) and must be broken before mining can take place. Although it is the usual terrestrial practice, chemical explosive blasting appears to be prohibited by the high cost to transport the explosives to the Moon. The ripper or plow greatly increases machine working depth. It has already been established that the slusher, unlike mobile loading equipment, is independent of traction. This traction independence allows the slusher to break difficult ground while still maintaining a light weight. More lunar geotechnical engineering data is needed, however, and the design of the ripper is unknown. The ripper probably needs an attached weight to force it into the regolith. A plow may be better than a ripper, as its shape helps pull it into the soil, making it less gravity dependent.

High-Tech Low-Tech Mix

The redesigned slusher exemplifies a design philosophy favored by the study group. The basic machine design is nearly 100 years old and has a track record proven in many applications. See figure 22. In a lunar application, the basic operating principles remain unchanged but the machine becomes lighter, stronger, and more efficient by liberal use of advances in materials science. Light, high-strength alloys or graphite fiber might replace steel in the machine's structural and wear members. Graphite fibers might replace steel cables. Other opportunities to improve the slusher should present themselves. Thus, the lunar machine is a low-tech off-the-shelf design with high-tech execution.

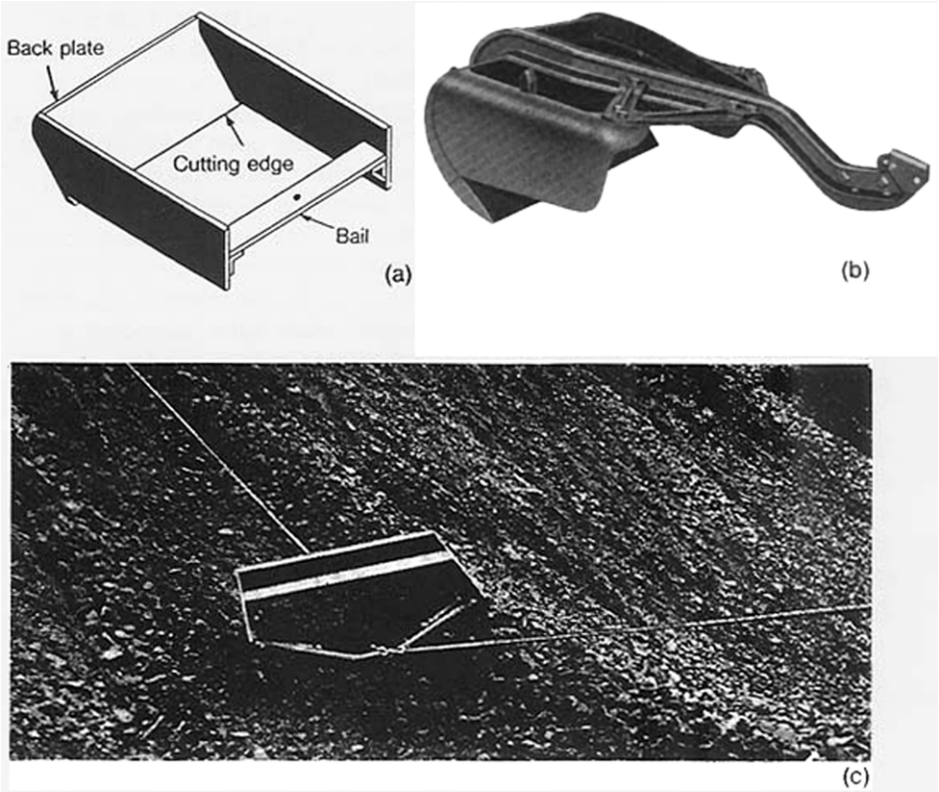


Figure 22

Box-Type Slusher Scrapers

a. Drawing of a Box-Type Scraper

b. Painting of a Full-Box Type Scraper

[Shown with a long bail and medium-length side plates.]

c. Photograph of a Box-Type Scraper

[Manufactured in the 1930s of steel plate construction in use on a stockpile.]

All three taken from Modern Methods for Scraper Mucking and Loading, *prepared, edited, and published by the Ingersoll-Rand Company in 1939.*

Two Environmental Factors

In addition to one-sixth gravity, there are two other significant lunar environmental factors worth noting: temperature extremes and electrostatic dust. Temperature extremes are easily answered by shutting down during the lunar night. Heating selected equipment components is feasible, if more expensive. Electrostatic dust is more of a problem. Machinery bearings must be protected, a problem exacerbated by the lunar vacuum, where lubricants may evaporate. One significant feature of the slusher is that it uses very few bearings, even in the mobile version. Lunar bearing designs and lubrication methods must be developed regardless of the mining method used.

Machine Specifications and Fleet Mix

The specifications and fleet mix I present are for the mobile lunar slusher. The reader should note that alternative methods, such as the stationary slusher, were included to illustrate lunar mining design problems and are not specified here. The data given below are for the proposed baseline mobile lunar three-drum system.

The needed raw material for a 100-metric-ton LOX-to-LEO project is 40 000 metric tons. The machine specified below is oversized by a factor of 2.5 or a yearly rate of 100 000 metric tons. This oversizing is to ensure the production is easily accomplished, while demonstrating that a significantly oversized machine is relatively lightweight. Even with this large oversizing, the hourly production is about 25 metric tons per hour. This rate is close to the lowest rate shown on the production table of one manufacturer (Ingersoll-Rand Form 4273A 5-G1 1971).

Specifications:

Yearly production	100 000 metric tons
Span and reach	50 meters
Mined depth	2 meters
Scraper capability	2 cubic meters
Mobile slusher weight	4.5 metric tons
Auxiliary vehicle weight	1.5 metric tons
Ballistic transporter	1 metric ton
Spare parts and tools	2 metric tons
Operation and maintenance	2 people
Foundry (optional)	5 metric tons
Total weight (without foundry):	9 metric tons

Fleet:

1 mobile slusher

1 auxiliary vehicle with small multipurpose crane

1 ballistic transporter

Lunar Mining Operations

Production Profile

The baseline self-propelled slusher excavates a triangular area 50 meters in base and height. At a mining depth of 2 meters, approximately 9000 metric tons are excavated per setup. Approximately one setup per lunar day yields a yearly raw material production of 100 000 metric tons. Mining would cease during the night, as the extremely low temperatures would make operation difficult. But milling could continue, as the mill is more easily protected from the environment. Production figures are based on terrestrial experience; lunar gravity will allow increases without increasing machine size. It should be noted that production can readily be increased by manipulating several machine variables without significantly changing machine weight. Variables such as bucket size, span, reach, and motor power all affect production. No attempt was made to optimize these factors; instead the machine was oversized to show a very basic feasibility. Empirical optimization is required during design and prototype testing.

Although the normal mining pattern is a V, mobilizing the power/loader unit allows more flexible patterns (fig. 23). The mobile unit allows the machine to excavate more convenient rectangular areas rather than triangular ones.

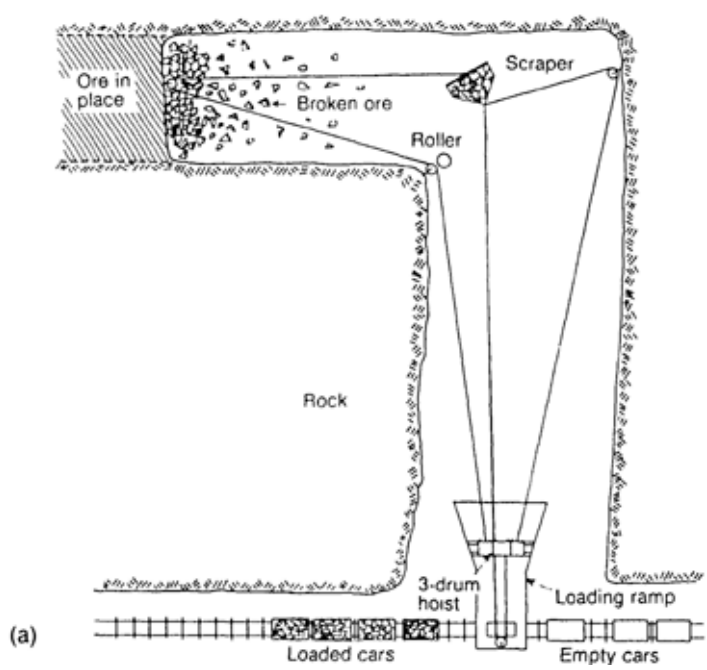
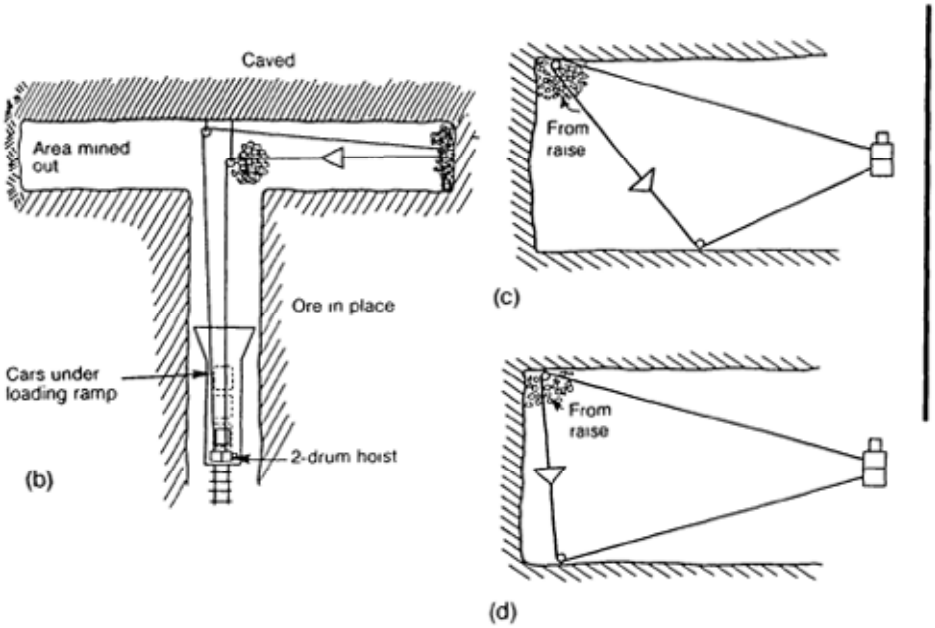


Figure 23

Various Slusher Mining Patterns

These underground slusher mining patterns demonstrate the slusher's flexibility in mining different shaped areas. Figure a *shows a three-drum slusher scraping around a corner. Figure* b *shows a two-drum slusher scraping around a corner, but note that it takes two scraping operations. Figures* c *and* d *show how a changing setup allows a two-drum slusher to mine outside its restricted narrow path. Both the two- and three-drum slushers can mine a wide variety of areas: triangles, rectangles, right angles, etc. However, each different setup requires downtime to reset the pulleys or the power/loader unit.*

Taken from Modern Methods for Scraper Mucking and Loading *by the Ingersoll-Rand Company, 1939.*



Some weight savings could be gained by using a two-drum slusher. With one outhaul cable instead of two, the machine excavates a straight line rather than a triangle. The decrease in flexibility may not be worth the small weight savings, but the two-drum solution should be investigated. By moving the power/loader unit or the pulleys, the two-drum slusher can be made to excavate a rectangular area, but the moves slow the rate.

Modular Components

Every opportunity should be taken to divide the slusher (and other equipment) into modular components. The modules should be as interchangeable and transportable as possible. Two general types of modules envisioned are large functional modules, such as mining units, material crushers, and electrostatic separators, and small equipment modules, such as electric motors and power distribution panels.

Modularity increases flexibility and reduces downtime without adding equipment weight.

1. A component needing repair can be replaced onsite with a working unit. The defective unit can then be repaired onsite or in the shirt-sleeve environment of a pressurized shop.

2. Quick component replacement allows production to continue when one component breaks. When many components break, a producing unit can frequently be assembled from the remaining units.

3. Catastrophic failure of a module, such as an electric motor, will not hamper production, as the whole unit can be replaced.

4. Increasing production simply means adding more components rather than redesigning or rebuilding the existing facilities. Upgrading one part of the operation with new designs or technology is facilitated by replacing the old components with the new.

Accomplishing modularity is relatively easy in small-production mining facilities. (By terrestrial standards, the lunar slusher operation is very small.)

Auxiliary Vehicle

A small, self-propelled auxiliary vehicle will probably be necessary, even with a mobile slusher or other mobile mining method. It will find use hauling broken components to the repair shop and replacement modules to their operating positions, as well as hauling people and materials back and forth. It should have a crane to aid in constructing habitats and repairing equipment. Adding a small conveyor to the vehicle would allow it to heap up loose regolith for habitat shielding. This general-purpose vehicle will be smaller than the vehicle required to move a stationary slusher from site to site.

Shop Facilities

A pressurized repair shop would facilitate complex repairs by providing a shirt-sleeve environment. There is no good reason to rewind an electric motor in a vacuum. Since lunar dust is ubiquitous and insidious, some system for removing dust from the shop and its equipment must be provided. Equipment from the outside must be cleaned of dust before it enters the shop.

However, a shop would add significant launch weight unless it could be fabricated on the Moon. Launch weight considerations dictate a careful mix of tools, equipment, and spare parts for the shop. The shop and repair activities are there to keep the mine operating while helping to keep transportation costs for tools and spare parts to a minimum.

In addition to tools and spare parts, the shop could eventually have a small adjacent foundry to cast pulleys, bearings, and other

easily fabricated parts. The foundry will probably not be in the shop but outside in the vacuum. This plan assumes lunar metal production.

Fiberglass ropes of lunar origin to replace Earth-made cables are also candidates for early lunar manufacture, as glass is a byproduct of LOX production. Glass manufacturing methods were not considered here.

Mine Waste Disposal

Depending on required products and milling processes, some fraction of the mined material will be waste which must be removed from the production area. This fraction can be quite significant (e.g., terrestrial copper operations yield only 10 kg of product per metric ton of ore; thus, 1990 kg of that tonne is waste). The LOX-to-LEO project will generate two types of waste. Fines waste is the soil fraction rejected by electrostatic separation. Slag waste results from the smelting process. Production of liquid oxygen from regolith that is 10 percent ilmenite will generate mostly fines waste, on the order of 90 percent of the material mined or 36 000 metric tons per year. Providing a vehicle for waste disposal would add significant launch weight, and the waste disposal options must be studied.

Robert Waldron and David Carrier* have both proposed a ballistic transport mechanism that could be usable in lunar mining. It is well suited to removing fines waste. Using a simple mechanism such as an Archimedean screw (see box) or conveyor flights, it is possible to ballistically transport fines waste several hundred meters away from the production area. Their preliminary calculations indicate that the mechanism could be built at a reasonable weight. A ballistic transporter, along with a storage and feed bin, could be added as part of the mill module or as a separate module. The ballistic transporter could also be used to heap up material for habitat shielding.

*Personal communications.

The following is one of a series of 5-minute radio programs. Entitled The Engines of Our Ingenuity, *the series is written by mechanical engineer John H. Lienhard and presented by the University of Houston's College of Engineering.*

Ceredi's Pump

Now and then I run into a student who says, "I like engineering just fine; but why should I hafta take philosophy?" He fails to see that what we do is shaped by the way we think about things—that our technology and our philosophy bend to fit each other. Here's an example:

Archimedes invented a really clever pump in the third century B.C. It's been used all over the world, ever since. It looks like a tube coiled around a long axle. You tilt the axle and put its lower end in water. Then you turn it. The open end of the tube picks up water and, as the coil turns, water passes from one loop to the next until it comes out at the upper end.

It's a pretty subtle gadget—not the sort of thing you just stumble across. Archimedean pumps were widespread in the classical world, and Roman authors described them. . . . Well, they tried to. We've just seen that they aren't easy to describe.

Archimedes' pump didn't do so well during the High Middle Ages when European attitudes were strongly shaped by Aristotle's philosophy. Aristotle very clearly separated motion into two kinds—motion in a straight line and rotary motion. These pumps mixed the motions. They used rotation to move water upward along an axis. They were anti-Aristotelian, and they were hard to find during the Renaissance.

(continued)

Water Screw as Illustrated in Daniel Barbaro's Vitruvius (1567)

It is difficult to understand how this water screw might have worked. But this illustration from Daniel Barbaro's commentary on Vitruvius' Ten Books on Architecture *shows that the device was known from classical times. Giuseppe Ceredi patented Archimedes' device in 1565, publishing his description of it the same year that Barbaro's book was printed.*

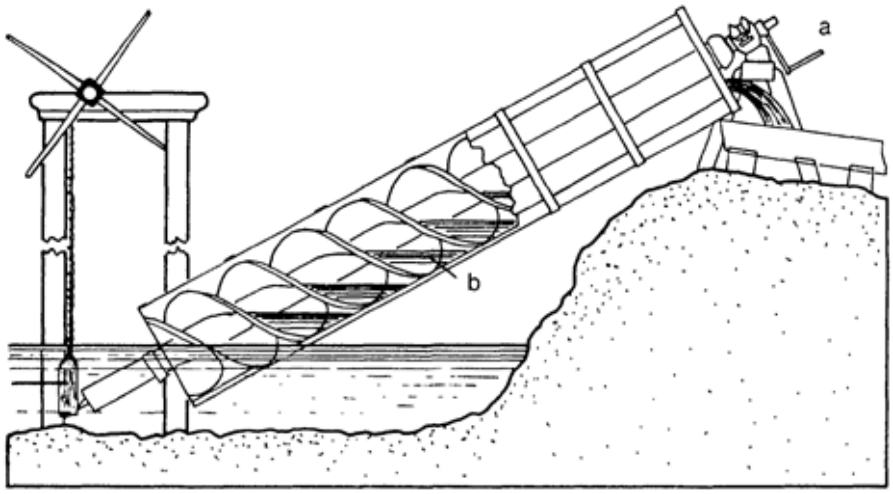
Taken from Stillman Drake, 1976, "An Agricultural Economist of the Late Renaissance," On Pre-Modern Technology and Science, *ed. Bert S. Hall and Delno C. West (Malibu, CA: Undena Publications), p. 70.*

Ballistic transport of the glassy slag waste from the smelting of ilmenite will be more of a problem. For regolith that is 10 percent by weight ilmenite, the slag waste produced will be on the order of 80 percent of the ilmenite or 3200 metric tons per year. Slag waste will contain much larger and more angular particles, which are less suited to ballistic transport. If the iron is extracted, the slag waste drops to 40 percent or 1600 metric tons per year. These figures are based on 100-percent separation efficiencies.

Costs and Time Line

Terrestrial three-drum slushers are relatively inexpensive yet rugged. A terrestrial slusher with the production profile outlined above costs on the order of $100 000. While the lunarized version proposed here adds several features to the terrestrial model, the redesign, addition of control circuits, and testing could be accomplished for less than $10 million. The same design simplicity that lowers the cost of operation will help keep down the research and development cost of the slusher.

After a mining site has been selected and a lunar base has been built, placing the slusher in operation is simple and can be accomplished in about 6 months. Setup time would include final operational testing on the Moon.



How an Archimedean Screw Works

This modern schematic drawing shows how an Archimedean screw works. As the handle (a) *is turned, a certain amount of water* (b) *is brought into the helical screw, which then brings the water up to a reservoir or trough.*

Ceredi's Pump *(concluded)*

Now, in 1565, a Renaissance agricultural engineer named Giuseppe Ceredi patented an Archimedes pump. He systematically described the installation and use of batteries of these pumps for both irrigation and drainage. But we wonder how he could be given a patent for a known device.

When you compare Ceredi's dimensioned drawings, flow calculations, and economic analysis, with the almost unreadable Roman descriptions, you begin to see why. Ceredi might well have found the idea in the old literature; but he put flesh and blood on it. After Ceredi's work, these pumps were quickly accepted across Southern Europe. They were not, as one author puts it, "something that would be created spontaneously by peasants." And they certainly weren't something that people would take up naturally in a world that didn't want to mix straight-line and rotary motion.

Ceredi had a right-brain ability to visualize. He had a left-brain ability to execute and organize detail. But he was also able to break the straitjacket of Aristotelian thinking. A few years later Galileo took up full-scale combat with Aristotelian ideas of motion. And Ceredi's reinvention of Archimedes' pump was a harbinger of that philosophical *revolution.*

Design, manufacture, and testing of a fully operational machine is a modest, well-defined task.

Conclusions

Any startup project in a new environment will have many unknowns. We do not even know all the questions, much less the answers. Mining ventures are very risky here on Earth and most of them fail. The space environment with its many unknowns adds greatly to the degree of difficulty. Keeping the project small, well defined, and simple will help ensure success.

Humans' experience working in space is very limited; our experience in nonterrestrial mining does not exist. Consequently, one significant but indirect benefit of the LOX-to-LEO project will be the experience gained in exploiting lunar materials. This experience will be the basis for later, more ambitious projects, either on the Moon or on other bodies.

Whatever lunar mining method is used, the slusher or something else, must be kept as simple as possible because simplicity means lower costs. The slusher is not particularly efficient or flexible, but it is simple and cheap.

The LOX-to-LEO project is very small compared to terrestrial operations, even small gravel pits. The small size allows consideration of nontraditional methods such as the slusher. The simplicity of the slusher has great advantages in a small operation. If a larger lunar operation is desired, consideration of other methods is mandatory. For example, machines such as the continuous miner should be particularly suitable to mining regolith. The continuous miner has wide application and has been proven in terrestrial coal mines. Traditional methods such as the truck-loader combination can also come into play. This mining combination has long been the workhorse for a wide variety of terrestrial mines.

More complex lunar mining methods may have a greater terrestrial transfer potential. A fully automated machine may find a significant terrestrial market. If so, such methods could amortize their development costs by supplying a wider market than the Moon.

The slusher itself has unresolved problems, even for the small LOX-to-LEO project. Only a few of these problems have been mentioned here. To ensure success, any lunar mining method must solve these problems effectively. Problem definition for a lunar mine has only just begun.

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Asteroid Mining

Richard E. Gertsch

The earliest studies of asteroid mining (e.g., Johnson and Holbrow 1977) proposed retrieving a main belt asteroid. Because of the very long travel times to the main asteroid belt, attention has shifted (Billingham, Gilbreath, and O'Leary 1979, O'Leary 1983) to the asteroids whose orbits bring them fairly close to the Earth. In these schemes, the asteroid would be bagged and then processed during the return trip, with the asteroid itself providing the reaction mass to propel the mission homeward. A mission to one of these near-Earth asteroids would be shorter, involve less weight, and require a somewhat lower change in velocity (ΔV). Since these asteroids apparently contain a wide range of potentially useful materials, our study group considered only them.

Asteroid Materials and Properties

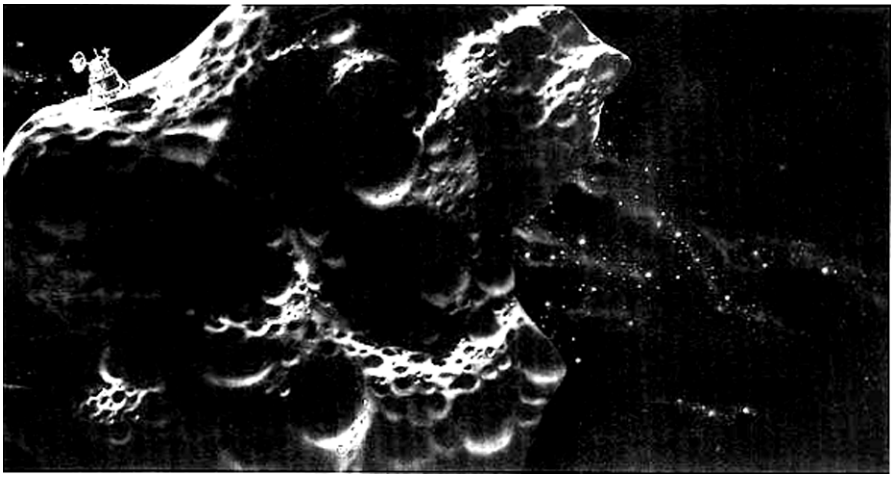
The forces driving the consideration of asteroid mining are their varied materials and favorable retrieval ΔV (see John S. Lewis's paper in this volume). Combining information from spectral studies of asteroids and laboratory analyses of meteorites, investigators have postulated near-Earth bodies rich in volatiles (water, halogens, and organics) and metals (structural, precious, and strategic). While no asteroid prospect has yet been identified, the possibility of obtaining such materials for cislunar operations from a source requiring low ΔV is exciting and should be pursued.

Furthermore, samples in the form of carbonaceous chondrites and similar classes of meteorites indicate that their parent asteroids may have favorable mechanical properties. Some of these materials break up easily at pressures as low as a few bars (10^5 N/m^2) (see table 17 in John Lewis's paper). This breakup pressure is much less than that for most terrestrial materials. For example, some material can be crushed by hand. Although other asteroids may be fundamentally tougher, impacts may have broken up their surfaces into regolith (soil). Thus our study group came to believe that material from a near-Earth asteroid should be easily excavated and rather easily crushed by mechanical comminution equipment already developed for terrestrial applications.

Asteroid Mining

Asteroids have resource potential, notably the potential for providing water, which can be decomposed into hydrogen and oxygen for propellant use. Asteroids may have rough cratered surfaces, as illustrated in this painting. If they are water-rich, they are likely to be similar to carbonaceous chondritic meteorites, which are very black, with extremely low albedos. Such asteroids may be rather soft and friable and thus easily mined.

Artist: Dennis Davidson



Asteroid Mission Selection

While the latest studies of retrieval and processing methods indicate that the project is feasible, the selection and the execution of an asteroid return mission are still fraught with problems. These problems stem from two basic causes: no candidate asteroid has been identified and the long trip time imposes severe limits on the mission. The results seem attainable but only with much more work.

Identifying an Asteroid Prospect

From the perspective of the terrestrial mining industry, lack of a specific asteroid candidate or prospect means that no project exists. Mining projects are so sensitive to actual site characteristics that an asteroid mining mission cannot be justified on circumstantial evidence. This is particularly true of an unmanned mission, where everything must work properly the first time and without human intervention.

Confidence that a feasible asteroid prospect exists in the near-Earth environment is based on statistical analysis. Given the known distribution of near-Earth asteroids and studies of their compositions, it seems probable that a candidate can be located, if enough resources are applied to the search effort (see Michael J. Gaffey's paper in this volume). Physical properties of prospective candidates—mineral grades, mineral variability, specific mechanical characteristics of the asteroidal material, and orbital characteristics—must be determined before significant development of an asteroid mission proceeds.

Nevertheless, a basic understanding of what an asteroid mission might entail is readily at hand. Using the possible orbits, mineral compositions, and mechanical properties of the near-Earth asteroids, one can construct a range of potential missions. The feasibility of such a mission can be established and comparison can be made to a lunar mission, such as the LOX-to-LEO project. Sensitivity analysis of asteroid mission profiles and comparisons to lunar projects can begin almost immediately. Criteria can be developed that will guide selection of candidate asteroid bodies. The expected range of flight characteristics, combinations of ore grades, ore types, mechanical properties, flight durations, and transportation costs can be determined and the range compared to that of a lunar project.

Long Mission Duration

Long travel times to near-Earth asteroids pose significant economic and operational problems. Physical sampling of the candidate body would take as long as the mining mission, so the flow of risk-reducing information is slow. The sampling mission would take a year or more, there may be a long wait for the next mission window, and then the mining mission would take another year or more. Thus, the lead time could be very long. When the mining mission finally flies, an expensive mining plant would have been in orbit a year or more before use. This unproductive time significantly raises the mission's cost. The round-trip time of 2 years or more lowers the rate of return on investment in plant and equipment.

Mission feasibility depends on the right choice of three basic types of missions: a long-duration manned mission, an automatic or teleoperated mission, or a mission in which the manned portion accepts high ΔV and the equipment arrives by slow Hohmann transfer orbit. Determining the proper choice will require extensive research and development, which, of course, increases mission cost. Each type has its advantages and disadvantages, both during the mission and in later technology transfer. The basic tradeoff question—manned or automatic/teleoperated—has yet to be answered.

Manned Versus Automated Missions

Manned Missions

While the problems and expense of a manned mission are obvious—long-term exposure to zero gravity, exposure to dangerous solar radiation, designing controlled ecological life support systems, and man-rating a deep space vehicle (just for starters)—our study group, with its terrestrial mining perspective, suspects that an asteroid mining mission will require human miners. The reason is our skepticism about the ability to economically automate such a mission. Not only has progress in terrestrial mine automation been slow, but also the prospect of applying such technology to an environment with so many unknowns is daunting.

Automated Missions

The benefits of automation are derived from economic considerations and not simply from eliminating people from the production loop. If automation decreases production costs, it should be used. This principle is important even in highly automated industries such as automobile manufacturing. Tasks that are

repetitive, and boring yet require precision are the best candidates for automation. In this realm, the experience of General Motors illuminates the point. GM's new, largely automated assembly plant has yet to reach production goals and has a myriad of problems. Increasing the production rate and maintaining the required quality while lowering or maintaining production costs justifies the increased capital cost of automation.

Some mines, particularly longwall coal mines, have successfully achieved partial automation of a relatively repetitive mining system. It was accomplished in small steps: One easily defined machine operation or task was automated while the rest of the operations remained manual. After debugging and redesign, the automated operation achieved the required degree of reliability. Then, another candidate for automation was selected and the process was repeated. Over several years, a reliable and integrated but not fully automated system may thus be painstakingly built. In general, terrestrial mine automation has been confined to remote sensing of mine parameters, such as ventilation and equipment status, and production monitoring.

Complete mine automation has been shown to have too great a capital cost to be effectively amortized over the production life of a mine. Furthermore, mining operations have a much greater number of degrees of freedom than does automobile manufacturing. Besides increasing capital (and R&D) costs, operations that are not exactly repetitive have more automation problems than do repetitive operations. Thus, mining costs are not lowered by automation as much as product manufacturing costs are. The fact that the harsh mining environment is much harder on equipment than is a closed plant environment only aggravates the problem.

This experience does not close the door on automatic/teleoperated asteroid missions. It does indicate caution when contemplating these missions. The automatic/teleoperated asteroid mining equipment must work perfectly. Even small equipment failures cause the mission to fail. An expensive R&D effort is needed to ensure such perfection. As with the lunar case, the lessons learned in flying an automatic/teleoperated asteroid mission may find extensive terrestrial application, helping to amortize the large R&D costs.

A Manned Alternative

One possible compromise in the manned/automated tradeoff is to send the equipment on a low ΔV flight and launch the human operators separately on a much shorter, high ΔV flight. The astronauts would mine the body, start the materials on a slow trip back to cislunar space, and themselves make a fast trip back. It should be noted that any manned mission would have the possibility of refining some or all of the fuel required for the return trip.

Teleoperated Missions

Teleoperation resolves some of the difficulties of automated operation. A greater range of the unforeseen problems the system will encounter become solvable. However, actions are carried out by the same actuation devices in both automation and teleoperation. This fact imposes limitations in mining operation control. The Viking lander case is illuminating. The Viking mission, which cost about $1 billion (in 1970 dollars, about $3 billion now), included an extendable scoop experiment that was teleoperated. Although the scoop was relatively simple in design and operation, with few degrees of freedom, first attempts to actuate it failed. A good deal of evaluation and effort ensued before the scoop was successfully operated.

Teleoperation from Earth would be somewhat hampered by a control delay due to the long distances and the speed of signal propagation. However, it seems likely that the effect could be overcome.

Mining in Zero Gravity

Although it might seem easier to move materials in zero gravity than on Earth, inertia, not overcoming gravity, is the major effect to consider. Little experience has been gained in weightlessness. One sample problem is that of holding fracturing and excavation tools to the face of an asteroid. On Earth, equipment hold-down is accomplished solely by gravity. Another sample problem is containing the excavated material, either large or small fragments. Rock fracturing places an initial velocity on the broken material. On Earth, gravity quickly collects the broken rock. In weightlessness, the broken rock will behave like out-of-control billiard balls, a potentially destructive game. Furthermore, the fines that are always generated by rock fracturing may obscure vision and clog equipment. Our study group did not have time to consider the full significance of working complex equipment in zero *g,* but we note that this problem needs in-depth study.

A Conceptual Asteroid Mining Method

The study group did not have the time or the resources to fully design a baseline asteroid mining method. This incomplete concept of an asteroid mining method is intended to illustrate how some of the problems could be overcome. As with the lunar proposal, the concept should be used to promote discussion of asteroid mining problems, but not to promote the method itself. Assuming that the ΔV for the available asteroid is small and that only a modest amount of material is needed, I propose the following method to accomplish a first mission.

After arriving at the asteroid, the operators place one or more cables around the body. The asteroid proposed to the group for study was no more than a few hundred meters in diameter. Placing a cable around the body appeared to us much easier than anchoring the end of a shorter cable. Anchoring in rock can be a difficult process. If augering is used in weightlessness, a method must be devised to hold the augering tool down while it is working. The most desirable asteroids have very low strengths, good for mining but poor for anchoring. Quite long cables are possible, on the order of 1000 meters. The cable is easily placed and provides easy movement of the mining tool. One disadvantage of a long cable is the mass; for example, a cable 1 inch in diameter weighs 1.6 pounds per foot on Earth (has a mass of 2.4 kg/m).

The cable holds a cutter head or other rock-fracturing tool in place and provides sufficient working force for it. The cutter head is designed to excavate in addition to fracturing the soft rock. A conical Kevlar collection bag is placed over the area to be mined and is held in place by the same cable (fig. 24). The flexible bag holds its shape because of the rotation of the asteroid. The spin also aids in collecting the fragmented asteroid material.

The cutter head travels back and forth along its restraining cable, cutting material until the collection bag is filled (fig. 25). The cutter is similar to the coal shear currently used in longwall operations but is designed to overcome the asteroid's low gravity and fling material past synchronous orbit so that centripetal force effects collection. Dust production around the cutter head remains a problem. Dusty environments obscure vision and thus increase problems in controlling teleoperated systems or in monitoring automated systems.

However, direct vision may not be so important on a body that proves to be homogeneous in structure and composition.

After the required amount of material is collected in the bag, it is “lowered” away from the body, allowing the bag and material to steal angular momentum from the asteroid. For low ΔV return flights, there may be sufficient energy available to slingshot the load back to Earth. Deceleration at Earth could be accomplished by aerobraking. The collection bag might be designed to act as an aerobrake shield in addition to being reusable. The bag could also serve as a retort for carbonyl or other types of processing during return.

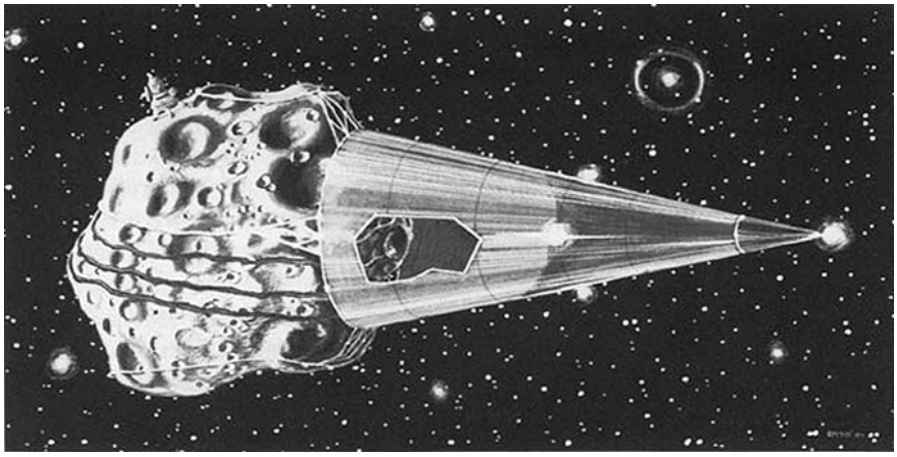


Figure 24

Concept for an Asteroid Miner

The shear breaks material and throws it away from the asteroid into the collection bag. The bag is moved when the shear moves to a new mining area. The collection bag can be used to transport the material to the Earth. The bag could also be used as an aerobrake shield or a processing container.

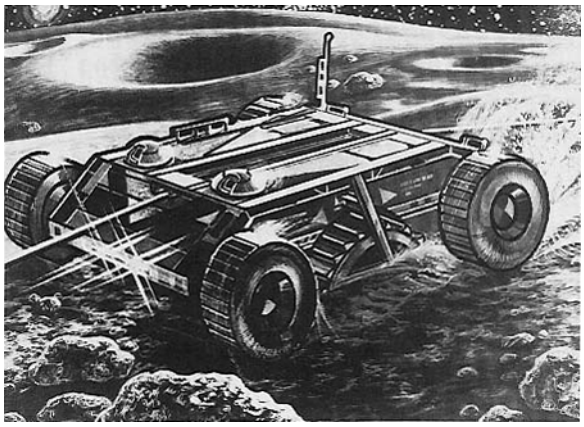


Figure 25

Detail of the Shear

The shear is derived from coal-cutting technology. It performs a dual role: it cuts the asteroid material and throws the material into the collection bag. In this illustration, the wheels are too small; larger, high-flotation wheels will help negotiate rough terrain. There should also be chutes to direct material past synchronous orbit and into the bag. And the shears conflict with the wheel path; they should be either inside or outside the wheels.

An alternative, but basically similar, method still uses the bag and cable. However, a large block of asteroid material is collected, not by mechanical excavation but by blasting material into the bag. Instead of a shear, which could have trouble negotiating the asteroid surface, an explosive is used. The cable holds in place a drilling machine, which drills a series of blast holes. The drill holes and charges are carefully designed to excavate a large section of the asteroid. The explosive charges breakout the desired amount of material, and the force of the explosion moves the material into the collection bag. Pattern drilling designed to create shaped explosions has achieved some success on the Earth and is finding more applications. The explosive method appears simpler in equipment and operation than the shear, but the blasting must have a very high degree of control. Uncontrolled fragmentation of the cabled body would be a disaster. I have not considered a suitable blasting agent. The reader can visualize this alternative method by imagining a drill rig instead of the shear in figures 24 and 25.

While the sizing of the return loads requires further study, the same basic mining scheme should be able to handle a range of sizes. It is not completely clear whether one large load or several smaller loads would be better, although several smaller loads might be more manageable, while allowing more flexible return flight plans.

Conclusions

Because it appears to be easier and cheaper to accomplish, the lunar mine is probably a better first project to exploit nonterrestrial materials than is the asteroid mine.

While not causing any increased transportation costs, the long, slow travel to and from the near-Earth asteroids would decrease the rate of return on capital investment.

As in the lunar LOX-to-LEO project, the asteroid mining system must be kept as simple as possible. Simplicity eases problems and lowers the costs of development, equipment, and operations.

A manned mission would make the mining operation much simpler, but it would greatly increase the complexity and cost of the deep space transport vehicle.

Teleoperation seems a good compromise between automation and manned missions, but the choice requires much more study.

Even if specific space program goals or higher costs eventually preclude an asteroid mission, the rich and varied asteroid materials require that the option of mining

an asteroid be studied. Given a goal of providing a range of materials for use in cislunar space, lunar projects must be demonstrated to be superior before asteroid missions are abandoned.

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Mining Nonterrestrial Resources: Information Needs and Research Topics

Jaak J. K. Daemen*

The following research topics have been generated by my reading of the draft reports "Exploring, Evaluating, and Mining Nonterrestrial Resources," "To Build a Mine," "Asteroid Mining," and especially "A Baseline Lunar Mine." For a mining engineer like myself who is totally unfamiliar with nonterrestrial operations, this is a fascinating and stimulating opportunity to take an entirely different viewpoint on operations that usually seem humdrum and routine. Being forced to reevaluate the basics might be as productive for our mining on Earth as it is necessary for nonterrestrial operations.

This paper presents an outline of topics that we need to understand better in order to apply mining technology to a nonterrestrial environment. The proposed list is not intended to be complete. It aims to identify representative topics that suggest productive research. Such research will reduce the uncertainties associated with extrapolating from conventional earthbound practice to nonterrestrial applications. No attempt is made to rank the topics. One objective is to propose projects that should put future discussions of nonterrestrial mining on a firmer, less speculative basis.

I offer no details about the actual pursuit of the various research topics. Each one could be approached by a fairly standard method; e.g., starting with a comprehensive literature survey, identifying relevant technical specialties and authorities in the field, detailing research needs, initiating specific projects, reviewing progress, making theoretical analyses, eventually culminating in system designs and experimental trials. It would seem highly desirable to have close interaction between mining experts and space experts, so that no easily avoidable oversights are made in these studies.

I have not used a formal analysis of information needs to select research topics; I make my suggestions purely on the basis of professional judgment. An explicit investigation of information needs and of their relative significance within an overall nonterrestrial mining program would be a desirable step in initiating research. An alternative method of initiating and scoping research, which might take less time, is to present issues to a group that includes both mine equipment designers and operators and space equipment designers and operators.

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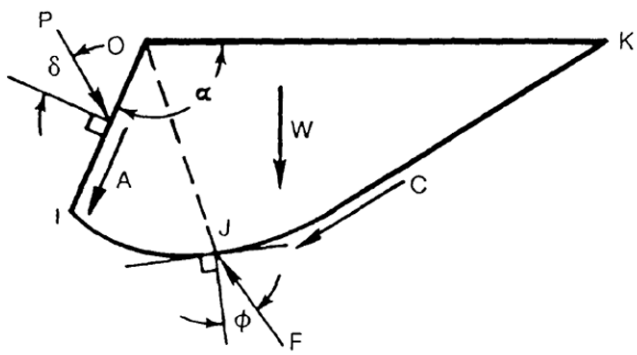
The topics identified are inconsistent in terms of their depth and scope. Some have been included to illustrate broad areas that need review; others, to illustrate much more narrowly focused items. Although this inconsistent scale results in some overlap among topics, I think it is appropriate because it points out that there are uncertainties in need of resolution at many different levels of technical detail.

Williamson (1985) has suggested that lunar-based mining may become operational by about 2020, and Glaser (1983) has suggested that nonterrestrial resources may be used even earlier. Profound changes may be required in equipment and in modes of operation to fulfill these suggestions. Now is the time to at least start evaluating whether or not such changes will be needed.

This list of proposed research topics is assembled and discussed from a mining engineering point of view. It is aimed at identifying and clarifying some typical information needs and uncertainties that will require resolution in order to implement mining practices on the Moon or in other space environments. We must recognize that much of the proposed research could make a substantial contribution to future development of mining on Earth. This point deserves emphasis for two reasons: First, technology transfer to terrestrial applications is an explicit NASA mission (stated, for instance, by Firschein et al. 1986, appendix), mandated by Congress. And, second, if the mining industry clearly recognizes the potential benefits for its own future, it is far more likely to cooperate in productive research. The potential for such mutual benefits needs to be expressed directly and specifically, because such potential may not be self-evident to the industry. In fact, a more likely reaction is serious doubt as to whether such “exotic and far out” investigations have any bearing at all on conventional commercial practice. At some point in the future, it may be well to revisit the topic of nonterrestrial mining from a terrestrial technology transfer perspective, focusing on the benefits such a program might deliver to the state of the art of mining technology.

1. The influence of gravity on mechanical excavation technology and on the performance of associated equipment



Force System Used for Plastic Analysis of Soil Gathering by Bulldozer

The frictional (P) *and adhesive* (A) *resisting forces, as well as the weight* (W), *depend on gravity. It is probable that the resisting forces are also influenced by operation in a vacuum.*

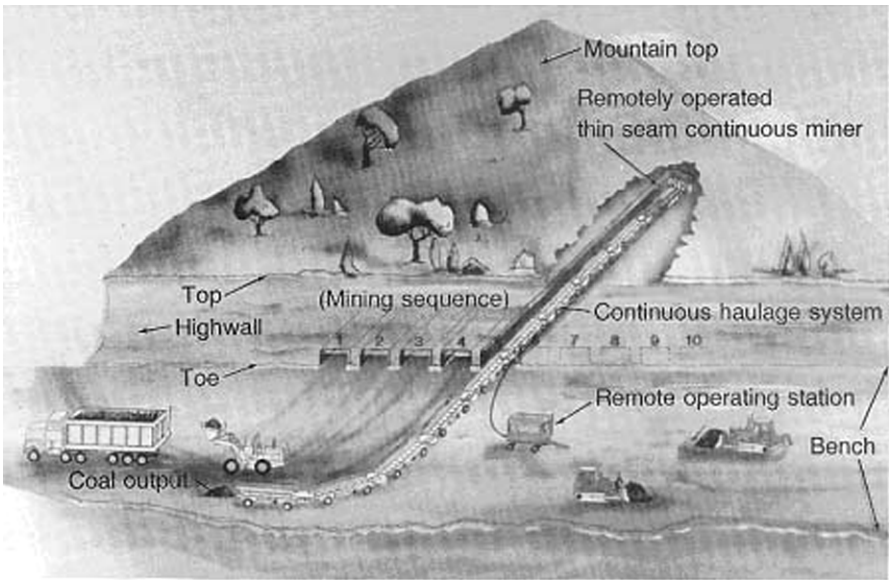
From Hettiaratchi and Reece 1974, as modified by Karafiath and Nowatzki 1978, p. 247.

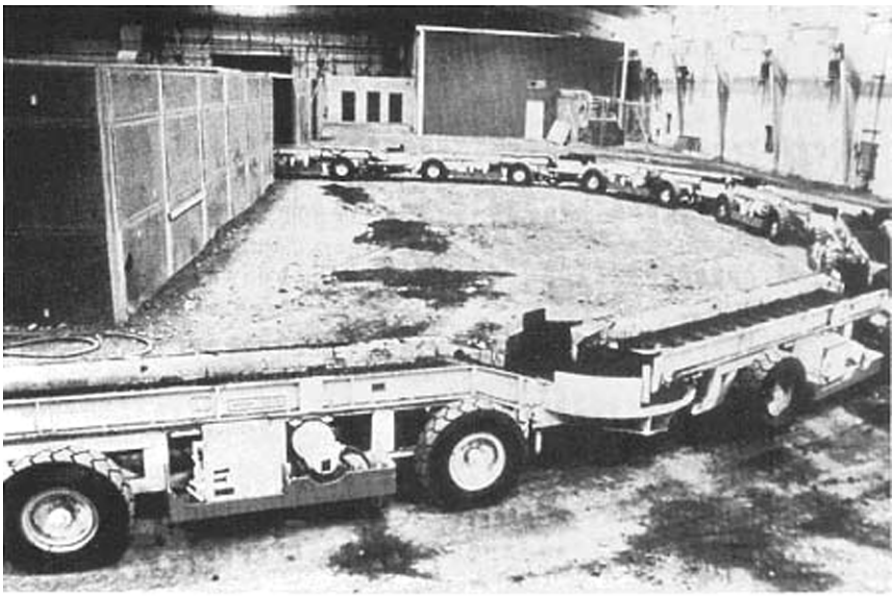
Key:

A	=	the adhesive component of the resisting force; it acts along the surface of the plane OI where the soil ruptures
C	=	cohesive strength of the soil
P	=	the frictional component of the resisting force; it acts at angle δ
δ	=	soil interface friction angle
F	=	the resultant of the normal and frictional forces
ϕ	=	angle of internal friction
W	=	weight of the soil being dozed
OIJK	=	body of soil being pushed up and out

Gravity force components enter into the mechanics of most excavation and loading methods. The significance of gravity is likely to differ with the excavation method, particularly with the mode of operation and with the configuration of equipment. Because differences in gravity will be significant between nonterrestrial and conventional earthbound excavation and loading, it would be desirable to evaluate the sensitivity of excavation and loading technologies to gravity. This comparative assessment should include such major performance aspects as power requirements, capacity, productivity, and breakout power. Classifying these aspects with respect to their sensitivity to gravity will provide insight into the relative performance of various systems under significantly different gravitational conditions. Such a classification will help identify preferred excavation methodologies for nonterrestrial applications. This assessment of the impact of gravity on excavation performance will also assist in identifying needed equipment design changes and in establishing correction factors for estimating production figures in a low-gravity environment.

2. The status of remotely controlled and automated mining





a. Computer-Based Remotely Controlled Highwall Mining System (HMS)

b. HMS Continuous Haulage Subsystem During Surface Evaluation

From Kwitowski et al. 1988.

The degree to which nonterrestrial mining operations will be run automatically or under remote control (i.e., the extent to which people will need to be present at or near the mining operation) will have major economic and logistical impact on the type of operation that can be implemented. Remote control over very short distances (that is, with an operator not more than tens of meters from the equipment) has become readily available for mine face operations (continuous mining of coal; longwall mining; drilling; train, truck, and loader movements; etc.). There has been some success in running underground operations from a great distance [see, for example, the article in *Coal Age,* vol. 92 (1987), no. 8, p. 61], admittedly on an experimental basis.

Even a cursory review of recent mining literature reveals the industry's considerable interest in the subjects of remotely controlled and automated mining (e.g., Atkinson, Waller, and Denby 1987; Hopkins 1987; Scales 1987; Stricklin 1987). It appears virtually certain that considerable progress will be made in these areas in the near future. However, we must acknowledge that highly optimistic announcements about forthcoming mine automation have been made repeatedly, and for at least two decades.

Given the potential importance of automated and remotely controlled mining for nonterrestrial operations, I think it appropriate to recommend an intensive effort to evaluate the current state of the art of such technologies, with emphasis on operations in hostile environments. Mining experience has shown that the environment poses severe problems, especially with regard to transducer performance (see, for example, Atkinson, Waller, and Denby 1987 and Stricklin 1987). I propose that an interactive investigation of such problems with authorities in other fields would be beneficial in identifying possible solutions. Specifically relevant may be remotely controlled equipment for handling nuclear materials, especially for reactor cleanup operations (Kring, Herndon, and Meacham 1987), as well as sensors, transducers, and transmitters developed for the space program (Stuart 1983; Wagner-Bartak, Matthews, and Hill 1983; Firschein et al. 1986). I think it likely that an integration of already existing knowledge may result in readily available improvements to the control systems typically used in mining.

Similarly, it may well be that cost considerations have so severely affected mining systems design that their reliability is unacceptable for space operations. Economic

tradeoffs in nonterrestrial mining are almost certain to be different from those in earthbound mining. Hence, it may well be that the reservations and concerns about control engineering which have been generated by mining experience may not be appropriate to space designs. An obvious first step in resolving these uncertainties is simply to assemble a group of experts with relevant backgrounds and have them discuss the problems.

3. Environmental effects on lunar surface mining

Environmental factors such as temperature, air pressure, dust, and visibility have a significant impact on mining operations and equipment. Of most immediate concern is the difference in temperature and atmosphere for nonterrestrial mining as compared to conventional earthbound mining. This difference has significant implications. The cold of the 2-week night on the atmosphereless Moon virtually eliminates the possibility of nighttime operations with conventional equipment because of the problem of material brittleness. And the heat of the 2-week lunar day, unshielded by an atmosphere, will impose demanding cooling requirements. A team of space equipment designers and mine equipment designers should be able to identify mechanical and electrical problems and potential solutions, as well as the redesign needs implied by these solutions. Daytime lunar surface operations, particularly rock loading, could be severely affected by perception problems induced by the bright sunlight and constantly changing shadows (discussed by Firschein et al. 1986, p. 112).

4. The applicability of conventional mining methods and equipment to lunar mining

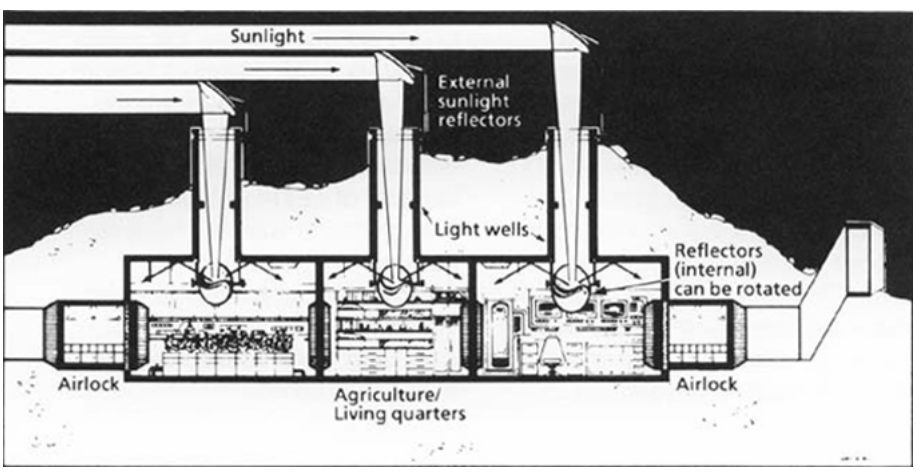
When one considers the applicability of Earth technology to lunar mining, one can focus rapidly on a likely lunar project and retrofit an available mining method to meet the characteristics of this particular project. However, I propose that program benefits might derive from a comprehensive analysis, at a preliminary scoping level, of the applicability of conventional earthbound mining methods and technology to lunar operations. Such an analysis could proceed from a comprehensive matrix, listing mining methods along one axis and lunar features (such as logistics, gravity, vacuum, temperature, perception problems) likely to affect mining along the other axis.

To each mining method, one can assign weights for the various differences between terrestrial and lunar operations. Initially the weighting could be done on the basis of expert judgment. But as soon as possible the weighting

should be based on a numerical analysis. For simple mining methods, the weights could be based on the mechanics of the system. For complex methods, the weighting may require a comprehensive numerical simulation of an entire sequence of operations. This technique would allow a formal assignment of level of difficulty likely to be encountered in applying the terrestrial technology to the lunar situation.

An effort of this type should be iterative. The initial list may include technology that is entirely inappropriate or exceedingly difficult to modify or implement. In parallel with such iterations, one might also expect a progressive refinement in the information needs about the most likely operational conditions.

5. Underground construction methods for lunar application



a. Underground Mining

Although the baseline lunar mine was conceived to be a strip-mining operation, there may be locations where the regolith is so thick that it could be mined by some undercutting scheme. Excavations could be driven below the material to be mined, and the material could be drawn into the excavations for milling. The light wells in this illustration could correspond to draw points for bringing material directly underground, and the agriculture/living quarters could correspond to the scene of all subsequent mining operations, which would thus be shielded from the hazards of the lunar surface environment.

As pointed out under topic 3, the environment will impose severe limitations on surface operations on the Moon. It therefore appears fully warranted to investigate the feasibility of moving mining operations underground. Lunar scientists can probably provide information on the subsurface lunar temperatures, and this information may encourage the investigation of going underground.

Operating underground on the Moon raises a number of intriguing questions. Conventional support systems such as concrete, steel, and shotcrete are likely to have an

b. Tunneling for Lunar Habitats

Perhaps the tunneling techniques developed for mining could be used to construct lunar habitats. The two astronauts in this illustration provided by Encyclopaedia Britannica *seem to be having no difficulty carrying a capacious pressurizable module for a tunnel. In gravity only 1/6 that of the Earth, the required weight-carrying strength of equipment as well as people could be reduced to 1/6 that required on Earth.*

NASA photo: S71-4049V

even less favorable weight-to-performance ratio than on Earth. Hence, the economics of their application need to be investigated in detail. As I briefly outline under topic 7, the preclusion of conventional support systems would not necessarily exclude underground construction in weak or disintegrated ground, but it would put a premium on developing reinforcement methods, integrated with the construction cycle, which minimize weight requirements. Given that the most frequently encountered and most severe problems for earthbound underground construction and mining arise from unexpected conditions (that is, sudden changes in ground quality), it is virtually certain that underground lunar construction should be preceded by markedly better site investigation and characterization than is the norm on Earth.

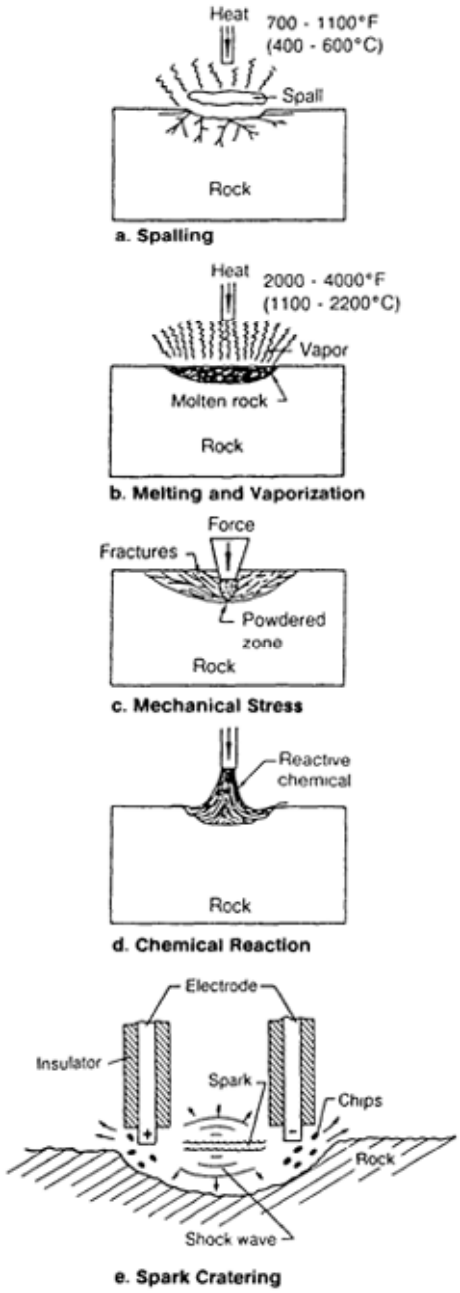
Underground construction on the Moon should have some significant advantages when compared to earthbound practice. Most underground construction problems are associated with water, because of excessive pressure, excessive flow, or both. Indeed, a standard if somewhat overstated saying among engineers holds that “a dry tunnel is an easy tunnel.” The absence of water will facilitate underground construction on the Moon. Moreover, the certainty of not

encountering water will eliminate the need to plan for the contingency.

The increased friction (more intimate physico-chemical bonding) in vacuum (Karafiath and Nowatzki 1978, p. 130) should assist in stabilizing underground excavations. It may also make excavation somewhat more difficult, but excavation per se usually is a relatively minor cost factor in underground mining. The low gravity will increase the weight-carrying capacity of equipment and reduce the energy requirements of muck haulage and particularly hoisting. Light levels, and hence visibility, may be easier to control underground than on the lunar surface.

Underground construction on the Moon will differ from underground construction on Earth in a number of important aspects. Its potential advantages over surface construction appear to warrant a comprehensive assessment of its merits. Such an assessment should address all aspects that affect life-cycle costing.

6. Rock drilling on the Moon



Methods for Disintegrating Rock

a. ***Spalling:*** *Inducing high thermal stresses by rapid application of intense heat.*

b. ***Melting:*** *Liquefying rock by raising its temperature.*

c. ***Mechanical Stress:*** *Inducing stresses exceeding strength by applying mechanical forces to the rock.*

d. ***Chemical Reaction:*** *Dissolving rock bonds.*

e. ***Spark Cratering:*** *In a variant of* c, *discharging sparks between electrodes to generate pressure pulses which in turn chip the rock.*

From Maurer 1980, pp. 1 and 509.

Different types of rock drilling are likely to be required on the Moon. Certainly core drilling will be desirable, if not essential, for collecting samples for rock characterization tests. But alternative, much less expensive hole-drilling techniques (in which the material from the hole is not kept intact) may be considered for such purposes as anchoring structures, explosive fragmentation, or even sample collection.

All conventional rock drilling methods, including diamond coring, rotary drilling of soft rocks, and percussion drilling of hard rocks will be affected by differences between lunar and terrestrial operating conditions. Most obvious are differences in gravitational pull, atmospheric pressure, and thermal conditions,

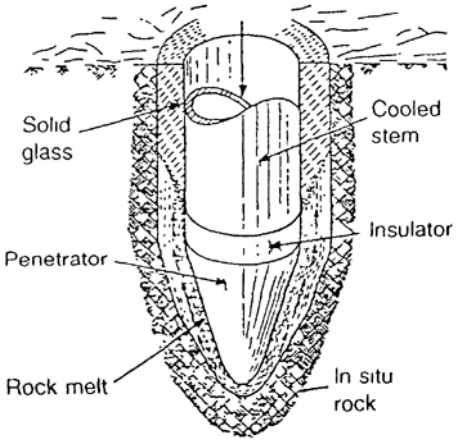
The very low gravitational forces on the Moon are likely to require a thrust system designed to assure adequate drilling progress. This could be a passive (weighting) system or an active (jacking) system. Regardless of which approach is taken, it seems very likely that drilling equipment will require significant modifications in order to provide the necessary thrust.

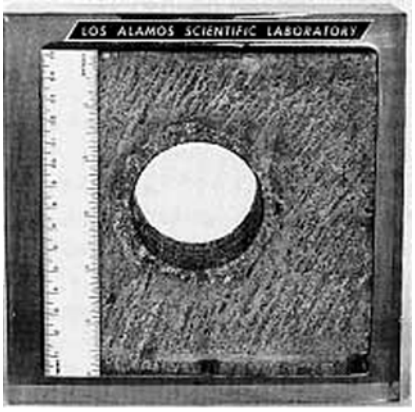
The lack of atmosphere on the Moon will create complications in providing and maintaining drilling fluids. In conventional practice such fluids are needed, in considerable quantities, in order to remove cuttings from the hole and to cool the drill bit. And on the dry and highly fractured surface of the Moon, these fluids would be easily lost. Cooling of the bit, as well as of the drilling motor, may be further complicated by the thermal environment on the Moon. This will certainly be a complication during daytime operations on the surface.

In sum, fundamental aspects of rock drilling are affected significantly. This impact will be reflected in needed changes to drilling equipment and operations. A first step in the investigation will be to determine as narrowly as possible the expected conditions under which drilling will have to be performed. This determination will in turn allow an identification of the basic parameters to be used in evaluating changes in fundamental drilling mechanics and hydraulics. Finally, such changes will lead to equipment modifications, if not to totally new drilling designs.

While this discussion has centered nearly exclusively on conventional drilling technology, I should point out that extensive investigations have been made of numerous, radically different drilling technologies (e.g., Maurer 1980). A variety of reasons, including high conversion costs, institutional inertia, and the fact that most novel drilling methods require large amounts of energy, have so far prevented the widespread implementation of such alternative drilling methods. The novel drilling and rock excavation method that has found most widespread application—water jet excavation—is inappropriate for space applications. For reasons similar to those discussed under the next topic (rock melting), tradeoffs will need to be made between energy use (high for novel technology, low for conventional drilling) and delivery weight (low for novel technology, high for conventional drilling).

7. Lunar construction by rock melting





Consolidating Penetrator

The schematic diagram (Sims 1973, p. 7) shows how this novel drill bit penetrates loose soil or porous rock by melting it. Then the cooled drill stem consolidates the melted rock into a dense glass lining. The photograph (courtesy of John C. Rowley, Los Alamos National Laboratory) shows a hole melted through volcanic tuff by means of a consolidating penetrator. Note the dense (and therefore strong) hole liner.

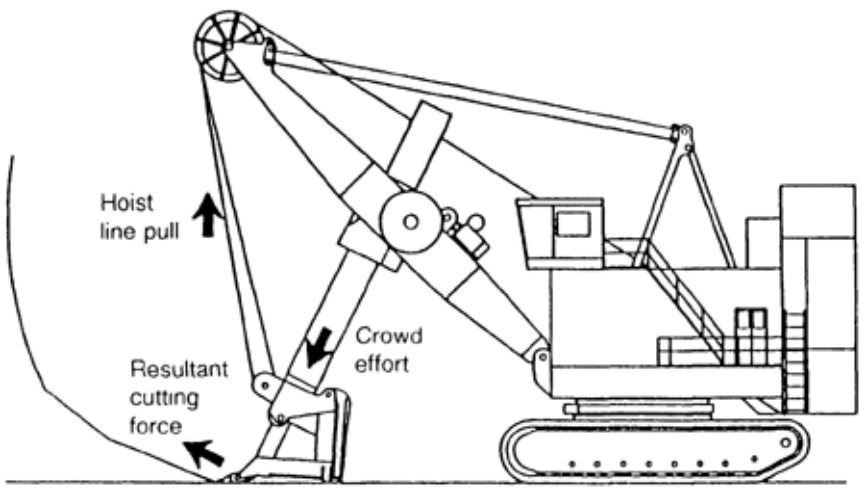
Many aspects of mining may have to be altered profoundly for operations in an environment with low gravity, extreme temperatures, and high vacuum, at locations where direct human access and support will be exceedingly expensive. Because the differences between conventional and space operations may be drastic, it may be appropriate for us to evaluate radically different approaches.

One option that deserves attention is a rock melting system. This rock excavation method has been extensively investigated by Los Alamos National Laboratory (Neudecker, Giger, and Armstrong 1973; Sims 1973; Rowley 1974; Hanold 1977). Rock excavation by melting has been developed to an operational level for small-scale applications (drilling holes) and is proposed for large-scale applications (excavating tunnels).

For space applications, the system has the attractive feature of being self-contained; that is, of requiring minimal deliveries. It can, for example, melt its own liner in situ (in weak ground), thus obviating the need for additional support installation. However, it may require excessively high energy. It is interesting to note that the developers of rock melting for full-size tunneling envisioned the use of nuclear power, and it has been argued that nuclear power is essential for large-scale lunar development (Ehricke 1983).

The rock melting approach option is included here to stress the desirability of taking a broad view to identify appropriate technologies; that is, going well outside the bounds of conventional solutions. Whether rock melting is an appropriate alternative to conventional mining remains to be seen. A scoping meeting involving Los Alamos personnel associated with rock melting would seem a desirable first step to determining whether or not further evaluation is warranted.

8. The implications of vehicle-traction on the Moon for mining operations



Simplified Force Diagram for a Conventional Mine Shovel

The cutting force of a shovel is a function of hoist line pull crowd effort, and front-end geometry. A large machine weight is needed to provide horizontal resistance to slippage during digging.

Courtesy of J. D. Humphrey, Dresser Industries

Traction is an important operational aspect of most vehicles. It is particularly important for vehicles that need to exert large horizontal forces; e.g., for excavating, loading, and hauling. Many types of mining equipment are very dependent on the development of adequate traction. This equipment includes excavation equipment such as bulldozer-mounted rippers and scrapers, front-end loaders, shovels, and drills, especially those for drilling angled or horizontal holes.

Comprehensive studies have been performed of vehicle traction on the Moon (among them, Karafiath 1970a,b; Nowatzki 1972). Even though these have addressed the operations of primarily small, lightweight roving vehicles, they provide fundamental insight into the traction of larger, heavier lunar mining vehicles. Moreover, experience with the lunar Rovers has provided an operational record by which to validate the traction models and predictions made for them.

Traction deserves attention because it is a major force needed for many mining operations. Because it is a function of gravity and of friction, the latter affected by vacuum, it will be affected by the space environment. Considerable experience is available to guide further research into this aspect of lunar mining.

9. Moon excavation technologies

Muck Pile

This is an example of a good muck pile, well-fragmented and largely remaining in one heap. Loading would be much more time consuming if the rock were widely dispersed, as it might be by conventional blasting in a low-gravity environment, without air resistance. The loading machine must have sufficient traction (created by both friction and weight) to be able to push the loading bucket into the muck pile.

Lunar mining may involve the removal of various types of ground, ranging from massive solid rock to loose, granular soils. This possibility suggests the need to investigate a range of material-removal technologies. It may be desirable, at this early investigation stage, to distinguish between the fundamental mechanics underlying the technologies and the technologies themselves. Both will be affected by operations on the Moon, but in different ways.

a. Hard rock excavation mechanics

In earthbound mining, hard rock is removed primarily by explosive excavation. Lunar blast design is likely to require significant changes from conventional blasting. An obvious consideration will be the need to control the broken rock pile. It is usually assumed that gravity plays no role in actual rock breakage by conventional blasting, but it plays a significant role in displacement of the broken rock

(and thus dominates the shape of the muck pile). Low gravity could result in extremely wide scattering of rock fragments, even more so in the absence of air resistance, and hence lead to exceedingly inefficient loading operations. An interesting challenge may be posed by the need to adjust blasting patterns from the traditional ones to those designed to minimize scatter in a low-gravity and high-vacuum environment.

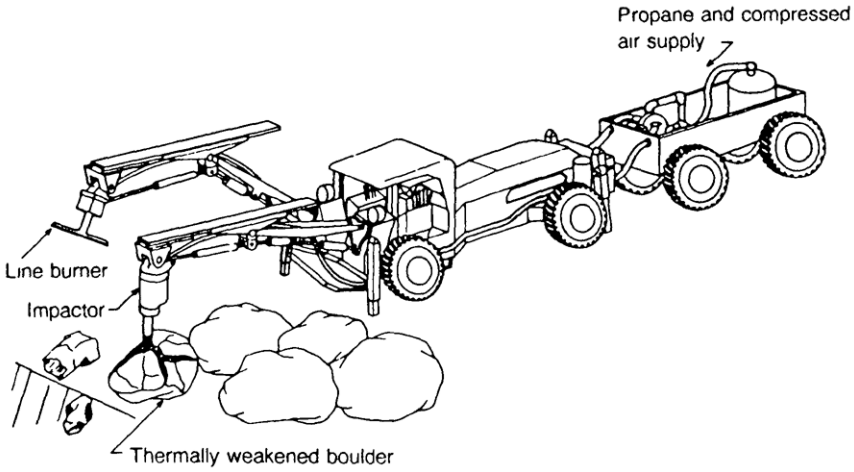
It is possible that vacuum might affect blasting performance, although it may not be a significant factor in low-permeability rock, at least at greater depths. The breakage induced by blasting is usually attributed in part to seismic effects and in part to gas pressure effects. Presumably gas pressure effects could attenuate much faster in a space environment than on Earth. This could affect fragmentation and almost certainly would affect heave and throw; i.e., rock movement.

Potential impacts of low gravity on mechanical excavation have been discussed under topic 1. Drastically different excavation technologies are summarized by Maurer(1980), and they deserve intense scrutiny for lunar applications.

b. Soft ground excavation mechanics

Mechanical excavation of loose, granular material on the lunar surface is likely to be facilitated by the lower gravity in terms of actually lifting the material, although this improvement may be partially offset by increased friction between particles. It is likely that the most significant detrimental effect will be on the forces that can be delivered by the equipment. Reduced equipment weight will reduce breakout forces and sliding stability. It is quite possible that even a simple force analysis of excavation systems will shed considerable light on lunar soil loading requirements and potential problems. Gertsch has suggested that we add mass to lunar equipment by building into it large volumes to be filled with lunar rocks. However, as he notes, the added mass would add to the problem of inertia in mobile equipment.

10. Potential asteroid fragmentation technology



Thermomechanical Boulder Breaker

A mobile thermomechanical boulder breaker could fragment rock by first weakening it by applying heat (in this concept by means of a burner) and then hitting it with a mechanical impactor.

From Thirumalai, Demou, and Fischer 1975, quoted by Maurer 1980, p. 653.

Technology for fragmenting rock particles has been researched and developed over many decades. Conventional fragmentation is primarily mechanical. Its effectiveness on a virtually gravity-free asteroid will depend in part on the degree to which the mechanical fragmentation system depends on gravity. We can conceptualize mechanical fragmentation systems that are independent of gravity; i.e., those that work by splitting or pinching. Also available are a variety of explosive, electrical, chemical, and thermal disintegration methods. These methods will impose different logistical requirements, depending on what supplies they need and on how operations are carried out. For example, the efficiency of several fragmentation methods would increase if the fragmentation took place in drill holes. But drilling holes in asteroids will pose unusual problems (see topic 6).

It may be desirable to distinguish between two classes of fragmentation problems, those where a single fragment (or a small number of fragments) is to be removed or reduced to certain dimensions, and those where a large number of particles are to be reduced in size. The latter class of applications is discussed under topic 15, crushing and grinding. The choice of technology most readily applicable to removal or controlled-size reduction of a single large block might well benefit from an evaluation of quarrying practice for building stone. Advanced rock disintegration techniques, some of which should have direct applicability to space operations, are summarized by Maurer (1980).

11. Automation, operator proficiency, and excavation efficiency

Eliminating the need for human operators would significantly enhance the economic attractiveness of nonterrestrial mining. Few attempts have been made at developing fully automated mining excavation cycles; i.e., operations without human intervention. The economic incentives for doing so on Earth are marginal, at best.

Fully automating the mechanical excavation and loading of broken rock is likely to result in drastic productivity losses. It is well established that the productivity of virtually all excavation and loading equipment is highly sensitive to the expertise of the operator. Human judgment and fast response to seemingly minor aspects of rock loading operations are significant production and safety factors. Of particular concern in this context is that misjudgment by an operator can result in serious, even disastrous, consequences, such as cables breaking and machines overturning. Control engineering will have to preclude such occurrences as well as assure a reasonable production level.

The importance of human judgment in excavation technologies suggests a number of avenues for research aimed at identifying candidates for automation and nonterrestrial application. Questions that can be raised include the following: Will the implementation of automatic operation be most difficult for equipment that is most sensitive to operator handling? Should automation be preferentially applied to excavation technologies that are robust or insensitive to operator errors? What tradeoffs are

acceptable between automatic control and productivity?

To allow automation, operations should be as simple as possible. This fact, explicitly recognized in the space program (e.g., Firschein et al. 1986, p. 103), unquestionably underlies the mining industry's reluctance even to attempt to automate most excavation methods. The few notable exceptions (longwall mining, tunnel boring) for which automation is being investigated are already fully mechanized (involve minimal human intervention during normal operations). These exceptions tend to be high-production systems. They are prone to frequent breakdown and require preventive maintenance. Maintenance is recognized as a major difficulty in implementing automation (e.g., Firschein et al. 1986, p. 355); it will require major developments in artificial intelligence software and robotics. The need for human reasoning capability is again apparent.

12. The influence of gravity on slusher mining

Gertsch identifies slusher mining as one of the more promising lunar mining methods. The performance of a slusher on the lunar surface (or in underground operations on the Moon) will be affected by the low gravity.

The lighter weight of the scraper (bucket) on the Moon may lower the loading efficiency of the slusher bucket, because the weight influences the vertical penetrating force into the material to be loaded. Conversely, the lighter weight lunar material may flow more easily up into the bucket. It is conceivable that artificial weighting down of the bucket, or a reconfiguration of the cable force system, might be required in order to assure adequate penetration into the lunar soil and to avoid riding of the (empty or partially filled) bucket over the material to be loaded. Conversely, friction, abrasive wear, and power requirements during both inhaul and outhaul may be significantly reduced by the low gravity.

The reduced effective weight of the bucket, which is likely to have a detrimental impact on the efficiency of the all-important bucket-loading phase, might also adversely affect the performance of the bucket as it is hauled in to the unloading point. Assuming a relatively rough and bumpy ride during inhaul, the bucket may not retain its full load. An analysis might suggest a reduction in hauling speed, but this might also affect production adversely. It is possible that bucket redesign and cable reconfiguration might compensate at least partially for the reduced effective bucket weight.

Given the interest by this group in the application of slusher mining to the lunar program, it may be appropriate to outline in some detail steps that could be taken to reduce the need for speculation about the performance of such systems on the Moon.

Obtaining a clear understanding of the mechanics of bucket loading would be a desirable step. This step could be initiated with a comprehensive literature survey. It is unlikely that much fundamental information is available about slusher bucket mechanics, but considerable analysis has been made of the mechanics of similar excavation elements, such as dragline buckets, bulldozer blades, front-end loader buckets, and scrapers. Integrating this knowledge in a framework emphasizing the mechanical differences between terrestrial operating conditions and lunar operating conditions would go a long way towards identifying potential problems. Such an integrating effort should be made by a group with a clear understanding of the fundamental mechanics of the machine (bucket) and material (broken rock). At a minimum, meetings should be organized with experienced bucket designers from various manufacturers. In order to obtain maximum contributions from such personnel, it may be preferable formally contract for their technical services. Equally important would be information exchanges with operators; e.g., by means of visits to mines.

On the basis of the initial analyses, it should be possible to make preliminary estimates of the influence of gravity on bucket loading performance. This information could in turn form the basis for designing experiments (for example, experiments using centrifuges) to verify the analyses. Similarly, it may be possible to instrument buckets and their cables and chains in order to obtain a better understanding of the distribution of forces during loading. An appropriate iterative sequence of bucket analyses, experiments, and design modifications should provide a considerably improved understanding of bucket mechanics, ultimately leading to adequate bucket designs for drastically different operating conditions.

While I have emphasized slusher bucket development, I should point out that any studies of this type, aimed at an improved understanding of the mechanics of loading broken rock, will be beneficial for eventual redesign of other systems that might be considered for nonterrestrial loading operations. These would include hydraulic excavators, electric shovels, front-end loaders, bulldozers, scrapers, draglines, and clamshells.

13. Wear-resistant materials for space mining applications

Equipment maintenance is one of the most expensive and time-consuming (in terms of production delay) aspects of mining operations. The most critical maintenance aspect of all excavation equipment is the wear rate of excavation elements (e.g., buckets, their teeth, drag cables). Similarly, components of equipment for haulage and for crushing and grinding, which are subject to repeated impact and abrasion, may require frequent resurfacing or replacement. Replacement schedules and parts requirements need to be estimated in order to develop realistic life-cycle cost estimates. If wear parts had to be provided from Earth and if conventional replacement schedules needed to be maintained, the transportation requirements of nonterrestrial mining would be considerable.

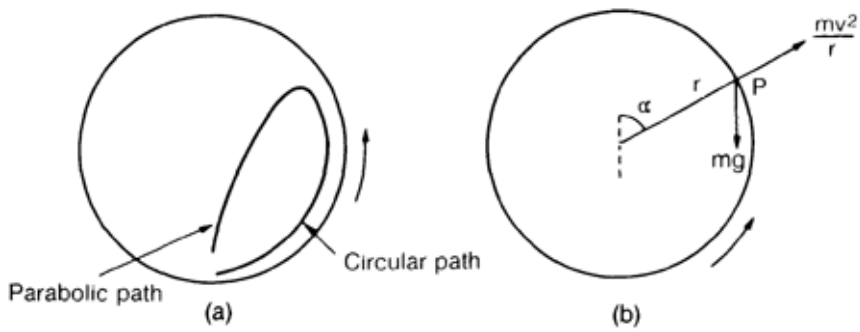
It is virtually certain that the thermal environment, with its extremes of cold and hot, will significantly increase the wear on some components. Less certain, but nevertheless possible, is that increased friction due to the vacuum environment (Karafiath and Nowatzki 1978, p. 130) may contribute to accelerated frictional wear.

Wear components, especially excavation components, tend to be made of very heavy steel alloys. Assuming that in parallel with lunar mining will proceed in situ manufacturing [including production of metals (Ehricke 1983)], it may be worthwhile to consider tradeoffs between transporting high-quality wear parts and producing lower quality wear parts locally.

14. Remote sensing of rock excavation characteristics

The potential of remote sensing to characterize the lunar surface for equipment mobility has been mentioned by Karafiath and Nowatzki (1978, p. 492). The significant impact vehicle traction may have on mining operations has been discussed under topic 8. With respect to mining itself, whether excavating hard rock or scooping up and loading soil, remote sensing will be equally important in determining strength, particle shape and size, interparticle friction, and other excavation parameters. While a final assessment of excavation feasibility will almost certainly require direct physical access, it is clear that remote sensing should be used to the greatest possible extent in determining excavation characteristics of possible mining sites. The importance of remote sensing obviously is well established in the space program, but we should note that interpretation in terms of minability may pose some unusual requirements.

15. Particle size reduction technology for applications in space



Tumbling Mill Action

a. Trajectory of the Grinding Medium in a Tumbling Mill

b. Forces Acting on Particles in a Tumbling Mill

Tumbling mills are widely used to reduce the size of broken rock particles. A particle being lifted up the shell of the mill will abandon its circular path for a parabolic path at point P, *where the weight of the particle is just balanced by the centrifugal force; i.e., where*

$$mg \cos \alpha = \frac{mv^2}{r}$$

This illustration of the forces acting on a particle clearly shows why gravity will affect grinding.

From Wills 1985, p. 186.

Mechanical reduction of particle size is usually not considered part of the mining cycle. It immediately follows the mining cycle, however, and optimizing the total sequence works better than optimizing the mining and milling operations separately.

Crushing is typically the first step in reducing the size of the mined rock. Most crushing systems depend on gravity feed and flow (Wills 1985, ch. 6). Gravity directly affects fragmentation in some systems (Motz 1978). Its influence may not be fully appreciated in others, as it has never been considered a significant variable. The forces acting on particles during crushing in a low-gravity environment will differ markedly from the forces operating in conventional situations. It appears likely that crusher geometries (e.g., jaws, cones, throats) might need to be modified for operations in an environment with drastically reduced gravity or that throughput rates might require considerable adjustment. Increased frictional force components may be beneficial in some crushing systems (Wills 1985, p. 169) but could be detrimental in others.

Grinding particles, either dry or submerged in liquids (Austin, Klimpel, and Luchie 1984; Wills 1985, ch. 7), is usually the final particle size reduction step. It is not obvious how significant the effects on grinding of a low-gravity, high-vacuum environment may be. In the most widely used tumbling mills, particle size reduction is accomplished primarily by impact. Gravity forces enter very explicitly into the design of these tumbling mills (Wills 1985, p. 186). Hence,

an analysis of gravitational effects should be straightforward. Such an analysis would be worthwhile because it addresses the most energy-consuming aspect, by far, of size reduction operations. Wet grinding, almost always preferred, clearly would pose problems in logistics (delivering or producing the liquid) and in containing and recovering the liquid.

Particle size classification is an important control procedure applied throughout the milling sequence. Most sizing methods depend on gravity to some extent. The final fine particle size classification most commonly is accomplished by differential settling in liquids, a method that would pose the same problems for space mining as would wet grinding.

The milling operations discussed here deserve consideration along with mining methods in order to optimize the entire sequence. Such an integrated optimization may shift the degree of fragmentation desired from the mining portion of the operation. The desired fragmentation may affect excavation, loading, and hauling.

Conclusions

The applicability of conventional mining technology to space mining can currently be evaluated only on the basis of judgment and speculation. I have presented a list of research topics that correspond to information needs which must be answered in order to put such evaluations on a firmer basis. In many areas, relatively simple analyses of the mechanics of the system and of the impacts on it of gravity, atmosphere, and temperature could add quantitative understanding of the operation of terrestrial mining technologies in nonterrestrial environments. Iterative interactions between space engineers and scientists on the one hand, mining engineers on the other, and the integrating researchers performing the analyses should assure that the investigations stay correctly focused. Such investigations could be of considerable benefit to the mining industry, and this terrestrial technology transfer aspect deserves specific recognition.

I have given examples of conventional mining technologies which might be adapted to nonterrestrial applications, as well as examples of technologies that have not found practical applications on Earth. I propose that two approaches be pursued in parallel: one starting from available technology and identifying needed adaptations; the second starting from likely ultimate objectives and developing solutions unencumbered by conventional practice and thinking.

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PART 2—Beneficiation and Extraction of Nonterrestrial Materials

William N. Agosto

The group that reviewed options for processing nonterrestrial materials was dominated by industrial materials scientists who tried to identify which processes utilizing space materials could be implemented in the near term.

The most practical process seemed to us to be the extraction of lunar oxygen and the extraction of metals and ceramics from the residues of the reduction process. The growth of space activity will be accompanied by increased demand for liquid oxygen for rocket propellant. In particular, any lunar base activity will require tens of tons of oxygen for each round trip to the Moon. And, of course, the oxygen and the intermediary product water will be needed for life support at the base. The reduced metals and ceramics may be considered byproducts or may develop into primary products. Some of the same processes would be directly applicable to recovery of products from asteroids. We also discussed other processes for directly utilizing asteroid metals.

Beneficiation and Oxygen Extraction Methods

Reduction of lunar ilmenite with hydrogen imported from Earth was judged to be an oxygen extraction option that could be implemented in the near term. Ilmenite, an iron and titanium oxide, is the most abundant oxide in the samples that have been brought back from the Moon.

Working for Lockheed Corporation at the Johnson Space Center, I reported the successful concentration of ilmenite in an Apollo 11 soil sample, using an electrostatic separator based on a commercial design and operated both in nitrogen and in a vacuum. This was the first research reported on the industrial behavior of actual lunar material. Additional research is needed to determine the characteristics of a system that could operate on the Moon.

A process not requiring beneficiation, because it extracts oxygen from the predominant silicates, was probably the first process considered for extraction of oxygen from lunar materials. The carbothermal process was developed by Sanders Rosenberg and colleagues at Aerojet-General Corporation in the mid-1960s, before we had been to the Moon. They assumed that ordinary rock-forming minerals, such as olivine and pyroxene, would be abundant, an assumption that proved to be mostly correct. Rosenberg and his colleagues performed a series of experiments demonstrating actual oxygen extraction from simulated lunar materials. In addition, they designed an oxygen production plant and did a parametric analysis

of mass, power, and cost. David McKay has combined several of their papers from that period and updated the cost analysis to 1989 dollars. This combined paper presents the basic concepts of the carbothermal process, gives the results of some of the laboratory experiments, and includes the design concept for a lunar oxygen plant. The paper is interesting both because of its historical value in presenting a lunar oxygen plant designed before Apollo 11 and also because the basic concept is still viable today as a candidate oxygen plant for a lunar outpost in the early 21st century.

In a review of proposed lunar oxygen production processes, including carbothermal reduction and electrolysis of basalts, Christian W. Knudsen and Michael A. Gibson, of Carbotek, Inc. (Houston), have concluded that hydrogen reduction of ilmenite is the simplest process proposed. Products of the reaction are iron, titanium dioxide, and water; oxygen is then extracted from the product water by electrolysis. Both batch and continuous-flow fluidized-bed processes for the reaction have been described. Although the preliminary results of bench-level tests on the batch process conducted by Richard J. Williams at JSC seemed promising, further engineering work by Knudsen and Gibson indicates to them that only a continuous process is practicable on a large scale. Knudsen and Gibson also considered hot pressing of the metallic iron and titanium dioxide residues of the reaction into cermet parts and bricks, as outlined by Agosto (1981).

Russell O. Colson and Larry A. Haskin discuss the direct electrolysis of molten lunar material to produce oxygen. In the magma electrolysis process, iron, silicon, or iron-silicon alloys are produced at the cathode and oxygen is produced at the anode. Potential byproducts include ceramics (spinels) and cast-rock products such as bars, beams, and sheets. Colson and Haskin argue that, compared to most other proposed processes, this process requires less energy per unit of oxygen and has the advantage of being relatively simple. Technology challenges include finding container and electrode materials that will withstand the corrosiveness of molten silicates. The work of a number of years has determined some of the fundamental properties of melt conductivity and some of the factors affecting the efficiency of oxygen production.

Solar furnace pyrolysis of lunar basalts in vacuum, as proposed by Elbert A. King and me (1983), is considered another highly promising process for nonterrestrial oxygen production. It does not require reagents imported from Earth. King (1982)

demonstrated the process on Earth using terrestrial basalts and samples of the Murchison meteorite heated to approximately 3000 °C in a furnace with a solar mirror 2 meters in diameter. Residues of metallic iron and oxides of aluminum, calcium, and titanium indicated the evolution of oxygen and volatile oxides of other elements. A bench-level research program is required to characterize, quantify, separate, and capture the oxygen and other volatiles liberated by the process. Residues of the process include metals (iron), semimetals (silicon), ceramics (Al-Ca-Ti oxides), and feedstocks rich in aluminum oxide for aluminum electrolysis.

Wolfgang H. Steurer, of the Jet Propulsion Laboratory, considered two vapor-phase processes: (1) the volatilization of oxygen by vacuum pyrolysis of oxides and (2) electrostatic separation of metals from high-temperature plasmas of nonterrestrial materials. The high temperatures and reactivities of such processes suggest that the technology will be difficult to develop. However, such processes may prove to be effective.

Metallurgy

David F. Bowersox, of Los Alamos National Laboratory, has described a novel anhydrous chloride process, used in the nuclear industry to recover plutonium, which could be adapted to extract iron and titanium from nonterrestrial basalts and ilmenite. All reagents and products of the process are recycled and, because it is waterless, the system is one-tenth the size of an aqueous system with the same metal output. It has the disadvantage of being a metal extraction process that does not directly yield oxygen or water, and it requires chloride salts, which are rare or absent on the Moon. However, as a successful operating anhydrous system that recycles all reagents and products, it merits serious consideration for nonterrestrial application.

Karl R. Johansson has reviewed the literature and found several bioprocesses for the beneficiation of lunar and asteroidal materials by the action of microorganisms. Notably, the extraction of metals by (1) oxidation-reduction reactions, (2) acid leaching, (3) pH alteration, (4) organic complexing, and (5) cellular accumulation of metals due to the action of bacteria on minerals. All these bioprocesses would require stringent radiation and temperature controls in closed aqueous environments having elements in which the Moon is deficient, like carbon, nitrogen, and hydrogen. However, Karl says that the process of microbe-enhanced vat leaching, which is used terrestrially to concentrate copper ores, might be applicable to extracting common lunar metals

like iron and manganese from lunar rocks and soils. In addition, bioaccumulation of metals by microbial cells might be used to concentrate rare (and often toxic) elements like copper, lead, mercury, cadmium, and silver and remove them from biological systems on the Moon. In his paper Karl also mentions metal reduction by anaerobic bacteria, the uptake of silicates by diatoms, and a tantalizing claim in the Russian literature of “silicate bacteria” that concentrate aluminum oxide by freeing silicates from aluminosilicate ores. However, human settlements and early lunar industrial operations would probably have to be well established before controlled bioprocessing systems could be set up in nonterrestrial locations.

If aqueous processing were to prove practicable, then leaching of useful elements from lunar and asteroidal materials by inorganic acids like hydrofluoric acid, without the introduction of microorganisms, might well be a more direct and productive method of extracting most of the major lunar elements (oxygen, silicon, aluminum, iron, magnesium, titanium) as well as many of the minor ones (sodium, potassium, manganese, chromium, phosphorus). See Criswell (1980).

Metallurgist Constance F. Acton has critically reviewed proposed processes for metal production, using the harsh criterion of terrestrial commercial viability. Iron in lunar soil may be the most easily obtained metal resource on the Moon through the low energy extraction techniques of magnetics and electrostatics. Its physical extraction presents many challenges, but it is likely to be one of the easier objectives for near-term lunar resource development (Agosto 1981). Acton points out the need for hard thermodynamic and kinetic data on all the reactions and the necessity for long-term bench-level testing and pilot plant facilitation of the most promising processes. She outlines the extensive effort required to prove a commercial metallurgy process through thermodynamic and kinetic chemical evaluation, bench-level feasibility studies, and pilot plant operations. Her assessments, based on terrestrial experience, of long lead times (20–50 years) and high R&D expenditures (hundreds of millions of dollars) to develop systems are challenges to the designer of lunar materials processing technology. However, the long lead times presume development of processes competitive with those of terrestrial suppliers. That assumption does not apply to the initial provision of products from lunar sources for use in orbit.

John Lewis, of the University of Arizona, presented to our group information on the gaseous carbonyl process. Carbon monoxide is reacted with metal at

low temperature to purify it or separate one metal from another. With a relatively low energy input, lunar metallic iron might be purified or trace elements, particularly platinum group metals, could be separated from asteroidal metal. Although considerable terrestrial experience is in hand, adaptation to the space environment remains a challenge for future investigation.

Nonterrestrial Cements

T. D. Lin, of Construction Technology Laboratories (CTL), the research arm of the Portland Cement Association, proposed to our workshop group the manufacture of cement from lunar oxides and in his paper proposes concrete as a building material for a space station and a lunar base. The major constituents of common types of cement occur in lunar highland anorthosites and lunar mare basalts. The high compressive strength and the mass of lunar-derived concrete would make it an effective shield against radiation and micrometeorite impacts and thus a candidate material for orbital and lunar structures. Concrete is fireproof, lends itself to modular construction, and can be reinforced with Moon-derived metals and fiberglass to improve its tensional and flexural strength. Lunar cement would also be useful as mortar to assemble building blocks of other materials, whether imported or nonterrestrial. Common concrete mixtures are about 10 percent water by weight, but drier formulations can be developed and the water can be recovered as the concrete dries. In any case, typical concretes, which consist of 2/3 to 3/4 aggregate materials bonded by cement, retain only 5 percent water when thoroughly dried, which corresponds to only a few tenths of a percent of Earth-derived mass in the form of hydrogen (Cullingford, Keller, and Higgins 1982). Suitable lunar aggregates could readily be obtained by crushing and grading rocks from the lunar surface.

I have proposed a method for concentrating lime (CaO) in lunar materials to Portland cement formula levels, using phosphates that might be lunar derived. A similar process was proposed by Ellis M. Gartner, of CTL, using terrestrial phosphate. Construction Technology Labs received 40 grams of lunar soil from the Johnson Space Center in 1986; from it CTL fabricated a lunar mortar sample, which was tested and proved usable. NASA is interested and the project has attracted favorable attention from the press. The apparent widespread interest in cement as a lunar product and public recognition of it may generate substantial support for its development.

The consensus of the group working on beneficiation and extraction of nonterrestrial materials was that there is a near-term need for bench-level data on lunar and meteoritic materials processing, such as (1) beneficiation of industrially valuable minerals in lunar soils and disaggregated lunar rocks and meteorites; (2) oxygen and metal extraction processes, like carbothermal reduction of silicates, hydrogen reduction of ilmenite, magma electrolysis, vacuum pyrolysis, and anhydrous chloride reduction using actual nonterrestrial samples; and (3) formulation of cementitious compounds from lunar oxides and aggregates. The above research should be conducted under conditions approximating, as closely as practicable, the expected operating environment. This work is necessary to make a credible case for nonterrestrial materials utilization to the materials science community.

Recommendations

1. Support for a thorough bench-level hardware investigation and demonstration of the beneficiation, primarily by electrostatic and magnetic means, of lunar soils and crushed rocks for minerals like ilmenite, anorthite, and pyroxenes, and valuable minor phases like metal, chromite, and phosphate.

2. Support for bench-level research and development of the carbothermal process, including additional testing to determine optimum pressure and temperature conditions for feedstocks of various compositions, such as simulated mare basalt and concentrates of ilmenite or pyroxene.

3. Support for a thorough investigation of the thermodynamics and kinetics of hydrogen reduction of lunar ilmenite, together with a bench-level laboratory research project to investigate the workability of hardware designs like those of Richard J. Williams and Christian W. Knudsen and Michael A. Gibson.

4. Support for additional studies of magma electrolysis, including laboratory work on the basic process, development of innovative electrodes and containers, and investigation of the effects of feedstock of different compositions. This effort should also include engineering evaluations and plant design concepts.

5. Support for a thorough investigation of the thermodynamics and kinetics of solar furnace vacuum pyrolysis of nonterrestrial materials. The effort should

include a bench-level research project to characterize, quantify, separate, and capture oxygen and other volatiles liberated by high-temperature vacuum pyrolysis of lunar and meteoritic materials, as well as thorough characterization and chemical analysis of resulting condensates and residues.

6. A literature search and evaluation of the anhydrous chloride process for plutonium reclamation reported by David F. Bowersox and its applicability to production of metals and ceramics from nonterrestrial materials.

7. Support for bench-level research on aqueous leaching of nonterrestrial silicates with inorganic acids like hydrofluoric acid, as well as beneficiation by bioprocesses derived from the action of microorganisms on nonterrestrial minerals.

8. A study of the application of the carbonyl process to the purification and extraction of lunar and asteroidal ferrous metals.

9. Support for the development of cement formulations from lunar materials and cement and concrete fabrication processes adapted to lunar and orbital manufacture and applications.

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Lunar Beneficiation

William N. Agosto

With the exception of igneous differentiation and possible fumarolic activity (volcanic exhalations), the Moon lacks all the major ore-forming processes that operate on Earth—aqueous concentration of crustal minerals, surface weathering of rocks, advanced fractionation of igneous rocks, and plate tectonic recycling the crust. For that reason, natural concentrations of industrially valuable minerals (ore bodies) are far less likely to be found on the Moon than on the Earth (see James Carter's paper, earlier in this volume). But that is all the more reason for devising beneficiation processes to concentrate and extract the useful mineral components in lunar rocks and soils. Another important consideration is that nearly complete reagent recycling will be required for most of the processes proposed for producing oxygen, metals, and ceramics on the Moon. Reagent recovery will be greatly simplified by using simple input ore minerals. Examples of such minerals are ilmenite, the most abundant lunar oxide and a source of oxygen, iron, and titanium; anorthite, the chief source of lunar aluminum; and metallic iron/nickel fragments that occur in lunar soil. In addition, there may be significant amounts of chromite, sulfides, and phosphates in terranes that are rich in chromium and KREEP (potassium, rare earth elements, and phosphorus).

As an example of a useful mineral that can be beneficiated, McKay and Williams (1979) have estimated ilmenite abundance by microscopic count to be 15 and 20 percent by volume in Apollo 11 and 17 basalts and 2 and 5 percent by volume in Apollo 11 and 17 soils. Reduction of lunar ilmenite with hydrogen imported from Earth appears to be one of the more practical schemes for obtaining lunar oxygen. While the reported concentrations are significant, a more highly concentrated ilmenite extract would improve the efficiency of the reduction process.

Electrostatic Concentration

In 1985, I reported designing mineral electrostatic separators based on commercial models. With my separators, I demonstrated the electrostatic concentration of lunar ilmenite in the 90- to 150-micrometer grain size fraction of Apollo 11 soil 10084,853 to levels above 60 percent at collection points near the high-voltage electrode after one pass through a slide-type electrostatic separator in a nitrogen environment (figs. 1 and 2). Ilmenite behaved like a semiconductor and was separable electrostatically because the other major soil components, including the metal-bearing agglutinates, behaved like nonconductors.

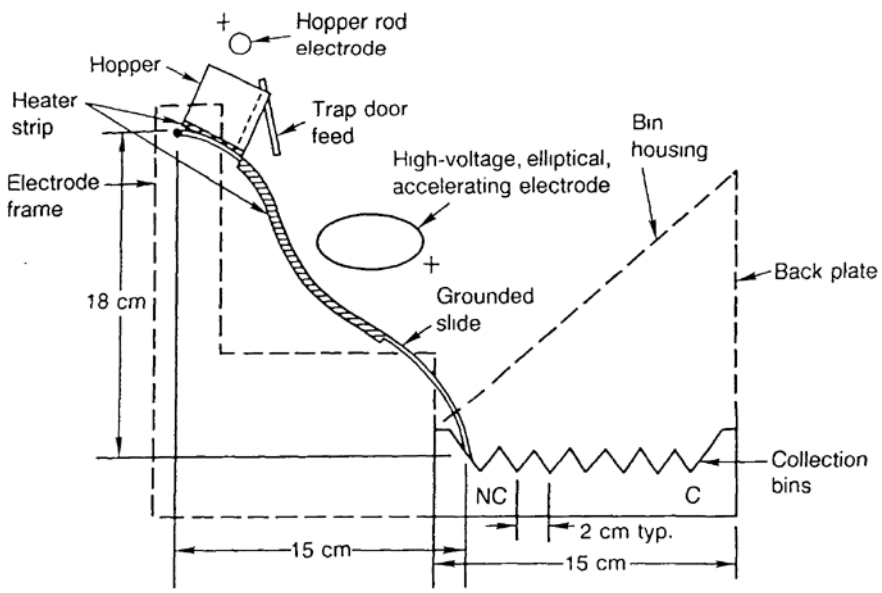

Figure 1

Mineral Electrostatic Separator, Slide Configuration

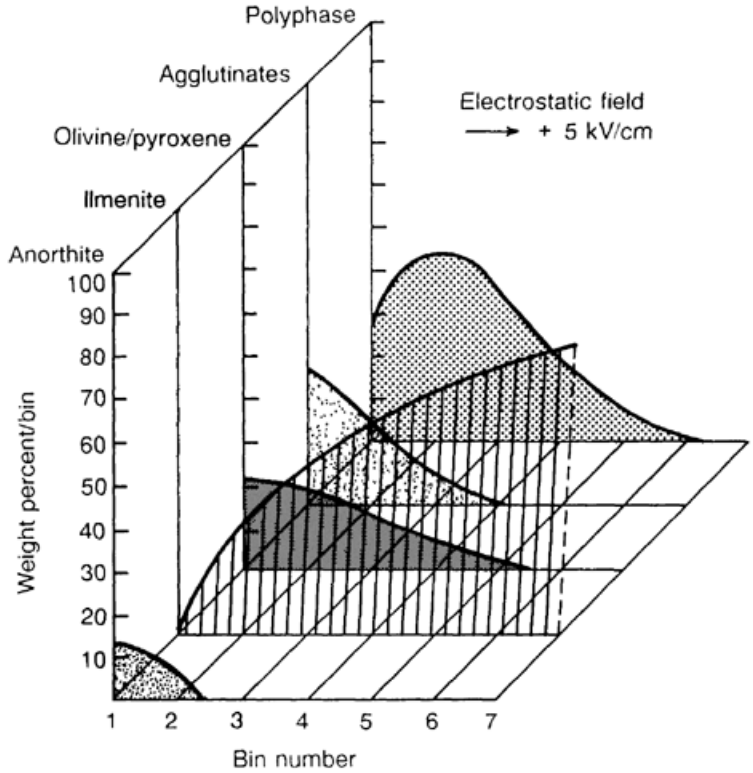

Figure 2

Electrostatic Separation in Nitrogen of Apollo 11 Soil 10084,853, 90–150 µm Fraction

Agglutinates are the major component of lunar soil, making up, on the average, 50 percent of the regolith. Most of the agglutinates contain finely dispersed metallic iron, which gives them a broad magnetic range that overlaps the magnetic susceptibility of other soil components, including ilmenite. For that reason, it is difficult to separate agglutinates from ilmenite by magnetic means. However, the nonconducting behavior of the agglutinates allows them to be separated from ilmenite electrostatically. During separation, the soil sample was heated to approximately 150 °C to drive off terrestrial water and enhance the contrast in conductivity between ilmenite and other mineral components (see fig. 3).

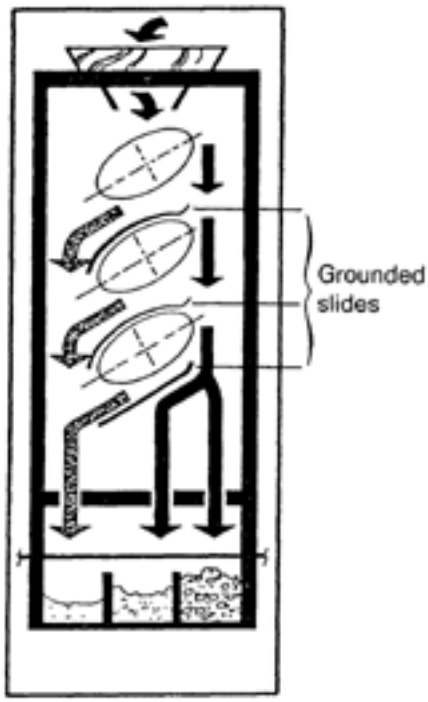

Figure 3

A Commercial Electrostatic Separator on the Lunar Surface

The mirror in this concept of an electrostatic separator on the Moon focuses solar radiation on the soil to be separated. Heating to about 100 °C will increase the conductivity of the semiconductor ilmenite while leaving the conductivity of insulators like agglutinates unchanged. The enhanced contrast in conductivity increases the separability of these components of the lunar soil. In the schematic, the arrows indicate the path of the soil feed and how it separates. The ellipses are cross sections of the high-voltage electrodes. The nonconducting materials fall to the far right. The middlings fall in the middle. The conducting and semiconducting materials fall to the far left.

In my electrostatic studies the lunar anorthite seemed to collect preferentially close to the grounded electrode (the feed hopper), but the slide design of the separator was not configured to take advantage of that.

The slide did enhance the density segregation of ilmenite by air (nitrogen) resistance. Ilmenite is almost twice as dense as the other major soil components. Accordingly, electrostatic separation of the ilmenite in a vacuum, where air resistance was not a factor, was not as successful, and the mineral reached a maximum concentration of only 30 percent in one pass under those conditions (fig. 4). This, however, amounts to a fourfold increase compared to the starting concentration of 7 percent.

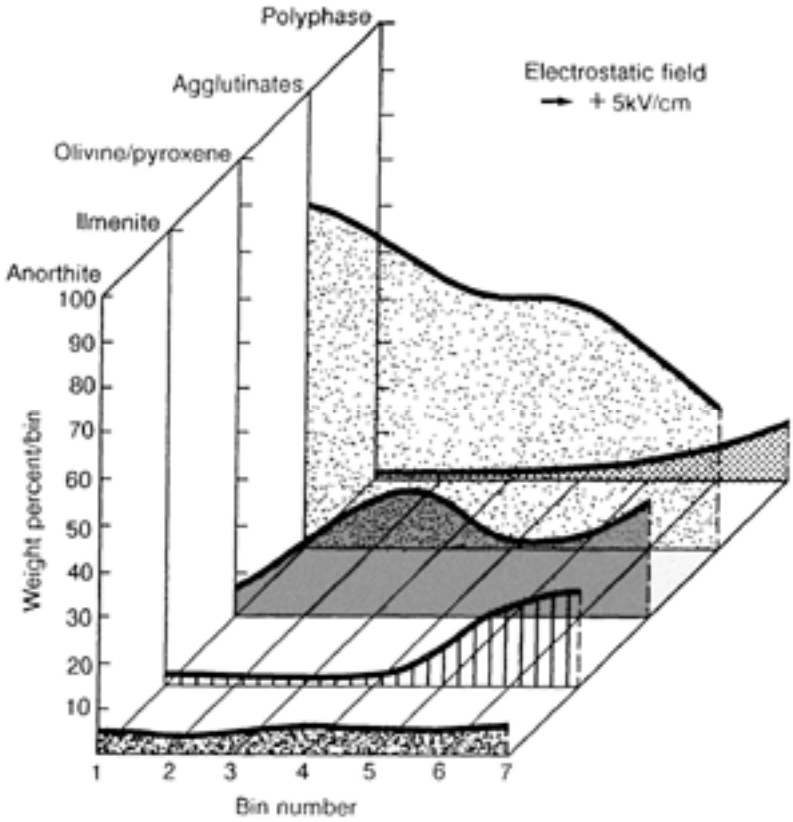

Figure 4

Electrostatic Separation in a Vacuum of Apollo 11 Soil 10084,853, 90–150 µm Fraction

To improve yield in the vacuum of the lunar environment would require redesign of the electrostatic separation apparatus. A vertical, free-fall design (as seen in fig. 3) might be the best approach for separating lunar soil minerals according to their electrical behavior and would be especially appropriate in the lunar environment, where fall times are about twice what they are on Earth.

Magnetic Concentration

Unlike Earth soils, all lunar soils contain naturally occurring, particulate iron/nickel metal (FeNi), which is believed to derive from meteorite impacts. Lunar soil metal is likely to be an accessible and useful resource. Goldstein and his associates (1972, 1973) reported soil metal contents of 0.15 percent by weight in the size range 74 μm to 1.0 mm of three Apollo 16 soils and 0.05 percent by weight in a comparable size range of two Apollo 14 soils. If these occurrences are typical of the lunar highlands and maria, respectively, then there are at least 7 billion metric tons of accessible FeNi metal in the top 10 cm of soil over the entire lunar surface. And there may be substantially higher concentrations of surface metal in regions where iron meteorites have struck the Moon.

In 1981, I proposed a magnetic beneficiation method for concentrating lunar soil metal, using off-the-shelf permanent magnet separators and autogenous grinders. Projected yield was 552 metric tons per year of 99-percent pure FeNi powder. The specific energy required to extract the FeNi metal magnetically was 0.4 kWh/kg, an order of magnitude less than that required to smelt iron from typical ores. A major advantage of the concentrated metal powder product is that it may be formable directly by flexible, low-power powder metallurgical techniques to make a variety of tools, machine parts, plates, struts, wires, electrical contacts, and magnets. Near-theoretical density for these parts may be achievable by powder pressing in the high lunar vacuum. Furthermore, the product can be toughened to steel specifications by adding the right proportions of lunar oxides or titanium to the metal powder before pressing.

An all-magnetic method for beneficiating soil FeNi may present problems because of the large volume of iron-bearing agglutinates that have ferromagnetic properties. But Goldstein did achieve concentration of soil metal grains in the laboratory, using a very low magnetic field gradient on the Frantz Isodynamic Magnetic

Separator, and a comparable technique might be adaptable to industrial operations on the Moon.

I suggest that metal particles first be separated from ilmenite and other soil components magnetically and then, because the ferromagnetic agglutinates may have separated with the metal particles, electrostatic separation could be used to eliminate the agglutinates from the desired metal fraction. Comparable combinations of techniques may be appropriate for extracting other soil components, like anorthite, chromite, and phosphates.

Lunar Soil Sizing

What volatiles are known to exist on the Moon tend to be concentrated in the fine soil fractions. For example, Gibson et al. (1987) showed that hydrogen implanted by the solar wind increases tenfold as particle size decreases—from 12 ppm in the 90- to 150-micrometer fraction to 127 ppm in the less-than-20-micrometer fraction of five representative regolith samples. Overall hydrogen content is about 40 ppm. At 75-percent recovery from the top meter of soil over the entire lunar surface, that is enough hydrogen to make a water lake 10 meters deep and 44 kilometers in diameter. The helium content of the soil is about the same as the hydrogen content. Furthermore, 0.04 percent of the lunar helium is the isotope ^{3}He, which is much rarer on Earth and which is a potentially important fusion energy fuel (Wittenberg, Santarius, and Kulcinski 1986). Helium-3 may be the only lunar product that can be returned to the Earth at a substantial profit. Accordingly, lunar soil sizing techniques will be vital to extracting rare and precious lunar volatiles. In addition, sized soil input is required to optimize mineral yield by electrostatic and magnetic separation methods.

Dry sizing techniques that may be appropriate to the lunar environment include electrical sizing, screening, and gas elutriation.

Electrical Sizing

In 1984, I measured the trend of increasing charge-to-mass ratio with decreasing grain size in terrestrial analogs of common lunar regolith minerals and subsequently demonstrated electrostatic sizing of terrestrial ilmenite over the particle size range of 500 down to 90 micrometers (figs. 5 and 6). The previous year, Peter Castle, at the University of Ontario, demonstrated ac electrical sizing of conducting spheres in a comparable size range. In both cases, air turbulence limited the smallest separable size to 90 micrometers. Accordingly, electrical sizing in a vacuum is indicated for grading of fines smaller than 90 micrometers.

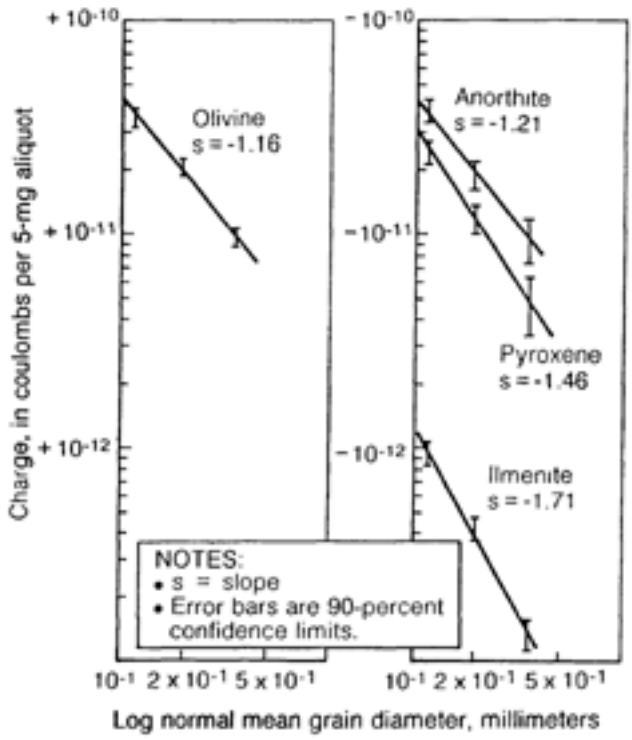

Figure 5

Contact Charge Acquired on Aluminum by Terrestrial Olivine, Anorthite, Pyroxene, and Ilmenite as a Function of Grain Size

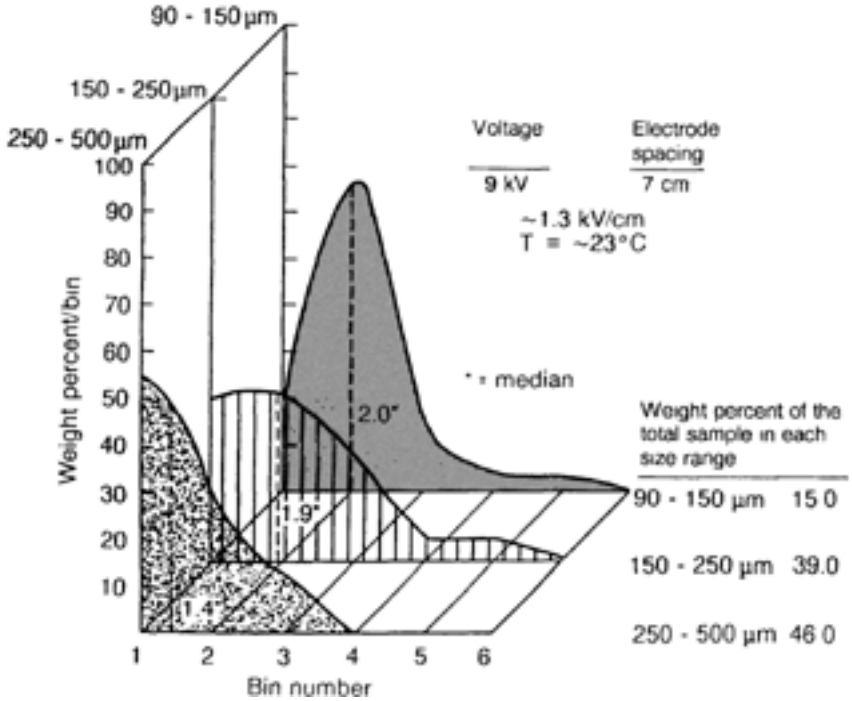

Figure 6

Electrostatic Sizing of Comminuted Ilmenite

Screening

Sieves are available for screening particles ranging from 5 to 30 micrometers at 5-micrometer intervals. It is unlikely, however, that such fine sieving can be accomplished without suspension of the fines in a gas or fluid medium. Even under those conditions, fines sieving is a laborious process. The fluid most likely to be available on the Moon is oxygen, and, since cryogenic temperatures can be relatively easily maintained there, it might be instructive to attempt lunar soil sieving in liquid oxygen. This may be a practical technique because it is unlikely that significant oxidation of lunar soil components will occur at liquid oxygen temperatures (below -183 °C). In addition, the only combustible component is FeNi metal, which is less than 1 percent of the soil by weight and which is predominantly encapsulated in glassy agglutinates.

Gas Elutriation and Classification

Gaseous classifiers, cyclones, and fluidized-bed separators operate by stratifying particles in a rapidly moving gas stream according to size and density. They are available on the market for sizing fine particles from 0.5 to 35 micrometers. These devices can deliver the narrowest size ranges (at best, at the small end, a spread of about 0.2 μm) on a commercial scale (kilograms to tons per hour). On the Moon, gas classification might be done in oxygen. The possibility and consequences of oxidizing reduced lunar soil phases under these conditions will have to be considered and experimentally determined. However, it appears unlikely that, by commercial standards, significant oxidation of soil components will occur in dry gaseous oxygen at sufficiently low temperatures (e.g., -20 °C) over the short period required for gaseous classification (minutes).

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The Onsite Manufacture of Propellant Oxygen From Lunar Resources

Sanders D. Rosenberg; Robert L. Beegle, Jr.;
Gerald A. Guter; Frederick E. Miller; and Michael Rothenberg

The Aerojet carbothermal process for the manufacture of oxygen from lunar materials has three essential steps: the reduction of silicate with methane to form carbon monoxide and hydrogen, the reduction of carbon monoxide with hydrogen to form methane and water, and the electrolysis of water to form hydrogen and oxygen. The reactions are as follows:

$$MgSiO_3 + 2\,CH_4 \xleftarrow{1625\,°C} 2\,CO + 4\,H_2 + Si + MgO \qquad (1)$$

$$CO + 6\,H_2 \xleftarrow{250\,°C} 2\,CH_4 + 2\,H_2O \qquad (2)$$

$$H_2O \xleftarrow{75\,°C} 2\,H_2 + O_2 \qquad (3)$$

The overall process is shown in figure 7. Figure 8 is a schematic flow diagram of the silicate reduction furnace used in this program.

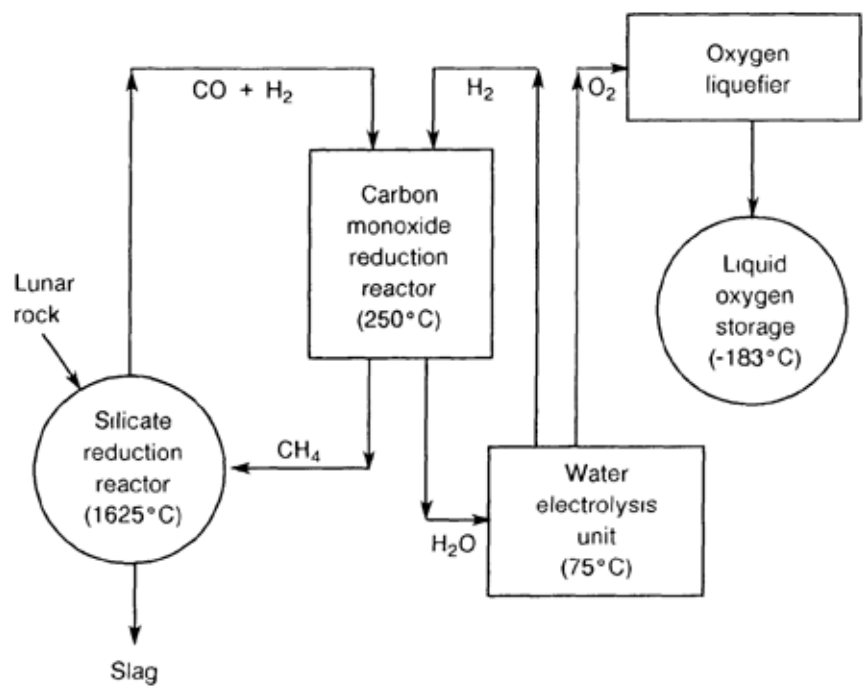


Figure 7

Oxygen From Lunar Silicates

The first of the three steps in the process of carbothermal reduction of silicates takes place in the silicate reduction reactor. Magnesium silicate, which typifies lunar rock, is reduced to carbon monoxide, silicon, and slag, using methane as the reducing agent. The step requires a very high temperature: 1625 °C.

$$MgSiO_3 + 2\,CH_4 \xrightarrow{1625\,°C} 2\,CO + 4\,H_2 + Si + MgO \qquad (1)$$

In the second step, the carbon monoxide is catalytically reduced with hydrogen to regenerate the methane and form water. This step takes place at the relatively low temperature of 250 °C.

$$2\,CO + 6\,H_2 \xrightarrow{250\,°C} 2\,CH_4 + 2\,H_2O \qquad (2)$$

In the final step, the water is condensed to a liquid (at 75 °C) and electrolyzed to regenerate the hydrogen used in step 2 and to produce the desired oxygen.

$$2\,H_2O \xrightarrow{75\,°C} 2\,H_2 + O_2 \qquad (3)$$

Since the methane and hydrogen are regenerated and recycled, this process ideally uses up only energy and the input metal silicates. Thus, the following reaction can be seen as the sum of the process.

$$MgSiO_3 \rightarrow O_2 + Si + MgO \qquad (4)$$

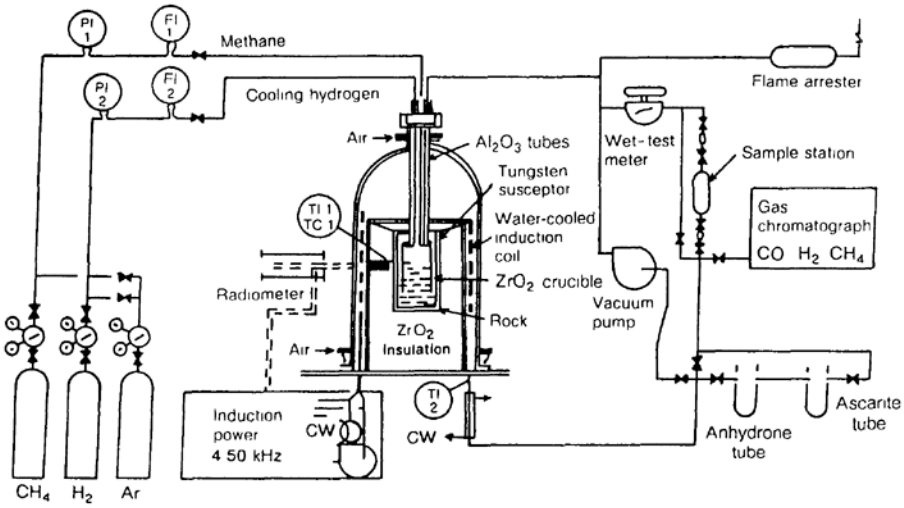


Figure 8

Silicate Reduction Furnace

TI = temperature indicator
TC = temperature controller
PI = pressure indicator
FI = flow indicator
CW = cold water

Reduction of Igneous Rock With Carbon and Silicon Carbide

A series of reactions of basalt and granite with carbon and silicon carbide were carried out to determine the temperature profile for the reduction reactions that may occur during the reduction of igneous rock with methane. The results of three of these runs are illustrated in figure 9.

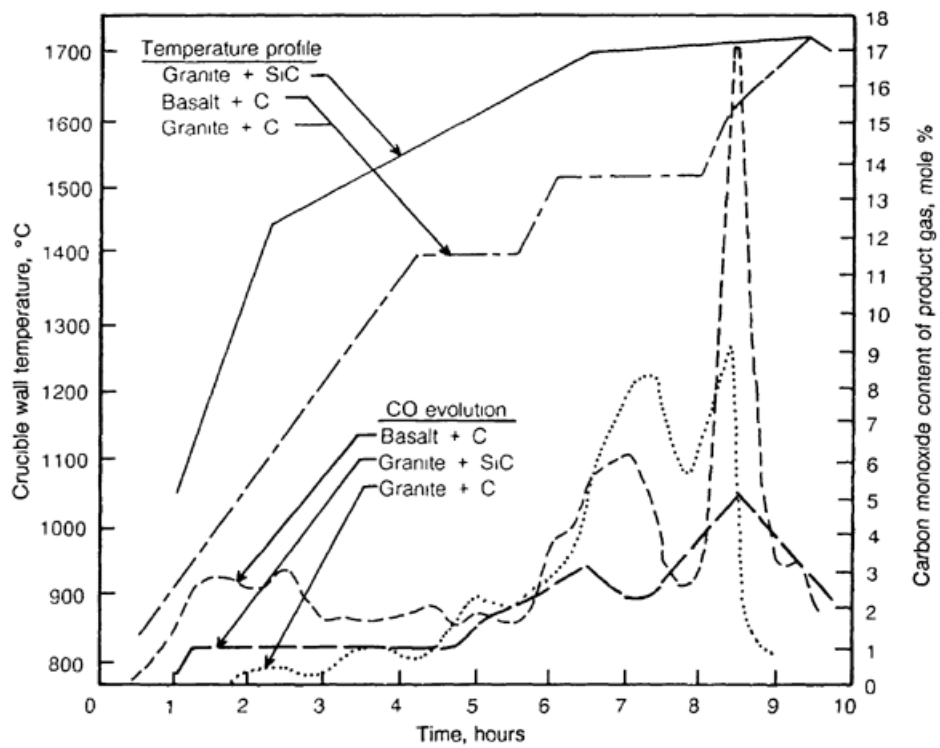


Figure 9

Reduction of Basalt and Granite With Carbon and Silicon Carbide

In the reaction of basalt (50 g) with carbon (5 g), the initial evolution of carbon monoxide resulted from the reduction of iron oxide. The basalt contained 11.86 percent iron oxide (as Fe_2O_3); the reduction of this oxide, if present as Fe_2O_3, would require 1.34 g of carbon. The carbon monoxide that evolved during the first 2.5 hours represented 1.0 g of the carbon. Other reducible materials present in the basalt were titanium dioxide (2.47%) and sodium oxide (3.73%). These oxides would consume 0.43 g of carbon. Consequently, only 35 percent of the carbon could have been oxidized by materials other than silicon dioxide. The recovery in the form of carbon monoxide of 89.1 percent of the carbon with which the reactor was charged indicates that a considerable portion of the silicon dioxide present in the basalt was reduced at temperatures as low as 1550 °C.

Three solid products were obtained: slag and metal remained in the zirconium dioxide crucible and sublimate was found at the top of the bell jar. The slag was composed mainly of aluminum oxide. The composition of the metal was 82 percent iron, 13 percent silicon, and minor amounts of titanium, vanadium, nickel, and copper. Of the sublimate, 61 percent was sodium, which is highly volatile.

In the reaction of granite (50 g) with carbon (5 g), much less carbon monoxide was produced at low temperature. This result is due to the lower percentages of reducible oxides in the granite; that is, iron oxide (2.05% as Fe_2O_3), sodium oxide (3.10%), and potassium oxide (4.90%). Complete reduction of these oxides would consume 0.85 g (17%) of the carbon introduced. A total of 73 percent of the carbon introduced was recovered as carbon monoxide; therefore, we conclude that silicon dioxide reduction accounts for most of the carbon monoxide evolved at 1550 °C and higher temperatures.

We believe that most of the rest of the carbon introduced reacted with silicon to form silicon carbide. The slag had nonmagnetic pieces of metal dispersed throughout and contained 2.3 percent carbon; that is, 20 percent of the carbon introduced.

In the reaction of granite (37.5 g) with silicon carbide (12.5 g), almost no reaction occurred below 1100 °C; about 7 percent of the silicon carbide was reacted between 1100 and 1500 °C. As the temperature was increased from 1500 to 1740 °C, the reaction rate gradually increased and then rapidly decreased when most of the carbon was consumed. About 83 percent of the carbon in the silicon carbide was recovered as carbon oxides. The dark, metallic looking slag contained an additional 10 percent of the carbon introduced as silicon carbide.

Figure 10

CO-H_2 Reduction Unit

DP = differential pressure transducer
FCR = flow control recorder
GC = gas chromatograph
PC = pressure controller
PI = pressure indicator (gauge)
PS = pressure switch
RV = relief valve
(S) = *gas sample*
[S] = *solenoid valves*
ΔT = Δ temperature recorder
TC = thermocouple
TI = temperature indicator (thermocouple point)
WTM = wet-test meter

Analysis of the metal recovered from the melt gave 59 percent iron, 28 percent silicon, and minor amounts of titanium, vanadium, nickel, and copper. The slag was composed mainly of aluminum oxide and silicon dioxide.

These results indicate that, if silicon carbide is formed by reaction of granite and carbon, excess granite will react with the carbide to produce silicon and carbon monoxide. The rate of the granite-silicon carbide reaction at 1740 °C is comparable to that of the granite-carbon reaction at 1625 °C.

Reduction of Carbon Monoxide With Hydrogen

The reduction of carbon monoxide with hydrogen to form methane and water was studied using a nickel-on-kieselguhr catalyst. A schematic flow diagram of the hydrogen-carbon monoxide reactor used in this program is shown in figure 10. The data for these runs are presented in tables 1 to 5 and figures 11 to 13. The various parameters that were studied are discussed in the following paragraphs.

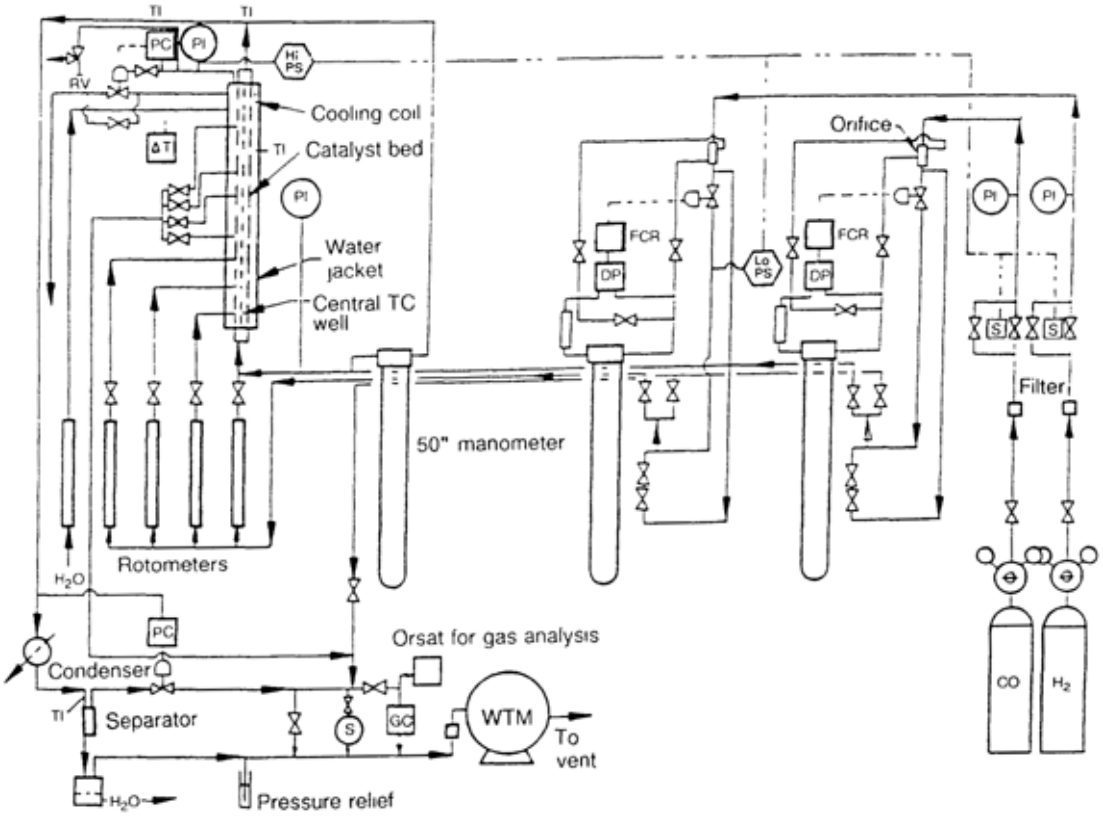


TABLE 1. *Reduction of Carbon Monoxide With Hydrogen To Form Water and Methane (and CO_2): Results of Selected Runs Between 45 and 57*

Run	H_2/CO mole ratio	Space velocity, hr^{-1}	Catalyst bed pressure, atm	Catalyst bed temp., °C	Material balance, %	CO conversion, mole %	Normalized product yield, mole %		
							H_2O	CH_4	CO_2
45	4.00	500	1.0	250	101.0	100.0	100.0	100.0	0.0
46	4.00	750	1.0	249	93.3	100.0	100.0	100.0	0.0
47	4.10	1003	1.0	252	99.0	100.0	100.0	100.0	0.0
48	3.96	1481	1.0	253	95.3	100.0	99.8	99.9	0.1
49a	4.06	1000	1.0	251	101.0	100.0	100.0	100.0	0.0
51	4.15	2010	1.0	265	98.6	100.0	100.0	100.0	0.0
52b	2.84	810	1.0	248	98.1	100.0	91.1	96.2	3.7
53	3.56	1000	1.0	254	94.5	100.0	100.0	100.0	0.0
54	3.14	998	1.0	254	95.0	100.0	98.3	99.1	0.8
55	3.03	1000	6.1	253	96.9	100.0	99.2	99.4	0.4
56	3.01	1500	6.1	231	95.4	100.0	97.3	98.5	1.3
57	3.02	1500	6.1	353	94.8	100.0	94.8	97.1	2.5

TABLE 2. *Analysis of the Gases Produced in the Reduction of Carbon Monoxide With Hydrogen, Selected Runs 45–57*

Run	Composition of product gas, vol. %				
	H_2	H_2O	CO	CH_4	CO_2
45	49.4	1.20	0.0	49.4	0.00
46	49.4	1.15	0.0	49.4	0.00
47	51.5	1.15	0.0	47.3	0.00
48	48.4	1.15	0.0	50.4	0.05
49a	50.8	1.15	0.0	48.1	0.00
51	53.0	1.15	0.0	45.9	0.00
52b	8.9	1.14	0.0	91.5	3.50
53	38.5	1.14	0.0	60.4	0.00
54	17.7	1.14	0.0	80.5	0.65
55	9.3	0.20	0.0	90.2	0.35
56	12.0	0.20	0.0	96.6	1.27
57	18.9	0.20	0.0	78.6	2.25

TABLE 3. *Reactant Gas Carbon Dioxide Content vs. Catalyst Bed Length*

Run	Space velocity, hr^{-1}	H_2/CO mole ratio	CO_2 analysis, vol. %		
			Initial third	Middle third	Outlet
45	500	4.0	0.4	0.0	0.00
46	750	4.0	1.6	0.0	0.00
47	1000	4.1	2.7	0.3	0.00
48	1481	4.0	4.6	0.8	0.05
51	2010	4.1	3.8	0.2	0.00
55	1000	3.0	4.9	1.0	0.35
57	1500	3.0	6.1	3.6	2.25

TABLE 4. *Reduction of Carbon Monoxide With Hydrogen To Form Water and Methane (and CO_2): Results of Selected Runs Between 63 and 67*

Run	Impurity mole % in H_2 stream	H_2/CO mole ratio	Space velocity, hr^{-1}	Catalyst bed pressure, atm	Catalyst bed temp., °C	Material balance, %	CO conversion, mole %	Normalized product yield, mole %		
								H_2O	CH_4	CO_2
63b	None	3.00	1000	6.1	254	99.5	100.0	97.6	99.0	0.95
64c	0.1 COS	3.00	1000	6.1	254	97.1	100.0	96.4	98.2	1.65
66b	1.0 NO	2.98	1005	6.1	255	98.8	100.0	98.6	97.2	1.87
66c	1.0 NO	3.44	1120	6.1	252	100.8	100.0	100.0	100.0	0.00
67b	0.5 PH_3	3.09	1024	6.1	249	100.6	100.0	97.2	98.2	1.52

TABLE 5. *Analysis of the Gases Produced in the Reduction of Carbon Monoxide With Hydrogen, Selected Runs 63—67*

Run	Composition of product gas, vol. %						
	H_2	H_2O	CO	CH_4	CO_2	NH_3	N_2
63b	6.0	0.20	0.0	92.9	0.9	----	----
64c	5.0	0.20	0.0	93.2	1.6	----	----
66b	4.0	0.20	0.0	93.3	1.8	0.2	0.5
66c	21.8	0.20	0.0	77.2	0.0	0.3	0.5
67b	10.0	0.20	0.0	88.4	1.4	----	----

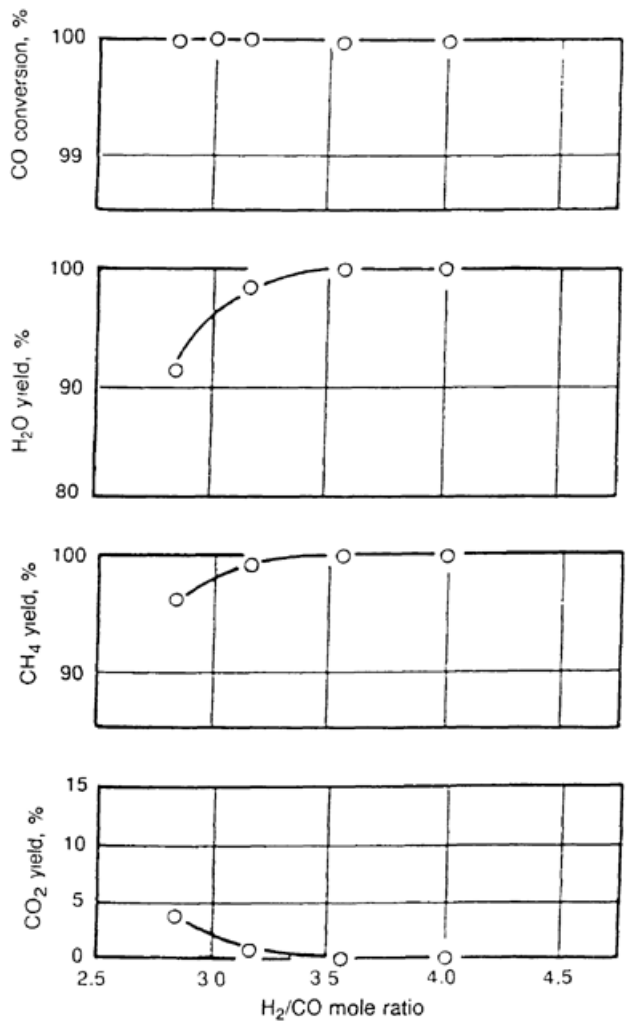


Figure 11

Carbon Monoxide Conversion and Yields vs. Hydrogen-Carbon Monoxide Mole Ratio *(1000 hr^{-1} space velocity; 250 °C; 1.0 atm)*

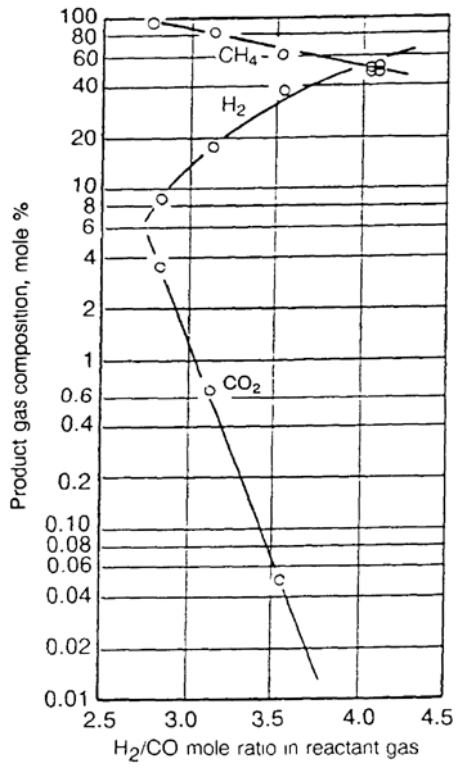


Figure 12

Product Gas Composition vs. Hydrogen-Carbon Monoxide Mole Ratio *(1000 hr^{-1} space velocity; 250 °C; 1.0 atm)*

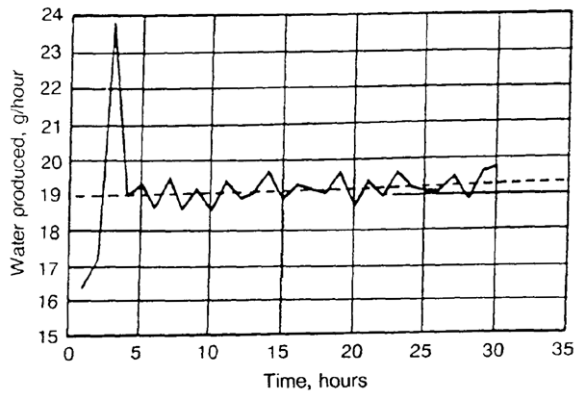


Figure 13

Water Production Rate vs. Time for Run 49 *(1000 hr^{-1} space velocity; 250 °C; 1 atm, 4:1 mole ratio)*

Temperature

Some catalyst activity was noted as low as 200 °C; the catalyst was found to be very active at 250 °C; so excellent conversions were obtained. Therefore, all the runs were made at a nominal catalyst bed temperature of 250 °C, except run 57, which was made at 350 °C. In run 57 we tried to increase the conversion at a 3:1 hydrogen-carbon monoxide mole ratio and a 1500-hr^{-1} space velocity by increasing the temperature; however, the conversion of carbon dioxide to methane and water decreased as the temperature was increased.

Pressure

The first nine runs were made at atmospheric pressure. The conversions were nearly complete at a 4:1 mole ratio even with space velocities of 2000 hr^{-l}. It was only at lower hydrogen-carbon monoxide mole ratios that the conversions decreased sufficiently to require raising the catalyst bed pressure. The last three runs were made at 6.1 atm to approach complete conversion at a 3:1 ratio. In comparing runs 54 and 55, it can be seen that increasing the pressure from 1 to 6 atm decreased the carbon dioxide yield from 0.8 to 0.4 percent and correspondingly increased the yields of water and methane.

Hydrogen-Carbon Monoxide Mole Ratio

The effect of hydrogen-carbon monoxide mole ratio on conversion and yields can be seen in figure 11. At a space velocity of 1000 hr^{-1}, at 250 °C and 1.0 atm, the catalyst gave complete conversion of carbon monoxide and carbon dioxide until we decreased the hydrogen-carbon monoxide mole ratio to less than 3.5:1. The carbon monoxide conversion remained complete but the carbon dioxide yield increased; at a 3:1 ratio, the carbon dioxide yield was approximately 2 percent.

The effect of hydrogen-carbon monoxide mole ratio on the product gas composition can be seen in figure 12. No carbon monoxide could be detected in the outlet gas for any of these runs. Within this range, the carbon dioxide content of the gas increased logarithmically as the hydrogen-carbon monoxide mole ratio was decreased below 3.5:1 (to about 1.5% at 3:1). The theoretical product yield at a 3:1 ratio is 100 percent methane, 0 percent hydrogen. The catalyst gave 85 percent methane, 13 percent hydrogen at the 3:1 ratio.

Space Velocity*

At a 4:1 mole ratio, no carbon dioxide was formed at space velocities up to 2000 hr^{-1}. At a 3:1 ratio, the carbon dioxide yield increased rapidly as the space velocity was increased above 1000 hr^{-1}.

Material Balance

With the exception of two runs, all overall material balances for the runs (see table 1) were under 100 percent. Most of the low material balances can be attributed to low water recoveries. Because the catalyst is known to be a good adsorbent for water, we hypothesized that some of the water was slowly being adsorbed on the catalyst. In order to prove that this was the case, a long-duration run (run 49) was made. See figure 13. The water production, which fluctuated about ±0.5 g/hr, gradually increased throughout the run (dotted line). After 30 hours, the liquid water production rate was 19.2 g/hr (about 96% of theoretical). At the rate of increase of water production (0.01 g/hr), it would have taken about 100 hr before the actual water production rate equaled the theoretical production rate. For long runs, the water balance should be no problem; in fact, we hypothesize that the small amount of water adsorbed on the catalyst may help to prevent carbon formation.

Heat Balance

In all runs, the majority of the heat was released in the initial third of the bed; however, in several runs at high space velocity (1500 or 2000 hr^{-1}) or low hydrogen-carbon monoxide mole ratios (3:1) or both, enough heat was released in the middle third of the catalyst bed to require some cooling. At the highest space velocities, temperature control was very difficult, because of the large amount of cooling air required to maintain the nominal catalyst bed temperature.

Pressure Drop

The relatively low pressure drop across the catalyst bed was excellent. It did not go up with time even at hydrogen-carbon monoxide mole ratios as low as 3:1. Run 49 was continued for 31 hours without shutdown; the pressure drop did not increase a measurable amount during this long period. The absence of a pressure buildup at the catalyst bed indicated no carbon deposition and a long, useful catalyst life.

* *Space velocity* is a measure of reactor capacity. It is the reciprocal of *space time,* which is defined as the time elapsed in processing one reactor volume of feed at specified conditions. Thus, *space velocity* is the number of reactor volumes of feed that can be processed within a given time. The higher the space velocity the better, provided the desired reaction occurs.

Catalyst Life

The catalyst was still active when it was removed after 14 runs (110 hr). As can be seen from the tabulation below, analyses of the catalyst before and after use showed no carbon deposition.

Time, hr	Carbon content of catalyst C-0765-1001-1, wt. %
0	5.08
110, initial third	5.02
110, middle third	5.11

As stated previously, there was no pressure buildup during the run, so this would not be a limiting factor on the life of the catalyst. However, impurities in the feed may prove to be a limiting factor. Temperature control is also vital, because carbon is definitely deposited on the catalyst at higher temperatures (400 °C and up). Catalyst life would probably be extended if the operating temperatures were started low when the catalyst was new and active and then gradually raised as the catalyst activity declined.

Catalyst Bed Length

At low space velocities, only the first inch or two of the catalyst bed was involved in the major portion of the reaction. As the space velocity was increased, more and more of the bed was involved until, at very high space velocities and low hydrogen-carbon monoxide mole ratios (runs 55 and 57), even the full length of the catalyst bed was unable to achieve complete conversion of carbon dioxide into methane and water. This effect is best shown by carbon dioxide gradients in the reactor taken for the various runs, as reported in table 3. Two additional advantages of a long catalyst bed are that it allows a margin of safety as the catalyst ages and becomes less active and that it allows the initial portion of the bed to act as a guard chamber to remove various catalyst poisons.

Lunar Surface Plant Design

Estimates of the weight and power requirements for a lunar surface plant using the Aerojet carbothermal process are given in this section of the paper. In making these estimates, we assumed that no water is present in, or obtainable from, the lunar material. Large differences in weight result when different cooling methods are employed, because of the large amount of waste heat produced.

Heat Rejection

Two different methods of heat rejection were considered in this study:

1. A dual-cycle refrigeration system to “pump” the heat up to a high rejection temperature
2. Direct heat rejection by radiation to space

The first method is based on standard refrigeration principles. It employs *n*-butane as the primary refrigerant, with water as the secondary refrigerant and the medium for transferring heat to a space radiator. Refrigeration is not used in the second method. Instead, we assume that a radiator is able to reject heat directly into 0 K space.

In the estimates for the different sections of the process, power requirements are given for these two different methods of cooling. In the following tables and figures, method 1 indicates the refrigerative technique and method 2 indicates the radiative technique. The details of the two methods are discussed later in this paper.

Reduction of Silicates With Methane

The estimates of heat and power requirements are based on the following changes:

$$MgSiO_{3(s)}\ (100\ °C) \longrightarrow MgSiO_{3(l)}\ (1627\ °C) \quad (5)$$

$\Delta H = 59.62$ kcal/mole

$$CH_4\ (500\ °C) \longrightarrow CH_4\ (1627\ °C) \quad (6)$$

$\Delta H = 21.76$ kcal/mole

$$H_2\ (500\ °C) \longrightarrow H_2\ (1627\ °C) \quad (7)$$

$\Delta H = 8.50$ kcal/mole

$$MgSiO_{3(l)} + CH_4 \longrightarrow 2CO + Si + MgO + 4H_2 \quad (8)$$

$\Delta H = 200.57$ kcal/mole $MgSiO_3$

The process flowsheet for this section is shown in figure 14.

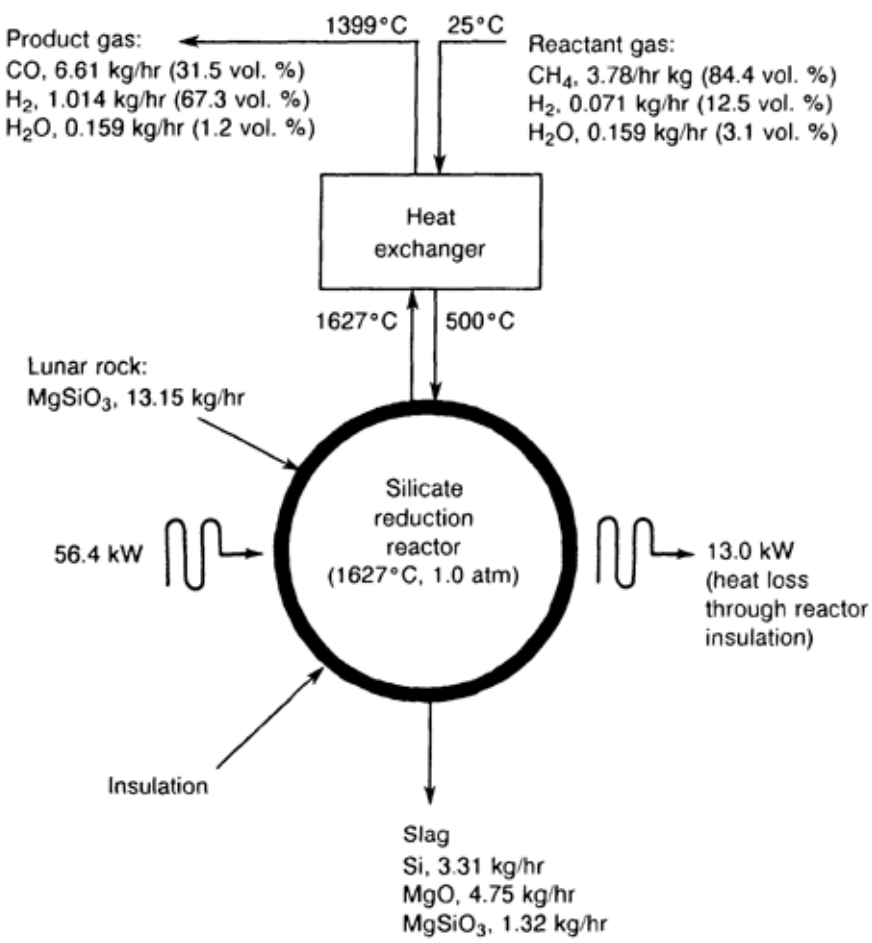


Figure 14

Silicate Reduction Reactor Section

Reduction of Carbon Monoxide

The estimates of heat and power requirements are based on the following changes:

$$CO + 3H_2 \xrightarrow{250\ °C} CH_4 + H_2O \quad (9)$$
ΔH = -51.61 kcal/mole

$$H_2\ (25\ °C) \longrightarrow H_2\ (250\ °C) \quad (10)$$
ΔH = 1.58 kcal/mole

$$CO(1399\ °C) \longrightarrow CO(250\ °C) \quad (11)$$
ΔH = -9.14 kcal/mole

$$H_2\ (1399\ °C) \longrightarrow H_2\ (250\ °C) \quad (12)$$
ΔH = -8.42 kcal/mole

$$CH_4(250\ °C) \longrightarrow CH_4(25\ °C) \quad (13)$$
ΔH = -2.25 kcal/mole

$$H_2O\ (250\ °C)_{(g)} \longrightarrow H_2O\ (25\ °C)_{(l)} \quad (14)$$
ΔH = -12.35 kcal/mole

The process flowsheet for this section is shown in figure 15. The operating temperature of 250 °C is used as a conservative value. Operating at higher temperature offers a modest advantage in reducing radiator weight.

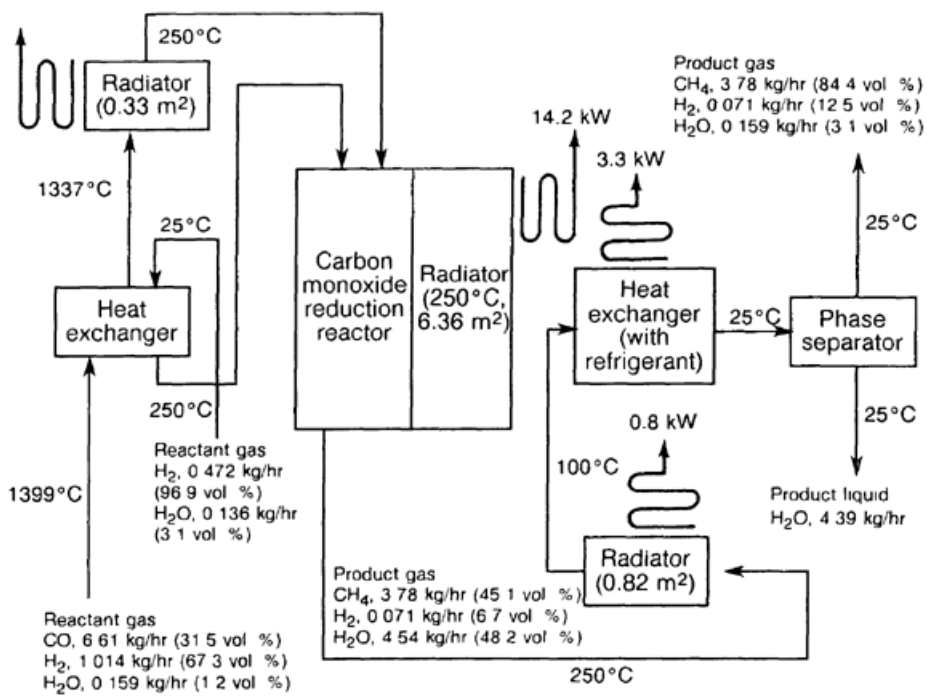
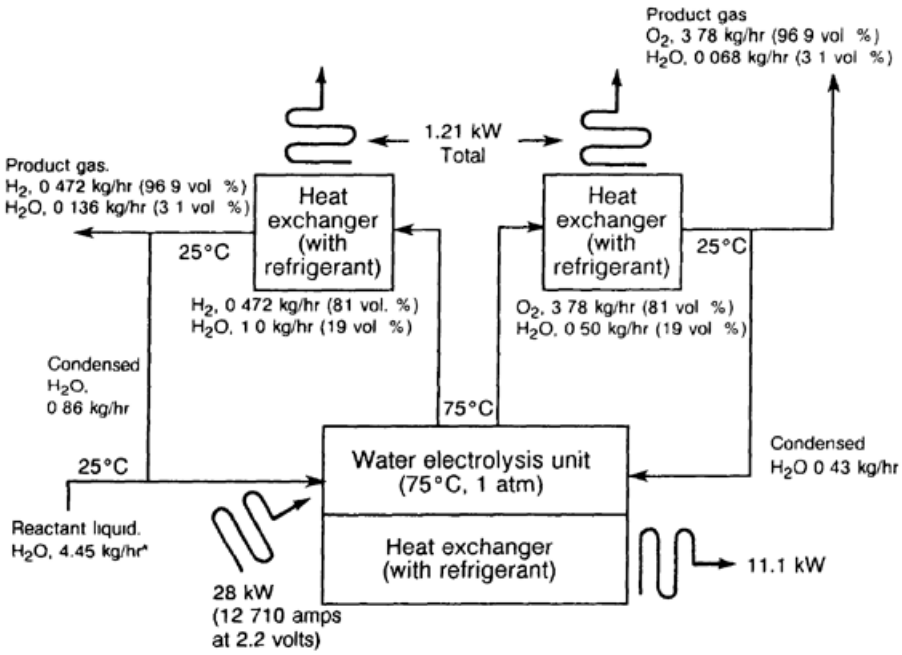


Figure 15

Carbon Monoxide Reduction Section

Water Electrolysis

Most of the weight of the electrolysis unit is that of the refrigeration cooling system and radiators used to reject low-temperature heat. The details of this section are shown in figure 16. A high-pressure electrolysis unit will allow operation at higher temperatures and higher efficiencies—a situation advantageous for both weight and power savings. However, the high-pressure electrolysis unit itself is heavier than a low-pressure unit and, because of added corrosion problems, requires considerably more maintenance. Consequently, detailed tradeoff analysis of low-pressure versus high-pressure electrolysis is needed.



* 4 25 kg/hr required for electrolysis
0.136 kg/hr recycled with hydrogen steam
0.068 kg/hr condensed in liquid oxygen cold trap and returned to electrolysis unit intermittently

Figure 16

Water Electrolysis Section

Oxygen Liquefaction

The oxygen liquefaction system is composed of Norelco type 12080 gas liquefiers. These units use helium as a refrigerant; some makeup helium is required. The details of this section are shown in figure 17. The amount of helium indicated in the tables is for a 1-year operation.

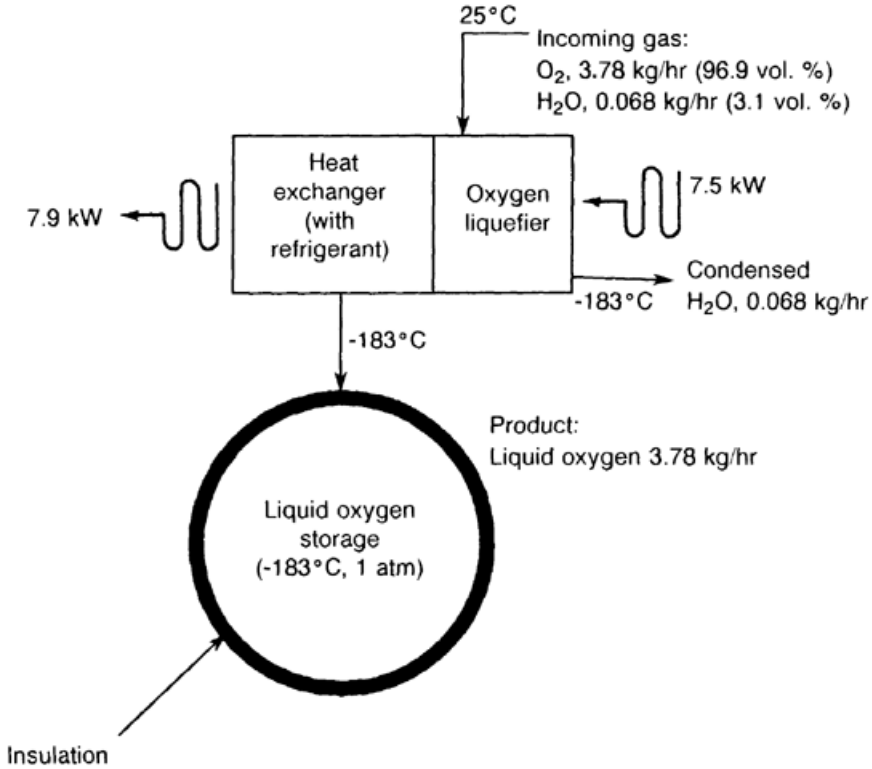


Figure 17

Oxygen Liquefaction and Storage Section

Oxygen Storage

The oxygen storage system consists of spheres of aluminum with walls 1.02 cm thick and an outer diameter of 3.20 m. Each sphere is capable of containing a 6-month supply of oxygen when it is produced at a rate of 2721 kg/month. These spheres are insulated to reduce boiloff. Boiloff oxygen is recondensed and returned to storage. The utilization of empty oxidizer storage tanks on lunar landing vehicles may eliminate the need for these storage spheres. Figure 17 summarizes the details of this section.

Refrigeration and Heat Radiation

The flowsheet for the refrigeration system used for method 1 cooling is shown in figure 18. The numerical values given are for a heat rejection rate of 0.29 kW. These values may be multiplied by the factor Q/0.29 to obtain correct values for any desired heat rejection rate of Q (kW).

Figure 18

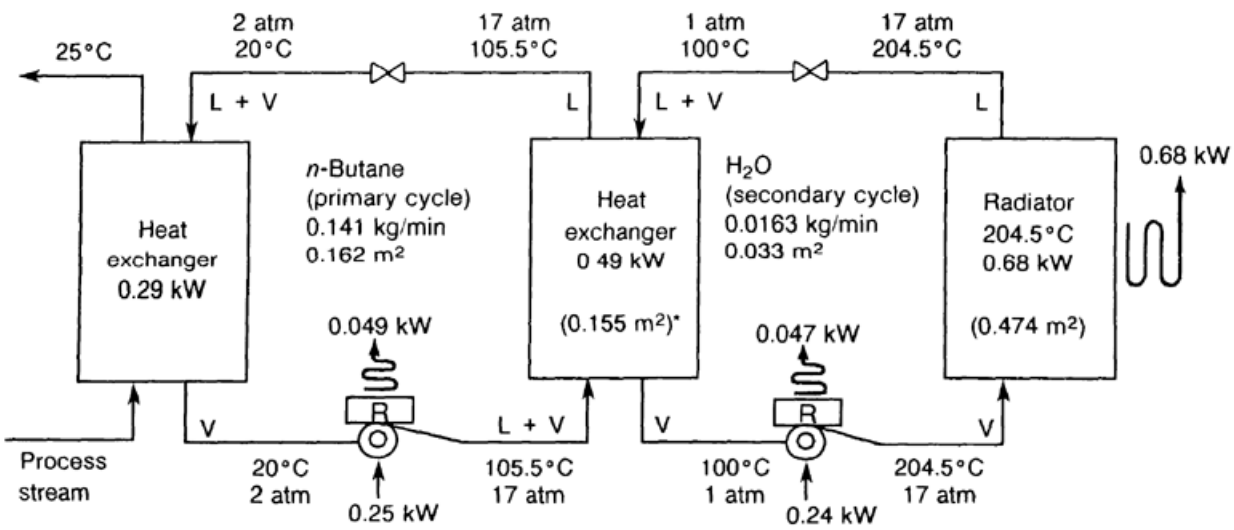
Refrigerative Cooling Method
(Dual Cycle)

|R| (O)\ = *compressor + radiator (compressor efficiency taken as 80%)*

—|><|— = *expander*

L = *liquid phase present*

V = *vapor phase present*



* For heat transfer between fluids

The liquid *n*-butane absorbs the heat at 20 °C (2 atm), vaporizes, and is compressed to 17 atm (105.5 °C). The stream gives up its latent heat to liquid water at 100 °C (1 atm) and condenses at 105.5 °C (17 atm). Upon flowing through the expander, the *n*-butane partially evaporates until its temperature and pressure are lowered to 20 °C (2 atm). It is then returned to the heat exchanger where the cycle is repeated.

The water cycle operates similarly but condenses within the radiator at 204.5 °C (17 atm) before it is recycled. The radiator operates continuously at this temperature. We assumed that the radiators would be stationary and lie parallel to the lunar surface, exposed to the full radiation of the overhead Sun (lunar midday)—an extremely conservative assumption.

The radiator material is assumed to have an absorptivity of 0.35 and an emissivity of 0.77. The heat rejection rates for this type of radiator are taken from "Lunar Logistic System" (MSFC 1963). The reported values are based on an estimated 80-percent efficiency. The radiator mass factors used in our estimates were 6.1 kg/m^2 surface area for a plain radiator, and 19.5 kg/m^2 surface area for a radiator with refrigeration. This latter value was also used for systems in which fluids condense or cool in tubes within or attached to the radiator. The 19.5 mass factor was obtained from "Lunar Logistic System" (MSFC 1963).

Compressor efficiencies are taken as 80 percent. The extra power required is rejected as heat from radiators attached to the compressors. Weights of standard compressor and motor units selected for use here were reduced by assuming that nonelectrical parts could be fabricated from lightweight aluminum alloys.

Refrigeration is not needed in method 2. The assumption is made that the radiator sees ~0 K space, either by being perpetually shadowed (for example, when located in depressions near the poles) or by being movable so as to present only an edge to the direct rays of the Sun. An iron-clad aluminum radiator would provide an emissivity of about 0.5 in a lightweight body. Reflectors on its underside and edge would prevent pickup of most of the radiation from the Moon's surface and from the Sun. The mass factor is taken as 9.8 kg/m^2 of surface. Once again, an 80-percent efficiency factor was used.

Total System Weight and Power

Table 6 lists the total system weights and power requirements for lunar oxygen plants of three capacities, using method 1 (refrigerative cooling). Table 7 does the same for method 2 (radiative cooling). The differences in weight and power requirements for the two methods are striking, indicating that heat rejection techniques are of major importance in lunar plant design. (See Abe Hertzberg's paper in volume 2, “Thermal Management in Space.”) In either case, scaling factors remain about constant.

TABLE 6. *Lunar Oxygen Plant Mass and Power Requirements, Using Refrigerative Cooling (Method 1)*

	Plant capacity (kg of O_2/Earth month)		
Section	2 720	5 440	10 880
Silicate reduction reactor, kg	344	533	943
Carbon monoxide reduction reactor, kg	415	829	1 659
Water electrolysis unit, kg	853	1 688	3 358
Oxygen liquefaction, kg	1 432	2 504	3 577
Refrigeration compressors, kg	445	789	1 406
Subtotal mass, kg	**3 489**	**6 343**	**10 943**
Liquid oxygen storage, kg	1 173	2 345	4 690
Total mass, kg	**4 662**	**8 688**	**15 633**
Silicate reduction reactor, kW	57.5	107.3	204.4
Water electrolysis unit, kW	28.0	56.0	112.0
Oxygen liquefaction, kW	7.5	15.0	22.5
Refrigeration compressors, kW	38.4	76.8	140.9
Total power, kW	**131.4**	**255.1**	**479.8**

TABLE 7. *Lunar Oxygen Plant Mass and Power Requirements, Using Radiative Cooling (Method 2)*

Section	Plant capacity (kg of O_2/Earth month) 2 720	5 440	10 880
Silicate reduction reactor, kg	344	533	943
Carbon monoxide reduction reactor, kg	278	555	1 110
Water electrolysis unit, kg	435	854	1 691
Oxygen liquefaction, kg	1 327	2 293	3 261
Subtotal mass, kg	**2 384**	**4 235**	**7 005**
Liquid oxygen storage, kg	1 173	2 345	4 690
Total mass, kg	**3 557**	**6 580**	**11 695**
Silicate reduction reactor, kW	57.5	107.3	204.4
Water electrolysis unit, kW	28.0	56.0	112.0
Oxygen liquefaction, kW	7.5	15.0	22.5
Total power, kW	**93.0**	**178.3**	**338.9**

This study indicates that a lunar plant employing the Aerojet carbothermal process to produce 2720 kg of oxygen per month would have a mass of approximately 4660 kg and require 132 kW_e using refrigeration cooling; a similar plant using radiative cooling exclusively would have a mass of approximately 3561 kg and require 93 kW_e. All estimates are based on a conservative approach to the problem.

Labor Estimates

We estimate that it will take no more than 8 hours' work to operate and maintain any of the three plants under study for 24 hours. One month of plant operation will require 240 work-hours. Based on a cost of $500 000/work-hour, the labor cost for the manufacture of 1 kg of oxygen using the 2 720-kg, 5 440-kg, and 10 880-kg capacity plants is $44 000, $22 000, and $11 000, respectively (1989 dollars).

Cost Comparisons

The dollar costs for the manufacture of oxygen on the Moon can be compared with the cost of delivering oxygen from the Earth by using a labor cost of $500 000/work-hour and a transport cost of $54 000/kg of payload. This cost comparison is given in table 8. The manufacture of 2720 kg of oxygen per month for 1 year would cost $1.71 billion (method 1, most conservative estimate), while the transport of an equivalent amount of oxygen would cost $1.80 billion.

TABLE 8. *Cost* Comparison: Lunar Oxygen Manufacture Versus Earth-Moon Oxygen Transport (1-Year Cost Savings)*

Plant capacity, kg O_2/Earth month	2 720	5 440	10 880
Kilograms of O_2 per year	32 640	65 280	130 560
$Cost of delivered O_2 [a]	$1\ 770 \times 10^6$	$3\ 536 \times 10^6$	$7\ 079 \times 10^6$
$Cost of plant delivery [a,c]	251×10^6	472×10^6	846×10^6
$Cost of labor [b]	$1\ 430 \times 10^6$	$1\ 430 \times 10^6$	$1\ 430 \times 10^6$
$Saved by lunar O_2 plant [c]	88×10^6	$1\ 637 \times 10^6$	$4\ 803 \times 10^6$
$Saved by lighter lunar O_2 plant [d]	147×10^6	$1\ 750 \times 10^6$	$5\ 088 \times 10^6$

*Original 1965 dollars have been converted to 1989 dollars using the NASA R&D inflation factor of 4.916 (~5).

[a]Delivery costof $54 000/kg

[b]Labor cost of $500 000/work-hour for 1/3 year

[c]Refrigerative cooling, method 1

[d]Radiative cooling, method 2

The cost of storing oxygen on the Moon is included in the cost of manufactured oxygen but not in the cost of transported oxygen. Utilizing propellant tanks from lunar landing vehicles to store oxygen on the Moon would reduce the cost of manufactured oxygen but not affect the cost of transported oxygen. If the storage cost were not included, the cost difference would be greater.

The data reported in table 8 dramatically indicate that much greater dollar savings will be realized by the manufacture of propellant oxygen on the Moon as the oxygen requirements are increased above 2720 kg/month.

Conclusion

We have shown with laboratory experimentation that the Aerojet carbothermal process is feasible. Natural silicates can be reduced with carbon or methane (see Rosenberg et al. 1965c for methane results). The important products are carbon monoxide, metal, and slag. The carbon monoxide can be completely reduced to form methane and water. The water can be electrolyzed to produce hydrogen and oxygen. A preliminary engineering study shows that the operation of plants using this process for the manufacture of propellant oxygen has a large economic advantage when the cost of the plant and its operation is compared to the cost of delivering oxygen from Earth.

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Processing Lunar Soils for Oxygen and Other Materials

Christian W. Knudsen and Michael A. Gibson

Two types of lunar materials are excellent candidates for lunar oxygen production: ilmenite, $FeTiO_3$, and silicates such as anorthite, $CaAl_2Si_2O_8$ (Kesterke 1971, Williams et al. 1979, Williams and Erstfeld 1979, Steurer 1982, Carroll 1983). Both are lunar surface minable, occurring in soils, breccias, and basalts. Because silicates are considerably more abundant than ilmenite, they may be preferred as source materials. Depending on the processing method chosen for oxygen production and the feedstock material, various useful metals and bulk materials can be produced as byproducts. Available processing techniques include hydrogen reduction of ilmenite and electrochemical and chemical reductions of silicates (Williams and Jadwick 1980, Williams 1985). Processes in these categories are generally in preliminary development stages and need significant R&D support to carry them to practical deployment, particularly as a lunar-based operation.

The goal of beginning lunar processing operations by 2010 requires that planning and R&D emphasize the simplest processing schemes. However, more complex schemes that now appear to present difficult technical challenges may offer more valuable metal byproducts later. While they require more time and effort to perfect, the more complex or difficult schemes may provide important processing and product improvements with which to extend and elaborate the initial lunar processing facilities. A balanced R&D program should take this into account.

Ilmenite—Semicontinuous Process

Primary hydrogen reduction of ilmenite is possible in a relatively clean reaction utilizing one-third of the contained oxygen (Williams and Erstfeld 1979):

$$FeTiO_3 + H_2 \surd Fe^0 + TiO_2 + H_2O$$

Hydrogen would be imported from Earth and the resultant water would be electrolyzed to produce oxygen and recycle the hydrogen. If there are gaseous losses, hydrogen is perhaps the easiest material to make up since it must be transported from Earth for propulsion use.

The biggest limitation to this process is the low equilibrium conversion of this reaction. Relatively small water vapor pressures will stop the reduction and cause it to reverse. One way to enhance conversion has been proposed by Williams (1985). It involves using heat removal to reduce the water partial pressure by condensation in a cold trap, with the water partial pressure limited to its vapor pressure at trap temperature. As water is formed in the reactor, a water vapor pressure gradient is established, and water vapor diffuses from reactor to cold trap and condenses. If diffusion and heat removal rates are fast enough in relation to the water formation rate, the reactor water vapor pressure can be held lower than its equilibrium value at reactor temperature and this lower vapor pressure leads to a higher hydrogen conversion for a given reactor temperature. Oxygen would then be produced and hydrogen regenerated by electrolyzing the liquid water. Diffusion calculations indicate, however, that the vapor pressure cannot be lowered in a system with large enough dimensions to be practical.

Ilmenite—Continuous Fluid-Bed Reduction

Given the same ilmenite reduction reaction carried out in a reactor with continuous feeding of fresh ilmenite, withdrawal of spent ilmenite, and recirculation of hydrogen gas as both the fluidizing and the reducing medium, a continuous system can be conceived (see fig. 19) if a suitable high-temperature electrolyte can be found to continuously electrolyze the water vapor formed. Zirconium oxide stabilized with either calcium oxide or yttrium oxide appears to be a suitable electrolyte (Weissbart and Ruka 1962, Smith 1966). The high heat-transfer coefficients expected in this process between the gas and the fluidized solids would reduce the necessary size of the equipment. However, this scheme requires the retention of fine reactor solids and high-pressure hydrogen gas and the use of rotating machinery to circulate the hydrogen and to feed the solids. These requirements lead to operational complexities.

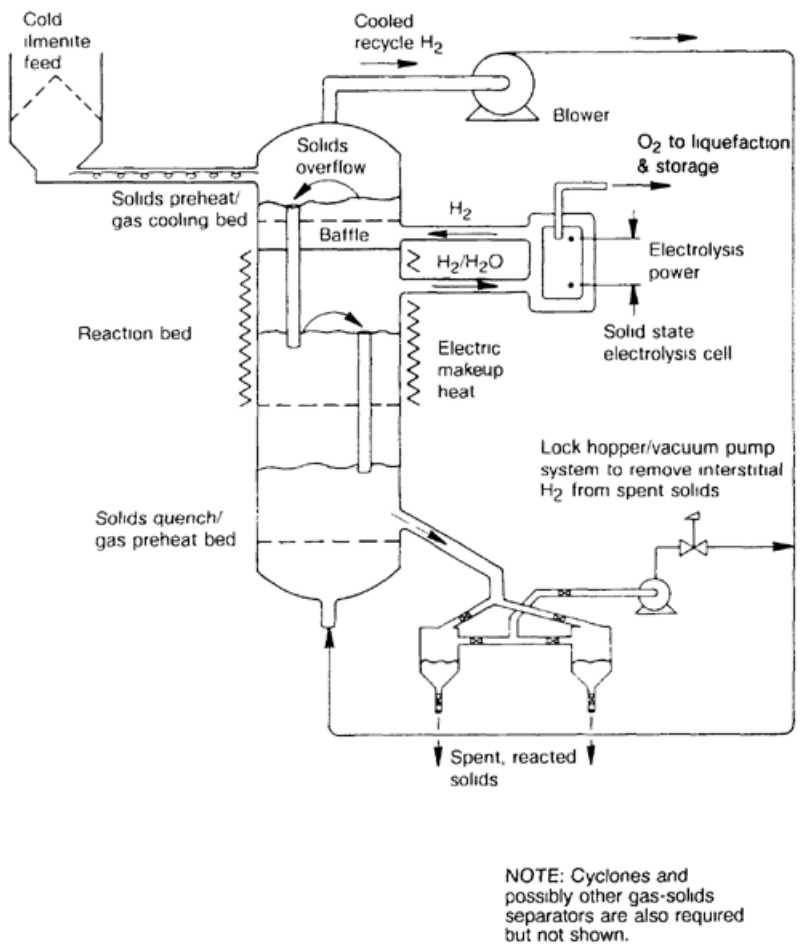

Figure 19

Oxygen From Lunar Ilmenite

In this concept for a lunar oxygen plant, ilmenite ($FeTiO_3$) is concentrated from lunar regolith and then fed into a three-stage fluidized bed. In the upper stage, the ilmenite concentrate is preheated by hot hydrogen passing through the powdered ilmenite. The hot ilmenite then goes into the second stage, which is the main reactor bed. Here, even hotter hydrogen reacts with the ilmenite, extracting one oxygen atom from each ilmenite molecule, forming H_2O, metallic iron (Fe), and TiO_2. The H_2O and excess hydrogen are extracted and circulated through an electrolyzer, which breaks down the H_2O. The released oxygen is then cooled, compressed, and stored as liquefied oxygen. The spent feedstock enters the third stage, where heat is extracted by hydrogen gas before the spent material is dumped from the reactor.

Utilization of Spent Ilmenite To Produce Bulk Materials

The hot, partially reduced ilmenite exiting the direct-reduction reactor might be pressed into blocks or bricks for use in structures or shielding. Further heating may be necessary in the pressing operation. Evidence of successful hot pressing of brick-making shales and fireclays (Crayton and Brownell 1974) and of ashes from the combustion of coal mine wastes (Gartner 1979) into structurally strong blocks or bricks indicates that this utilization of spent ilmenite should be investigated.

Silicates—Electrochemical Reduction

In the case of silicates, hydrogen reduction is not thermodynamically favorable and proposed processing steps include direct electrochemical reduction, reduction with carbon plus chlorine, reduction with aluminum, and reduction with methane (Kesterke 1971; Carroll 1983; Colson and Haskin, immediately following; Williams and Erstfeld 1979; Anthony et al. 1988; Rosenberg et al., immediately preceding).

Kesterke studied direct electrochemical reduction to extract elemental oxygen from silicate-bearing melts experimentally. He used an iridium anode and LiF/BaF_2 fluxing agents in a molten electrolyte/silicate bath at 1050 to 1250 °C. Molecular oxygen was produced directly at the anode, but Kesterke found that fuming led to loss of volatile LiF from the electrolyte cell. More importantly, Kesterke concluded that the recovery of the fluoride fluxing agents from the spent electrolyte bath was prohibitively complex. Given experimental observation that SiO_2, the major oxide constituent of Kesterke's melt, experienced little electroreduction, we conclude that large quantities of flux would have to be supplied from Earth or suitable substitutes found on the Moon near the facility.

In all of Kesterke's experiments, a solid deposit of varying size accumulated on the cathode. In this deposit, iron, aluminum, sodium, silicon, and barium were major constituents; manganese, titanium, calcium, molybdenum, and boron were present in significant quantities (the boron and molybdenum probably came from the experimental apparatus); and nickel, zirconium, copper, and

chromium were present in lesser amounts. Iron would probably be the first metal produced from a lunar melt since it is the first major product of sequential electrolysis. Further electrolysis of the iron-free melt might yield other metals when processes are perfected.

Further work (including Carroll 1983) suggests that electrolysis techniques may be developed without fluxing materials and with a nonconsumable anode for oxygen production (see the paper immediately following by Colson and Haskin). Preliminary experiments indicate that molten rock or soil is conductive enough to support electrolysis.

Lunar application of electrolysis would yield oxygen directly as well as a number of important metals. Considerable improvement of electrode and containment materials are needed, as are lunar-derived fluxing materials for processes requiring a flux. Ultimately, development of a continuous or semicontinuous process would be desirable to provide uniform product quality and significant production rates.

Silicates—Chemical Reduction

The carbon-plus-chlorine silicate reduction process has several technical difficulties, as outlined in Williams and Erstfeld's thermodynamic study (1979). First, there are uncertainties about the numerous possible products of a high-temperature reaction of chlorine with complex silicates and carbon and about the ability to regenerate the chlorine and carbon quantitatively. Second, the oxygen must be extracted by high-temperature electrolysis of a CO/CO_2 mixture, which will deposit carbon that will probably be hard to remove continuously. Finally, a solid electrolyte of stabilized zirconium oxide (the probable choice for the CO/CO_2 electrolysis) is likely to be corroded severely to $ZrCl_4$ when in contact with hot, chlorine-bearing gases.

More recently (1988), Anthony and colleagues have developed a process that uses aluminum metal to reduce silicon in an anorthite-rich melt containing a flux (see fig. 20). The aluminum oxide is decomposed by electrolysis,

producing oxygen and metallic aluminum, which is then recycled. Because anorthite contains abundant aluminum, excess aluminum is produced by the process and can be recovered either as a metal or as an alloy with silicon. Calcium or calcium oxide is subsequently removed from the melt, so the flux can be recycled.

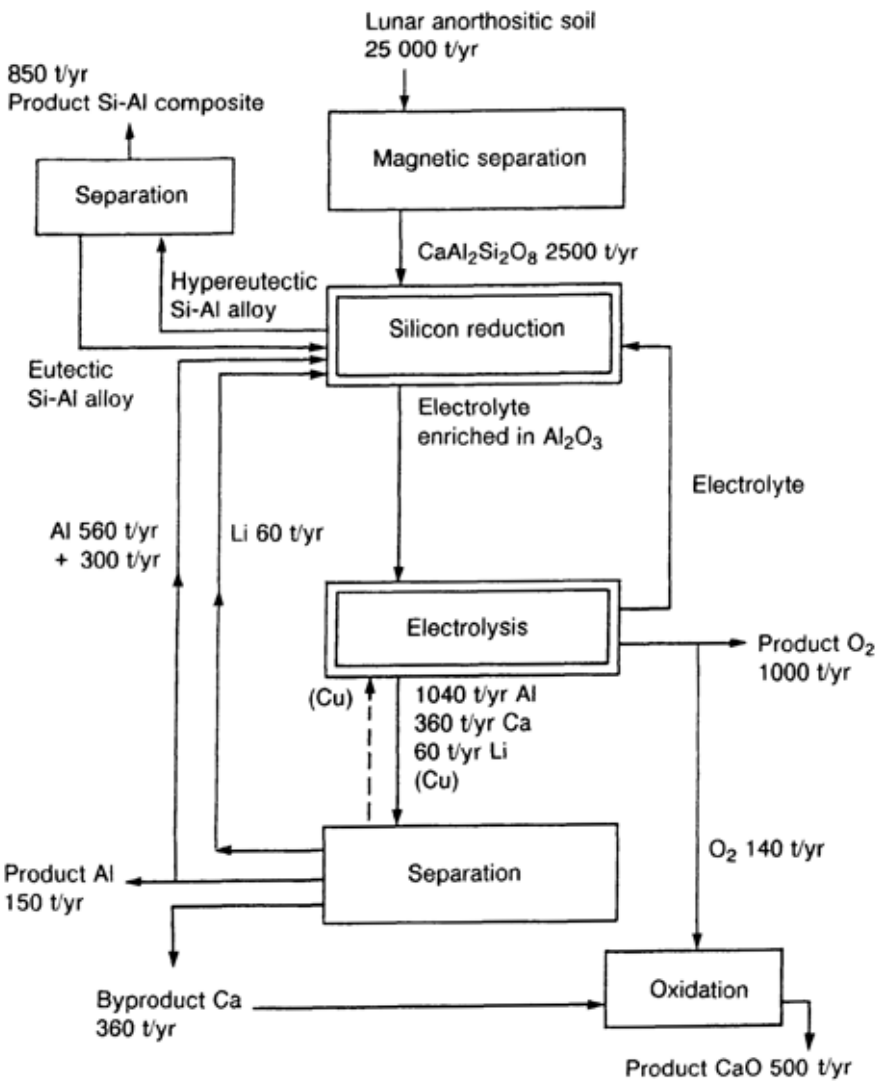

Figure 20

EMEC Process To Produce Oxygen and Byproducts From Lunar Anorthositic Soil

This plant, conceived by EMEC Consultants, is scaled to produce 1000 metric tons of oxygen per year. As byproducts, such a plant will also produce a silicon-aluminum alloy (suitable for casting into structural beams), pure aluminum, and calcium oxide (suitable for use in cement).

The process uses aluminum metal to reduce the plentiful silicon in the mineral anorthite, the most abundant mineral on the Moon. The aluminum oxide is subsequently separated into aluminum and oxygen by electrolysis. Some of the aluminum is recycled to produce more silicon, and some can be used for construction purposes. The calcium from the anorthite can be separated and reoxidized to form an important constituent of cement.

The EMEC process has the advantage that it can produce elemental silicon, elemental aluminum, and casting alloys of silicon and aluminum with low melting temperatures. Also, it can use most of the soil or rock as feedstock, if appropriate highland sites are chosen. This process has the disadvantage that it does require some feedstock beneficiation to eliminate most of the iron-rich minerals. Other disadvantages are that it must have inert electrodes that will not dissolve in the molten flux and it involves a somewhat complex step to recover the flux from the calcium oxide or calcium metal. However, the process is still attractive and the technology can borrow heavily from the existing aluminum-producing industry.

Carbothermal or methane reduction is another process that appears to have potential. It is proposed to operate at approximately 1625 °C on molten silicates (Rosenberg et al., immediately preceding; see also NASA handout 1972). This process has the advantage of utilizing the whole soil, not just a beneficiated portion; thus, it requires the processing of a smaller amount of lunar soil. It does introduce corrosion problems. But perhaps the biggest challenge is the complexity and large heat exchange surface required because the methane must be regenerated at about 250 °C by hydrogen reduction of carbon monoxide. Exothermic heat from this lower temperature step cannot be used to drive the primary reduction, which proceeds only at much higher temperatures. Nevertheless, methane reduction is clearly a viable candidate among the various chemical reduction processes proposed for silicates, especially if a use for lower level heat is available.

Summary

Of the processes discussed, ilmenite reduction appears to offer the most straightforward chemistry, the lowest operating temperature, the least materials problems, and the easiest to replicate working fluid. Its development needs to be pursued, but other processes need to be advanced simultaneously to develop a variety of processing routes and product possibilities.

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Oxygen From the Lunar Soil by Molten Silicate Electrolysis

Russell O. Colson and Larry A. Haskin*

Introduction

In 1835, a lunar fantasy published as a factual account in the New York *Sun* (see French 1977) generated great economic interest in the Moon. This fantasy reported, among other things, the existence of huge gems on the Moon. Within a few weeks the story was shown to be a hoax, but the interest it generated remained. Now, the Apollo missions have dimmed hopes that such traditional treasures will be found on the Moon. These missions provided no evidence that the Moon ever experienced the plate tectonic processes or the major water and gas transport processes which have produced most gem minerals and ore deposits on Earth. Even if gem minerals and ore deposits had formed, they would probably have been destroyed or dispersed by meteoroids hitting the surface of the Moon. Besides, the cost of acquiring gems from the Moon will be prohibitive for the foreseeable future; if the most common lunar rocks were sold as souvenirs, they would carry a higher price than rubies.

Nevertheless, just as it was not the fantastic Fountain of Youth but rather the real land and plentiful natural resources that proved to be the wealth of the New World, so the treasures of the Moon will be found in less romantic notions. "Water is worth more than gold to a parched desert wanderer," runs a trite statement. But the statement is true for the Moon, and for the Moon can be extended to include oxygen. In fact, production of lunar oxygen for life support and fuel in low Earth orbit and beyond is already seen as an economic incentive to build a Moon base (e.g., Mendell 1985).

In general, because of the high energy cost of launching material into space from Earth's substantial gravity well, materials already in space (on the Moon, for example) gain value for construction projects there. Such materials could be used "as found" or after only simple processing. Lava tubes on the Moon could serve as early lunar shelters (Hörz 1985). In near-Earth space, lunar basalt could be used as heat shielding for vehicles reentering the Earth's atmosphere and could provide built-in protection for orbiting platforms (e.g., Nozette 1983). More extensively processed bulk materials for space construction might include concrete (see Lin 1985 and also Lin's subsequent paper in this volume) and glass (Blacic 1985) from the Moon.

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Also because of the high cost of exporting materials from the Earth to the Moon, it is reasonable to imagine that a Moon base would, in the longer term, approach self-sufficiency, as eloquently proposed in the book *Welcome to Moonbase* (Bova 1987). What lunar resources make such a scenario feasible? The answer is found in the most common materials and conditions known on the Moon—the soil, the rocks, and the reliable supply of sunlight.

All the common soils on the Moon are rich in oxygen (about 45% by weight), silicon (about 21%), iron (6 to 15%), aluminum (5 to 13%), calcium (8 to 10%), magnesium (about 5%), and titanium (up to 6%). No ore bodies like those found on Earth have been proven to exist on the Moon, but some rock types have concentrated certain minerals; namely, ilmenite (rich in iron, titanium, and oxygen), anorthite (rich in calcium, aluminum, silicon, and oxygen), and olivine and pyroxene (rich in magnesium, iron, silicon, and oxygen). The chemical elements these soils and minerals contain are valuable in applications that range from construction to propulsion. And it may be economically possible to extract volatile elements present at low concentrations (such as carbon, hydrogen, and nitrogen) by heating the lunar soil (e.g., Haskin 1990).

The most promising early use for lunar resources is likely to be for energy. Energy for space transportation can come from lunar oxygen and hydrogen. Proposed energy exports include solar energy collected on the Moon and converted to microwaves (e.g., Criswell and Waldron 1985) and fuel in the form of ^{3}He for nuclear energy (e.g., Wittenberg, Santarius, and Kulcinski 1986) as well as chemical propellants (e.g., Thompson 1951, Arnold 1980, Mendell 1985). Considerable interest in chemical propellants has revolved around the extraction of oxygen (Mendell 1985), the most abundant and possibly the most immediately valuable of these lunar energy resources. It will be used as oxidant for fuel in the Earth-Moon system, and perhaps ultimately for flights to Mars if it can be provided at less cost than oxygen brought from the Earth (see, for example, Davis 1983 and Mike Simon's paper in volume 2, "Utilization of Space Resources in the Space Transportation System").

Oxygen From the Moon

Accepting, then, that oxygen, rather than gigantic gems or gold, is likely to make the Moon's Klondike, we have chosen to investigate the extraction of oxygen from the lunar soil. Unlike the Klondike, this strike will not be made by the prospector

who discovers the location of the oxygen ore, for it is everywhere on the Moon. This strike will be made by the inventor who discovers the robust, economical process for extracting the oxygen. We think the process that will pan out will be electrolysis of molten soil. (See figure 21.) We are investigating it because it is conceptually simple and because its nontraditional character fits the nontraditional lunar materials and conditions.

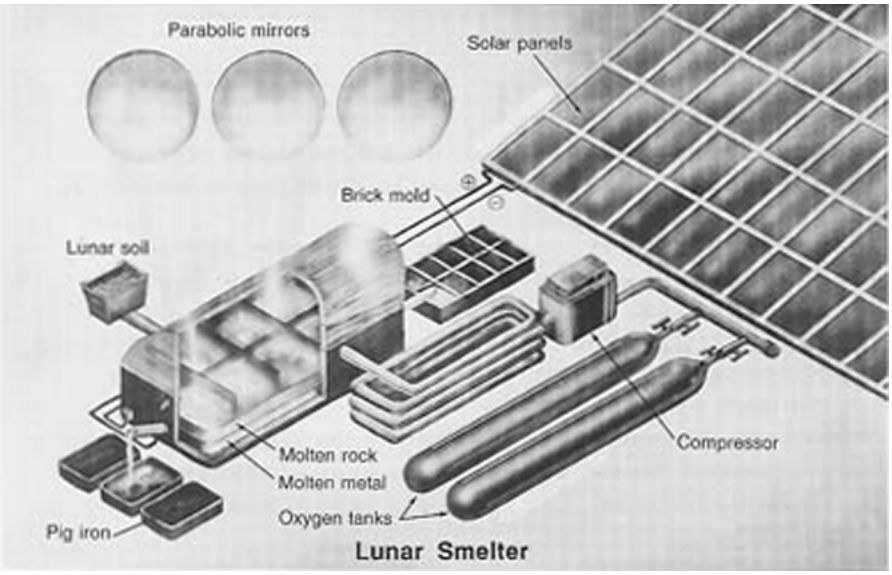

Figure 21

Electrolysis of Lunar Soil To Produce Oxygen and Iron (and Bricks)

In this early concept of the direct (without a flux) electrochemical reduction of lunar silicates, solar heat is used to melt the initial batch of lunar soil. Solar energy is also captured by panels of solar cells and turned into electricity, which charges both the anode and the cathode of the electrolysis unit. (We now think nuclear power may be more practical. In the absence of an efficient solar energy storage device, nuclear power would be needed to continue the electrolysis during the lunar night.) The oxygen that evolves at the nonconsumable anode is compressed and stored as a liquid. The molten metal that gathers at the cathode (itself molten metal) is bled off to form pig iron and other alloys. The residual slag might be formed into bricks or beams for structural purposes.

Illustration: Washington University in St. Louis

In our study of molten silicate electrolysis, we have taken the approach that the first step in developing the process is to understand its fundamental chemistry. This includes understanding the primary reactions that take place at the electrodes, the kinetics and energies of those reactions, competing reactions that might reduce the efficiency of oxygen production, and how melt resistivity changes with temperature and melt composition. The answers to these questions tell us whether the process is theoretically viable and competitive, presuming appropriate technologies can be developed to implement the process in real life and minimize dynamic problems arising during electrolysis (such as remixing of the product with the feedstock or insufficient mixing of the silicate melt). We have also begun investigating other specific questions about silicate melt electrolysis, such as durability of container and electrode materials and the nature and composition of the product. Our results are summarized here and are reported in more detail in Haskin et al. 1990, Colson and Haskin 1990, and Haskin and Colson 1990.

Process Theory

In molten silicate electrolysis, metal cations are reduced at the cathode to form metals, and silicate polymer chains are oxidized at the anode to form oxygen. The primary cathode reactions that produce metal are the following:

$$Fe^{2+} + 2\,e^- \rightleftarrows Fe^0 \quad (1)$$

$$Si(IV) + 4\,e^- \rightleftarrows Si^0 \quad (2)$$

The primary anodic reaction producing oxygen is reaction (3).

$$4\,(SiO^-) \rightleftarrows 2(Si\text{-}O\text{-}Si) + O_2 + 4\,e^- \quad (3)$$

The kinetics of these reactions are fast compared to the current densities expected in actual electrolysis, and reaction kinetics is not a serious constraint on the electrolysis process.

The efficiency of production is decreased and the energy required to produce a given amount of product correspondingly increased because of competing reactions at the anode and cathode. The most serious competing reaction at the anode in melts with high iron concentrations is oxidation of Fe^{2+}.

$$Fe^{2+} \rightleftarrows Fe^{3+} + e^- \quad (4)$$

The efficiency of oxygen production (defined as moles O_2 produced/ 4 times moles electrons* passed through the melt) depends primarily on the concentration of Fe^{2+} cations, with efficiency of oxygen production decreasing as Fe^{2+} increases.

The electrical conductivity of the melt also has a significant effect on the power requirement of the electrolysis process. We investigated the dependence of melt conductivity on melt composition and found that conductivity increases in a predictable fashion as the proportions of the oxides of silicon and aluminum in the melt decrease and as the proportions of the oxides of iron, magnesium, and calcium increase.

Power Requirements

The power requirement for molten silicate electrolysis can be numerically related to the oxygen production efficiency, the melt conductivity, and the dimensions of the electrolysis cell as follows, Power to drive the electrolysis equals E • I, where I, the current required to get oxygen at the desired rate, is proportional to oxygen production rate/oxygen production efficiency. E, the potential required to drive the electrolysis, is roughly equal to $E_c - E_a - I(R_{cell})$, where $E_c - E_a$, the potential required to drive the reaction(s), is a function of the cation reduced (the absolute value of $E_c - E_a$ increases in the order Fe < Si,Ti < Mg,AI < Ca) and the concentrations of the cations in the melt. R_{cell}, the resistance of the electrolysis cell, is equal to $L/\kappa A$, where L is the distance between electrodes, A is the electrode surface area, and κ is the melt conductivity.

Calculated from this relationship and those above, the energy requirements expected for a realistic range of the variables L, A, O_2 eff, and κ are shown in figure 22. A comparison is made to energy requirements estimated for other processes. The estimated energy requirements for the molten silicate electrolysis process compare favorably with those for other processes even at the less favorable end of the range for the selected critical variables.

*A mole of electrons is Avogadro's number (6.023×10^{23}) of electrons.

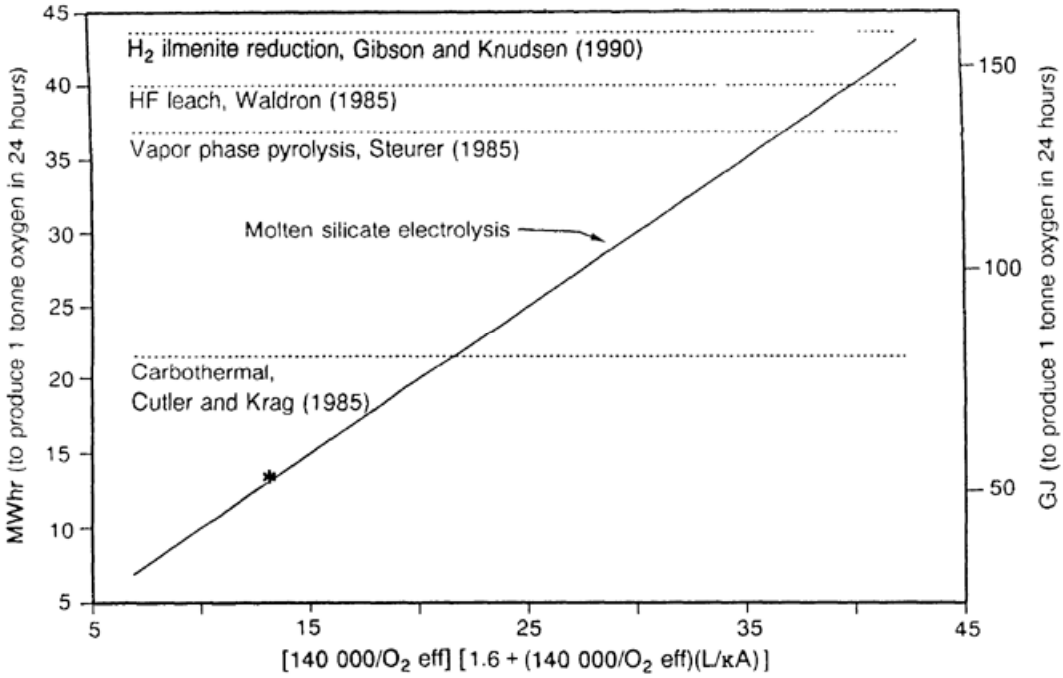

Figure 22

Energy Requirements for the Molten Silicate Electrolysis Process

The energy requirements for the molten silicate electrolysis process for extracting oxygen from lunar soil depend on the variables L (distance between electrodes), A (surface area of electrodes), O_2 eff (efficiency of oxygen production, defined in the text), and κ (melt conductivity).

The abscissa plots a term which numerically models the dependence of energy required for the electrolysis on these designated variables, as described in the text and in more detail in Haskin et al. 1990 and Colson and Haskin 1990. It can be seen from the expression that the energy requirement increases as O_2 eff, κ, and A decrease and L increases. The range of values along the abscissa is a range we believe can realistically be achieved. The range is from O_2 eff = 90%, $\kappa = 1\ cm^{-1}\ ohm^{-1}$, $A = 30\ m^2$, and L = 0.5 cm to O_2 eff = 50%, $\kappa = 0.08\ cm^{-1}\ ohm^{-1}$, $A = 30\ m^2$, and L = 1 cm.

Presumably, an operating electrolysis cell could be maintained such that values for O_2 eff, κ, A, and L are the most advantageous (require the least energy).

The energy requirement calculated by Haskin et al. (1990) for a hypothetical electrolysis of a lunar soil is shown by an asterisk.

The term plotted along the abscissa has no bearing on the energy values reported for the alternative processes, which are shown for comparison purposes. These values are arbitrarily drawn as horizontal lines because they do not depend on the abscissa variables. It is seen that the energy required by the molten silicate electrolysis process compares favorably with that estimated for alternative processes.

Products of Molten Silicate Electrolysis

We have identified several products of silicate electrolysis, partly on the basis of our experiments and partly on the basis of phase diagrams for equilibrium processes. The main products are oxygen produced at the anode and a suite of metals and metal alloys produced at the cathode and consisting of iron, silicon, or iron-silicon alloys containing 0.2–1 percent titanium and chromium. The metal compositions vary as a function of imposed potential and magma composition. (Theoretically, but not yet observed in our experiments, aluminum, magnesium, and calcium could be reduced at increasingly negative potentials and at higher melt temperatures.)

The mineral spinel precipitates from the residual melt at sufficiently low temperature or with sufficient removal of silicon and oxygen. This material varies in composition from an iron- and chromium-rich spinel to a magnesium- and aluminum-rich spinel, depending on the composition of the magma and the extent of electrolysis.

The remaining molten silicate will be an important byproduct; it can be cast into bars, beams, and sheets, or its CaO- and MgO-enriched composition may make it suitable for use in cements. The so-called “waste heat” carried off with the products or radiated by the cell is another potentially useful byproduct.

Electrode and Container Materials

The primary disadvantage of the molten silicate electrolysis process is that these high-temperature silicate melts are very corrosive, and suitable materials for containers and electrodes are yet to be tested. We discuss here four general types of possible electrode or container materials.

One type of material is simply inert to the silicate and its products. As an example, platinum has been used extensively in experimental petrology as an inert container for silicate melts at temperatures as high as 1650 °C. However, although platinum does not react with silicate melt, it does combine with silicon to form an alloy that melts below 1000 °C. Because silicon is expected to form at the cathode and accumulate in the container, platinum is unsatisfactory as a cathode or container. Platinum does appear to be a suitable anode material (Haskin et al. 1990).

The second type of material involves a steady-state equilibrium. An “iron skull” container or cathode could be formed by balancing the heat generated by the electrolysis with heat lost to

the surroundings to form a solid skin of product or feedstock enclosing the silicate melt and metal product.

The third type of material would be in thermodynamic equilibrium with the silicate melt and electrolysis products and would therefore not react with them. Because the product is Si-Fe metal, Si-Fe alloys might serve as the cathode material (Haskin et al. 1990). Similarly, the presence of spinel ($MgAl_2O_4$) on the liquidus of the residual silicate of the electrolysis process suggests the use of spinel as the containing material.

The fourth type of material would be destroyed by the process, but slowly. This option detracts from one of the intended advantages of unfluxed silicate electrolysis—the absence of any need to resupply reagents or other materials from Earth or to recover them from the products. Nevertheless, such an option may prove to be the most cost-effective.

Problems and Work Yet To Be Done

As discussed above, our first steps in the study of molten silicate electrolysis have been to investigate the fundamental chemistry of the electrolysis and to address some specific questions such as the product composition. We have not addressed certain complexities of the process such as (1) problems that might arise in scaling up from our small experiments to a factory-size process, (2) the problem of designing a system that will effectively transfer the corrosive electrolysis products from the cell, (3) the problem of maintaining the cell at high temperature so that the silicate melt does not freeze and destroy it, (4) the problem of getting ore from the lunar surface to the cell, and (5) the still untested state of our proposed container and electrode materials. Our purpose thus far has been not to demonstrate that molten silicate electrolysis in its current state of development is the best process, but to determine whether, theoretically and experimentally, it might be the best process if certain technological hurdles can be overcome. As do all the proposed methods for extracting oxygen from lunar materials, the silicate melt electrolysis method requires considerable work before an operational factory can be built.

Criteria for Comparing Processes

Several other promising processes for extracting oxygen from lunar materials have been proposed and are being studied, including reduction of ilmenite by hydrogen gas (see the preceding paper by Knudsen and Gibson), reduction by carbon monoxide gas (see the paper by Rosenberg et al.

preceding Knudsen and Gibson's), extraction by processing with hydrofluoric acid or fluorine (e.g., Waldron 1985; Burt 1989, 1990), and electrolysis using a fluxing agent to reduce the melting temperature and increase the electrical conductivity of the melt (e.g., Keller 1989). Understanding which of these processes is the most convenient, reliable, and economical is one of the goals of current research efforts. At present, we are the primary investigators of the molten silicate electrolysis method (also called the "magma electrolysis" method) for extracting oxygen from lunar materials, and our work to date has increased our confidence in its promise. Here, we compare our method, as we now assess it, with other proposed technologies. We recognize the fine line between advocacy and objectivity (Johnson 1980), and we realize that only the test of time and adequate experimentation can determine which technology is the most appropriate.

Informed speculation and preliminary studies of these and other extraction processes have proceeded for over three decades, but slowly for the following reasons: (1) The exact characteristics of nonterrestrial resources are, in most cases, only poorly known, although our knowledge of lunar resources is at least based on experience on the Moon's surface and materials collected there. (2) Conditions on the Moon (vacuum, intermediate gravity, extreme temperatures, and nontraditional ores) are foreign to Earth experience in mining and materials extraction. (3) Lunar conditions (with which we have little experience) and the uncertain future demand for lunar materials make significant investment of time and money in the development of specific processes seem risky. Thus, many studies have been of the paper, rather than the laboratory, variety.

Given the nontraditional ores and conditions on the Moon, it can be argued that nontraditional extraction processes may prove more practical there than transplanted terrestrial technologies (e.g., Haskin 1985). We form certain general criteria for judging the various processes as discussed below (and elsewhere in this volume).

The successful lunar process must rely on proven resources, preferably abundant ones. Especially in the short term, the cost of searching for specialized or superior ore bodies (which may or may not exist) could overwhelm the cost of extracting the desired material from less specialized ore. The use of a common material also requires that a process should accommodate a substantial range of feedstock compositions and

thus be relatively insensitive to the selection of a Moon base site. The process should use a feedstock that is easily mined and requires minimal processing. It should operate automatically or by teleoperation from Earth. Particularly in the early days of Moon base development, the process and accompanying mining, beneficiation, and other operations should not require a large fraction of the astronauts' time or of the available power.

The process should not be compromised by, and if possible should take advantage of, lunar conditions such as 2-week days (with dependable sunlight—there are no cloudy days), large temperature swings between day and night, vacuum, intermediate gravity, abundant unconsolidated lunar "soils," clinging dust, and the absence of traditional processing agents such as air, water, coal, and limestone.

The process should be simple, with few steps and few moving parts. It must be easy to install and robust against physical jarring during transport and installation. Initially, all operations on the lunar surface will be awkward and expensive. Thus, the simplest technologies that can produce crucial products will presumably be the first technologies developed (Haskin 1985). Keeping the process simple will make it easier to automate, will require fewer replaceable parts, and should reduce operational problems, resulting in less downtime and fewer people needed to operate the plant. Simplicity can also decrease development time and cost. However, simplicity must be balanced against flexibility to yield more specialized products later on in the development of the Moon base. For example, some compromise should be reached between the ability to extract a single product from lunar soil and the ability to extract several valuable products by a more complex process or processes.

The process must require little or no continuing supply of reagents from Earth (such as fluorine, hydrogen, nitrogen, or carbon). One of the principal costs of setting up and maintaining a lunar factory will be the need to bring supplies from Earth (see Simon's paper in volume 2). If the process uses reagents that need to be recovered, their use raises power and mass requirements (in contrast to on Earth, where cheap reagents often need not be recovered) and increases the complexity of the process (since additional steps are required to recover them).

In addition to applying these first-order criteria, we can make rough comparisons of various processes for extracting oxygen by asking the

following questions. How much power is required to produce a given amount of oxygen? What fraction of the feedstock is converted into products? What are the products of the process? What technology must be developed before the process is viable? What plant mass is required to produce oxygen at a given rate? What must yet be learned about the theory of the process before any or all of the questions above can be answered? Exact answers to these questions cannot be obtained until much more research is done, but in the next section we describe a possible magma electrolysis operation, pointing out its advantages as judged by these criteria. Similar comparisons between various methods for extracting oxygen were made earlier by Eagle Engineering (1988).

A Proposed Lunar Factory

We envision a single-step, single-pot, steady-state electrolysis process using common lunar soil as feedstock with little or no preprocessing. As the soil is fed into the cell, it is melted by "excess" electrical heat released into the melt owing to resistance. The total electrode surface area would be about 30 square meters each (because each electrode is divided into fins, as in a car battery), and the total cell volume about 1 cubic meter. The operating temperature would be between 1300 °C and 1600 °C depending on the type of container and electrode materials that are ultimately developed. The cell would produce 1.4 tonnes iron-silicon metal, 1 tonne oxygen, and about 3.5 tonnes slag in 24 hours, with an energy requirement of about 13 MWhr (or 47 GJ). The process would satisfy many of the criteria set forth above for early lunar technologies, including use of common and easily mined lunar soil as feedstock, absence of a need to supply reagents from Earth, and simplicity of the process combined with multiple products. Mass, size, and power requirements of the process are also competitive with alternative processes (table 9). The low energy and mass requirements of the process are particularly important because the major expense in establishing a lunar oxygen factory is the cost of transporting the plant materials (including the required power plant) to the Moon (see Simon's discussion in volume 2).

TABLE 9. *Comparison of Proposed Processes for Producing Oxygen From Lunar Soil*

	Electrolysis	Typical range for alternative processes*
Feedstock	Common soil	Common soil to beneficiated soil to ilmenite
Mass of mined material (per 1000 tonnes O_2)	4 670 tonnes	4 600–120 000 tonnes
Reagents required	None	None to C, H, F
Temperature	1250–1400 °C	700–3000 °C
Plant energy (per tonne O_2)	13 MWhr (47 GJ)	20–40 MWhr (72–144 GJ)
Plant mass (per 1000 tonnes O_2 per year)	3–10 tonnes	5–80 tonnes
Product	Oxygen, Fe-Si alloy, slag	Oxygen with pure oxides or metals to oxygen plus slag
Primary advantage	Simplicity	E.g., good Earth analogs for process, many usable products, no consumables used, low-T operation
Primary disadvantage	Corrosive silicate, high-T operation, difficulty restarting after cooldown	E.g., complexity, high-T operation, low oxygen/reagent ratio, low product/ore ratio, high energy or mass required

*Values calculated from Eagle Engineering 1988 and references therein.

Conclusions

All the processes that have been suggested for extracting oxygen from lunar materials and probably many that haven't yet been suggested deserve our careful consideration in determining which is the "best" process to be implemented on the Moon. However, all the processes require substantial additional study before we are able to judge their relative worth for extracting lunar oxygen; and, before an operational plant can be built, even more study will be required.

We note that there is not much time (we hope) before the chosen process will be needed on the Moon. If we are to ensure that an oxygen production plant is included in the early planning and development of a lunar base, we need to progress quickly in assessing the various proposed processes so that the concept of a lunar oxygen plant can become a part of everyone's idea of what a lunar base should be.

Although it is certainly too early to decide which oxygen extraction process is the best one, our preliminary work with magma electrolysis has increased our confidence in its promise. We feel that its theoretical advantages listed above, including relatively low energy requirements, low mass, simplicity, and versatility with respect to feedstock, are sufficient to warrant its consideration as one of the processes most likely to be used in the early mining of oxygen from the Moon.

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Vapor Phase Pyrolysis

Wolfgang Steurer

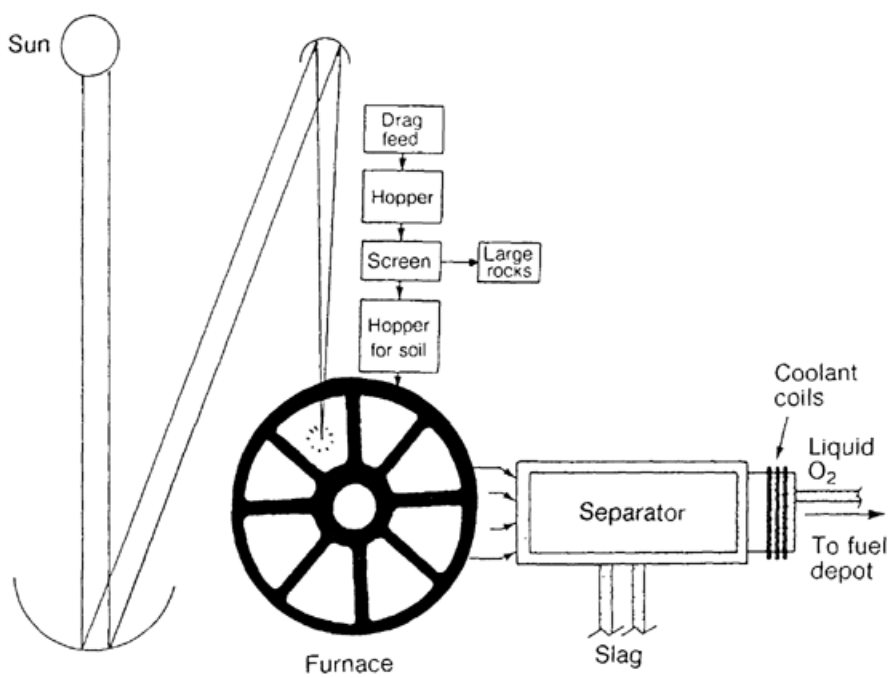
The vapor phase pyrolysis process is designed exclusively for the lunar production of oxygen. In this concept, granulated raw material (soil) that consists almost entirely of metal oxides is vaporized and the vapor is raised to a temperature where it dissociates into suboxides and free oxygen. Rapid cooling of the dissociate vapor to a discrete temperature causes condensation of the suboxides, while the oxygen remains essentially intact and can be collected downstream. The gas flow path and flow rate are maintained at an optimum level by control of the pressure differential between the vaporization region and the oxygen collection system with the aid of the environmental vacuum.

The process is illustrated in figure 23 in the form of a conceptual facility. The particle feedstock is dispensed from a gravity feed unit to a crucible. There it is vaporized and dissociated by means of thermal energy supplied by a solar concentrator whose focal point is at the crucible. The beam enters the vacuum-sealed unit through a self-cleaning window at a distance where the concentration is still low enough to preclude overheating of the window.

Figure 23

Vapor Phase Separation Processor

The vapor phase pyrolysis method of oxygen production starts with soil being screened so that the larger rock fragments are removed. The soil is then transferred from the hopper to chambers of the furnace, which in this concept rotate from the hopper position to the focus of the solar concentrator. Along with that rotation, the crucible is sealed so that the gases extracted when the soil is heated do not return to the lunar vacuum. The beam enters the sealed unit through a self-cleaning window at a distance where the concentration is still low enough to preclude overheating of the window. Thermal energy is concentrated at the crucible in the furnace, where it vaporizes the soil and dissociates (ionizes) the vapor to produce a plasma. The dissociated gases pass through a rapid cooling system (separator) which condenses the suboxides, and the remaining oxygen is liquefied.



The dissociated gases pass then through a rapid cooling separator at a yet-to-be-determined optimum flow rate and flow pattern. The cooling column may, in reality, be considerably longer than shown in the sketch. The produced oxygen may be collected as gas in a balloon (with a shade/shield to protect it from the Sun's heat and from micrometeorite strikes) or liquefied. The problems of oxygen storage and liquefaction are common to all oxygen-producing processes and are, therefore, not addressed here.

The preferred raw material, in view of the ease of acquisition, is lunar basalt in the form of regolith (soil). Since it consists of a variety of metal oxides, numerous individual species are obtained during dissociation. For SiO_2, TiO_2, and Al_2O_3, for example, the major (minor) species produced are

$$SiO_2\ O_2 + SiO\ (+ SiO_2)$$
$$TiO_2\ O_2 + TiO\ (+ TiO_2)$$
$$Al_2O_3\ O_2 + AlO_2\ (+ AlO + Al_2O + Al_2O_2)$$

The relative importance of the individual dissociation species can be measured by their partial pressures which, in turn, increase rapidly with the processing temperature. For a mixture of oxides representative of lunar soil, the partial pressures of the species evolving from three major oxides in the temperature regime from 2000 to 3000 K are listed in table 10. (To convey a clear overview, negligible pressures below 10^{-6} atm are given in orders of magnitude only.)

An examination of table 10 substantiates the following conclusions: (1) The processing temperature should be close to 3000 K (the limit for solar heating). (2) The gas composition is dominated by O_2 and SiO. The oxygen pressure at 3000 K of roughly 1/10 of an atmosphere is more than adequate for production rates.

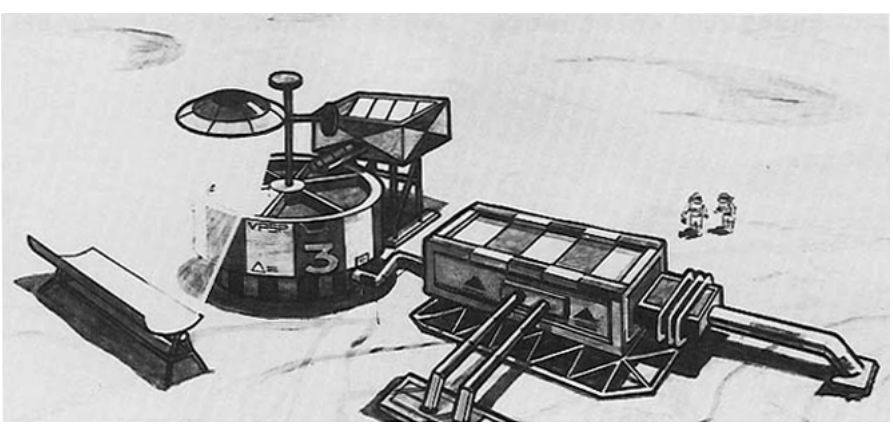


TABLE 10. *Partial Pressures of Dissociation Species of Lunar Regolith at Three Temperature Levels*
[In atmospheres (1 atm = 10^5 N/m^2)]

Gas species	2000 K	2500 K	3000 K
O_2	3.2×10^{-6}	1.5×10^{-3}	8.1×10^{-2}
AlO	(10^{-12})	(10^{-8})	1.8×10^{-5}
AlO_2	(10^{-11})	(10^{-7})	5.8×10^{-5}
Al_2O	(10^{-16})	(10^{-11})	(10^{-8})
Al_2O_2	(10^{-17})	(10^{-12})	(10^{-9})
SiO	6.5×10^{-6}	3.0×10^{-3}	1.6×10^{-1}
SiO_2	(10^{-7})	1.4×10^{-4}	1.1×10^{-2}
TiO	(10^{-10})	1.0×0^{-6}	1.0×10^{-4}
TiO_2	(10^{-11})	(10^{-7})	1.3×10^{-5}
FeO	1×10^{-6}	2.0×10^{-4}	5.9×10^{-3}

The oxygen yield as a fraction of the raw material throughput is determined from the partial pressure and molecular weight of each species by the relationship

$$O_2/\text{throughput} = \frac{p_{O_2} \times M_{O_2}}{(p \times M \text{ of each species})}$$

The resulting oxygen yield is on the order of 20 percent.

The processing energy required for vaporization and dissociation of the entire throughput is 5100 kWhr/t and for cooling 2000 kWhr/t, adding to a total of 7100 kWhr/t. Using the oxygen yield of 0.20, this translates into 35 500 kWhr/tonne of oxygen produced.

Most of this amount could be provided by solar thermal energy using suitable concentrators; however, some electrical power will probably be needed. Additional energy would be required for support operations, such as material acquisition, transport, and beneficiation, or conditioning of the oxygen for storage. To answer the

energy supply question, a more specific design and further analysis of possible tradeoffs are necessary.

While vapor phase pyrolysis is basically a continuous process, periodic shutdown is necessary for removal of the condensed suboxides from the cooling system.

In summary, vapor phase pyrolysis may be a viable process for producing oxygen from lunar materials. It is straightforward and does not require complex equipment. Its biggest disadvantage is the large amount of energy it requires. However, this energy requirement might be reduced by efficient use of solar energy, by recovering heat from the slag, and by using the recovered heat to preheat the feedstock. While such techniques would add complexity, the savings in energy might be worth the cost in added equipment. In any case, vapor phase pyrolysis clearly deserves additional development work.

Plasma Separation

Wolfgang Steurer

This process employs a thermal plasma for the separation and production of oxygen and metals. It is a continuous process that requires no consumables and relies entirely on space resources. The almost complete absence of waste renders it relatively clean. It can be turned on or off without any undesirable side effects or residues. The prime disadvantage is its high power consumption.

In the basic concept, the process consists of the following steps: Granulated raw material, such as lunar regolith, is vaporized, dissociated, and finally brought to a temperature where a thermal plasma is obtained. The plasma permits electromagnetic manipulation and separation of the ionized species according to their positive or negative charges.

In the process discussed here, a unique concept is introduced and designated “selective ionization.” Metals exhibit a low ionization potential, below 9 eV, while the lowest ionization potential of gases is 13.6 eV (oxygen). In a thermal plasma, where the degree of ionization is related to temperature, this gap in the ionization potential defines a temperature range, between 8 000 and 10 000 K, in which metals approach 100-percent ionization while the atomic oxygen remains essentially neutral (ionized O_2 less than 1 percent). Under these conditions, only metals respond to electromagnetic forces and, consequently, can be separated from the neutral oxygen.

To substantiate this effect, theoretical data were generated for the metals of interest and for oxygen by programming the well-accepted Saha equation. The data on the number densities of the positive ions, neutral species, and electrons at temperatures from 4 000 to 14 000 K were translated into percent ionization. The results, plotted in figure 24, clearly show the wide gap in the degree of ionization for the metals concerned and oxygen between 8 000 and 10 000 K.

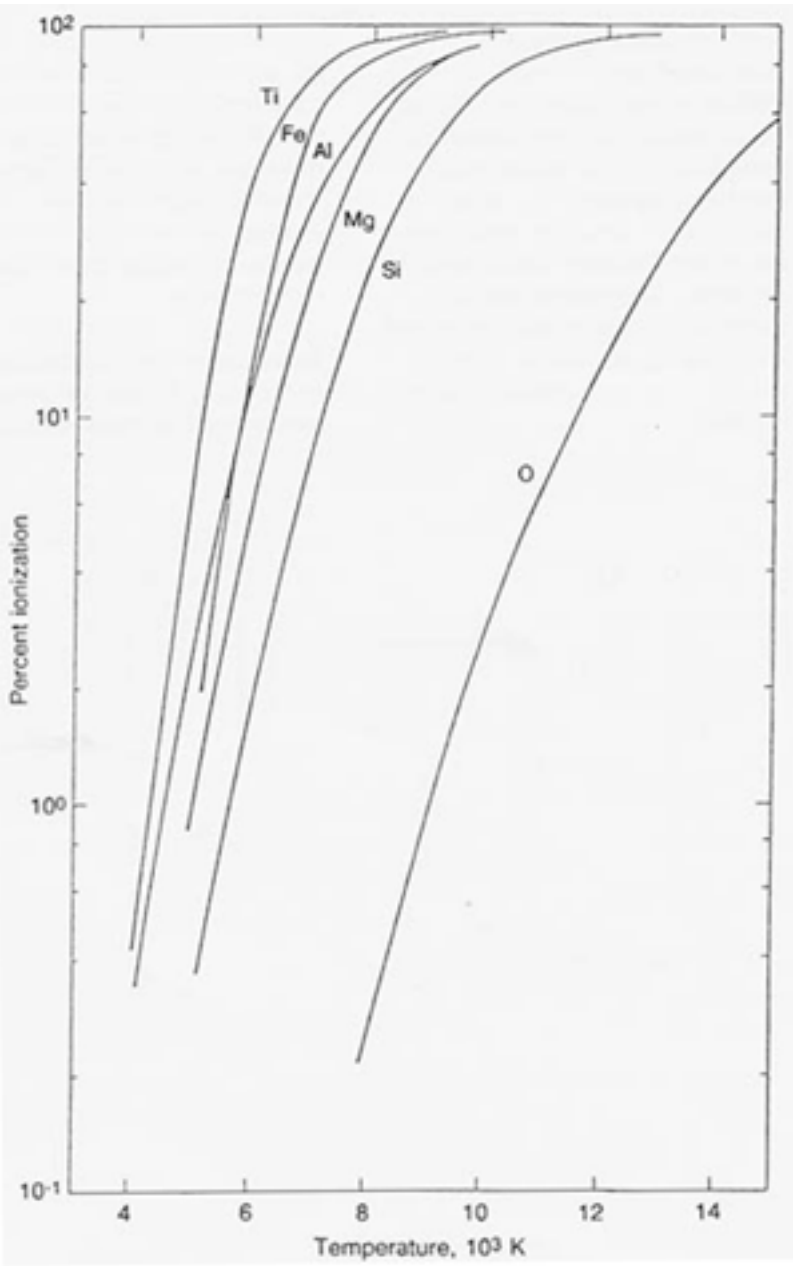


Figure 24

Percent Ionization of Metal and Oxygen vs. Temperature

In the proposed process, the dissociated gas is heated to 9 000 K by inductive coupling and the selectively ionized plasma is passed through an electrostatic field for separation. As shown in figure 25, the positive metal ions are diverted toward the cathode half-shell. The neutral oxygen continues to flow downstream and is recovered at the end of the column in an appropriate collection system.

A conceptual processing facility is shown in figure 26. The ions of each individual metal follow a specific trajectory and deposit, therefore, at distinct distances in the electrostatic system. This fact implies the possibility of recovering individual metals rather than a metal mixture.

While the process is basically continuous, it requires periodic removal of the metal deposits

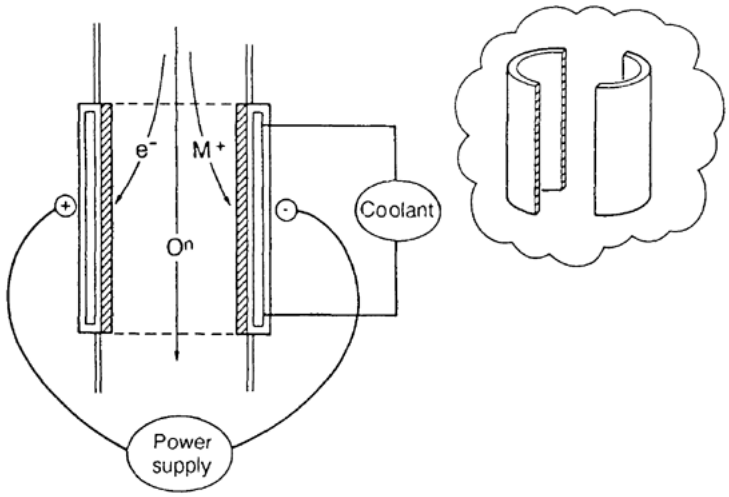


Figure 25

Selective Ionization and Electrostatic Separation

from the cathode. Since there is essentially no waste, the combined process yield of metals and oxygen approaches 100 percent. Conservative yield factors (fraction of throughput) are as follows:

Metals	0.51
Oxygen	0.39
Total	0.90

Total energy requirements are approximately 13 300 kWhr per tonne of all products. Of this, 4500 kWhr/t can be satisfied by direct solar heating/vaporization /dissociation. The remaining 8800 kWhr/t has to be supplied in the form of electric power. This figure has to be increased by a factor of 2.2 for power conditioning and losses, resulting in an actual power consumption of 19 360 kWhr/t. A yearly combined production of 500 tonnes of metals and oxygen, equivalent to 125 kg per hour, calls for an electric power generation capacity of 2400 kW (installed).

This assessment is based on the use of inductive heating for plasma generation. There may be other alternatives, such as laser heating, which may simplify the problem of plasma containment. However, the effect of such alternate concepts on power requirements is not expected to be substantial.

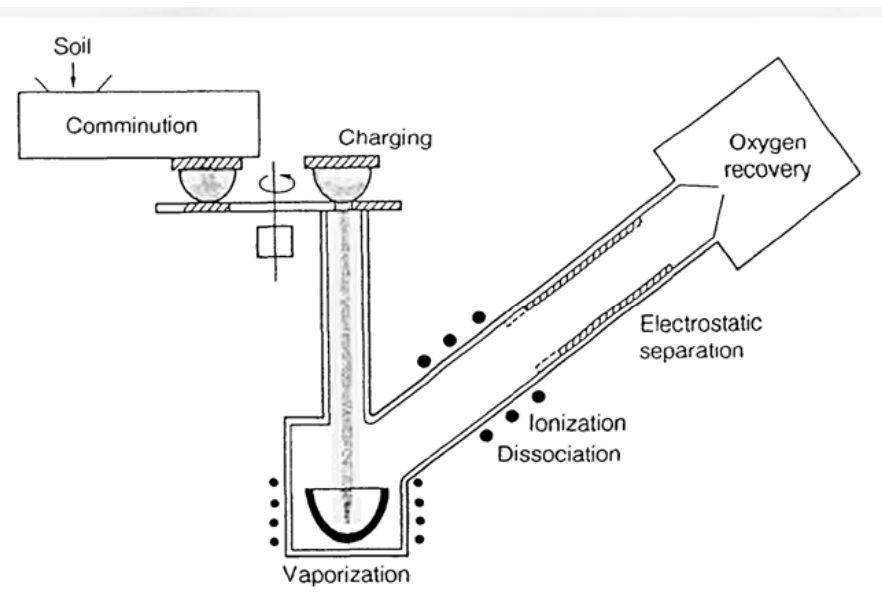


Figure 26

Plasma Separation: Conceptual Apparatus

Processes for Metal Extraction

David F. Bowersox

The cost of transportation from Earth to the Moon is so high that proposals for industrial efforts on the Moon are often limited to native (lunar) materials. This restriction, fortunately, can be greatly eased if recyclable elements are shipped from Earth and reused. The initial, nearly prohibitive costs are alleviated by the repeated operation. The expenses of the reagents, like those of the shelter and special equipment, are spread over a relatively long program. This report describes the processing of plutonium at Los Alamos National Laboratory (LANL), an operation illustrating concepts that may be applicable to the processing of lunar materials. The toxic nature of plutonium requires a highly closed system, just as the expense of transporting reagents to the Moon requires a highly closed system for processing lunar surface materials.

To illustrate the benefit of using a closed pyrometallurgical process on the Moon, let us take the reduction of ilmenite as an example. Ilmenite ore can be isolated and beneficiated, and usable quantities of oxygen, iron, and titanium can be extracted from the ore. The first step might be a hydrogen reduction step, in which hydrogen is reacted with the ilmenite ore to produce water and a slag of iron mixed with titanium dioxide. By following this step with electrolysis of the water, we can recover the hydrogen and produce oxygen for life support and propulsion.

Let us now consider expanding the ilmenite process by adding a step in which the iron-titania slag is treated so as to obtain metallic iron and titanium dioxide or, even better, metallic iron and metallic titanium. Two additional processes are suggested—a carbonyl process for separating the metallic iron from the slag or from titanium and a pyrochemical process to produce titanium metal.

The carbonyl process would separate iron (or nickel or other metals) from titania (TiO_2) or titanium metal by the reaction

$$Fe + 5CO \rightarrow Fe(CO)_5$$

The compound can then be decomposed and the carbon monoxide recycled. This well-known method is compact and requires very little power.

The pyrochemical reduction of TiO_2 to metallic titanium may be carried out in a manner analogous to the process used to extract plutonium from scrap residues. Although the process is not directly applicable to nonterrestrial industrialization in its detailed steps, the success of this method indicates that it should be

excellent for space programs if it can be applied to the extraction of other metals.

First, because of the solubilities and densities of the phases, the system is compact. Pyroprocessing requires approximately one-tenth the volume of aqueous processing. Operations could be remote and automated. Processes are either batch or semicontinuous, depending on the desired throughput. Reagents are generally recyclable, and residues, when produced, are in compact, dense form.

The major steps for plutonium processing are outlined in figure 27. The roasting step (1) would not be necessary in any nonterrestrial application; the starting material would already be in oxide form. The oxide, calcium metal, and excess $CaCl_2$ are reacted (step 2) in a magnesium oxide crucible where the plutonium is reduced to the metal by the reaction

$$PuO_2 + 2Ca \xrightarrow{CaCl_2} Pu + 2CaO \quad (2)$$

The calcium oxide dissolves in the calcium chloride and the metallic plutonium settles as a button, which is mechanically separated from the salt. In a nonterrestrial application, titanium and iron could form a metal button and then be separated by vacuum distillation or the carbonyl process. And the reactant metal could be calcium or perhaps aluminum. We at LANL are developing a method for recovering the calcium chloride for recycling.

If, in the plutonium process, the americium concentration is greater than 1000 ppm, it is lowered by equilibration at 800 °C with sodium chloride/potassium chloride eutectic salt containing magnesium chloride as an oxidizing agent (step 3). The reactions are

$$2\ Am^0 + 3\ MgCl_2 \rightleftarrows 2\ AmCl_3 + 3\ Mg \quad (3)$$

$$2\ Pu^0 + 3\ MgCl_2 \rightleftarrows 2\ PuCl_3 + 3\ Mg \quad (4)$$

$$2\ Am^0 + 2\ PuCl_3 \rightleftarrows 2\ AmCl_3 + 3\ Mg + 2\ Pu^0 \quad (5)$$

Under the conditions of the plutonium process, the salt contains most of the americium and 4 percent of the plutonium, while the plutonium, magnesium, and about 100 ppm americium are in molten form. The salt can be treated with calcium to extract the americium and plutonium and subsequently be reused. Although this is an important part of the plutonium process, it would not be necessary in a titanium recovery process. In both cases, however, because there is excess calcium and magnesium in the metal

button, heating above the melting point is necessary to remove these volatiles. The product of this step is a solid metal, typically in the form of a solid metal cylinder formed by chill casting.

In the fourth step, purification of the metal, the cylinder of plutonium is placed in the anode cup of a magnesium oxide crucible, a sodium chloride/potassium chloride eutectic added, and electrolysis conducted at 750 °C. The impure plutonium is ionized by giving up electrons at the anode. Then the ions migrate to the cathode to get electrons and deposit as pure plutonium. The reactions are

$$Pu\ (impure) \rightarrow Pu^{3+}\ (anode) \quad (6)$$

$$Pu^{3+} \rightarrow Pu^{0}\ (pure)\ (cathode) \quad (7)$$

Input	Process	Output
	Step 1: Oxide Preparation	
Heat, O_2 $\rightarrow$		$\rightarrow$ O_2
	Pu (scrap) + O_2 $\rightarrow$ PuO_2 (s)	
	Step 2: Metal Production	
Ca, $CaCl_2$ $\xrightarrow{850^{o}\ C}$		$\rightarrow$ $CaCl_2 \bullet CaO$
	$PuO_2 + 2\ Ca \xrightarrow{CaCl_2} Pu + 2\ CaO$	
	Step 3: Metal Preparation	
NaCl • KCl, $MgCl_2$ $\xrightarrow{800^{o}\ C}$	Americium removal (molten salt extraction)	$\rightarrow$ NaCl • KCl, $MgCl_2$, $PuCl_3$, $AmCl_3$
	Metal shaping, volatile recovery	$\rightarrow$ Pu skull
	$2\ Am^{0} + 3MgCl_2 \rightleftarrows 2\ AmCl_3 + 3\ Mg$	
	$2\ Pu^{0} + 3\ MgCl_2 \rightleftarrows 2\ PuCl_3 + 3\ Mg$	
	$2\ Am^{0} + 2\ PuCl_3 \rightleftarrows 2\ AmCl_3 + 3\ Mg + 2\ Pu^{0}$	
	Step 4: Metal Purification	
NaCl • KCl $\xrightarrow{750\ °C}$		$\rightarrow$ NaCl • KCl, $PuCl_3$ (10%), $AmCl_3$
		$\rightarrow$ Pu^{0}(impure)
	Pu^{0}(impure) Anode $\rightarrow$ Pu^{0}(pure) Cathode	

Figure 27

Pyroprocessing of Plutonium at Los Alamos

Approximately 10 percent of the plutonium is in the salt phase and 10 percent remains in the anode as a solid when the electrorefining is completed. The cathode metal is 99.99-percent pure plutonium. The salt can be reused or treated to remove the plutonium trichloride, and the anode metal can be oxidized to remove impurities and then reduced in the metal production step.

This process has been developed over a period of years and is used successfully at Los Alamos National Laboratory. Changes are being made to optimize the process. However, the concept, with its compactness and its recycling of reagents, seems particularly transferable to nonterrestrial processing. The process requires no water, and the availability of high vacuum and heat sources (such as a solar furnace) should be advantageous in developing a successful process off Earth. In the space context, the availability of a reactant metal may be a problem. If aluminum could be scavenged from space vehicles, or lunar calcium be used and recycled, the economics would be enhanced.

Bioprocessing of Ores: Application to Space Resources

Karl R. Johansson

Introduction

The role of microorganisms in the oxidation and leaching of various ores (especially those of copper, iron, and uranium) is well known. (Among the review articles and reference books on this subject are Brierley 1978 and 1982; Brock, Smith, and Madigan 1984; Decker 1986; Ehrlich 1981; Kelly, Norris, and Brierley 1979; Krumbein 1983; Lundgren and Silver 1980; and Torma and Banhegyi 1984.) This role is increasingly being applied by the mining, metallurgy, and sewage industries in the biobeneficiation of ores and in the bioconcentration of metal ions from natural receiving waters and from waste waters high in toxic metals (Belliveau et al. 1987, Ehrlich and Holmes 1986, Hutchins et al. 1986, Nicolaidis 1987, Olson and Brinckman 1986, Olson and Kelly 1986, Thompson 1986, Torma 1987a and b, Tsezos 1985, Volesky 1987, Woods and Rawlings 1985). See figure 28.

Figure 28

Bacterial Processing of Metal Ores

Although most concepts of processing lunar and asteroidal resources involve chemical reactors and techniques based on industrial chemical processing, it is also possible that innovative techniques might be used to process such resources. Shown here are rod-shaped bacteria leaching metals from ore-bearing rocks through their metabolic activities. Bacteria are already used on Earth to help process copper ores. Advances in genetic engineering may make it possible to design bacteria specifically tailored to aid in the recovery of iron, titanium, magnesium, and aluminum from lunar soil or asteroidal regolith. Biological processing promotes the efficacy of the chemical processes in ore beneficiation (a synergistic effect).

Taken from Brierley 1982.

The question of harnessing bacteria for the beneficiation of ores on the Moon, on asteroids, or on Mars has been raised and must be seriously considered in the context of the utilization of space resources. Because of the almost total lack of organic matter on the Moon, it is fortunate that most bacteria known to participate in acid leaching of ores are autotrophic (derive all their carbon from carbon dioxide) as well as chemolithotrophic (derive energy through oxidation of reduced inorganic compounds or elements; e.g., hydrogen sulfide or ferrous ions). Furthermore, they satisfy all of their nutritional needs with inorganic substances, including certain trace elements known to be present in the Moon's regolith. But the development of biological processes to extract and purify ores on the Moon is severely constrained by the environmental conditions: the lack of elemental oxygen; the limited carbon, nitrogen, and hydrogen; the apparent lack of water; and the extremes of temperature and radiation. Thus, microbial ore processing must be established within a gas-tight enclosure. The enclosure must allow replenishment or augmentation of nutritional needs, retain moisture, maintain a suitable temperature, and protect the cells from radiation. See figure 29.

Figure 29

Enclosure for Microbial Ore Processing

A variety of pressurized enclosures have been proposed for a lunar base. In this concept by Fluor Daniel and Rockwell International, a large hangar-like enclosure functions as a workshop and servicing area. A microbial ore-processing complex could be totally enclosed by such a building. Ore could be introduced through airlocks and processed in a moist atmosphere at an appropriate temperature. Spent ore could be removed through airlocks, and waste products could be recycled. The key point is that the harsh environment at the lunar surface can be suitably modified to provide an optimum environment for ore processing.

Artist: Renato Moncini

Various kinds of interactions between microorganisms and metals are known: (1) beneficial as well as toxic effects of metals on metabolism, (2) oxidation-reduction reactions, (3) solubilization of metals through acids produced by microbial growth, (4) precipitation of metals by pH increases, (5) conjugation of metals and organic compounds, (6) metabolic transformation of metals, and (7) accumulation of metals either on the inside or on the outside of cells. In this paper I will consider the processes that are particularly important to the technology of metal recovery. Some of them may have application in the space environment. However, essentially no research has been done with this application in mind.

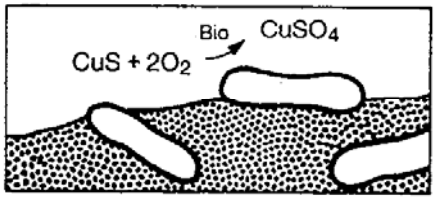
Acid Leaching of Ores

Acid leaching is a hydrometallurgical process resulting in the solubilization of ore minerals through chemical and biological oxidations and reductions of sulfur, iron, and certain other metals.

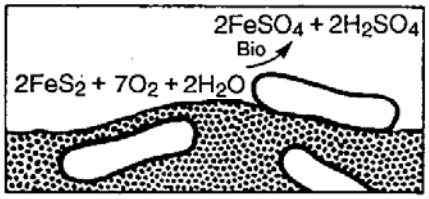
The Chemistry

The chemistry of the process is complex and greatly affected by pH, oxidation-reduction potential, dissolved oxygen, and temperature. (Some of the authorities describing this chemistry are Hutchins et al. 1986; Kelly, Norris, and Brierley 1979; Lundgren, Valkova-Valchanova, and Reed 1986; Torma and Banhegyi 1984; and Torma 1987a.) For example, bacteria can catalyze and drive the following oxidations:

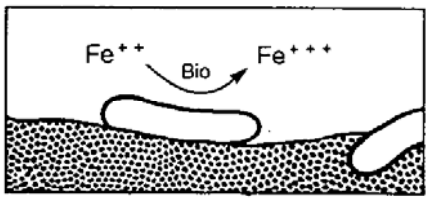
$$^{*}MS + 2\ O_2 \rightarrow MSO_4 \quad (1)$$



$$^{*}MS + 5\ O_2 + 2\ H_2O \rightarrow MSO_4 + 2\ H_2SO_4 \quad (2)$$



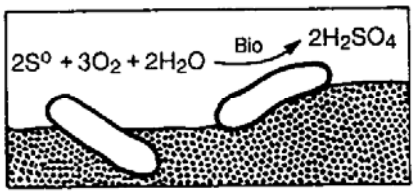
$$Fe^{++} \rightarrow Fe^{+++}$$
(ferric iron is regenerated) (3)



$$2\ S^0 + 3\ O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4 \quad (4)$$

*M = Fe, Cu, Mo, Sb, Pb, Ag, Co, Ni, Cu-Fe, As-Fe, Ni-Fe, Zn-Fe, Cu-Se, etc.

(Thionate, tetrathionate, thiosulfate, and sulfite are also oxidized by some bacteria.)



$$H_2S + 2\ O_2 \rightarrow H_2SO_4 \quad (5)$$

Chemically, ferric sulfate (largely generated through bacterial oxidation of ferric sulfide or ferrous ions) and sulfuric acid (largely generated through bacterial oxidation of ferric and other metal sulfides, elemental sulfur, or hydrogen sulfide) oxidize and solubilize numerous minerals; for example,

$$2\ FeS_2 + 2\ Fe_2(SO_4)_3 \rightarrow 6\ FeSO_4 + 4\ S^o \quad (6)$$

$$Cu_2S + 2\ Fe_2(SO_4)_3 \rightarrow 2\ CuSO_4 + 4\ FeSO_4 + S^0 \quad (7)$$

$$Bi_2S_3 + 3\ Fe_2(SO_4)_3 \rightarrow Bi_2(SO_4)_3 + 6\ FeSO_4 + 3\ S^0 \quad (8)$$

$$CuFeS_2 + 2Fe_2(SO_4)_3 \xrightarrow{\text{Chemical}} CuSO_4 + 5FeSO_4 + 2S^0$$

Another example of ferric sulfate leaching

$$UO_2 + Fe_2(SO_4)_3 \rightarrow UO_2SO_4 + 2\ FeSO_4 \quad (9)$$

$$UO_2 + Fe_2(SO_4)_3 \xrightarrow{\text{Chemical}} UO_2SO_4 + 2FeSO_4$$

Solubilization of uranous oxide

$$2\ {}^*M + O_2 + 2\ H_2SO_4 \rightarrow 2\ MSO_4 + 2\ H_2O \quad (10)$$

$$^*MO + H_2SO_4 \rightarrow MSO_4 + H_2O \quad (11)$$

The Bacteriology

The principal bacteria catalyzing reactions 1 through 5 are mixed populations of *Thiobacillus ferrooxidans, Leptospirillum ferrooxidans, Thiobacillus thiooxidans,* and several other species of acidophilic thiobacilli. There also exist some thermophilic thiobacilli which are facultative autotrophs inasmuch as they can utilize certain organic substrates in the environment. *Thiobacillus ferrooxidans* is unique in that it derives energy from oxidations of sulfur and reduced iron, copper, and tin; it also fixes nitrogen. *Thiobacillus thiooxidans* cannot oxidize iron; rather, it oxidizes sulfur and probably zinc sulfide. *Leptospirillum ferrooxidans* will

oxidize only the soluble form of iron (Fe^{++}), but in conjunction with certain other sulfur-oxidizing thiobacilli it will synergistically oxidize pyrite (FeS_2) as well as chalcopyrite ($CuFeS_2$).

Another group of bacteria, the genus *Sulfolobus,* which is widely distributed in volcanic vents and thermal springs, is able to oxidize sulfur and iron at temperatures of 80 ºC, or even a few degrees higher. Sulfolobi are also able to grow in the absence of molecular oxygen provided Mo^{6+} or Fe^{+++} are present to serve as electron acceptors, thereby replacing O_2 as the ultimate electron acceptor. They are facultative heterotrophs and occupy a unique niche in the bacterial kingdom as *Archaebacteriaceae,* a family possessing a cell membrane composed of a long-chain, ether-linked hydrocarbon monolayer (instead of a phospholipid bilayer) and lacking a peptidoglycan cell wall, which is found in all other bacteria (Kelly and Deming 1988). Whether these and certain other archaebacteria play a significant role in thermophilic leaching of ores can only be surmised.

A filamentous, moderately thermophilic, sulfur-oxidizing, autotrophic bacterium, *Thermothrix thiopara,* also flourishes in volcanic vents and in thermal springs (Brierley 1982) and may play a role in the leaching of ores. Similarly, the filamentous, mesophilic bacteria *Thiothrix* and *Beggiotoa,* which oxidize sulfide to elemental sulfur, have potential for ore beneficiation.

The Commercial Leaching Operation

The release and recovery of metals from ores are facilitated by methods designed to amplify the requisite oxidation-reduction reactions (Brierley 1978, Brierley 1982, Campbell et al. 1985).

Dump leaching: This operation is usually applied to the extraction of copper from low-grade oxide or sulfide ores which are hauled as uncrushed stones from open-pit mines to enormous dumps (see fig. 30). The dumps are sprinkled with water and the percolate is collected in a natural or artificial catch basin. The copper is removed from the acidic leachate by cementation (with iron), electrolysis, or solvent extraction; the solution is then recycled through the dump. The operation continues for years during which time sulfur- and metal-oxidizing bacteria grow extensively to perpetuate the leaching process.

$$CuSO_4 + 5Fe \xrightarrow{\text{Chemical}} FeSO_4 + Cu^0$$

Cementation

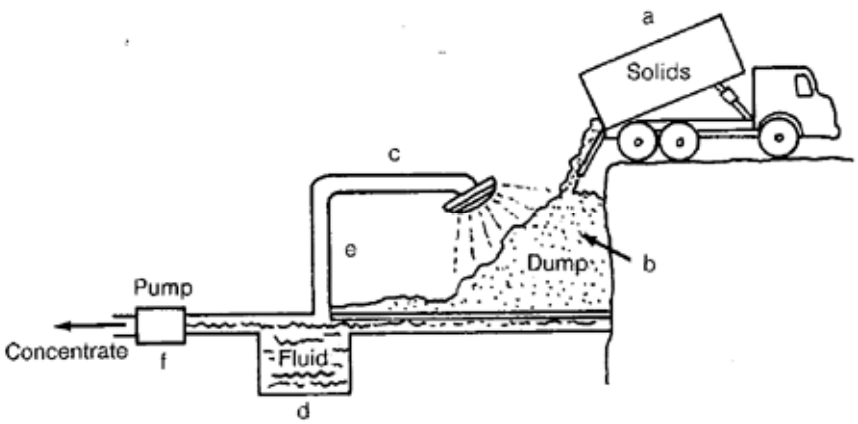


Figure 30

Dump Leaching

Uncrushed stones of low-grade oxide or sulfide ores (a) *are hauled from the mining pit to a dump* (b)*, where they are sprayed with a water solution* (c)*. The influent solution, aided by the growth of sulfur- and metal-oxidizing bacteria, leaches metal salts from the ore. The salt-rich leachate is collected in an effluent pond* (d) *and either recycled immediately* (e) *to pick up more of the metal-containing salts or pumped* (f) *to the processing plant for removal of the metal.*

Heap leaching: This operation is identical in principle to the dump process but employs crushed, medium-grade ores piled on an impermeable basin from which the leachate is recovered, the solute is removed from it, and the leachate is concentrated and recycled (see fig. 31). This leaching operation is usually completed in a matter of months. To encourage the desired aerobic state, aeration tunnels are generally installed.

Figure 31

Heap Leaching Operation at the Gold Quarry Mine in Northeast Nevada

In this operation, a solution containing 125 ppm sodium cyanide is sprayed on the ore heap. The solution percolates down through the ore, dissolving gold from it. The gold-enriched percolate is then trapped by a plastic sheet, which channels the solution to a collecting pond, where it is pumped to the plant for removal of the gold and recycling of the solution.

The sodium cyanide heap leaching process is used on ores having an average gold concentration of 0.03 ounce/ton (0.9 ppm) and is economically attractive down to 0.01 ounce/ton (0.3 ppm). The mine shown is the largest gold leaching operation in the world.

This process does not use bacteria. However, somewhat analogous processes use bacteria in acidic solutions to extract copper from sulfide ores in heap or dump operations.

Courtesy of Komar Kawatra, Michigan Technological University, and Leonard Kroc, Newmont Gold Company.

Vat leaching: Vat leaching is a purely chemical process by which concentrates of copper oxide ores are extracted by agitation with measured volumes of sulfuric acid. Research indicates that sulfidic ores can be extracted economically by the vat process using bacterial leaching (Brierley 1982, Torma and Banhegyi 1984).

In situ leaching: In selected mining sites that are inaccessible or abandoned because the high-grade ore has been recovered, acid leaching solutions are applied directly to either shallow or deep deposits and the leachates subsequently collected via wells. The process is confined to copper and uranium ores. Naturally occurring bacteria may augment this chemical process. It has been speculated that populations of appropriate thiobacilli and other sulfur-oxidizing bacteria could be injected into the locus to hasten and enhance the extraction. However, such a method is beset with difficulties, largely because the pathway of percolation is impossible to predict or control, thus endangering the quality of ground and surface waters. On the waterless Moon, the pollution of ground waters would not be a problem, but the extravagant use of water transported from Earth would be prohibitive.

In my opinion the only beneficiation operation having any potential for application on the Moon, or other space body, would be microbe-enhanced vat leaching, inasmuch as the bacteria must be provided with a confined, minimally sized Earth-like environment, as I have indicated. The oxygen for the bioprocessing unit would come from the reductive chemical processing of ilmenite, or other oxide ore, via electrolyzed water resulting from the reaction. Thus, chemical processing of lunar ores (or some other local means of producing oxygen) must precede any biobeneficiation for it to be economical. It seems unlikely that bioprocessing of ores would ever become a part of a closed or semi-closed regenerative ecological system unless the chemical beneficiation process proved to be ineffective (an unlikely prospect) and oxygen from eucaryotic photosynthesis could be spared for the bacterial processing of ores. Most likely, if cost-benefit analysis indicated any virtue to bioprocessing, the operation would be conducted outside of any human settlement and tended either by robots or humans in suitable “space suits.”

Other Microbial Transformations of Metals

Anaerobic (Reducing) Conditions

In the absence of molecular oxygen, anaerobic or facultatively anaerobic bacteria are able to

reduce sulfur or metals leading to the formation of sulfidic ores and reduced forms of iron, copper, and other metals.

Sulfate-reducing bacteria: Two large groups of chemosynthetic, heterotrophic bacteria are able to oxidize certain organic acids and utilize sulfate, sulfur in other oxidized states, and elemental sulfur as electron acceptors. These bacteria, classified in such genera as *Desulfovibrio, Desulfotomaculum,* and *Desulfuromonas,* are found in anaerobic aquatic habitats containing the various oxidized states of sulfur, which are reduced to hydrogen sulfide, thus leading to the deposition of sulfidic ores.

Photosynthetic bacteria: Among the photosynthetic bacteria are two groups that utilize hydrogen sulfide under anaerobic conditions as a source of electrons in reducing carbon dioxide:

$$CO_2 + 2\ H_2S \rightarrow CH_2O + H_2O + 2\ S^0 \quad (12)$$

In one group, the "purple sulfur bacteria," the sulfur is deposited intracellularly. In another group, the "green sulfur bacteria," the sulfur is deposited outside the bacterial cell and subsequently oxidized to sulfate in the presence of hydrogen gas (source of electrons). These, and other photosynthetic bacteria, are anaerobic and thus unable to utilize oxygen as the final electron acceptor. The purple sulfur bacteria comprise ten genera (e.g., *Thiospirillum, Thiocystis,* and *Amoebobacter*); the green sulfur bacteria comprise four genera (e.g., *Chlorobium* and *Pelodictyon*).

Bacterial reduction of metal ions: Some strains of members of the genera *Thiobacillus* and *Sulfolobus* are able to reduce Fe^{+++} to Fe^{++}, obtaining reducing power from elemental or reduced sulfur, which is oxidized in the process. A number of other soil bacteria are able to reduce ferric iron as well. Manganese is both reduced and oxidized by various marine and soil bacteria. Ferromanganese nodules found in the oceans are laid down slowly through the bacterial reduction and oxidation of ferric and manganese ions (Summers and Silver 1978, Ehrlich 1981, Ehrlich and Holmes 1986).

Biotransformations of Some Toxic Metals and Metalloids

Within any land or aquatic ecosystem, toxic and nontoxic cations, whether naturally or artificially introduced, may be absorbed and metabolized by certain species among the indigenous microflora. In the process, inherent toxicities are often neutralized or modified. An excellent case in point is mercury which is highly toxic (binds

sulfhydryl groups) as Hg^{++} but is enzymatically reduced by various mercury-resistant microorganisms to its volatile and nontoxic state as Hg^0 (Belliveau et al. 1987, Decker 1986, Hutchins et al. 1986, Thompson 1986).

Likewise certain toxic metals are methylated through the action of methylcobalamin excreted by a number of different aquatic and soil bacteria. This methylation does not necessarily detoxify the metal. In the case of mercury, the methyl and dimethyl forms can subsequently be concentrated in certain organisms, especially fish. Other metals that can be methylated by bacteria include tin, cadmium, lead, and arsenic.

Some bacteria can cleave certain organic mercurials into Hg^{++} plus an organic residue. Arsenic as As^{3+} can be oxidized by a number of bacteria to AS^{5+}; in either state of oxidation, arsenic is toxic, but far less so in the pentavalent state. Reduced arsenic reacts with sulfhydryl groups; oxidized arsenic simulates phosphate in metabolic pathways. As oxoanions, tellurium and selenium are toxic to many bacteria. Some bacteria are able to reduce these salts to Te^0 or Se^0, thereby destroying their toxicity.

Since lunar rock contains virtually the same spectrum of toxic metals as found on the Earth (Morris et al. 1983), the biobeneficiation of ores on the Moon could be compromised by the presence of toxic cations in ore slurries, unless the bacteria introduced into the vats are resistant to high levels of cations of the more abundant toxic metals, including those to be recovered. Resistance to toxic metals is genetically endowed and can be introduced through gene recombination techniques in at least some of the bacterial species involved in the beneficiation of ores or in the removal of toxic cations from an aquatic environment (Belliveau et al. 1987, Ehrlich and Holmes 1986, Hughes and Poole 1989, Hutchins et al. 1986, Nicolaidis 1987, Pooley 1982, Torma 1987a, Trevors 1987, Tsezos 1985, Woods and Rawlings 1985).

Leaching of Ores by Growth of Heterotrophic Microorganisms

Sometimes sufficient organic matter is found in ores to support the growth of diverse microbes, resulting in the production of organic acids (e.g., lactic, citric, acetic, glutamic, and glycolic) which lower the pH, helping to solubilize the metals and encouraging the development of an acidophilic microflora of thiobacilli. This may be viewed as a synergistic effect.

On the other hand, alkaline leaching may be encouraged in the presence of organic nitrogen

(protein, amino acids, purines, pyrimidines, etc.) as a result of deaminations catalyzed by heterotrophs, yielding ammonia which, in aqueous solution, becomes ammonium hydroxide. Some metals, notably copper, cobalt, and zinc, are compounded by ammonium hydroxide.

Calculations suggest it is not feasible to harness heterotrophs for the leaching of ores. Enormous quantities of decomposable organic matter would need to be provided in order for either acid or alkaline leaching to function at a commercial level (Kelly, Norris, and Brierley 1979). The use of organic wastes from sewage treatment plants has been investigated (Hutchins et al. 1986).

Bioaccumulation of Metals

Some microorganisms are capable of assimilating large amounts of metals from solution. The outlook for exploitation of such organisms for the removal of toxic ions or for the concentration of useful metals is very bright indeed (Ehrlich and Holmes 1986, Hughes and Poole 1989, Torma 1987a and b, Volesky 1987). Of course, all living creatures require certain trace elements which are found in low concentrations within all cells, though they would be toxic in higher concentrations. Certain microorganisms, however, are endowed with the capacity to assimilate large amounts of certain metals, even toxic ones.

Electrostatic Attraction

A variety of functional groups, or ligands, on cell surfaces carry positive or negative charges, conveying a net charge to the cell. Other things being equal, the intensity and sign (+ or -) of the charge depends on the pH of the extracellular environment. In most natural environments the pH is higher than the cell's isoelectric point; therefore, the cell will have a net negative charge and will passively attract cations, much like an ion exchange resin. However, there is some selectivity, suggesting the existence of specific binding sites for particular cations on the various surface structures. Certain fungi and bacteria, for example, bind large quantities of uranium ions, in some instances to the extent of 15 percent of the cells' dry weight. A yeast was found to bind mercury to its cell walls in amounts equivalent to the weight of the cell walls themselves. Certain species of algae and fungi concentrate copper to the extent of 12 percent of the cells' dry weight. Other metals bound by electrostatic attraction include Fe, La, Cd, Ca, Mg, Pb, Ni, Mn, Zn, Ag, K, and Na.

Surface Deposition or Precipitation (Biosorption)

Massive amounts of metals or insoluble metal compounds can be deposited on the surfaces of some microorganisms. This deposition will occur in some instances when the metal is metabolized; in other instances no transformation of the metal is required for its deposition (Belliveau et al. 1987, Ehrlich and Holmes 1986, Olson and Kelly 1986, Thompson 1986).

Those species of bacteria that reduce tellurite or selenite to metallic Te or Se deposit the metals on their surfaces, accumulate them intracellularly, or both. Some bacteria will aggregate insoluble lead compounds on their surfaces. Most common is the precipitation of ferric compounds and manganic oxides. While many bacteria can oxidize the manganous ion, sheathed, filamentous bacteria in the genera *Hyphomicrobium* and *Metallogenium* and in the *Sphaerotilus-Leptothrix* group become heavily coated with manganic oxides. Also, *Sphaerotilus-Leptothrix* and a group of stalked bacteria in the genus *Gallionella* acquire heavy deposits of oxidized iron, largely ferric hydroxide. Apparently, gallionellae derive energy through the oxidation of Fe^{++}, while the sheathed, filamentous group merely attract the insoluble ferric hydroxide to their sheaths. The genus *Zoogloea,* which is common in activated sludge sewage operation systems, produces copious quantities of polysaccharide slime having high affinity for Cu^{++}, Cd^{++}, Co^{++}, Ni^{++}, Zn^{++}, and Fe^{+++} (Hutchins et al. 1986). The production of extracellular polysaccharide slimes is common to many bacteria; chemically, they vary considerably from species to species, even from strain to strain (Ehrlich and Holmes 1986, Thompson 1986, Torma 1987a, Volesky 1987).

Intracellular Transport of Ions

Both monovalent (Na^{+}, K^{+}, Li^{+}, Tl^{+}, and $NH4^{+}$) and divalent cations are specifically transported to satisfy nutritional needs of microorganisms. In some cases, rather high intracellular concentrations of certain metals are achieved. Often, the same transport mechanism will function for several cations; e.g., Mg^{++}, Co^{++}, Mn^{++}, Ni^{++}, and Zn^{++} in *Escherichia coli.* Others are more specific, although in all such systems various other cations will compete with a particular cation for uptake, in some cases even inducing efflux of ions. Fungi appear to concentrate metals or metalloids to a somewhat greater extent than do most bacteria (Hutchins et al. 1986, Summers and Silver 1978, Tsezos 1985).

Many of the metal ions are toxic, although the toxicity varies considerably from species to species (Belliveau et al. 1987, Ehrlich 1981, Summers and Silver 1978). Sometimes the inhibition of bacterial growth is synergistic. For example, *Klebsiella aerogenes* has been shown to be inhibited to a greater extent by Cd and Zn than by the sum of the individual toxicities of the two cations. The presence of clays, certain anions, and organic matter of various kinds often markedly reduces metal toxicity. Not surprisingly, metal chelators (e.g,, ethylenediamine tetraacetic acid and citric acid) suppress the toxicity of many cations toward microorganisms. Clearly, toxicity is an important consideration in harnessing microbial cells to concentrate metals or metalloids.

An interesting case is found with the diatoms, which encase themselves in siliceous shells in an amazing variety of beautiful shapes. The uptake of silicates by diatoms has been shown to be competitively inhibited by germanic acid, thereby suggesting a means of recovering germanium from natural sources (Kelly, Norris, and Brierley 1979; Krumbein 1983), (See below for another aspect of silicate uptake.) Incidentally, the Russians for over 20 years have referred to “silicate bacteria,” which they claim, in English abstracts, will free silicates from aluminosilicate ores, thereby beneficiating aluminum oxide (Alexandrov, Ternovskaya, and Blagodyr 1967; Andreev, Lycheva, and Segodina 1979; Andreev, Pol’kin, and Lyubarskaya 1982; Rohatgi, Trivedi, and Rohatgi 1984).

Not to be overlooked is the uptake of oxoanions, especially sulfate, the transport of which has been shown in *Salmonella typhimurium* to be competitively inhibited by chromate, selenite, molybdate, tungstate, and vanodate (descending order of effectiveness).

Natural Chelators

Some naturally occurring, low molecular weight compounds (citric acid, aspartic acid, and a number of dicarboxylic acids) have long been known to chelate various metal ions. Many microorganisms produce organic compounds that can do the same thing. Such organic compounds are collectively called “ionophores,” the best known of which are siderophores (iron-attractors) (Nielands 1981; Brock, Smith, and Madigan 1984). Microbes that produce siderophores are believed to have evolved as the rising oxygen content of the Earth’s atmosphere caused oxidation of much of the iron into its insoluble oxide and hydroxide states. To capture the minute quantities of free ferric ions that exist, microbes capable of synthesizing chelators of ferric iron arose. Incidentally, animals

(including humans) trap iron through iron-binding proteins such as lactoferrin, transferrin, and ferridoxin, the latter being particularly abundant in the liver. Many pathogenic bacteria and fungi compete with the infected host for iron through the formation of siderophores. The siderophores—phenolates, hydroxamates, or cyclic peptides—are capable of binding ferric iron, which is subsequently transported into the cell, released, reduced enzymatically, and secreted back into the environment for recycling.

Recently, an ionophore for silicate, another ion very sparingly available, has been found in diatoms (Bhattacharyya and Volcani 1983).

Other metal-binding organic molecules, not chelators, abound in living systems. Of particular note is metallothionein, which binds a variety of cations by virtue of its available sulfhydryl (-SH) groups (Kagi and Kojima 1987).

Conclusion

As I emphasized in my introduction, the rigors of the Moon, or other space environments (asteroids, Mars, Phobos, Deimos, a station orbiting the Earth) are inimical to terrestrial life forms, including, of course, microorganisms. While it would be a far simpler matter to provide, on the Moon for example, conditions conducive to microbial existence than those conducive to human life, no ore could be beneficiated by bacteria there without the provision of a gas-tight container affording certain minimal conditions. No doubt the partial pressures of O_2, N_2, and CO_2 could be held to levels substantially lower than those found on the Earth—how much lower would have to be determined experimentally. The water supply would need to be adequate and continuous. Full radiation protection would be necessary, and temperature fluctuations would need to be minimized. It might well be best to select thermophilic bacteria for this endeavor.

Once a biobeneficiation reactor was constructed and all support systems were activated, it would be inoculated with appropriate strains of bacteria. More than likely, lyophilized (freeze-dried) cultures, probably of genetically engineered strains, would be reconstituted onsite in an aqueous solution, containing a mixture of nutrients brought from Earth as a dehydrated powder. The culture would be added to the moistened ore bed once the operator was satisfied that the cells were growing within the culture vessel. Initially, a leaching solution of dilute sulfuric acid would be added. The enclosure would have to be tight enough to retain all water vapors as well as the atmospheric gases.

As the size of the operation increased by expanding the size of the incubator, more water would need to be added. Unless sufficient sulfur or reduced sulfur in the ore was available for biological oxidation, additional sulfuric acid would be required. As the bacteria became established (as measured by the growth of a subculture or by microscopic examination of samples from the reactor or by chemical determination of the ratio of the concentrations of Fe^{+++} and Fe^{++}), further additions of the culture would become unnecessary. Before the biological operation was established, chemical reductive processing of oxide ores (e.g., ilmenite) would need to be functioning well to provide the necessary water and oxygen.

One problem with the foregoing scenario is that some of the minerals or elements in the ore might be toxic to the bacteria. Studies conducted more than 15 years ago revealed that lunar fines or their extracts inhibited as well as stimulated or proved innocuous to a variety of microorganisms (Silverman, Munoz, and Oyama 1971; Taylor et al. 1970; Taylor et al. 1971; Taylor and Wooley 1973). Silverman and colleagues found that, while the lunar substrate stimulated pigment production by the bacterium *Pseudomonas aeruginosa,* it inhibited pigment production by the bacterium *Serratia marcescens.* Others (Walkinshaw et al. 1970, Walkinshaw and Johnson 1971) found that lunar soil enhanced chlorophyll production and early development of ferns, bryophytes, and a number of seed plants. In keeping with these pioneering studies of the interplay between lunar materials and living organisms, I undertook to make a preliminary study (Johansson 1984) of the effects of leachates of lunar fines on the growth of the common colon bacillus, *Escherichia coli,* in a glucose medium with minimal mineral salts. I found that, depending on its concentration, the leachate either enhanced or inhibited the growth of the bacteria. The specific elements or minerals responsible for the various biological responses to the lunar materials have not been identified.

Prior terrestrial research would be necessary to provide guidance on dealing with a toxicity problem, if it could be identified in advance by appropriate tests of lunar materials. Means of dealing with such a problem could include the addition of hydrogen sulfide, chelators, or certain mineral salts known to block specific toxic ions. There is a vast literature on handling toxicity, but research specifically applied to lunar or asteroidal materials is needed.

Another biological approach to the problem of recovery of certain metals from lunar ores might be the application of metal-binding agents produced, at least initially, on Earth. Candidate substances include ionophores and metallothionein.

The introduction of the micro-organisms needed for the bioprocessing of lunar ores would probably not be an early event in the establishment of an outpost on the Moon. If a human habitation with recycling (of water, oxygen, carbon dioxide, nitrogen, sulfur, and other essential nutrients) was established, the cultures needed in the mining operation would be useful as part of the microflora of that ecosystem. The thiobacilli and other bacteria involved in the leaching of ores are important in the cycles of sulfur, nitrogen (some fix N_2), carbon, and oxygen on Earth (see fig. 32).

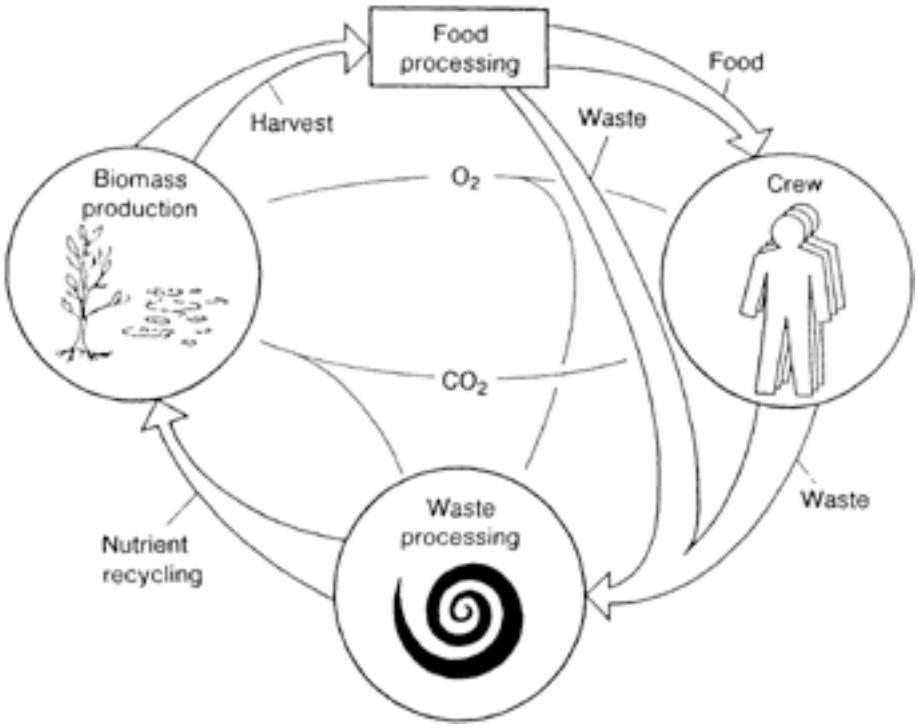


Figure 32

Regenerative Life Support System

In a controlled ecological life support system, as diagramed here, biological and physicochemical subsystems would produce plants for food and process solid, liquid, and gaseous wastes for reuse in the system.

A bioprocessing unit, in which bacteria oxidize and catalyze the extraction of metals from their lunar or asteroidal ores, could be incorporated into this regenerative system. The bioprocessing unit would contribute to the gas and nutrient recycling, the biomass inventory, and the waste processing of the larger regenerative life support system.

One concern is the availability in the lunar soil of the sulfur needed for the ore-beneficiating bacteria to gain energy and by the same process to produce the sulfate for the acid leaching process. In this regard, carbonaceous chondritic asteroids might yield material more suitable for biological ore beneficiation than would the Moon. Of course, sulfur from the Earth could be added to the beneficiation enclosure on the Moon. A fringe benefit of using asteroidal material would be its content of organic matter, which desirable heterotrophic bacteria might possibly utilize for their carbon needs.

Another question that needs to be answered is whether the low level of nitrogen in the lunar regolith (Gibson 1975) is sufficient to enable significant bacterial colonization. It may be necessary to provide, at the onset, nitrogen in the form of nitrate. (Ammonium nitrogen would work but some of it would be oxidized to nitrate, thus imposing a demand on atmospheric oxygen.) The amount of phosphorus may also not be adequate for bacterial life on the Moon. These bacterial nutritional problems would also apply to the development of an ecosystem supporting human life.

In summary, bioprocessing using bacteria in closed reactors may be a viable option for the recovery of metals from the lunar regolith. Obviously, considerable research must be done to define the process, specify the appropriate bacteria, determine the necessary conditions and limitations, and evaluate the overall feasibility.

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Processing of Metal and Oxygen From Lunar Deposits

Constance F. Acton

Metallurgical Processing

Introduction

Metallurgy—the art and science economically concentrating, extracting, refining, and fabricating metals and alloys—has existed on Earth from antiquity. Gold, silver, and copper—elements that can occur as metals in their natural state—were used as long as 10 000 years ago. Metals extraction technology can be traced back at least 6000 years. Recently, major advances have been made in metallurgical processing. This developed field may now be ready for application to the production of metals in space.

Table 11 shows the steps involved in the production of mineral-based materials for commerce.

TABLE 11. *Steps in the Production of Mineral-Based Materials for Commerce*
[From Dresher 1974]

I Exploration	II Production of raw materials	III Beneficiation of raw materials	IV Extraction and production of metals. Primary composition processing of minerals for nonmetallic uses. Processing and conversion of fuels.	V Fabrication of materials with specific composition	VI Properties and uses of materials
	←----------	**Mineral science and technology**	---------- →		
←---------- → **Geological sciences**				← ---------- → **Materials science**	
		←---------- → **Metallurgical engineering: Extractive (minerals-based)**		←---------- → **Adaptive (metals-based)**	

The first step is exploration to define potential sources of raw materials. The Apollo Program has defined some lunar resources; further exploration will undoubtedly find additional ones. Whether or not a metal-bearing deposit is classified as an ore, a reserve, or a resource is a question of economics. An ore is a resource that can be extracted at a profit. A reserve is a resource currently uneconomical to mine or greater than existing demand. A resource becomes a reserve or an ore if the proper technologies and economic conditions are developed.

The concentration of most metals in the crust of the Earth (or the Moon) is extremely low. And even the most abundant elements on Earth—iron, aluminum, silicon—cannot generally be extracted from common rock at a profit. A metal must be sufficiently concentrated in a mineral before it is mined. Then the useful constituents of an ore must be separated from the residue (gangue) by the process of beneficiation. In this process, the ore minerals are concentrated by physical separation, exploiting differences in such properties as particle size, shape, and size distribution; specific gravity; magnetism; and electrostatics.

The importance of the beneficiation step cannot be overemphasized. Only after the ore minerals have been concentrated can economical metal extraction take place. On the Moon, some whole rocks may be ores for abundant elements, such as oxygen, but beneficiation will be important if metallic elements are sought from raw lunar dirt.

In the extraction process, a beneficiated metallic ore, such as an oxide, sulfide, carbonate, or silicate mineral, is converted to the reduced metal. Such minerals are the stable forms of metals in the Earth's or the Moon's environment. In the case of the important iron ore mineral magnetite (Fe_3O_4), the free energy of formation at 0 °C is more than 120 kcal/mole O_2 according to the reaction

$$3/2\ Fe + O_2 = 1/2\ Fe_3O_4$$

This explains the natural tendency of metallic iron to rust in air; that is, to convert to its thermodynamically stable oxide form. A very useful pictorial representation of the relative stability of metal oxides is an Ellingham diagram (fig. 33). These diagrams are also available for chlorides, fluorides, and sulfides.

Figure 33

Ellingham Diagram

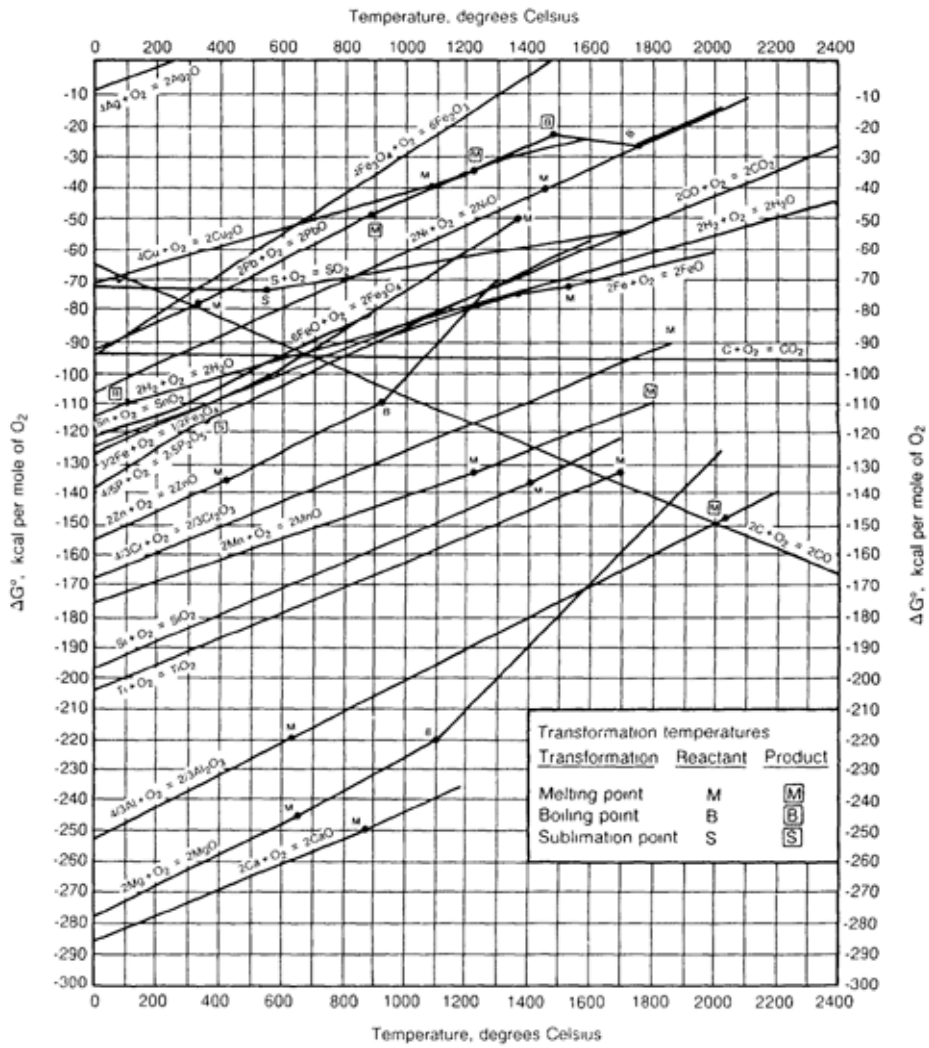
This diagram shows the standard free energy of formation of a number of oxides as a function of temperature. Accuracy varies between ±1 and ±10 kcal.

At 25 °C the oxides produced by these reactions form with these free energies:

(1)	$4Ag + O_2 = 2Ag_2O$	*-5.18*	*kcal per mole of O_2*
(2)	$2C + O_2 = 2CO$	*-65.62*	
(3)	$4Cu + O_2 = 2Cu_2O$	*-69.96*	
(4)	$S + O_2 = SO_2$	*-71.79*	
(5)	$2Pb + O_2 = 2PbO$	*-90.5*	
(6)	$4Fe_3O_4 + O_2 = 6Fe_2O_3$	*-93*	
(7)	$C + O_2 = CO_2$	*-94.26*	
(8)	$2Ni + O_2 = 2NiO_2$	*-103.4*	
(9)	$2H_2 + O_2 = 2H_2O$	*-116.42*	
(10)	$2Fe + O_2 = 2FeO$	*-116.8*	
(11)	$3/2Fe + O_2 = 1/2Fe_3O_4$ $(3Fe + 2O_2 = Fe_3O_4)$	*-121.2*	
(12)	$2CO + O_2 = 2CO_2$	*-122.9*	
(13)	$Sn + O_2 = SnO_2$	*-124.2*	
(14)	$6FeO + O_2 = 2Fe_3O_4$	*-134.4*	
(15)	$4/5P + O_2 = 2/5P_2O_5$ $(4P + 5O_2 = 2P_2O_5)$	*-146.1*	
(16)	$2Zn + O_2 = 2ZnO$	*-152.1*	
(17)	$4/3Cr + O_2 = 2/3Cr_2O_3$ $(4Cr + 3O_2 = 2Cr_2O_3)$	*-166.8*	
(18)	$2Mn + O_2 = 2MnO$	*-173.6*	
(19)	$Si + O_2 = SiO_2$	*-192.4*	
(20)	$Ti + O_2 = TiO_2$	*-203.8*	
(21)	$4/3Al + O_2 = 2/3Al_2O_3$ $(4Al + 3O_2 = 2Al_2O_3)$	*-251.18*	
(22)	$2Mg + O_2 = 2MgO$	*-272.26*	
(23)	$2Ca + O_2 = 2CaO$	*-288.8*	

The more energy is given off during the formation of an oxide, the more likely that oxide is to form and the more stable that oxide is. By the same token, the more negative the free energy of formation of an oxide, the harder it is to break that oxide down into the elemental metal and oxygen. Thus, the metals on the lower lines of this chart can reduce the metallic oxides on higher lines.

After Richardson and Jeffes 1948.



The larger the negative free energy of formation, the more stable the oxide. It can readily be seen that at 0 °C the relative stability for oxides increases from iron through silicon and titanium to aluminum. The metals in the more stable oxides (lower on the chart) can chemically reduce the metals in the less stable oxides (higher on the chart). Also shown are lines for carbon and hydrogen, common reductants used in terrestrial extractive metallurgy. The challenge is to find procedures to extract the element of interest economically.

In some terrestrial cases, metals may be economically extracted at a higher than normal rate of energy consumption per unit of metal produced because cheap electrical energy is available; for instance, siting an aluminum smelter near a hydroelectric supply. In such a case, the rate of energy consumption may be 10–50 percent more than the general industry practice. The economics of utilizing metals from resources in space are driven by transportation costs rather than energy costs. Many processes proposed for extraction of lunar materials are energy-intensive. Thus, the cost of energy on the Moon will be an important factor in developing processing technology. For example, concentrated solar heat will be cheaper than electricity and should be utilized where possible.

Geochemical Availability

Skinner(1976) has provided a lucid analysis of the geochemical availability of various elements on Earth. The basic concepts are directly applicable to the Moon. The most abundant metals in the Earth's crust are silicon, aluminum, iron, calcium, magnesium, sodium, potassium, and titanium (see table 12). For comparison, the composition of a typical lunar mare basalt [sample 10017, as analyzed by Wänke et al. (1970)] is also shown. To a first approximation, the compositions of terrestrial and lunar rocks are not too different.

TABLE 12. *Major Chemical Elements in the Earth's Crust and in a Typical Lunar Mare Basalt*

Element	Continental crust, weight %	Lunar sample 10017, weight %
Oxygen	45.20	40.7
Silicon	27.20	19.6
Aluminum	8.00	4.4
Iron	5.80	14.6
Calcium	5.06	8.2
Magnesium	2.77	4.8
Sodium	2.32	0.347
Potassium	1.68	0.206
Titanium	0.86	7.0
Hydrogen	0.14	---
Manganese	0.10	0.148
Phosphorus	0.10	---
Total	99.23	100.001

The geochemically scarce metals are those which do not normally form separate minerals but are present as substitutional atoms in common rock; for instance, lead or zinc may occur at ppm levels in orthoclase ($KAlSi_3O_8$). To release lead from the silicate structure, the entire mineral has to be chemically broken down, an extremely complex and energy-intensive process. "The mineralogical barrier" described by Skinner (see fig. 34) refers to the point at which the easily processed minerals, such as sulfides, are so rare that mineral beneficiation techniques cannot be applied economically. At this level, the increased energy required to extract trace metals from silicates must be expended. Although the diagram is conceptual, the energy jump for the mineralogical barrier is 2 to 3 orders of magnitude higher than the energy required for the processing of typical ore minerals on Earth.

On Earth, mainly by means of free water, nature has concentrated the rarer metals in ore deposits. Such deposits are unknown on the dry Moon. On the Moon, metallic iron can be concentrated from soils, and iron and titanium oxides (ilmenite) and iron sulfides (troilite) can be concentrated from soils or disaggregated rocks. Essentially all other known lunar ores are above the mineralogical barrier and will require considerable energy for their extraction. Examples include silicon and aluminum from anorthite and iron or magnesium from pyroxene.

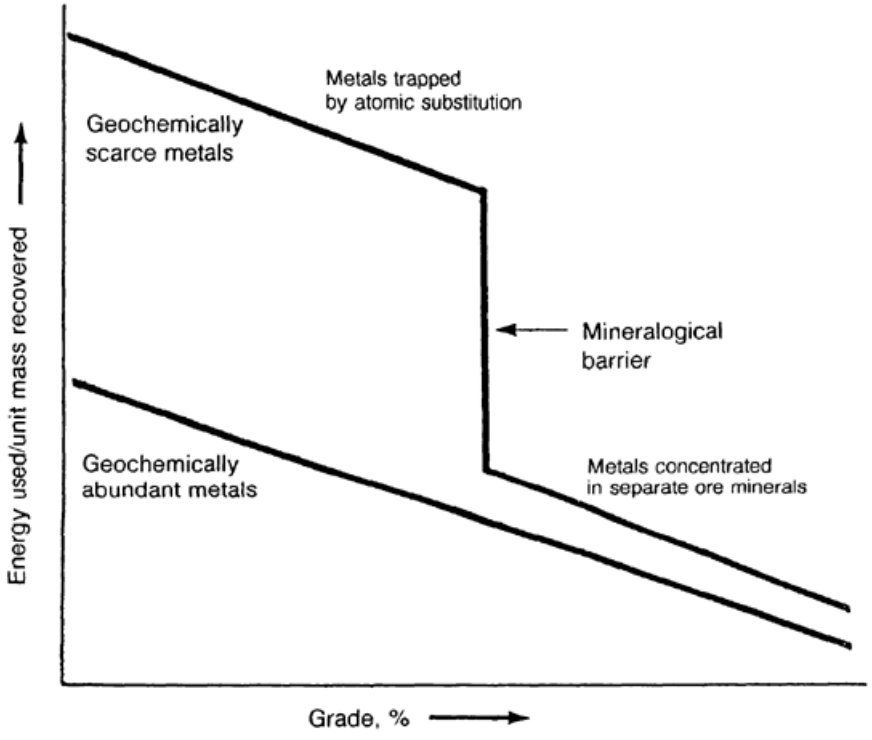


Figure 34

The Mineralogical Barrier

The relationship between the grade of an ore and the energy input per unit mass of metal recovered is shown for both scarce and abundant metals. A steadily rising amount of energy will be needed to produce even geochemically abundant metals from the leaner ores of the future, but the amount of energy needed to produce scarce metals will take a tremendous jump when the mineralogical barrier is reached. At that point, when ore deposits are worked out, mineral concentrating processes can no longer be applied, and the silicate minerals in common rocks must be broken down chemically to separate the atoms of scarce metals from all the other atoms.

From Skinner 1976.

Extraction Technology

Extraction of various metals from mineral ores has developed into three subdisciplines: pyrometallurgy, electrometallurgy, and hydrometallurgy. In each subdiscipline, a different mechanism provides the driving force to reduce the combined metal to its elemental form.

In pyrometallurgy the force that drives the chemical reduction of a metal oxide is high temperature. For many of the less stable metal oxides, carbon reduction at elevated temperatures is possible. This technology has been used successfully for iron smelting. (See figure 35.) For the more stable metal oxides, such as TiO_2 and Al_2O_3, carbon reduction proceeds spontaneously (that is, the free energy becomes negative) only above 1630 °C and 2000 °C, respectively. The disadvantages of high temperature extraction include

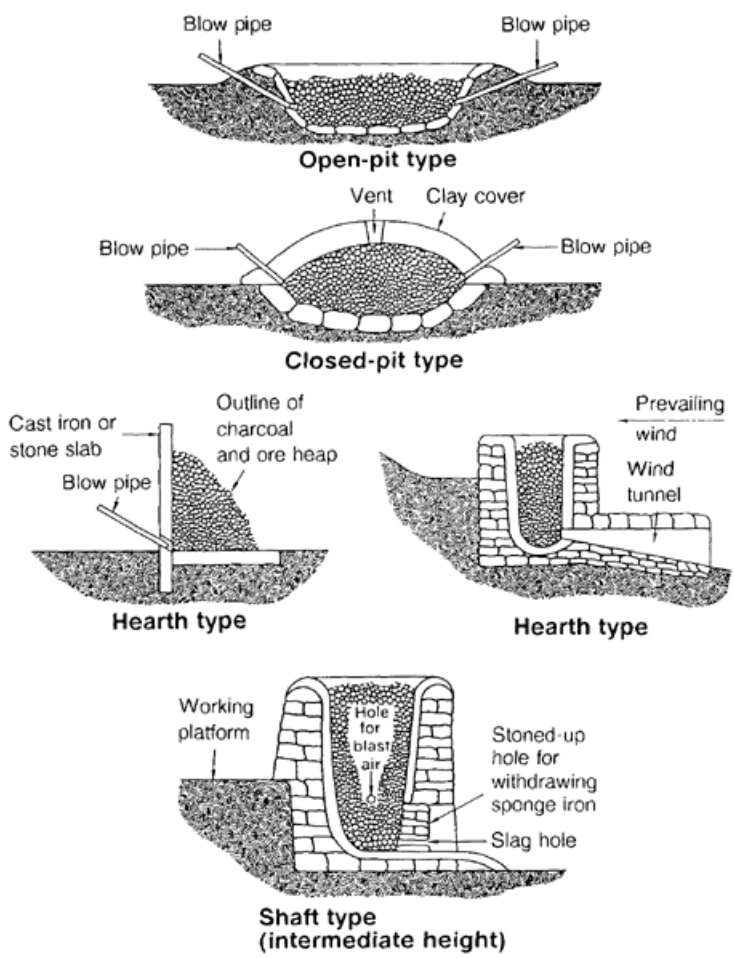


Figure 35

Iron Smelting

Iron smelting was discovered by ancient humans, changing the course of civilization. The basic process is one in which carbon (charcoal) is mixed intimately with iron oxide. Burning of the carbon produces carbon monoxide, which reacts with the iron oxide to produce metal and carbon dioxide, which is vented from the smelter. Many configurations were used in early smelters to optimize the delivery of oxygen and remove the metal and slag (residue) from the process. The slag consists primarily of impurities in the oxide ore.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 1-2.*

the large amount of energy required for heating, the difficulty in finding suitable container materials, and the problem of reoxidation of the molten metal.

In electrometallurgy an electrical rather than a chemical driving force is used to reduce the metal oxide. An example of a well-developed electrometallurgical technology is the extraction of aluminum from Al_2O_3 by electrolysis in molten fluoride salts.

Hydrometallurgy exploits the fact that certain minerals are soluble in aqueous solutions such as sulfuric acid. Once dissolved, the metal ions can be recovered by low-temperature electrolysis, precipitation, chemical reduction, ion exchange, or solvent extraction. (See figure 36.)

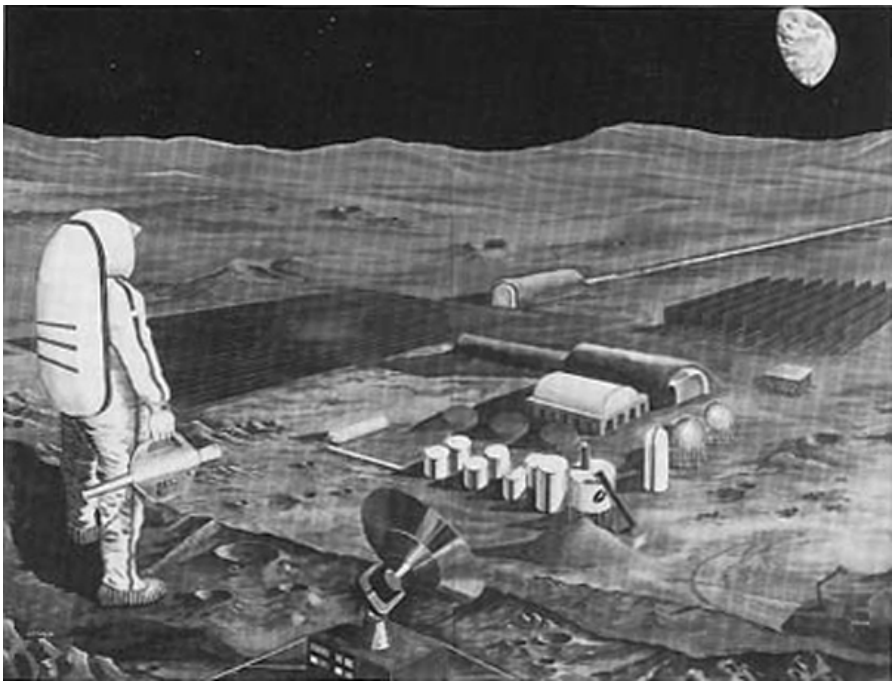


Figure 36

Chemical Extraction Plant on the Moon

In this artist's concept of a lunar chemical plant, metals and oxygen are extracted from lunar soil using relatively low-temperature aqueous chemistry. First, lunar soil and crushed rock are leached in aqueous hydrofluoric acid (HF) in the tank with the chute and chimney, making metal fluorides. The metal fluorides in solution are further processed in the tall and short cylinders and then electrolyzed in the light-colored building with the pillars, producing oxygen and metals at the electrodes. Oxygen is liquefied and stored in the spherical tanks (two large ones and many small ones under a roof). The HF is recovered, recycled, and stored in the vertical cylinder on the right. The horizontal cylinder on the left holds the water needed for this aqueous process. The upright panels in the background to the right radiate the excess heat generated by the process. The flat solar panels in the background to the left supply power to the electromagnetic launcher in the middle background, which will shoot lunar products to orbit. The soil-covered buildings in the middle provide workshops and housing for the lunar pioneers.

Artist: Scott Berry

Courtesy of William N. Agosto, Lunar Industries, Inc.

The scarcity of water and the abundance of solar energy available at nonterrestrial sites suggest that pyrometallurgy or electrometallurgy will be favored as processing technologies there. Processes that conserve volatile substances by recycling will be essential to minimize the transport of makeup chemicals, as will be processes that limit the consumption of special materials, such as fluxes or anodic substances, which would have to be transported to space.

This discussion of geochemical availability and extractive metallurgy implies that extraction of minor elements in space is questionable unless specific natural concentrations are discovered or energy becomes very inexpensive. The relative costs of scarce and abundant metals will become even more disparate in the future on Earth as well as in space. It may be more cost-effective to substitute the lesser properties of an abundant metal like iron or aluminum than to attempt to extract a geochemically scarce metal. This line of thought suggests that effort be directed to extracting iron on the Moon rather than to recovering scarcer metals (such as those from the platinum group) from asteroids. When exploration and timing difficulties are added to the energy consumption considerations, the case for going after the rarer precious metals becomes yet weaker.

Proposed Extraction Schemes

Introduction

In the following section, a variety of plausible processing technologies are described. In general it may be said that these technologies are derived from a limited amount of terrestrial experience and are totally untested in application to the extraction of nonterrestrial resources. Work must be initiated in the near future to sort out these and other proposals, for it is the experience of the metallurgical industry that such processes require much development and testing, at bench-top and pilot-plant levels, before production facilities are achieved. Development times of 10 to 25 years have been experienced, and many false steps have been taken. For example, an Alcoa plant for extraction of aluminum metal from anorthite by carbochlorination and electrolysis of aluminum chloride was constructed at a cost of $25 million, only to be shut down after a short operating time because of technical problems.

Many process schemes have been proposed for recovering a variety of metal products and volatiles from a variety of lunar feedstocks. A collection of pyrometallurgical, electrometallurgical, and hydrometallurgical approaches have been proposed, with varying amounts of research and engineering data to support them.

The participants in this study looked at scenarios for the development of space resources in the next 25 years. The materials subgroup of study participants reached the consensus that, within this timeframe, oxygen production from lunar resources will be the major objective of the space program. The participants also assessed what metals recovery technologies can be implemented and suggested what time would be required to develop more complex metal processing technologies.

Recovery of Meteoritic Iron

History and thermodynamics teach us that the most appropriate metal to recover first is iron. The most basic approach to recovering iron on the Moon is to process the meteoritic iron found in lunar soils. Small chunks of meteoritic iron have been found in lunar samples, but most metal exists in the form of micron-size particles, particles encapsulated by or attached to silicates or glasses.

The first processing effort should be to concentrate this elemental iron by mineral beneficiation techniques (such as magnetic separation). Current knowledge does not suggest that regions of elevated metal content can be found, but additional information on the abundance and ease of separation of the metal is needed. In addition, trace elements in the iron must be identified. Alloying elements or solutes can have a profound effect on the iron's mechanical properties. The iron and steel industry has probably never looked at iron alloys of lunar composition, because carbon and other solutes are always introduced in the smelting process.

The utilization of meteoritic iron is suggested as a first approach because it does not require the energy-intensive and chemically complex step of extraction. However, a process for separating the metal from adhering silicate minerals must be developed. The recovered lunar iron can either be processed directly into parts by powder metallurgical techniques or be melted at about 1550 °C and cast into ingots for wrought products.

Even though this is the simplest process for producing lunar iron and the technologies for beneficiation, melting, and pressing or casting and forming are fairly

well developed on Earth, the application of these technologies in the lunar environment will present many challenges.

Processing of Lunar Ilmenite

The next simplest process for recovering iron is to reduce it from ilmenite ($FeTiO_3$). For the reaction

$$FeTiO_3 + H_2 = Fe^0 + TiO_2 + H_2O$$

the free energy at 1000 °C is 5.86 kcal/mole. This gives a very low equilibrium constant $K_c = 0.103$ at 1000 °C. Thus, the reduction of ilmenite to reduced iron plusTiO_2 is not strongly favored thermodynamically and may not proceed to completion. Furthermore, the reaction will not proceed to the right unless H_2O (g) is removed from the system. Thus, if thermodynamically favorable, the rate of reaction must be determined.

Another ilmenite reduction scheme based on a commercial process has been suggested for the Moon (Rao et al. 1979). In it the ilmenite is reacted with carbon to reduce FeO to Fe^0. The iron from the ilmenite is chlorinated at 800 °C in a fluidized bed reactor while the TiO_2 remains unchanged. The $FeCl_3$ gas is condensed and could be reacted with oxygen gas at 300–350 °C in a second fluidized bed to produce Fe_2O_3. The Fe_2O_3 could then be reduced with either carbon or hydrogen gas below 1000 °C to produce low-carbon steel or iron. The CO or H_2O formed would be recycled to recover the oxygen. Alternatively, the $FeCl_3$ could be reduced directly to metallic iron with hydrogen at 700 °C. The hydrogen chloride formed as a byproduct would be recycled. The flow diagram for this conceptual process is shown in figure 37.

The residue in this process is TiO_2, which can be further processed to recover titanium metal. Since titanium forms a highly stable oxide, it cannot be reduced with carbon or hydrogen. It can, however, be reduced with calcium metal. A process has been developed to perform this reduction by pelletizing TiO_2 and calcium metal powders and heating at 925–950 °C for several hours. The CaO is then preferentially dissolved by acid leaching. Disadvantages here are that the acid and water must be recycled and that water is not available at the site. Calcium metal could be provided from processing of anorthite for aluminum.

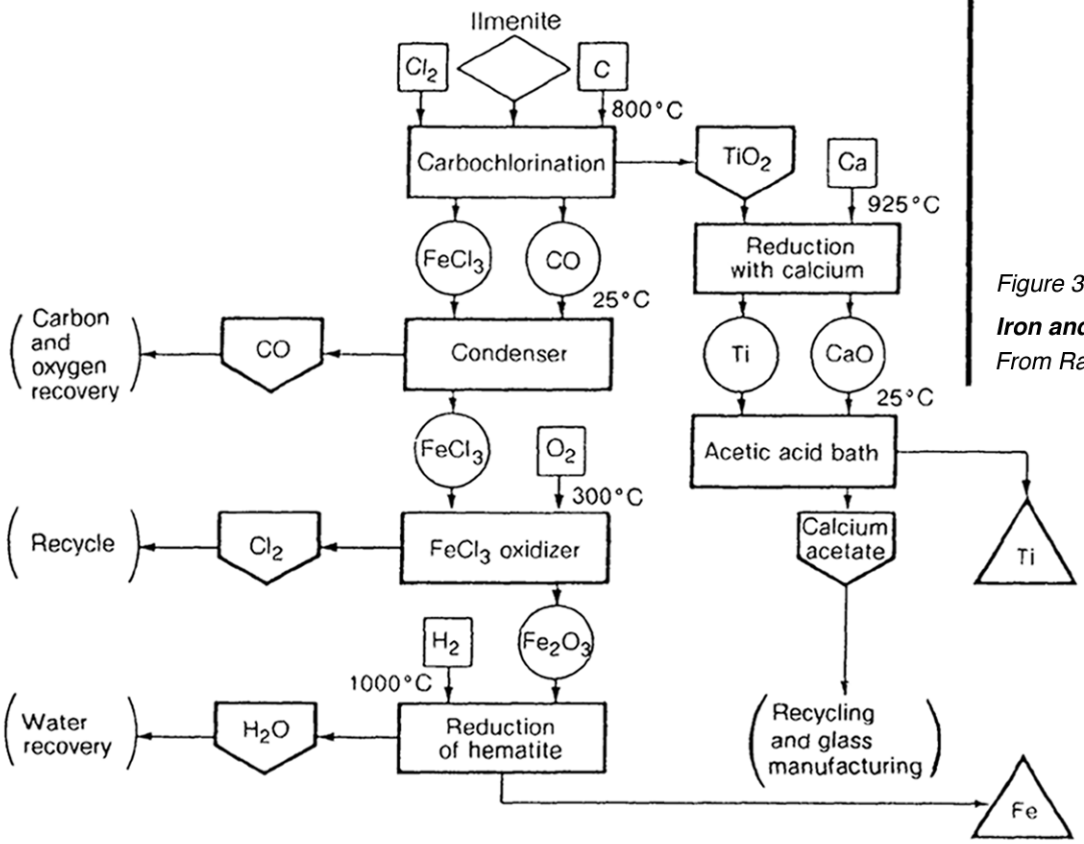


Figure 37

Iron and Titanium Processing

From Rao et al. 1979.

The most likely end product of ilmenite processing is a partially reduced mixture of Fe, FeO, TiO_2, and other impurities. There are several possible options for using this type of product.

The simplest is not to try to recover the iron but rather to use the material as is to form “cermet” blocks for construction. Assuming that 50- to 200-µm particles are produced from the fluidized bed reactor, sintering may be successful at temperatures just below the melting point of iron. To evaluate this option further, considerable test work on pressing (using, for example, a hot isostatic press) should be done on simulated residues. If this option proves unsuccessful, the iron-titania residue may simply be stockpiled until such time as more advanced processing technology is developed for the lunar site.

If iron recovery is required and the chlorination process does not prove feasible, simply melting the iron out of the residue may successfully produce a crude iron alloy suitable for structural uses. Alternatively, a low-temperature carbonyl process could be utilized to extract the iron.

Other Proposed Processes

For lunar processes to be successfully developed, certain guidelines must be kept in mind. These include the following:

- Pyrometallurgical and electrometallurgical operations are favored. Because of the lack of available water on the Moon, hydrometallurgical operations will require additional development to recover process water with high efficiency.

- Reductants such as chlorine, hydrogen, and carbon, if not obtainable from lunar sources, must be brought from Earth and therefore should be recycled to minimize their resupply.

- The processes should be tailored for the high-vacuum, low-gravity space environment. Alternatively, methods for providing inexpensive pressurized volumes would have to be developed.

- The oxygen produced in the metal recovery process will be more important than the metal recovered, at least in the early phases.

The NASA SP-428 paper (Rao et al. 1979) was written by recognized metallurgical experts who did a competent job of assessing the available thermodynamic and kinetic literature for several aluminum, titanium, iron, magnesium, and

oxygen extraction processes. Their analysis of the research done and needed may stand up to scientific scrutiny by their peers. None of their candidate processes, however, has been sufficiently tested to provide the data needed for process plant design by a competent engineering company.

A number of other processes have been referred to at this workshop. These include acid leaching, alkali leaching, fluorination, electrolysis, basalt vaporization, plasma smelting, and sulfide processing. Some of these processes can be summarily dismissed for such reasons as requiring large amounts of water or of a nonlunar reductant, impracticality of recycling, or requiring extraordinary amounts of energy. For those few which may warrant less cursory evaluation, the basic scientific data have not yet been provided.

Process Development

What is needed *at a minimum* to establish credibility in the scientific community is compelling thermodynamic and kinetic data for any proposed system.

Before any research work can begin, it is obvious that a comprehensive literature review must be done. Any pertinent thermodynamic data must be critically evaluated. The feed material must be realistically characterized in terms of physical and chemical properties. The stoichiometry and phase relations for the system must be known.

The thermodynamic properties of the system should be determined experimentally. The extent of deviation from calculated thermodynamic values for condensed and vapor phases should be measured. Appropriate phase diagrams should be constructed relating phase composition, free energy of formation, and temperature; e.g., phase diagrams for the elements in the ilmenite (Fe-Ti-O) and for the products of the ilmenite reduction process ($Fe\text{-}Ti\text{-}O_2\text{-}H_2$) for temperatures between 700 and 1000 °C. The vapor phase and residue should be accurately analyzed as well.

If the thermodynamic data indicate an attractive extraction process, the kinetics and heat and mass transfer properties must next be systematically investigated.

It should be noted that experimental programs for high-temperature processes are extremely difficult and may require several years' effort.

Assuming that the proposed process has been demonstrated by such a bench-scale program to be feasible, it is appropriate before proceeding further to do an economic evaluation of the process. Operating and capital costs should be assessed, and special considerations, such as mass and energy requirements, need to be carefully analyzed.

If the process still appears attractive, then a terrestrial pilot plant is mandatory. If the process does not work on Earth, it probably cannot be made to work on the Moon. A great deal of consideration would have to go into designing a pilot plant that would yield useful information regarding a plant at a nonterrestrial site. Even for the very simplest of processes, it is clear that its development for use on the Moon would require an intensive research and development program. If begun now, the most optimistic program for an ideal process would probably take 20–50 years and involve hundreds of millions of dollars.

Thus, if lunar resources are to be used in the early 21st century, there is a clear need to begin a research and development program now. It should proceed through the stages presented in table 13.

TABLE 13. *Research and Development Program for a Lunar Metal Recovery Process*

Stage	Time	Personnel	Cost	Comments
1. Technology review	6 months	Metallurgical specialists	Modest	
2. Experimental research	3–5 years	Researchers at several institutions concurrently	Considerable	Although iron, aluminum, silicon, and titanium should all be evaluated, priority should be given to iron, which is thermodynamically the least stable oxide and the metal with the largest body of known technology.
3. Pilot plant	2 years or more	R&D engineers	Significant	
4. Plant design	2–3 years	Engineering and construction team	Unknown until phases 2 and 3 are completed	All of the process technology developed would be translated into hardware amenable to lunar operation.
5. Hardware construction	3–5 years	Manufacturing and construction personnel	Unknown until phase 4 is completed	Hardware could be constructed on Earth or on the Moon or both.
6. Plant startup	1–2 years	Engineering and construction team	Unknown until phase 4 is completed	

A fair amount of speculation on metal recovery processes has been made, but so far little of the work can stand up to scientific scrutiny. To build a workable lunar materials recovery plant, the logical program described must be followed. Sufficient amounts of capital and work time by qualified metallurgical personnel must be provided.

Experts in the fields of mineral science and metallurgy must contribute to the development of the required new process technology. The most effective means of achieving this objective is by joint cooperative efforts between established metallurgical experts and specialists in the planetary sciences. If the space program attempts to develop metallurgical capabilities in-house, the timing objectives for the new technology will be impossible to meet.

Applicability of Space Technology to Terrestrial Metal Processing

Metallurgical technology on Earth has developed slowly with a limited base of trained technologists and R&D funding. The research is very difficult experimentally, complex, and hard to scale up. Hence, process development is slow.

It seems obvious that even a minor R&D effort by the space program would be a major contribution to the existing body of knowledge. Although it is impossible at this time to judge what metal processing technologies will be developed for space in the next 25 years, it is of interest to use some general guidelines to speculate, as follows.

Chloride and fluoride systems offer interesting potential for metal extraction. Such processing schemes would provide a technology base for a terrestrial metallurgical breakthrough that would reduce energy consumption per unit output. Along with the process chemistry, the development of recycling technology could clearly be advantageous in dealing on Earth with ever increasing environmental limitations.

Development of electrochemical, electrode, or electrolysis technologies for metal extraction, refining, or processing could advance the currently rather empirical state of the art on Earth for certain metals.

The development of a computer interface with metallurgical process technology would likely advance the state of metallurgy by several orders of magnitude and is

one of the most exciting prospects for change.

Metals produced by new technology on the Moon will not contain the solutes usually contained in their counterparts on Earth, such as carbon and sulfur in steel. Physical and mechanical properties of a whole new cadre of alloys will be measured. The creation of such uncontaminated alloys will advance the field of materials science since the effect of impurities on properties can be zeroed out. Such new alloys may be used on Earth for unique applications, now impossible to fulfill.

And new metallurgical technology developed to extract metals from alternate mineral feedstocks could have strategic and possibly commercial value on Earth.

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Concrete: Potential Material for Space Station

T. D. Lin

Introduction

To build a permanent orbiting space station in the next decade is NASA's most challenging and exciting undertaking. The space station will serve as a center for a vast number of scientific projects. Because of high launch costs, aluminum and fibrous composite materials, light and strong in nature, are being considered for the construction. To my knowledge, concrete has been totally neglected in the search for suitable materials.

In 1981, Construction Technology Laboratories, a division of the Portland Cement Association, initiated a study of the feasibility of using concrete for structural components of a space station. The idea of using concrete in space may seem absurd to many scientists and engineers. Nevertheless, the study shows that concrete is not only suitable but also economical for space station construction.

Concrete

Concrete is basically a mixture of two components: aggregate and cement paste. The paste, composed of Portland cement and water, binds the aggregate into a rocklike mass as it hardens. In general, concrete consists of three parts aggregate and one part paste by weight.

Since the invention of Portland cement in 1824, concrete has been a widely used construction material and a popular subject for study by the engineering community. Using current concrete technology, a compressive strength of 6000 psi [41.4 megapascals (MN/m^2)] can easily be attained with the proper mix design. Concrete made with superplasticizer has a strength of 10 000 psi (69 MN/m^2), and treatment of superplasticized concrete with silica fume (Malhotra and Carette 1983) raises its strength to 17 000 psi (117 MN/m^2).

Reinforced Concrete

The flexural strength of plain concrete is generally low, about 1/10 its compressive strength. However, concrete reinforced with steel rods has found common use in the construction of high-rise buildings, nuclear containment structures, and pressurized liquid nitrogen tanks. The strength design method recommended by the Building Code Requirements for Reinforced Concrete (ACI 318-83) assumes that the concrete takes up the compressive stresses and the reinforcing steel takes up the tensile stresses.

Concrete reinforced with either steel or glass fibers has greatly increased flexural strength, strain energy, and ductility. Test data reveal that concrete reinforced with 4 percent steel fibers by weight

possesses nearly twice the flexural strength of plain concrete (Hanna 1977). Other studies indicate that these fibers act as crack arresters; that is, the fibers restrict the growth of microcracks in concrete (Romualdi and Batson 1963).

Lunar Materials

To produce concrete in space, lunar rocks will make excellent aggregate. Concrete specimens made with terrestrial basalt similar to lunar basalt have been tested in our laboratories. As expected, basalt concretes have compressive strengths of 6000 psi (41.4 MN/m^2) and higher. Moon dust, a pozzolanic substance similar to fly ash (a byproduct of coal-fired power plants producing electricity), can be used to reduce cement requirements by as much as 15 percent without degrading concrete quality (McCrone and Delly 1973).

Once a lunar base is established for the extraction of lunar oxygen (Davis 1983), water produced in the oxygen extraction process can be used for making concrete. The hydrogen needed to extract the oxygen may itself be extractable from the lunar soil, where it has been implanted by the solar wind to a concentration of 100 ppm (Carter 1985). However, if hydrogen extraction proves to be economically infeasible, the hydrogen can be brought up from the Earth.

A study of mare basalt and highland anorthosite (NASA CP-2031) brought back by the Apollo 17 astronauts reveals that it is possible to manufacture on the Moon both glass fibers (Subramanian and Austin 1978) and a cement which is relatively high in aluminum oxide (Takashima and Amano 1960) by sintering lunar materials in a solar furnace. Concrete made from this type of cement is strong but crumbles when it absorbs moisture. On the dry Moon, such a cement offers the advantage without the disadvantage.

Because of the low gravity and the lack of an atmosphere on the Moon, the transport of construction materials from the lunar surface to Earth orbit can be accomplished with tremendous energy savings in comparison to shipping them from the Earth's surface (Chapman 1984).

Mixing and Casting

Concrete would be mixed and cast in a Space Shuttle external tank that provides temperature, pressure, and humidity controls. Figure 38 shows a conceptual space concrete plant. Two rockets at the ends of a tube protruding from the module spin the system to provide the desired centrifugal force (0.5 *g*). Centrifugal force makes conventional mixers usable in a weightless environment.

Concrete materials would be pumped from storage bins through tubes to the mixers. From the intake position, the mixers turn 90° to an upright position and then rotate around their own axes to agitate the mixture. By rotating another 90° so that the feed openings face outward, the mixers allow the fresh concrete to be discharged into receiving buckets, from which spiral mass drivers can pump the wet concrete to the casting location.

After discharging into forms, the concrete would be consolidated, using appropriate vibrators, and finished with large trowels by human operators, working in the shirt-sleeve environment. In terrestrial construction, forms are generally removed 7 days after casting. However, a low-gravity environment will put less stress on the curing concrete, and therefore it will be possible to shorten the 7-day requirement to 1 day by decreasing the spin rate of the system. Since water will be expensive to manufacture in space, condensers can be utilized to capture the moisture evaporated during the curing period. As soon as the concrete has dried sufficiently, the structure is ready to be moved out of the module. The application of slip-forming techniques will make it possible to build a continuous cylindrical space station of any size.

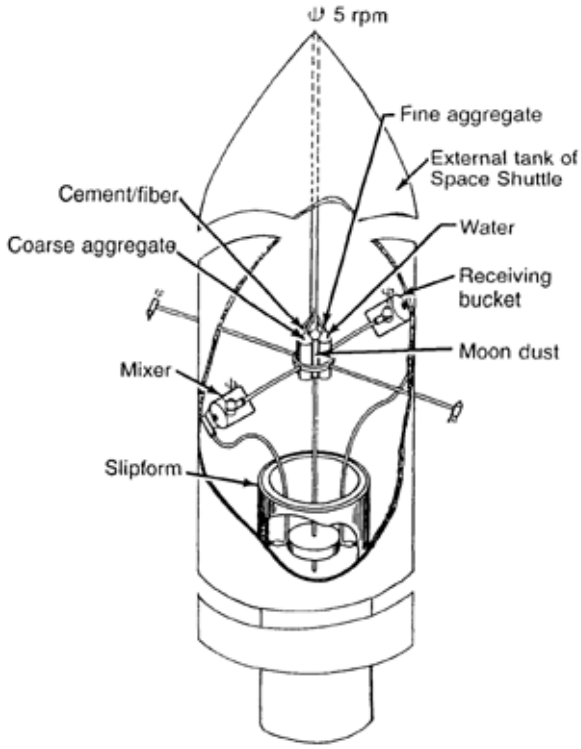

Figure 38

Conceptual Concrete Plant in Space

Advantages

A concrete space station has the following advantages.

1. *Large mass:* An orbiting station is charged with kinetic energy, of which the velocity is a relative factor and the mass an absolute factor. In the event of a collision, a larger mass that possesses greater momentum will always have the dynamic advantage over a smaller one. Reinforced concrete structures have this advantage over less massive structures.

2. *Compartmentalization:* One of the strong features of concrete is that it can be cast at room temperature into any monolithic configuration. A concrete space structure should be compartmentalized to prevent total destruction in case the station is hit by something or a fire occurs.

3. *Concrete strength:* In near-Earth space, temperature may vary from -200 °F (-130 °C) in the dark to +200 °F (+93 °C) facing the Sun (Heppenheimer 1977). The effect of temperature on material strength is an important consideration in structural design. Some materials soften when heated, and others become brittle when cooled. Figure 39 shows that the strength of concrete heated to 200 °F (93 °C) is practically unaffected (Abrams 1973). And the strength of concrete *increases* as the temperature goes below the freezing point. Figure 40 shows the strength-temperature relationship for normal weight maintained at 75-percent relative humidity. Surprisingly, the strength at -150 °F (-100 °C) is 2-1/2 times the strength at room temperature and at -250 °F (-160 °C) is 2 times that at room temperature (Monfore and Lentz 1962). [The strength of concrete in an oven-dry condition remains constant in the temperature range from -250 °F (-160 °C) to +250 °F (+120 °C).]

4. *Heat resistance:* Whereas aluminum softens at 600 °F (320 °C), concrete is thermally stable up to 1100 °F (600 °C) (Harmathy 1979). Its low thermal conductivity and high specific heat make it an excellent heat-resistant construction material.

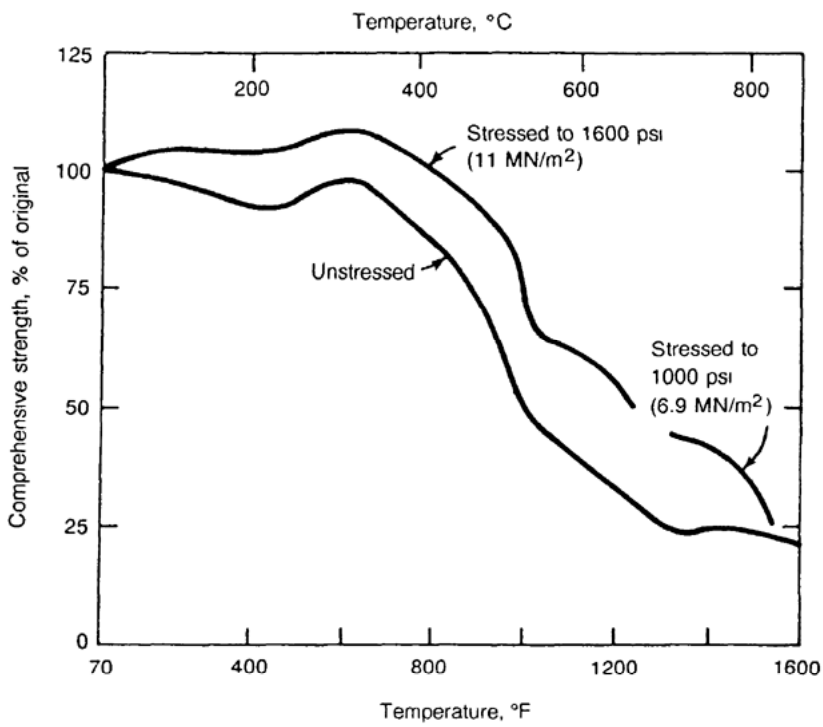

Figure 39

Effect of Temperature on Compressive Strength of Siliceous Aggregate Concrete

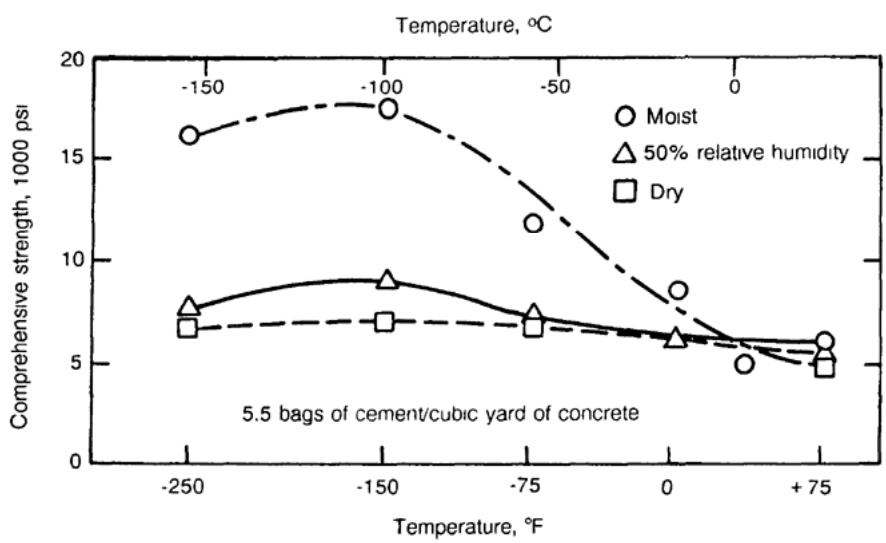

Figure 40

Effect of Low Temperatures on Strength of Moist Concrete

5. *Radiation shielding:* Most radiation energy will be converted into heat energy in the course of attenuation in an exposed body. A simple fact explains why concrete is good for radiation shielding. In general, a hardened concrete consists of 95 percent aggregate and cement and 5 percent water by weight. In the energy released from a fission explosion 97 percent is from gamma rays and 3 percent from fast-flying neutrons. Both aggregate and cement—nonmetallic and inorganic—are excellent materials for absorbing gamma-ray energy, whereas water is the best substance for absorbing neutron energy. Although the percentages for concrete composition are not exactly equal to those for fission energy, they are close to proportional. Because of its radiation-shielding property, concrete is used in the construction of nuclear power plants. Thus concrete would provide a large margin of safety against the hazard of naturally occurring radiation on the Moon.

6. *Abrasion resistance:* In addition to asteroids and meteorites, there are micrometeorites and cosmic dust traveling in space with a relative speed of 25 miles/sec (40 km/sec) (Heide 1964). These microparticles may abrade the surface of the space station because of the enormous differential velocities. Concrete possesses high abrasion resistance, resistance which increases proportionally with concrete strength. The relative depth of a crater made by a microparticle is less in a thick concrete wall than in a thinner wall made of another material.

7. *Effect of vacuum:* In a vacuum, the free moisture in concrete may eventually evaporate, but not the chemically bonded water. Figure 39 shows that the loss of free moisture, which generally takes place around 212 °F (100 °C), has no adverse effect on concrete strength.

A shortcoming that a pressurized concrete structure may have relates to the airtightness of concrete. To overcome this difficulty, an epoxy coating or other sealant can be applied on the internal surface of the concrete structure.

Conclusion

Reinforced concrete has many material and structural merits for the proposed space station. Its cost-effectiveness depends on the availability of lunar materials. With such materials, only 1 percent or less of the mass of a concrete space structure would have to be transported from Earth.

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Lunar Cement

William N. Agosto

With the exception of water, the major constituents of terrestrial cements are present at all nine lunar sites from which samples have been returned.

Two examples of the most commonly used cement formulations (Mindess and Young 1981) are listed below.

Typical Portland Cement

Major constituents	% by wt.
CaO	63
SiO_2	22
Al_2O_3	6
Fe_2O_3	2.5
MgO	2.6
SO_3	2.0
K_2O	0.6
Na_2O	0.3
	99

High Alumina Cement

Major constituents	% by wt.
Al_2O_3	50
CaO	39
SiO_2	6
Fe_2O_3	1
MgO	1
SO_3	1
	98

All the above oxide constituents are found in lunar soils, basalts, and anorthosites except that iron oxide is in the ferrous form (FeO) and sulfur occurs as FeS in basalts and in sparsely scattered particles of meteoritic metal in the soil. However, with the exception of relatively rare cristobalite (SiO_2), these oxides are not present as individual phases but are combined in silicates and in mixed oxides [e.g., ilmenite ($FeTiO_3$)].

Lime (CaO) is most abundant on the Moon in the plagioclase ($CaAl_2Si_2O_8$) of highland anorthosites. The anorthosites are approximately 90 percent anorthite containing 20 percent lime by weight (McKay and Williams 1979).

It may be possible to enrich the lime content of anorthite to levels like those in Portland cement by pyrolyzing it with lunar-derived phosphate in a reaction like

$$\underset{\text{whitlockite}}{Ca_3(PO_4)_2} + \underset{\text{anorthite}}{CaO \bullet Al_2O_3 \bullet 2SiO_2} \xrightarrow{\text{vacuum solar furnace}} \underset{\text{slag}}{4CaO \bullet Al_2O_3 \bullet 2SiO_2} + 2P + 2.5\ O_2 \qquad (1)$$

If workable, reaction (1) increases lime content from 20 percent by weight in anorthite to 50 percent by weight in the slag. A similar reaction has been proposed by Ellis M. Gartner of Construction Technology Laboratories, the research group of the Portland Cement Association. That reaction includes carbon as a reductant and uses apatite as the lunar phosphate. However, reductants may not be required in the high vacuum of the lunar environment. Both phosphate reactions need to be thermodynamically tested at the bench level.

Phosphate consumed in reaction (1) can be regenerated by reacting the phosphorus product with lunar augite pyroxenes at elevated temperatures in a reaction like

$$\underset{\text{augite}}{11(Ca_{.273}Mg_{.273}Fe_{.45})SiO_3} + 2P \rightarrow \underset{\text{whitlockite}}{Ca_3(PO_4)_2} + 5Fe + \underset{\text{silica}}{8SiO_2} + \underset{\text{enstatite}}{3MgSiO_3} \quad (2)$$

Colleagues and I (1980) have suggested that reaction (2) may be the process generating phosphate in certain stony-iron meteorites (the mesosiderites). In the meteorites, phosphorus is derived from meteoritic metal, where it occurs as a phosphide in an intermetallic phase. The same phosphide phase is found in metallic particles of lunar soil, which are derived from meteorites. These can be magnetically beneficiated as a source of iron, nickel, phosphorus, and cobalt (Agosto 1981). The soil metal contains as much as 11.5 percent by weight phosphorus, with an average of about 1 percent phosphorus (Goldstein and Axon 1973). Lunar phosphate has also been found as a minor component of KREEP (potassium, rare earth elements, phosphorus) soils and basalts, notably Apollo 14, at a maximum of about 1 percent by weight.

Thus, the lunar soil could provide both the phosphate needed for reaction (1) and the reduced phosphorus needed for reaction (2). Alternatively, terrestrial phosphate could be transported to space as a reagent, with phosphorus losses in recycling replenished from lunar sources.

The oxide components for Portland cement may also be produced from the silicate minerals in the abundant lunar mare pyroxenes [like the augite used in reaction (2)] by the vacuum solar pyrolysis used in reaction (1) but without the need for a phosphate reagent (Agosto and King 1983). Sufficient sulfur for the formulation of cement might also be derived from the FeS in soil metal.

It may also be possible to obtain high alumina lunar cement directly by solar pyrolysis of anorthite derived from highland anorthosites. The oxide components of anorthite are alumina (Al_2O_3), lime (CaO), and silica (SiO_2). In a solar furnace, the silica would vaporize preferentially, leaving a residue enriched in lime and alumina within the composition range of high alumina cements (Agosto and Gadalla 1985).

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PART 3—Manufacturing and Fabrication

Sankar Sastri, Michael B. Duke, and Larry A. Haskin

Introduction

The ability to use nonterrestrial materials and energy and to utilize the special properties of space environments will allow the space enterprise to grow at an increased rate. We can envision a self-sufficient space economy, with centers of resource extraction and manufacturing off Earth that provide sustenance to colonies of people. However, in the next 25 years, the infrastructure for using space resources will concentrate on more limited goals, those that will have high leverage on the space economy.

Four general goals for use of nonterrestrial resources are

1. To decrease the cost of transporting various systems beyond low Earth orbit (LEO) by providing propellant or reaction mass at a reduced cost

2. To reduce or eliminate the transportation costs for systems emplaced on other planetary surfaces and in space by using indigenous materials

3. To increase supplies of energy to Earth orbit and the Earth

4. To provide previously unattainable products by utilizing the special materials and unique processing capabilities afforded by space environments

Several possibilities exist to make major augmentations to our space capability by providing access to materials in space:

1. Provision of liquid oxygen can significantly reduce the need to transport propellant from Earth to low Earth orbit and reduce the cost of transportation to and from a lunar base.

2. Provision of material can decrease the costs of insulation and of shielding against radiation and impact for satellites in Earth orbit and human habitats beyond low Earth orbit.

3. Structural material, including pressurizable volumes, could be provided for Earth orbit or lunar bases.

4. Byproducts from nonterrestrial processing systems could begin to make living in space easier.

5. Energy collected in space could be used directly or by conversion to electricity to carry out space manufacturing enterprises.

6. Space debris could be recovered and reused or put to a new use.

This report is deliberately conservative. Previous studies Criswell 1980) have demonstrated that nearly anything one wants to make in space can be made from the raw materials available on the Moon or on near-Earth asteroids. We have looked instead at what is most easily accomplished in the next 25 years.

The accessibility of material and energy off the Earth and the leverage that these nonterrestrial resources can exert on the space transportation system are important influences on the long-term goal of exploring the solar system. The next 25 years will provide the learning experience necessary to advance that activity more rapidly. The concept of “bootstrapping”—using the production capability to manufacture additional production equipment and expand production more rapidly than if all the production equipment had to be transported from Earth—can be tested and the ability to sustain human settlement beyond Earth can be demonstrated.

Research on separation of lunar materials and manufacture of useful products from them is in its infancy. Many avenues are left to be investigated. A few possible processes and products are described below.

Products

The least complicated technologies will not necessarily be the most cost-effective ones to manufacture products from nonterrestrial materials. It is nevertheless appealing to imagine that early space manufacture can be done by simple means. It seems that simplicity ought to correlate with economy or at least with probability of early application. Thus, we have chosen to explore the oxygen, metal, and silicate products that might be obtained from simple treatment of well-characterized materials from near-Earth space.

The ground rules of the exercise are these:

1. Starting materials are those substances found in greatest abundance at the lunar sites visited by the Apollo astronauts. More exotic lunar ores and water at the poles are excluded from consideration. So are all asteroidal materials, their exact nature being still unknown.

2. Raw materials for manufacture are materials in “as found” condition or materials upgraded or separated by only the simplest means.

3. Products are for use on the Moon or in orbit, not on Earth.

4. The additives, catalysts, and processing materials that must be supplied from Earth will be kept to a minimum.

5. Oxygen, perhaps extracted from ilmenite-rich material, will be an important early lunar product.

6. Materials used in space applications will be those available and adequate, not necessarily those traditionally envisioned or preferred.

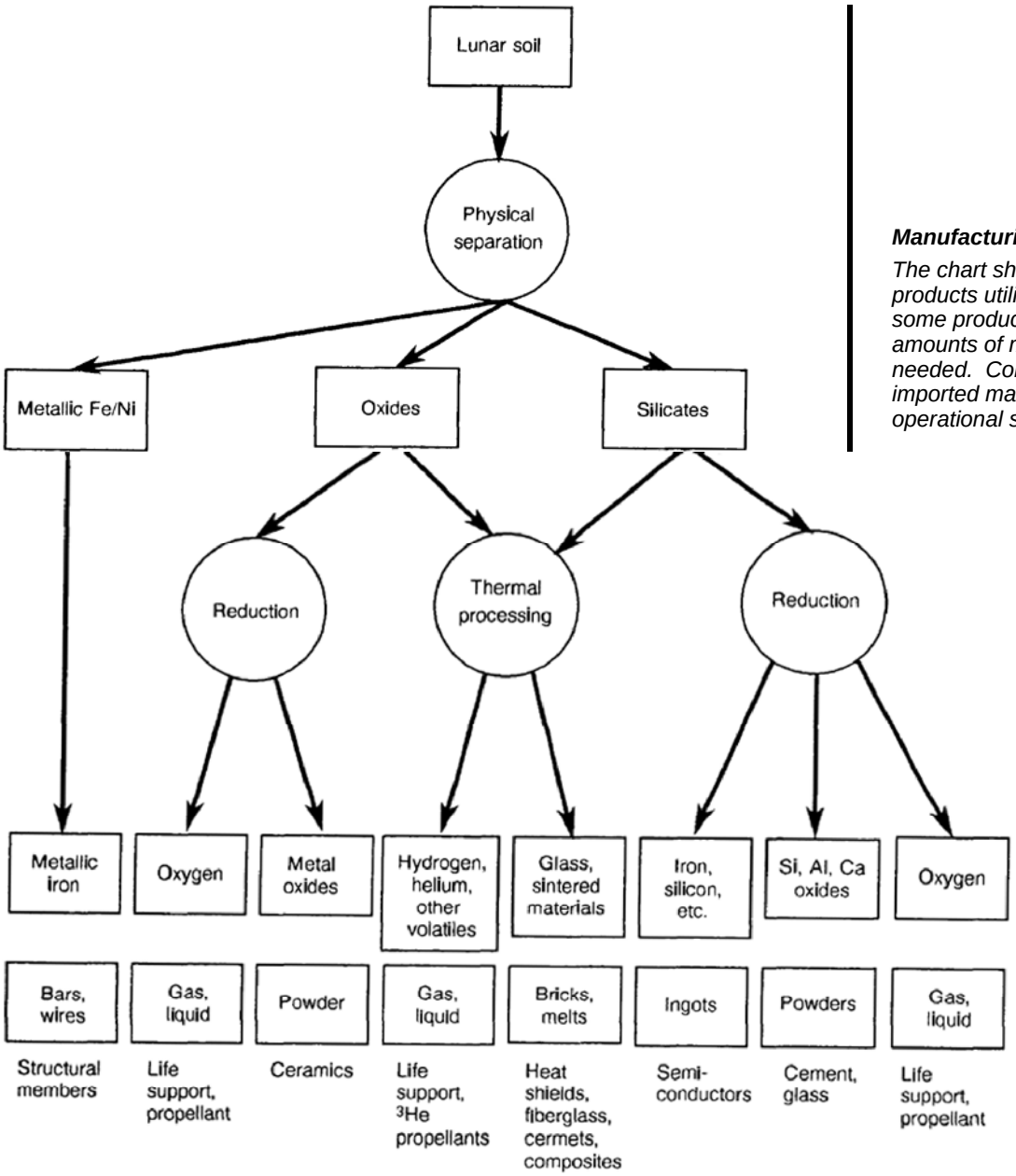
7. The quality of material used may not match that of similar material produced on Earth, and sizes and quantities will be adjusted accordingly.

8. The complex components that are necessary will be imported from Earth.

9. Steps in manufacture must be few, easy, and reliable.

10. Assembly and application of products must be simple and rapid and tolerances relatively loose.

11. All processes up through assembly should be reasonably automated but tended. Equipment should be easy for its operators to repair, optimize to actual conditions, and adapt to new feedstocks and applications.



Manufacturing on the Moon

The chart shows various sources and products utilizing lunar materials. For some products with special uses, small amounts of material from Earth may be needed. Conservation and recycling of imported materials will be important in operational systems, such as life support.

The scenario that could result from application of these ground rules to common materials at Apollo sites is limited but far from stifling. To make the problem tractable for this exercise, we have chosen to constrain our list of materials and products even more narrowly than the rules specify. Nevertheless, the examples we treat should be sufficient to illustrate the possibilities and the limitations.

The following are designated as starting materials:

I. Unprocessed lunar regolith

   A. Bulk soil
      1. Mare-derived; high-iron, high-silicon, low-aluminum, low-calcium
      2. Highland-derived; low-iron, high-silicon, high-aluminum, low-calcium
      3. Mixed origin; intermediate-composition

   B. Rocks
      1. Mare basalt [$CaAl_2Si_2O_8$ (plagioclase) and $(Mg,Fe)SiO_3$ (low-calcium pyroxene)]
      2. Highland igneous rocks
         a. Anorthite (primarily plagioclase)
         b. Dunite [primarily $(Mg,Fe)_2SiO_4$ (olivine)]
         c. Troctolite (mixtures of plagioclase and olivine)
         d. Norite (mixtures of plagioclase and low-calcium pyroxene)
      3. Breccias (physical mixtures of rock, mineral, and glass fragments)

II. Minimally processed regolith (no chemical extraction)

   A. Magnetic iron-nickel alloys plus iron-bearing glassy “agglutinates” (separated magnetically)

   B. Ilmenite concentrate, $FeTiO_3$ (separated electrostatically)

   C. Plagioclase concentrate (separated paramagnetically or electrostatically)

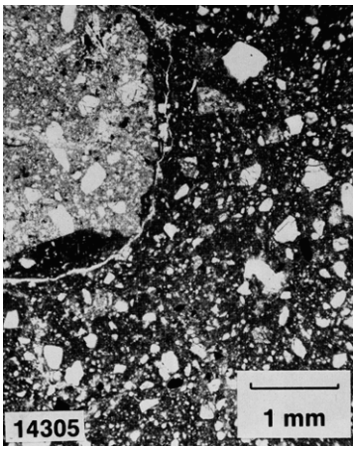
   D. Residues from separations of A through C

   E. Volatiles (H_2, N_2, He) driven off thermally

(a)

(b)

(c)



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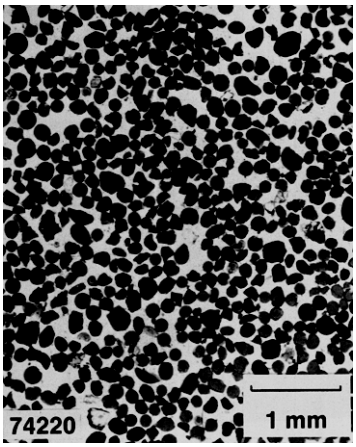

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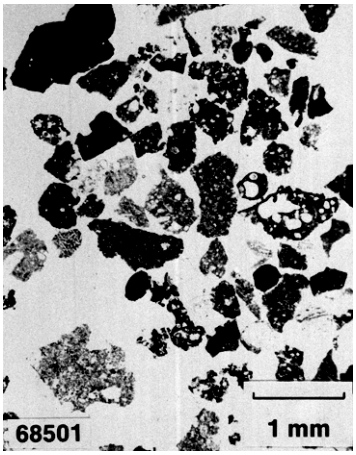

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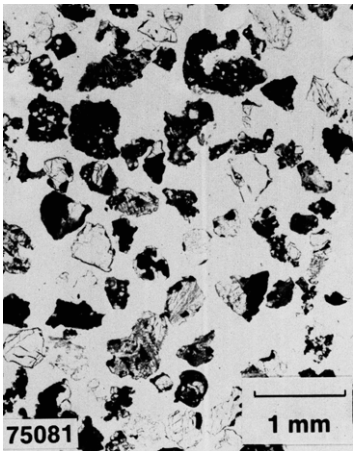


Intermediate Products

Lunar rocks and the regolith consist of minerals and glasses, which can be separated by several means. Here, a variety of lunar materials are shown as they appear in very thin slices viewed with a microscope in transmitted light.

a. Basalt, consisting of intergrown crystals of plagioclase feldspar (clear), olivine and pyroxene (dark, transparent), and ilmenite (black, opaque).

NASA photo: S91-53214

b. Norite, consisting primarily of plagioclase feldspar and low-calcium pyroxene, in coarse grains.

NASA photo: S91-53230

c. Breccia, showing very fine-grained material enclosing larger rock fragments.

NASA photo: S91-53235

d. Orange soil. This is a peculiar soil consisting primarily of beads of orange glass of basaltic composition, probably formed in a volcanic fire fountain.

NASA photo: S91-53220

e. Fragments from typical highland regolith. Agglutinates are fused regolith material, which formed tiny gas bubbles as they melted and were quenched.

NASA photo: S91-53246

f. Typical millimeter-size fragments in mare regolith. At millimeter sizes, most lunar regolith grains are complex, consisting of more than one mineral. At smaller sizes, a higher fraction of the grains consist of only a single mineral.

NASA photo: S91-53247

Mineral separation (beneficiation) techniques utilize the different properties of the minerals and glasses to separate them. The techniques include size, magnetic, specific gravity, and electrostatic separation. Mixed grains are more difficult to separate by physical means.

Chemical Processes

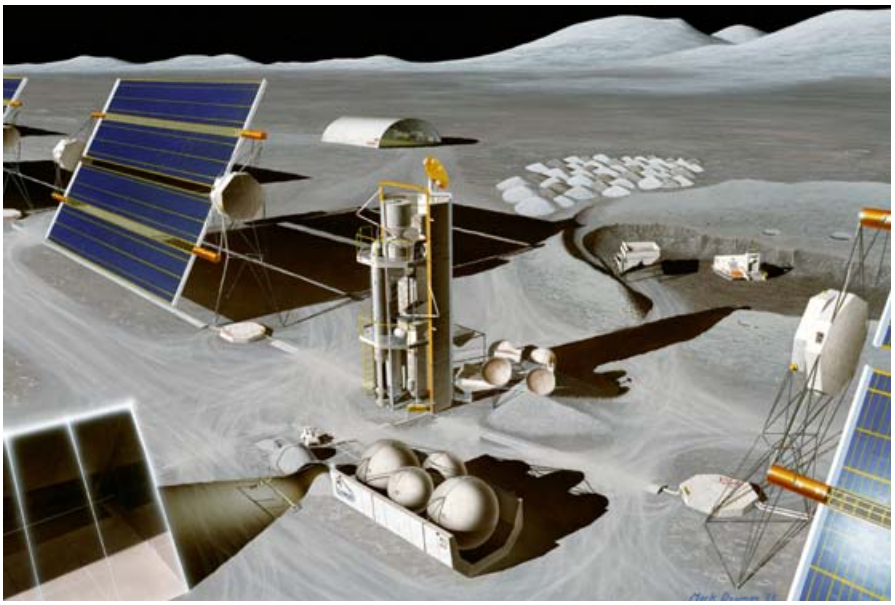
a. Ilmenite Reduction

A facility such as this could use hydrogen to chemically reduce ilmenite ($FeTiO_3$), thus producing iron metal, titanium dioxide, and water. The water is then electrolyzed, to split the hydrogen and oxygen. The hydrogen is recycled to the reduction process, and the oxygen is liquefied and stored for use. The oxygen has use in the transportation system as propellant, in life support systems, and in other chemical processing, thereby offsetting the need to import it from Earth.

The residue from the process may have uses as well. It typically would consist of an intimate mixture of iron (alloyed with small amounts of silicon and titanium) and titanium dioxide (rutile). The metal can be separated either by melting or by a chemical process (e.g., carbonyl processing). The titanium dioxide may find use as a ceramic material. The combined slag from the process may find use as a structural material through allowing it to sinter (compact and harden) while it cools from high temperature.

Artist: Mark Dowman

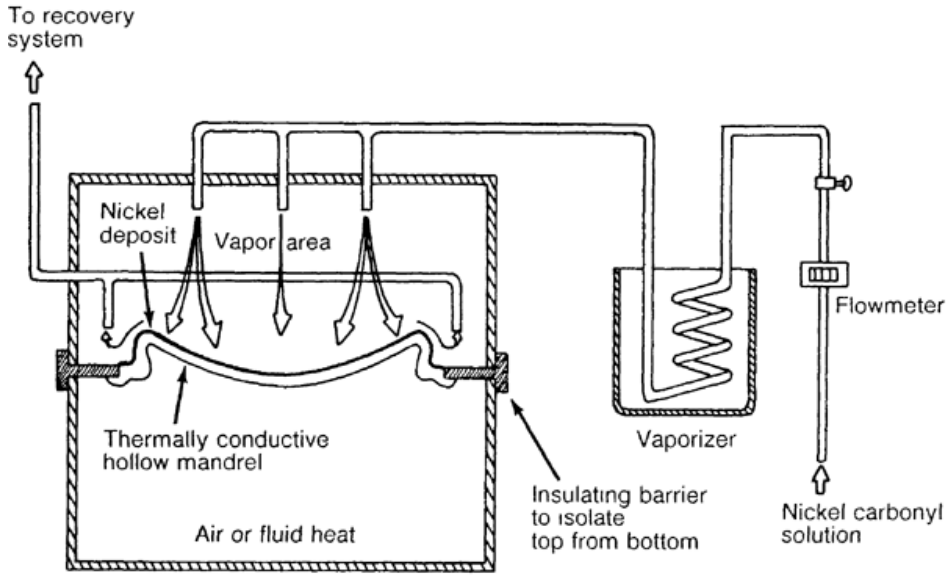
NASA photo: S88-33648

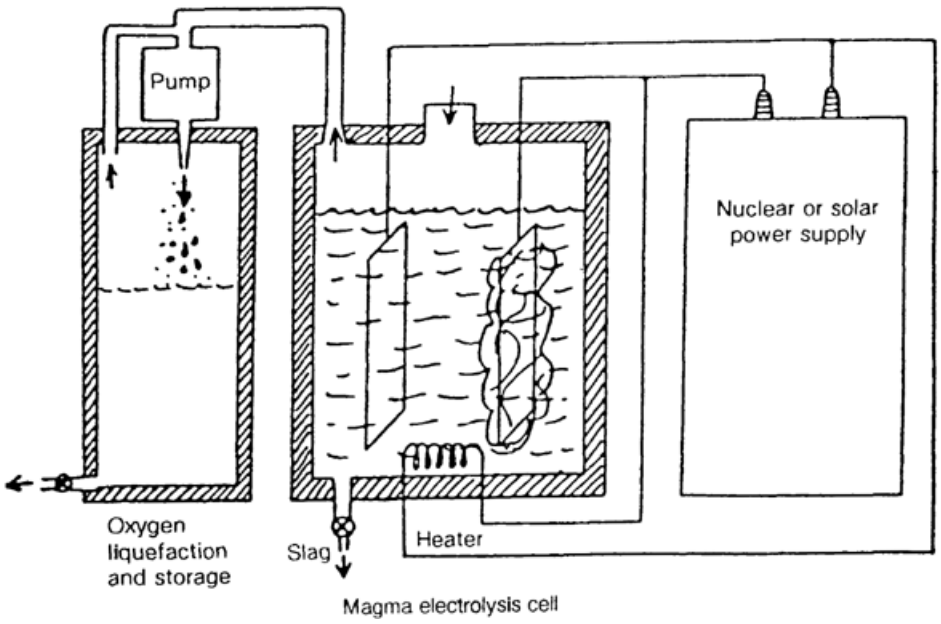


b. Carbonyl Processing

Carbonyl processing (the Mond process) is a well-known procedure for extracting nickel from metal by reaction with carbon monoxide gas. The metals in the residue from the hydrogen reduction of ilmenite could be separated from one another and from the rutile by the carbonyl process. Or the process could be applied to meteorites found in the lunar regolith to separate the nickel and iron in them. In addition, as depicted in the illustration, the gaseous carbonyl can be used to directly deposit metal coatings or even metal objects.

Courtesy of Vaporform Products; taken from Meinel 1985, p. 157.

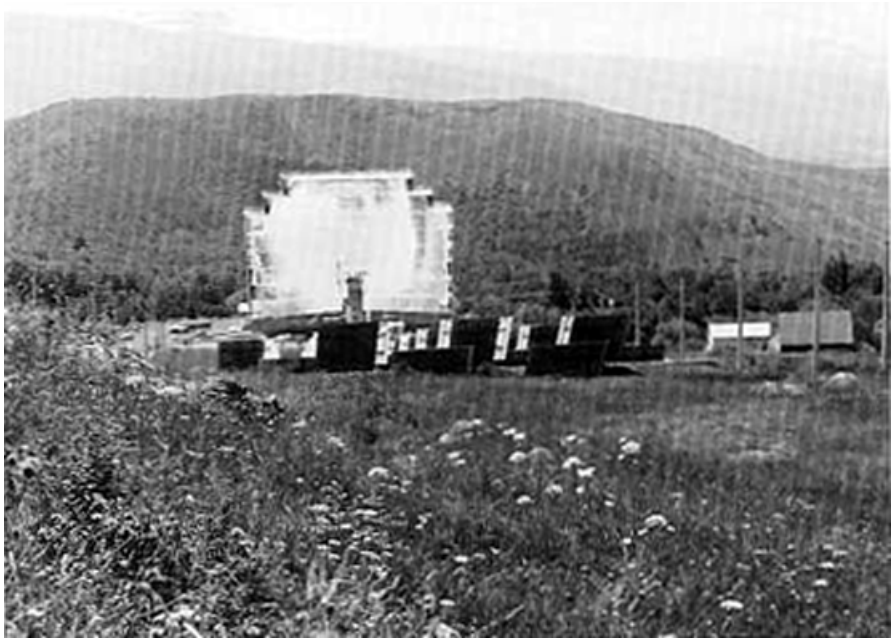




c. Electrolysis

Silicate electrolysis is similar in concept to the simple electrolysis cell used to dissociate water into hydrogen and oxygen. Instead of water, molten silicate forms the solution which conducts electrons from the cathode to the anode. As those electrons are transferred, the iron in the silicate is reduced to metal and oxygen is released. Recent studies (Lindstrom and Haskin 1979) have shown that some titanium and silicon can also be reduced to metal in this manner. The electrodes are the critical element of the electrolysis cell. If they become corroded or damaged, the cell will cease to function. If the rate of deterioration is high and new electrodes need to be brought from Earth regularly, part of the benefit of using the indigenous materials is lost.

From Lewis, Jones, and Farrand 1988, p. 116.



d. Solar Furnace

It is possible to separate some elements from molten materials simply on the basis of their volatility. Solar concentrators, such as this one in Odeillo, France, can achieve temperatures higher than 3500 °C. If typical lunar rocks are heated to the vicinity of 2000 °C, first sodium and potassium evaporate, then silicon and iron, leaving primarily a mixture of calcium, aluminum, magnesium, and titanium. Some reduction to metal may occur. The resulting residue may be quite similar to compounds used in Portland cements on Earth.

Photo: Elbert A. King

III. Maximally processed regolith (chemical extraction)

A. Elemental oxygen (product of reduction of lunar material)

B. Residues from oxygen smelting (e.g., from the ilmenite reduction process): rutile (TiO_2), elemental iron, silicate impurities, all intimately mixed

C. Products from carbonyl processing of metal concentrates
   1. High purity iron metal
   2. High purity nickel metal
   3. Rutile plus silicate impurities

D. Products of electrolysis of basalt
   1. Iron metal, with perhaps up to 2 percent manganese and chromium
   2. Iron metal with several percent titanium
   3. Iron metal with several percent silicon

E. Products from solar furnace evaporation of silicates
   1. Calcium aluminate cement
   2. Metals, including iron and silicon

Indigenous conditions assumed are vacuum, sunlight, low gravity on the Moon, and microgravity in near-Earth space. Tools and facilities that should be available include solar furnaces and electrical power at megawatt levels.

From this set of starting materials and facilities, the following classes of products are possible. These are evaluated with respect to properties attainable without further change or purification. Additional equipment needed to produce the products from the starting materials is identified. Also, additives that in small quantities could greatly improve the caliber of these products are identified. Gases, such as oxygen, hydrogen, carbon dioxide, and helium, are useful as generated and do not require further processing.

I. Metal-based

A. Extruded products—beams, rods, wires

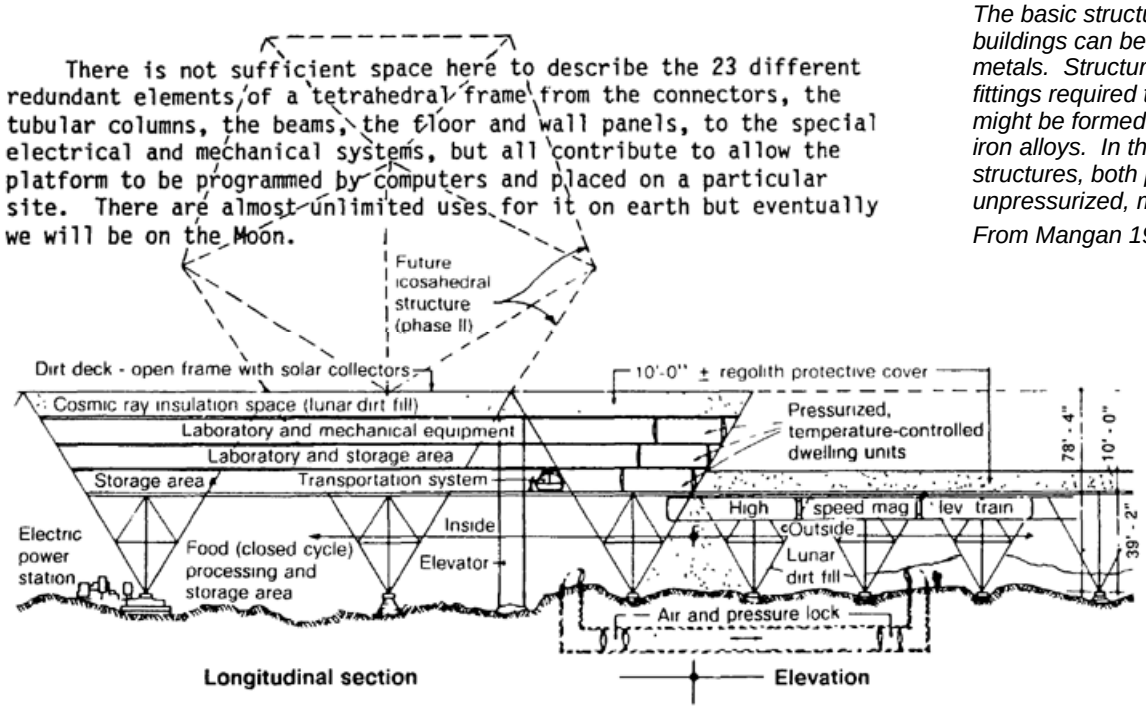
B. Cast products—beams, rods, containers

C. Rolled parts—plates, foils, beams

Structural Framework

The basic structural framework for buildings can be produced from lunar metals. Structural members and the fittings required to join them together might be formed by extruding lunar iron or iron alloys. In this manner, extensive structures, both pressurized and unpressurized, might be built.

From Mangan 1988, p. 380.



The Expandable Platform on the Moon

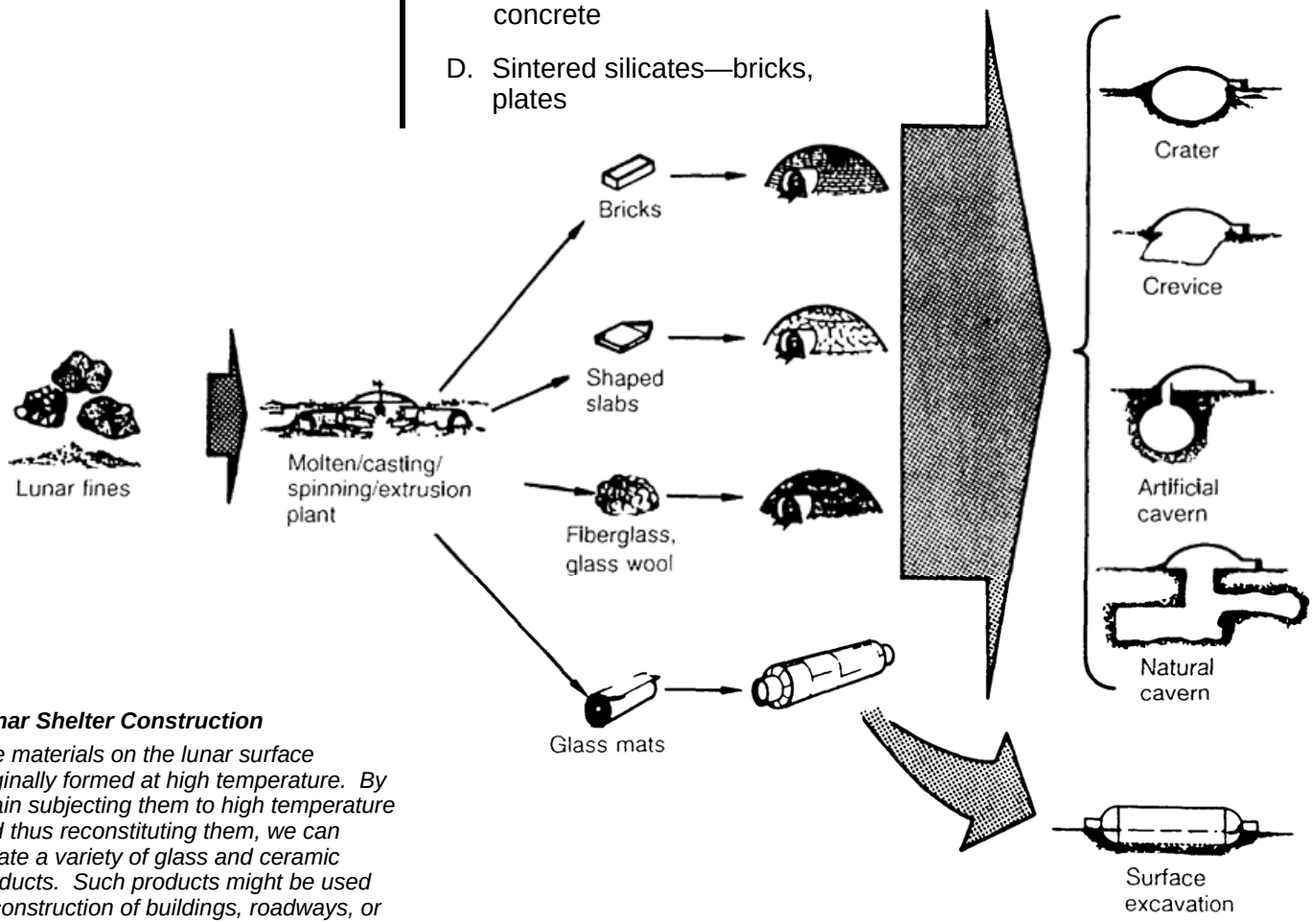
II. Silicate-based

A. Glasses—fibers, rods, light pipes, beams, bricks, coatings, sheets

B. Ceramics, cermets*—containers, bricks, pipes

C. Composites—cement, concrete

D. Sintered silicates—bricks, plates



Lunar Shelter Construction

The materials on the lunar surface originally formed at high temperature. By again subjecting them to high temperature and thus reconstituting them, we can create a variety of glass and ceramic products. Such products might be used in construction of buildings, roadways, or rocket landing pads. Construction materials derived from lunar regolith could be used in combination with excavations of the subsurface to expand habitable volume.

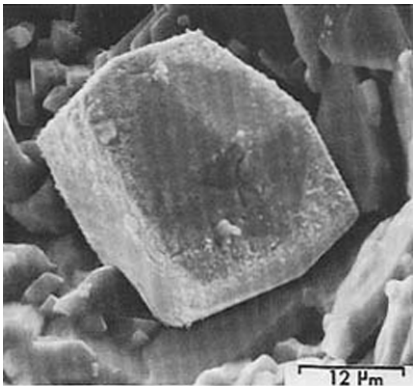
*A *cermet* [*cer* amic + *met* al] is a strong alloy of a heat-resistant compound (as titanium carbide) and a metal (as nickel) used especially for turbine blades. Also called a *ceramal.*

Iron and Alloys of Iron

Sankar Sastri

All lunar soil contains iron in the metallic form, mostly as an iron-nickel alloy in concentrations of a few tenths of 1 percent (Nozette 1983). See figure 1. Some of this free iron can easily be separated by magnetic means (Shedlovsky et al. 1970; Goldstein, Axon, and Yen 1972). It is estimated that the magnetic separation of 100 000 tons of lunar soil would yield 150–200 tons of iron. Agglutinates (glass-bonded aggregates of soil fragments) contain metallic iron which could be extracted by melting and made into powder-metallurgy products (Romig and Goldstein 1976, Criswell 1981). However, agglutinate metal is so finely dispersed that it may be difficult or impossible to separate.

(a)



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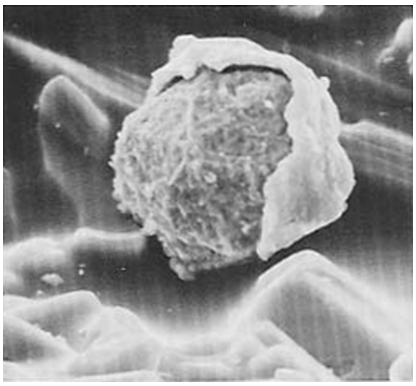

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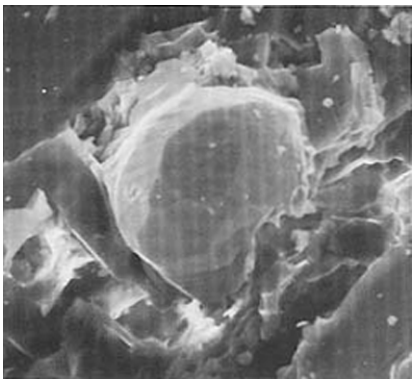


Figure 1

Iron in Lunar Soil

Many of the highly recrystallized breccias from Apollo 14 contain vugs with well-developed crystals that extend from the vug walls and bridge open spaces. Many of the larger vugs contain metallic crystals of iron or nickel-iron.

a. This photograph taken with a scanning electron microscope (SEM) shows a euhedral iron crystal. The tetrahexahedron has an axis of four-fold symmetry projecting toward the upper right of the photograph. The crystal contains no detectable nickel (less than 1 percent).

b. This SEM photograph shows a nickel-iron crystal that contains about 12 percent nickel. Because the tetrahexahedron was photographed along an axis of three-fold symmetry, it appears to be hexagonal. The crystal is partially covered with a coating of iron sulfide, presumably troilite. The rough texture of the nickel-iron crystal may have been caused by a former coating of troilite.

c. The crystal habit of such nickel-iron particles commonly is not obvious. Only at magnifications above 1000X can crystal face development be observed. The near spheroidal shape of this particle is typical of those photographed with the scanning electron microscope. This nickel-iron crystal contains about 4 percent nickel.

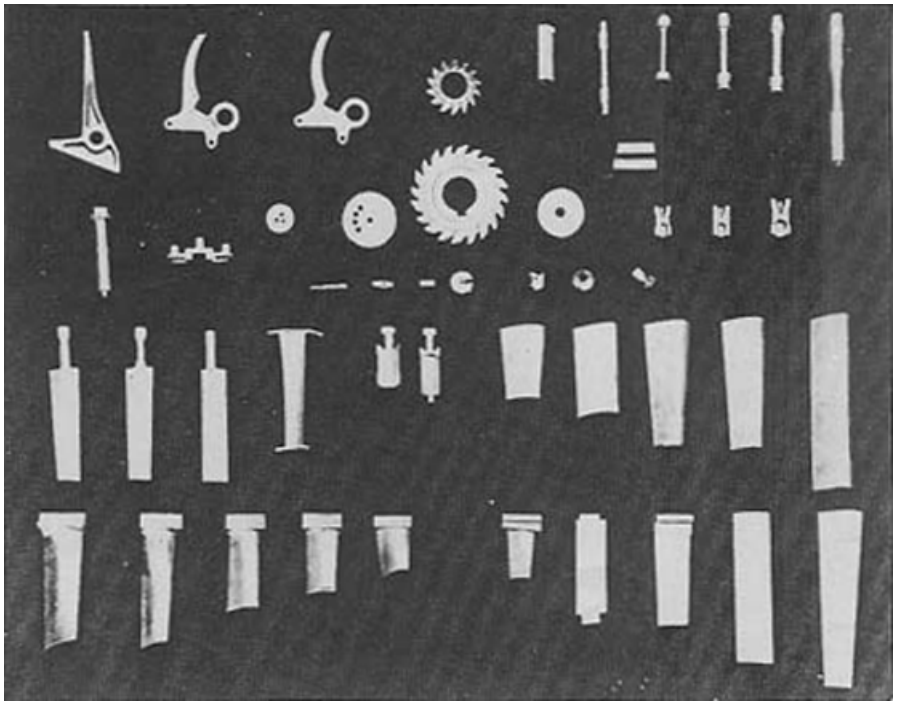
These crystals are thought to have been deposited from a hot vapor during the cooling of the large ejecta blanket from the impact that formed the Imbrian Basin on the Moon. Such a process is only one source of the metallic fragments in the lunar soil. Other iron-nickel fragments are pieces of meteorites that have crashed into the Moon.

Photographs and their interpretation taken from McKay et al. 1972, pp. 745–746.

The basalts in the lunar maria contain up to 17 percent chemically combined iron, primarily in ilmenite, olivine, and pyroxene. And ilmenite ($FeTiO_3$) concentrations in lunar soil are of fairly high grade compared to deposits on Earth. A variety of extraction schemes have been proposed for recovering metallic iron from these silicates and oxides: electrolysis of molten lava (Lindstrom and Haskin 1979), a carbochlorination process (Rao et al. 1979), solar furnace evaporation (King 1982), a carbonyl process (Meinel 1985), a hydrofluoric acid leach process (Waldron 1985), and hydrogen reduction of ilmenite (Williams 1985). Even though considerable work is needed to evaluate and test these processes for feasibility in a lunar environment, the abundance of iron and its relative ease of separation suggest that metallic iron and its binary alloys may find wide application in large-scale space operations.

Characteristics and Potential Uses

Table 1 provides a list of the characteristics and potential uses of the pure iron and iron alloys which might be readily produced from lunar materials.



Casting Iron Parts

Iron parts are cast on Earth by pouring liquid metal into molds. Many intricate parts that would be difficult to machine can be made in this manner. The lunar equivalent could use iron or iron alloy produced as a byproduct of oxygen extraction and poured into "sand" molds made from lunar soil.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 40-6.*

TABLE 1. *Applications of Iron and Alloys of Iron*

Name	Composition	Characteristics	Uses
Ingot iron	Pure iron (industrial grade)	Ultimate tensile strength (UTS) 290–331 megapascals (MN/m^2) or 42–48 $\times 10^3$ psi Elongation (el) 22–28%	Structures, beams, plates
Iron whiskers	Single-crystal pure iron fibers	0.00004-in. diameter UTS as high as 3448 MN/m^2 (500 $\times 10^3$ psi)	Structures Electronics parts
Iron powder	Free of carbon and sulfur	10- to 40-micron powder	Propellants Small powder-metallurgy parts—mechanical, electrical, and magnetic
Carbonyl iron powder		UTS 193–275 MN/m^2 (28–40 $\times 10^3$ psi) el 30–40%	Propellants Powder-metallurgy parts Coatings for containers, walls
Iron-silicon alloy	Fe and Si form a solid solution up to 4.5% Si	UTS 345–414 MN/m^2 (50–60 $\times 10^3$ psi) el 8–22%	Structures, beams Motor transformer parts
Iron-nickel alloys	Fe and Ni form a continuous series of solid solutions	For 47–55% Ni, UTS 483–621 MN/m^2 (70–90 $\times$ 103 psi) and el 30–50% Ni increases UTS without loss of ductility	Structures Containers
Iron-titanium alloys	Fe and Ti form a eutectic solution	Ti increases hardness and strength	Structures Containers
Iron-manganese alloys	A range of Fe-Mn alloys are possible	For 1% Mn, UTS 414 MN/m^2 (60 $\times 10^3$ psi) and el 40% Mn increases strength, hardness, and hardenability	Structures, beams
High-purity iron	Ultra-pure	Extremely difficult to produce on Earth High corrosion resistance Can produce high-strength, defect-free single-crystal or directionally solidified parts	Pressure vessels Solar mirrors Sheets Containers

The simple alloys described in table 1 may be relatively straightforward products of lunar metallurgy. Little is known, however, of the composition of the metal phase that forms directly from each of the processes described above. Process technology needs to be defined to establish the feasibility of providing the alloys.

Processes for Working Iron

A list of terrestrial manufacturing processes that might be used on iron and iron alloys in a nonterrestrial facility is shown in table 2. Criswell (1980) evaluated 200 manufacturing techniques and found more than 40 of them appropriate for a near-term, evolutionary space manufacturing facility. We consider all of the processes given in table 2 to be plausible for early application; however, when evaluated using the ground rules of our exercise, the processes that I discuss after the table appear to be the most feasible.

Casting

Casting, one of the oldest processes in the world, involves pouring liquid metal into a mold and allowing it to solidify in that shape (fig. 2). The casting process has to be modified for application in free space because gravity is so limited. Casting at a lunar facility in 1/6 gravity should be straightforward; however, mold construction techniques require study, particularly if indigenous materials are to be used for the molds.

TABLE 2. *Terrestrial.Manufacturing Processes That Might Be Used on Lunar Iron*

Casting	Powder metallurgy	Hot working and cold working	Joining
Sand casting Shellmolding Die casting Investment casting Permanent molding Centrifugal casting	Compaction and sintering Hot isostatic pressing	Forging Rolling Extrusion Wire drawing Machining	Welding Brazing Soldering Fastening

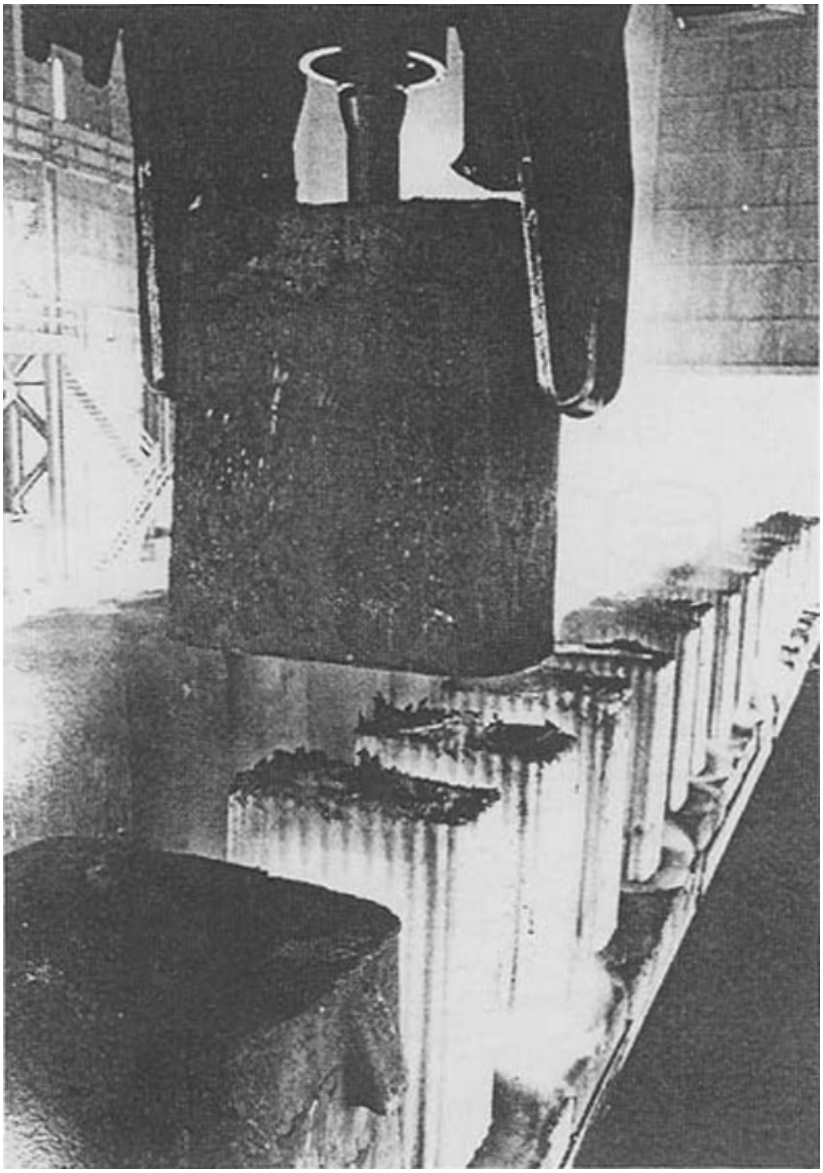


Figure 2

Casting of Metal Ingots

Refined steel is poured from a refractory-lined ladle into molds of the desired size. The casting operation depicted is a continuous process, where large quantities of metal are being produced. A lunar operation would be on a much smaller scale and could produce castings that are directly usable, as well as the starting materials for rolled or extruded products. The ingot molds would be maintained at elevated temperature, waiting transfer to a rolling facility, in which they would be formed into bars or sheets.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 20-2.*

Powder Metallurgy

Powder metallurgy consists of compacting fine metallic powder into a desired shape and sintering the shape (fig. 3). Lubricants may be required to separate pressed parts from the die. The absence of atmosphere in space prevents the formation of oxides or other contaminating layers on the powders and thus may promote the formation of high quality parts.

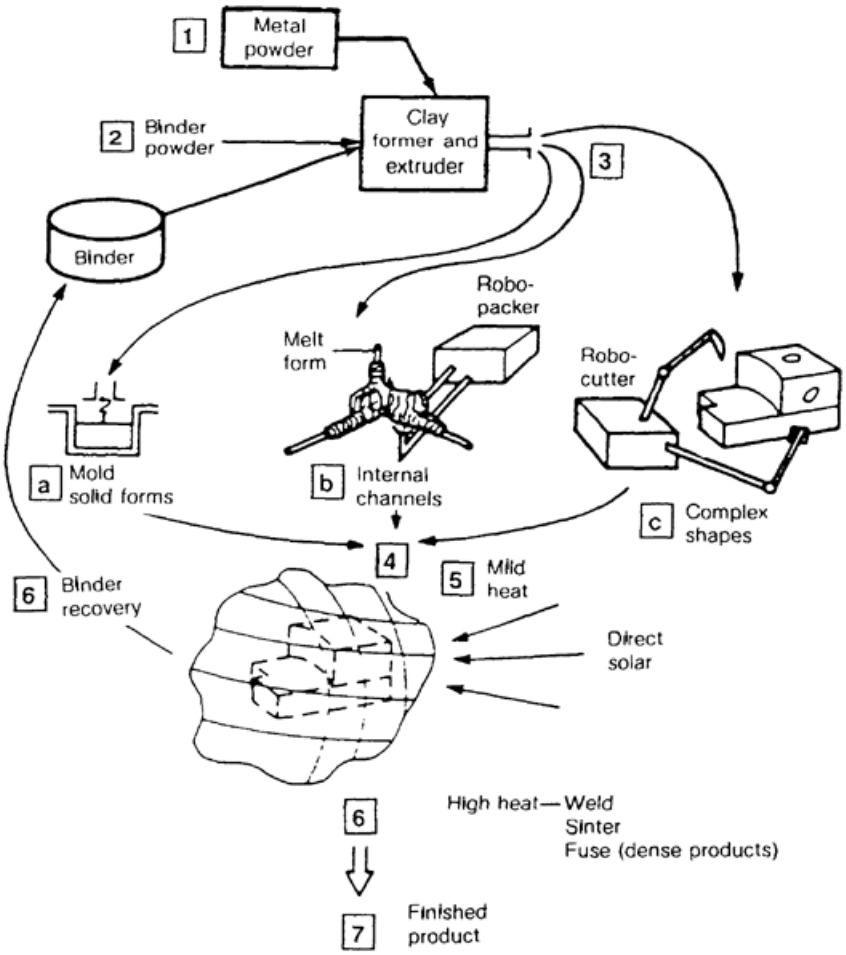


Figure 3

Powder Metallurgy

An alternative process for forming objects of metal is to compress and heat a metal powder in a mold. Iron powder derived from the metal in lunar soil or from byproducts of oxygen extraction may be molded in this manner for small manufactured items.

Here we see three ways in which the technique might be used. A metal powder [1] and a binder powder [2] are formed into a "clay" and extruded [3]. This clay is then used to create solid forms in a mold [4a], to shape intricate internal structures by molding metal powder around a meltable form [4b], or to make complex shapes [4c], which are then heated [5]. Similar techniques could be used for ceramics.

Taken from Criswell 1981, p. 397.

Rolling

Rolling consists of passing a metal between two rolls which revolve in opposite directions, thereby decreasing the cross sectional area and increasing the length of the feedstock (fig. 4). Larger ingots are rolled into blooms having a cross section of more than 6 inches and finally into shapes such as plates, bars, rods, I-beams, and angles (fig. 5). Rolling should be readily adaptable to the space environment, as it does not depend on gravitational forces.

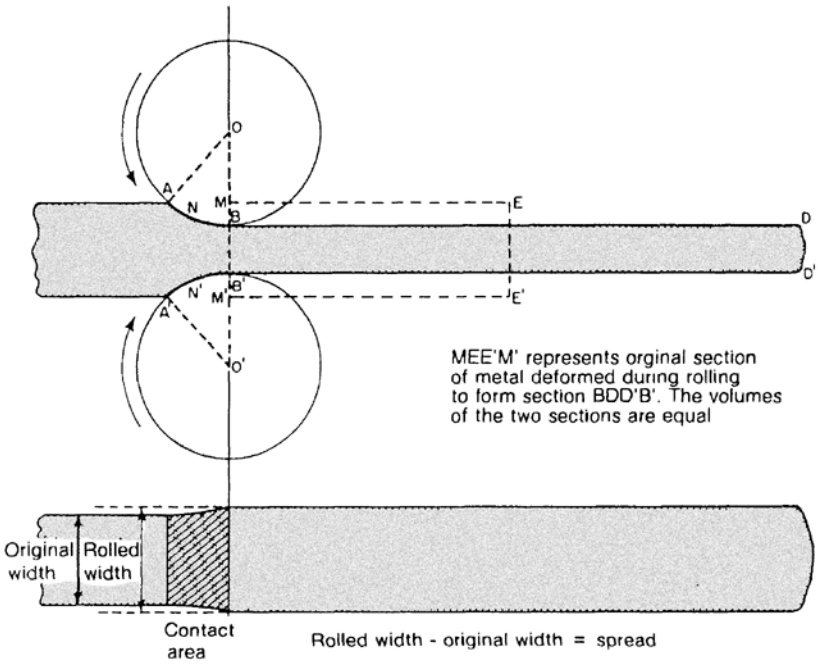


Figure 4

Rolling Steel

Hot steel in a plastic state can be rolled into a variety of products. Various types of rolling mills have been designed, depending on the type and properties of the desired product. Typically, an ingot of steel will pass through a series of rolls that gradually shape the steel. This diagram shows the basic principle.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 22-9.*

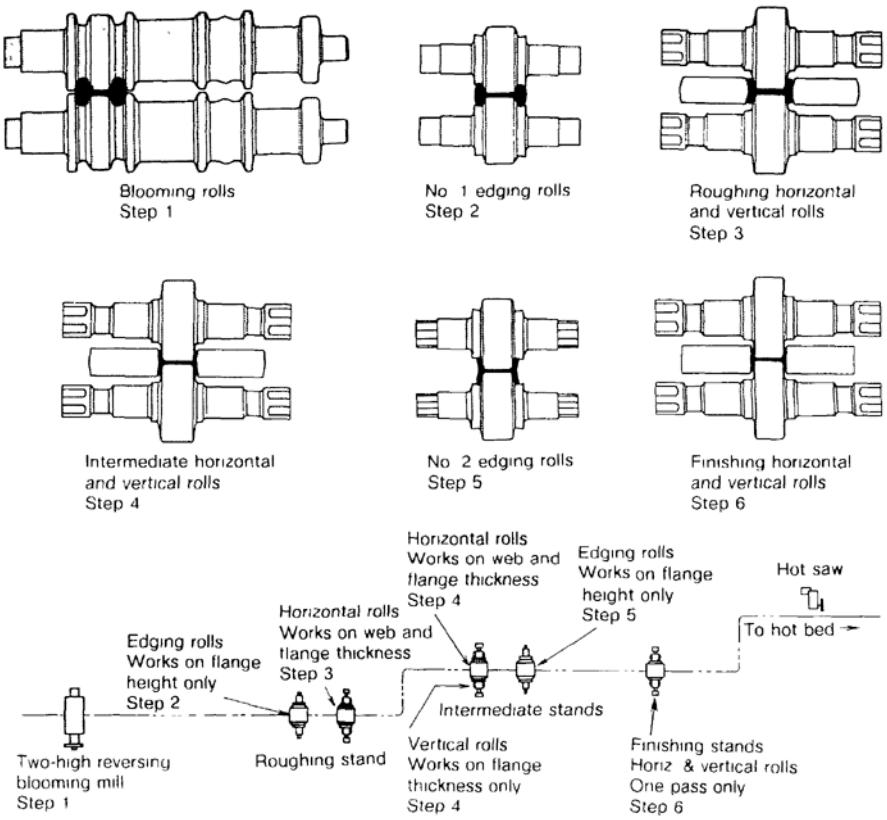


Figure 5

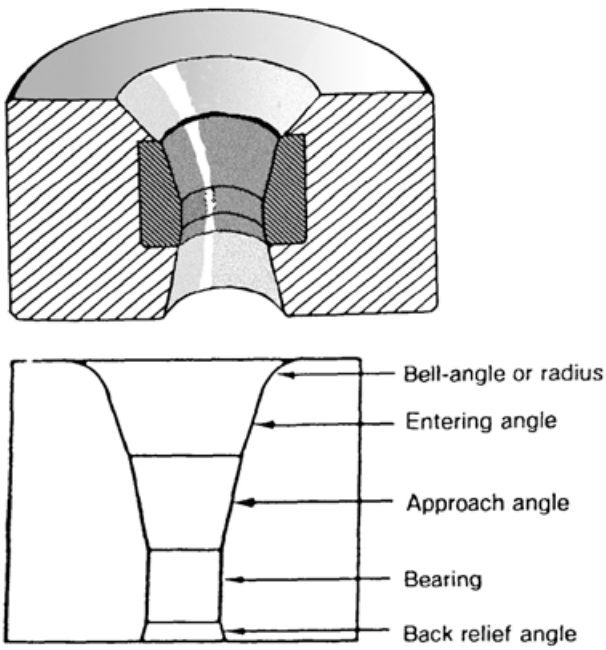
Shaping Bars

Rolling mills can produce a variety of shapes. Here, the rolled bar passes through several shaping steps on its way to becoming an H-bar.

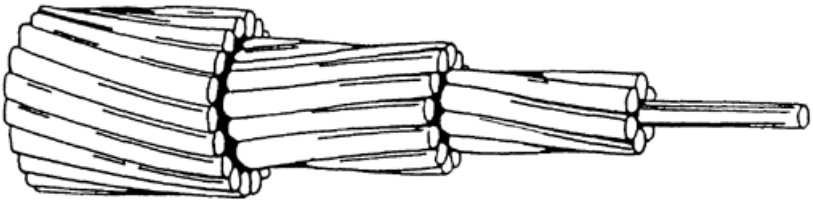
Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., fig. 23-3.*

Extrusion

Extrusion is essentially a hot working operation where a metal is extruded through a die or orifice that controls the cross sectional shape (fig. 6). Some common extruded shapes are rods, tubing, and window frames. Extrusion should be easily adapted to space operation.



(a)



(b)

Figure 6

Wire

a. Die for Wire Pulling

b. Arrangement of Wires in a Cable

When bar stock has been produced, one of the further fabrication processes is the pulling of wire. In this process, a heated bar is pulled through a die, reducing its cross-sectional area by 10–45 percent. Several successively smaller dies may be necessary to produce wire of the appropriate diameter. Wires have a variety of uses. Two principal ones at a lunar base may be in cables used to prestress concrete structures and as supporting cables for structures.

Courtesy of the Association of Iron and Steel Engineers, reprinted from The Making, Shaping and Treating of Steel, *10th ed., figs. 31-13 & 31-14, and 9th ed., fig. 30-43.*

Cold Welding

Cold welding consists of joining two flat, clean surfaces of a metal by contact and application of pressure. Cold welding works by joining the surfaces at the molecular level. In space and on the Moon, where oxide layer formation is retarded (if not eliminated), cold welding has high potential. In particular, using ceramic rollers to cold roll ultra-pure metals may result in a low-cost way of cold welding. On the other hand, extreme care has to be exercised to keep the surfaces of high-purity metals separate so that undesired cold welding does not take place spontaneously.

Vapor Deposition

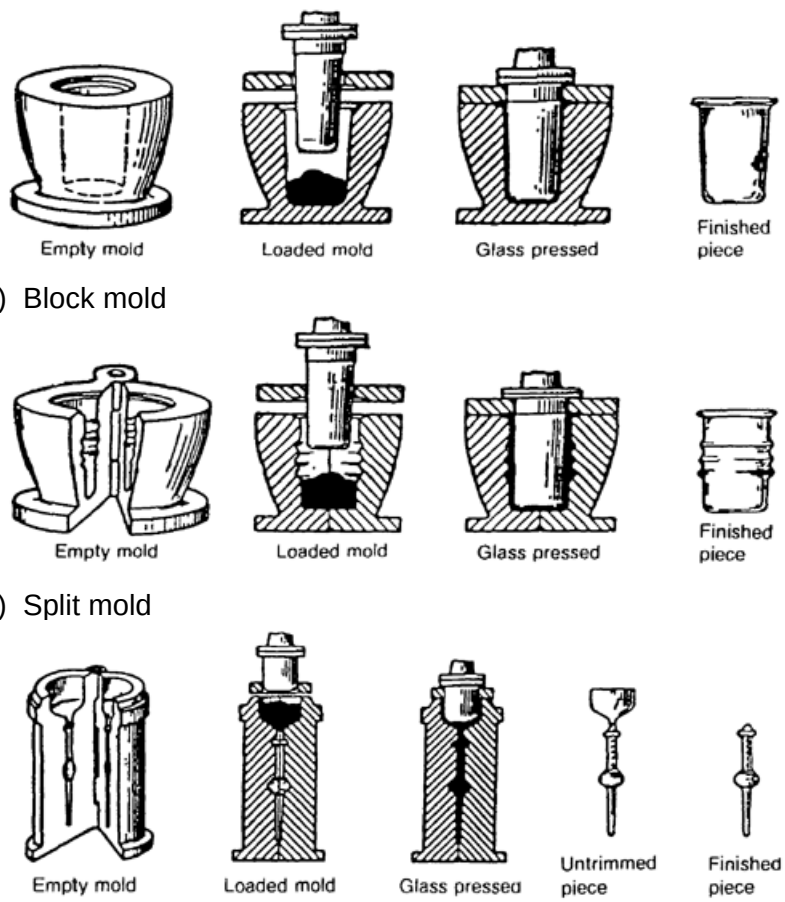
Vapor deposition involves allowing vapors of a metal to contact a surface in a closed chamber. On the surface metal layers build up atom by atom. The presence of vacuum makes this process a viable one in a space manufacturing facility. It is particularly suitable for applying thin coatings, such as making highly reflective mirrors.

Although these procedures are plausible for space manufacturing, all are in need of testing and demonstration to ensure that they can be used with typical nonterrestrial metals.

Glass and Ceramics

Larry A. Haskin

A variety of glasses and ceramics can be produced from bulk lunar materials or from separated components. Many glassy materials have been described in previous studies (Mackenzie and Claridge 1979, Criswell 1980). They include sintered (heated and pressed) regolith, quenched molten basalt, and transparent glass formed from fused plagioclase. No research has been carried out on lunar material or close simulants, so properties are not known in detail; however, common glass technologies such as molding and spinning seem feasible (fig. 7). Uses of glass include structural applications (bricks, slabs, beams, windows) and specialty applications (fiber strengtheners, insulation, heat shields, cables, light pipes). See figures 8 and 9.



(a) Block mold

(b) Split mold

(c) Font mold

Figure 7

Glass Forming

The material on the lunar surface has a high silicate content. Some of these silicate materials could be the constituents of transparent glasses, which could have a variety of uses at a lunar base. Various processes are available for fabricating objects from glass. Here, molds are used for glass pressing. The liquid glass is poured into the mold, which is compressed. When the glass has cooled, the object is extracted from the mold.

From Shand 1958, p. 164.

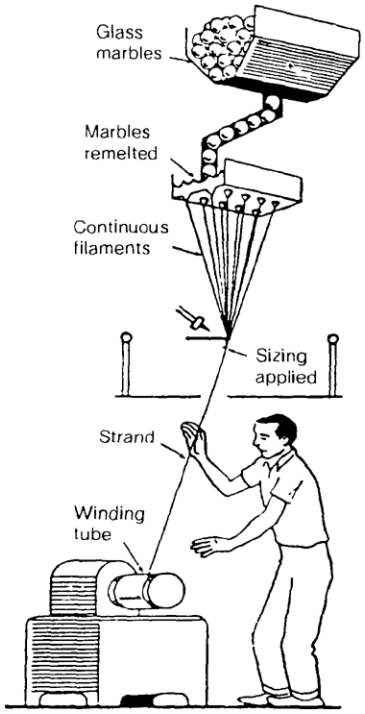


Figure 8

Glass Drawing

When silicate glasses are melted, they are viscous and thus can readily be drawn by special machines into fibers or rods or tubes. Glass fiber textiles and mats, which are commonly used terrestrially as thermal and electrical insulators, could be used as construction materials in a space facility.

From Shand 1958, p. 385.

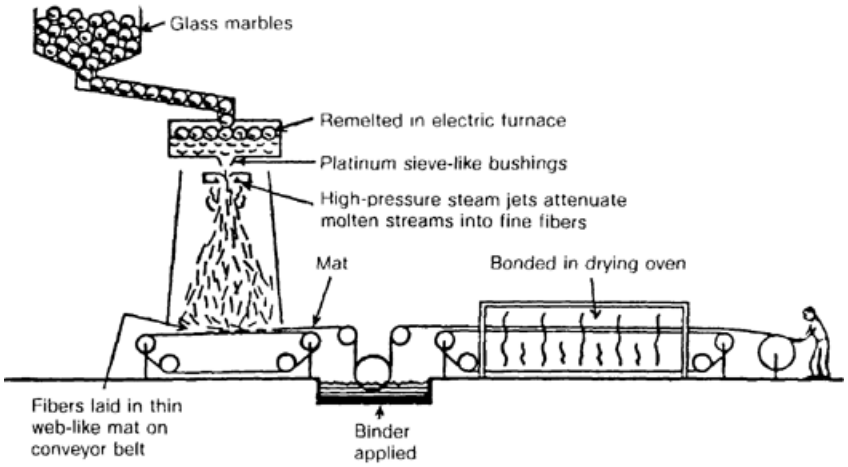


Figure 9

Fiberglass

Another product that could be formed from lunar soil is fiberglass, which might find use as a structural material, perhaps combined with organic or metallic materials. On Earth, fiberglass tanks are commonly used for storage of fluids, such as in standard water heaters.

From Shand 1958, p. 384.

Among the high-leverage uses of fused silicate materials in the proposed utilization of nonterrestrial resources are the fabrication of heat shields for orbital transfer vehicles traveling from the Moon to Earth and the use of sintered or melted and sand-cast soil for structural support in unpressurized lunar shelters. The work of Blacic (1985) indicates that lunar glasses made under the anhydrous, hard-vacuum conditions on the Moon could have very high strengths and thus be quite applicable to structures in space. Prestressed beams made with sintered bricks, using fiberglass or iron bars as tendons, may find early application as structural members.

Ceramics like those used on Earth could be produced by chemical processing of raw lunar material; for example, fractional volatilization of plagioclase could lead to melts for ceramic applications. The recombination of plagioclase with the residue of the ilmenite reduction process (metallic iron and titanium dioxide) could yield cermets with interesting properties. Ceramics might find uses similar to those of glasses.

Alternative means of preparing glasses and ceramics appear to be direct heating using solar concentrators (Ho and Sobon 1979), electrical resistive heating, and microwave heating. Direct use of waste heat from nuclear reactors used in space or on the Moon may also be practical but might require complex heat exchangers, heat pipes, and other devices for thermal control. The microwave heating concept is described in more detail in the first appendix to this part. It offers an efficient means of converting electrical energy into heat, delivered locally and in a controlled manner to the target to be heated. Additional work is necessary to define optimum thermal processing systems for glass and ceramic products and the properties of the heated lunar material. It will be desirable to have access to good simulants of lunar regolith or increased quantities of real lunar soil to further such necessary research.

The production of more complex ceramics, composites, and even semiconductors may prove desirable at some point during the development of a lunar base. Although perhaps not within the scope of most easily obtainable materials, semiconductors produced from lunar materials could have a major effect on the means of producing electricity on the Moon. Silicon-based photovoltaic devices could be constructed using silicon reduced from silicate minerals, covered with thin glass layers made from silicon

dioxide, supported by iron, aluminum, or glass structures, and supplied with iron wires to conduct currents. Lunar ilmenite has interesting semiconductor properties (see fig. 10) and might be usable in converting sunlight to electricity. The preparation of photovoltaic devices is now well known on Earth; however, adapting these processes to a lunar environment would be quite challenging.

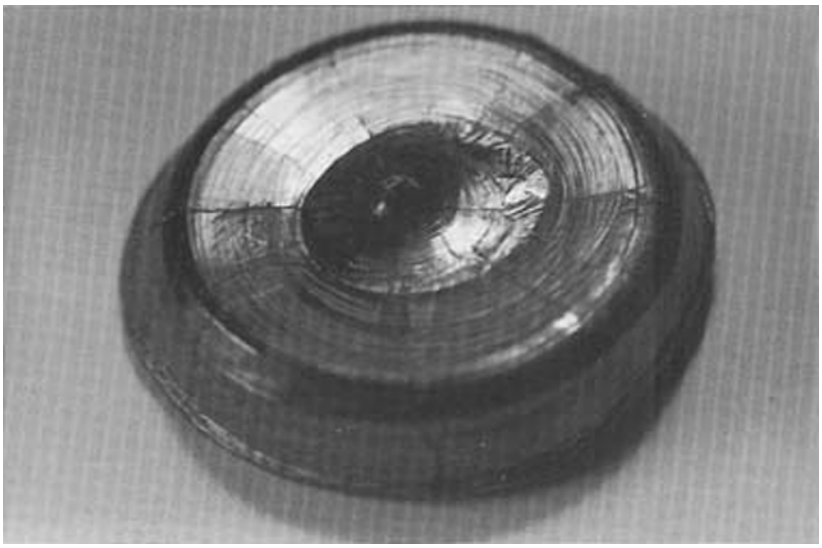


Figure 10

Semiconductors

Lunar ilmenite is a natural semiconductor. Here, a "boule" of ilmenite of lunar composition has been fabricated in a furnace as a single crystal. Cut into thin wafers, provided with electrical leads, and exposed to the Sun, this semiconductor would cause an electrical current to flow. Although rather low in its efficiency of converting light to electricity, ilmenite is so abundant on the Moon that it may be an attractive alternative to photovoltaic devices brought from Earth.

Courtesy of R. K. Pandey, Electronic Materials Laboratory, Texas A&M University, College Station, TX.

Cement and Concrete

Gene Corley and Larry A. Haskin

The most commonly used construction material on Earth is concrete made with Portland cement. Three quarters or more of the mass of concrete is aggregate, usually sand and gravel. Portland cement, made by sintering limestone, iron ore, and clay, has as its principal constituents anhydrous calcium silicates and aluminates whose typical compositions are $3CaO \cdot SiO_2$, $2CaO \cdot SiO_2$, $3CaO \cdot Al_2O_3$, and $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$. The first three are essential to good concrete strength. In addition, cured concrete contains about 5 percent (by weight) water, a result of the hydration reactions that bind the Portland cement component around the aggregate.

The principal constituent of concrete—aggregate—is abundant on the lunar surface. Lunar mare basalt is similar to terrestrial basalt, which has been used to make concrete with high compressive strength.

To produce lunar cement, high-temperature processing will be required (see fig. 11). It may be possible to make calcium-rich silicate and aluminate for cement by solar heating of lunar pyroxene and feldspar, or chemical treatment may be required to enrich the calcium and aluminum in lunar soil. The effects of magnesium and ferrous iron present in the starting materials and products would need to be evaluated. So would the problems of grinding to produce cement, mixing, forming in vacuo and low gravity, and minimizing water loss.

The need for water, a substance not known to exist on the Moon [but oxygen is an element in most lunar compounds and see Carter (1985) for the abundance of hydrogen in the lunar soil],

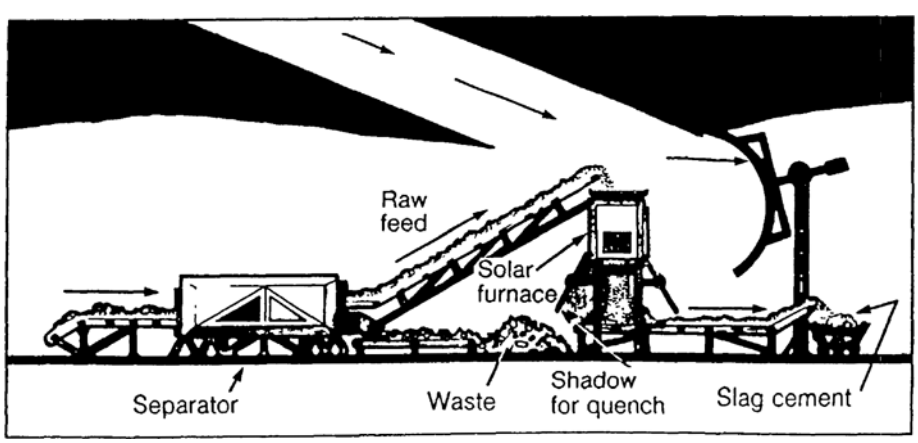


Figure 11

Slag Cement Production Facility

Cement for the concrete might be made by heating lunar anorthitic feldspar to drive off the more volatile components and concentrate its calcium and aluminum oxides. It seems possible to make a usable cement on the lunar surface by relatively simple means. Feedstock separated from lunar soil would be melted in a solar furnace and then quenched in shadow to form a reactive glassy product. When this product is mixed with water and allowed to react and dry, it should make a coherent cement suitable for many structures at a lunar base.

appears to be the most serious deterrent to extensive use of concrete in space. Nevertheless, the convenience of using concrete in space construction has great potential and such use merits close attention. Water may not always be as scarce a commodity as it is now (see fig. 12), and, for some applications, concrete might prove cost-effective even if water had to be furnished. This possibility becomes more realistic if lunar oxygen is made available so that only hydrogen has to be imported. The hydrogen content of cured concrete can be as low as 0.5 percent (by weight).

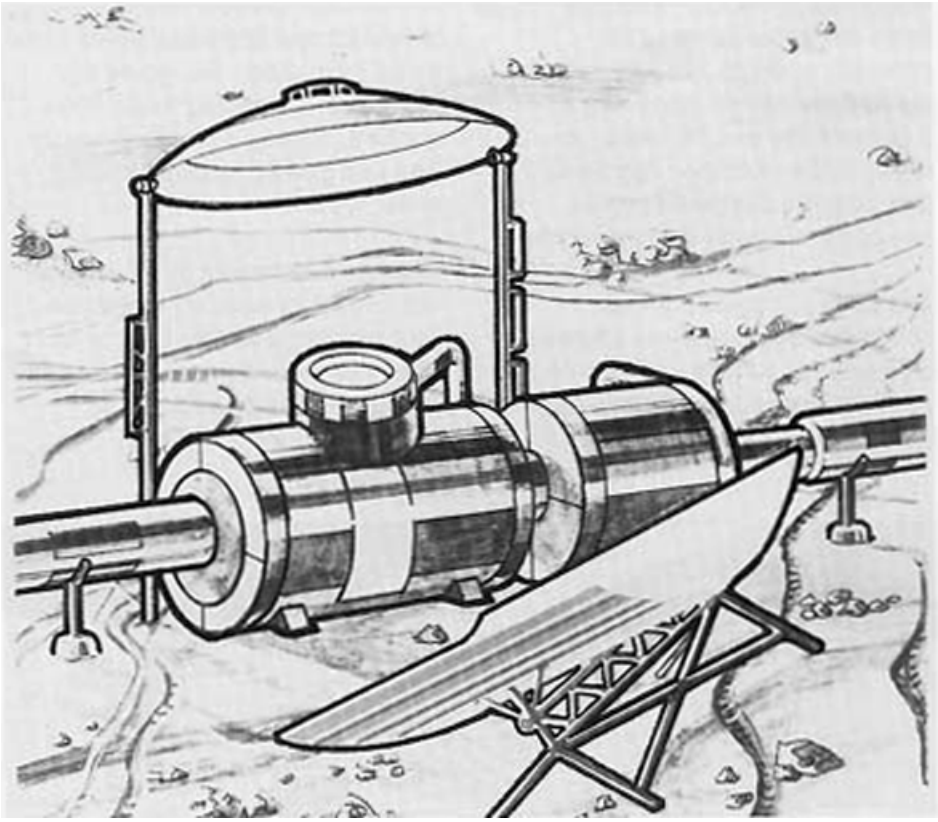


Figure 12

Water on the Moon

Although scarce on the Moon as compared to on Earth, there is enough hydrogen in lunar material to provide about 1 kilogram of water per cubic meter of lunar soil. This water, in turn, could be used to make about 20 kilograms of concrete. The hydrogen could be extracted by solar heating of the finer grained fraction of the lunar regolith, then reacted with ilmenite to form water (and leave an iron-rich residue).

A possible product of interest might be concrete beams reinforced with glass fibers. If imported hydrogen could be used with perfect efficiency, each metric ton could yield 6 kilometers of beams with a cross section 10 by 10 centimeters. The same amount of hydrogen could yield a wall 10 centimeters thick, 3 meters high, and 24 meters long. Thus, where bulk plus reasonable strength is required or where complex shapes are needed, concrete may be a plausible material to use. See figure 13.

A more complete discussion of concrete's properties and potential uses is found in the second appendix to this part.

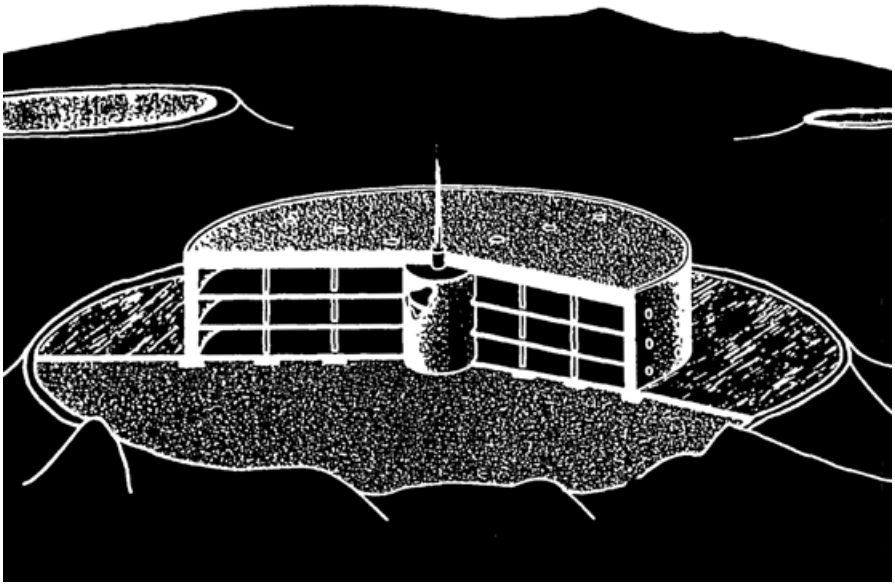


Figure 13

Concrete Structure

Concrete can be made from rocks, sand, cement, and water. The rocks and sand are readily available on the lunar surface. Cement could be made from lunar soil, although considerable processing would be required to produce the right composition. Even the hydrogen for the water might be found in the lunar soil.

The facility shown here, which could house 300 people, would require about 36 metric tons of hydrogen, to be brought from Earth. All other constituents of the concrete would be lunar. If the same 36 metric tons were brought from Earth in the form of space station modules, the assembled structure would provide space for only 8–10 people.

Application of Manufactured Products

Sankar Sastri and Michael B. Duke

As table 3 shows, a wide range of useful products can, in principle, be manufactured from the following materials:

1. Lunar regolith or basalt
2. Regolith or rock beneficiated to concentrate plagioclase or other minerals
3. Iron, extracted from lunar soil or rocks by various means
4. Naturally occurring or easily obtained materials that have cementitious properties
5. Byproducts of the above products

TABLE 3. *Products Derived From Lunar Materials*

	Sintered regolith	Glass and ceramics	Cement	Metal
(a) Basic construction materials and their sources				
Beams	X	X	X	X
Plates, sheets	X	X	X	X
Transparent plates (windows)	—	X	—	—
Bricks, blocks	X	X	X	—
Pipes, tubes	—	X	X	X
Low-density materials (foams)	—	X	—	—
Fiber, wires, cables	—	X	—	X
Foils, reflective coatings	—	—	—	X
Hermetic seals (coatings)	—	X	X	X
Formed objects	—	X	—	X

TABLE 3 *(concluded).*

	Sintered regolith	Glass and ceramics	Cement	Metal
(b) Applications and their parts, listed under their source materials				
Aerobraking heat shields		Low-density thermal protection material		Structural beams
Pressurized habitats	Radiation protection, insulation	Windows, seals	Internal structural plates (floors), beams	Pressure vessels, tanks
Photovoltaic arrays		Semiconductors	Foundation structure	Support structure, wires
Agricultural systems	Radiation protection, insulation	Windows, seals, high-pressure pipes	Structure, low-pressure pipes	Tanks, machine parts, wires

In addition to oxygen, which can be obtained by several processes, either from unbeneficiated regolith or by reduction of concentrated ilmenite, these materials make the simplest requirements of the lunar resource extraction system. A thorough analysis of the impact of these simplest products on the economics of space operations is not possible at this point. Research is necessary both to define optimum techniques and adapt them to space and to determine the probable market for the products so that the priority of various processes can be assessed.

However, as figures 14–17 show, we can envision simple to quite complex construction projects on the lunar surface even in the early stages of lunar operation. And the growth of an industry to make lunar products for use off the Moon is a possibility, though a more distant one.

Figure 14

Aerobraking Heat Shields

When spacecraft, such as the Space Shuttle, enter the atmosphere of a planet at high velocity, the frictional heat must be dissipated and the interior of the spacecraft protected from high temperature. The thermal protection system of the Space Shuttle consists of reusable glass tiles, made out of silicon dioxide, which have very low thermal conductivity and remove the heat by radiation, conduction, and convection in the atmosphere. In contrast, the Apollo heat shield was an ablatable structure, the exterior of which melted and was sloughed off as the spacecraft reentered.

The principal components of these heat shields are a supporting structure and the thermal protection material itself. If lunar material can be used to make heat shields (either reusable or ablatable), the cost of transporting such shields to the Moon can be avoided. This could significantly reduce the cost of transporting lunar products to Earth.

Artist: Doug McLeod

NASA photo: S90-41673

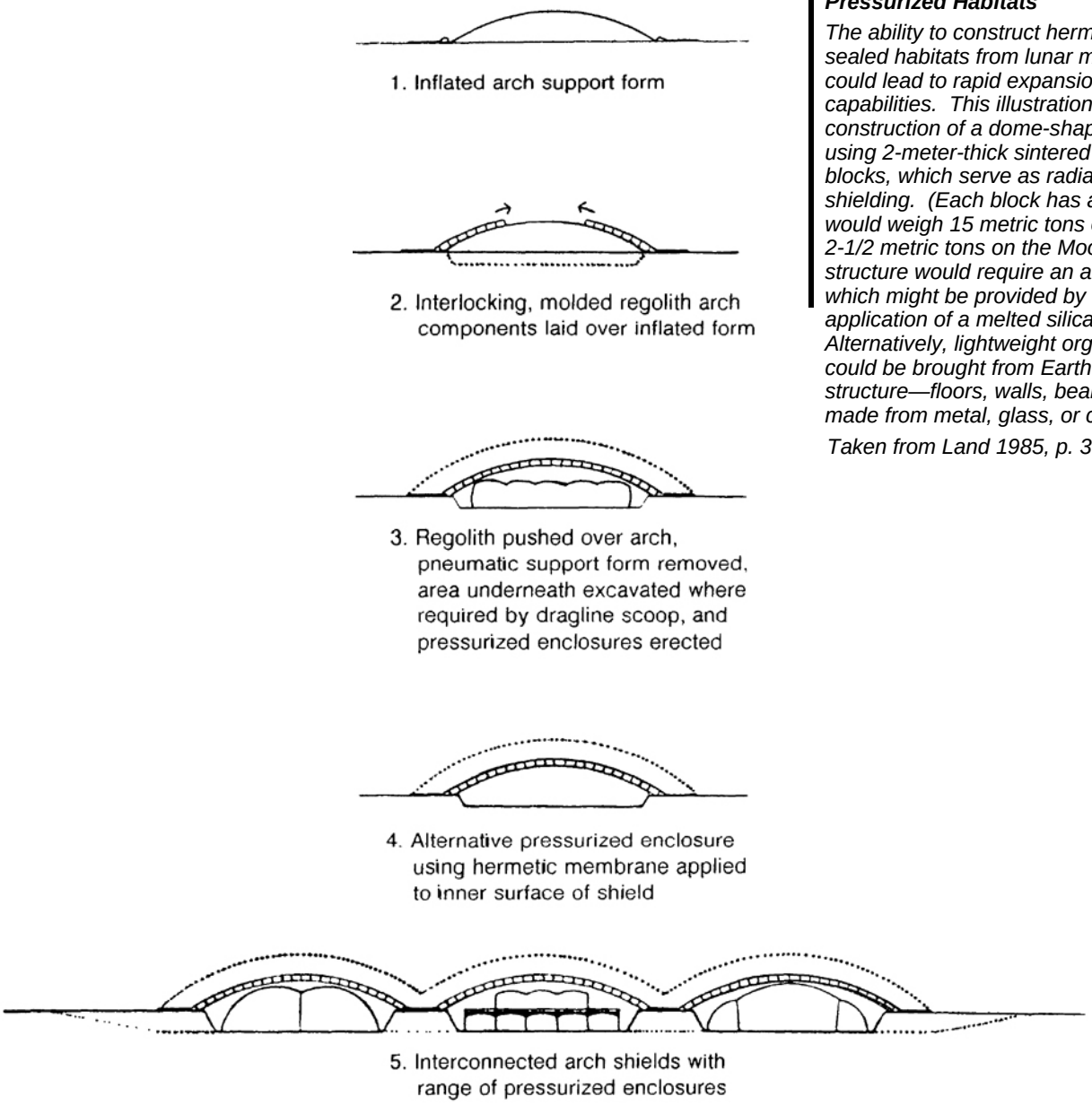


Figure 15

Pressurized Habitats

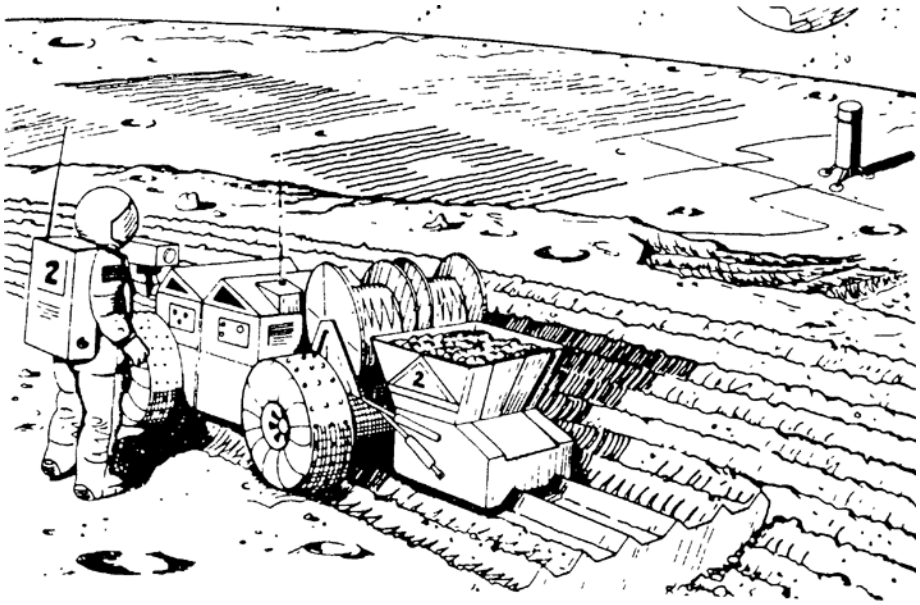
The ability to construct hermetically sealed habitats from lunar materials could lead to rapid expansion of lunar capabilities. This illustration shows the construction of a dome-shaped structure using 2-meter-thick sintered regolith blocks, which serve as radiation shielding. (Each block has a mass that would weigh 15 metric tons on Earth, 2-1/2 metric tons on the Moon.) This structure would require an airtight seal, which might be provided by the application of a melted silicate glaze. Alternatively, lightweight organic seals could be brought from Earth. Internal structure—floors, walls, beams—could be made from metal, glass, or concrete.

Taken from Land 1985, p. 368.

Figure 16

Lunar Photovoltaic Farms

A combination of items manufactured on the Moon might be used to produce a lunar power system. Photovoltaic semiconductor materials are deposited on prepared ridges in the lunar soil. Iron wires will carry the electricity to microwave transmitters. Microwave reflectors consisting of lunar ceramic and iron wires can beam the microwaves to space, even all the way to Earth. Thus, a relatively small lunar processing facility can rapidly develop substantial quantities of electricity using primarily indigenous materials.



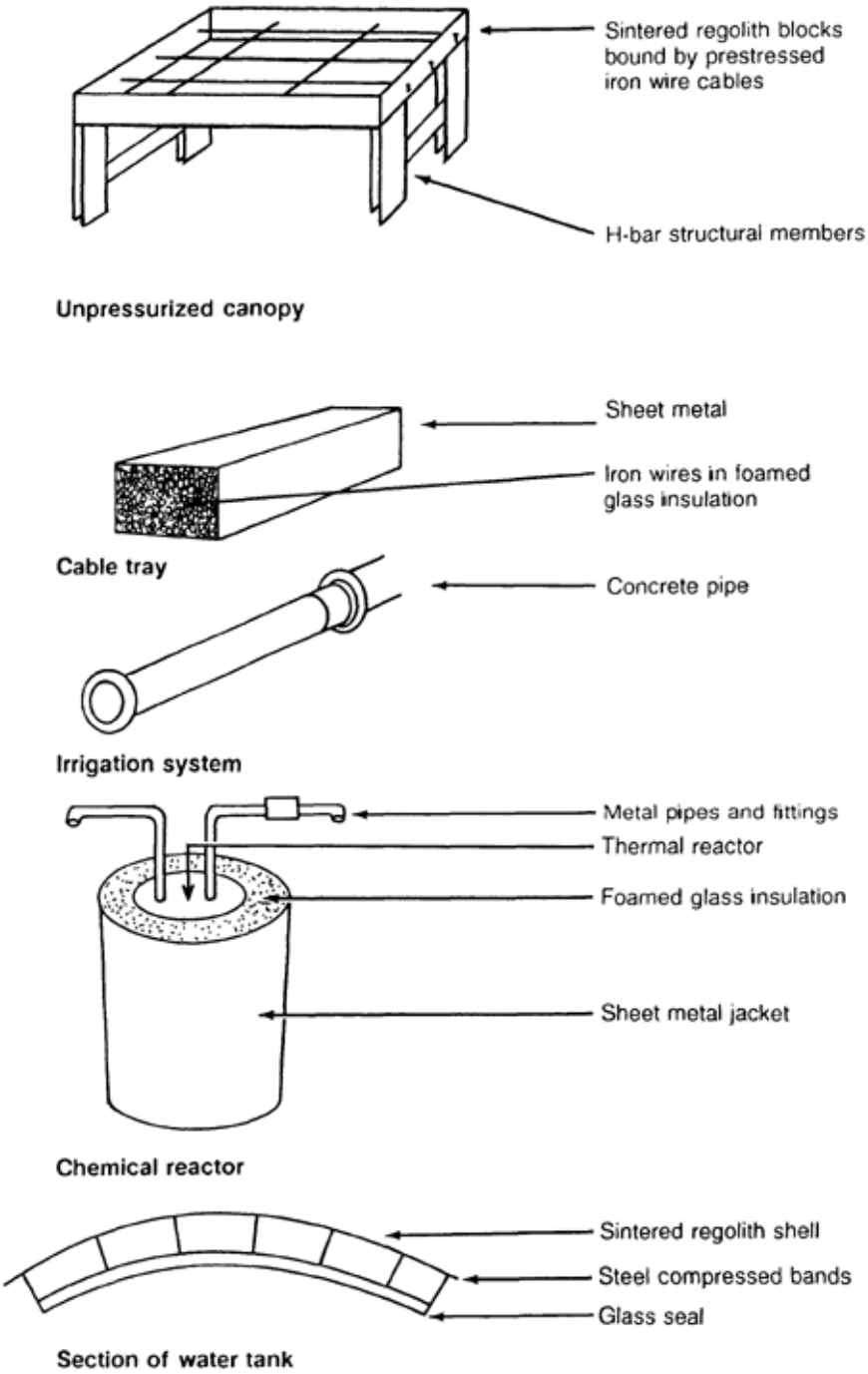


Figure 17

Agricultural Systems

Many applications of lunar materials could be found in a "home-grown" lunar agriculture facility. Structural members are similar to those for the habitat described in figure 15. Internal plumbing—tanks and pipes—could be made from glass, metal, or concrete. Plants may be grown in modified lunar soil. The lunar farm is also an essential component of the environmental control system for the lunar base, purifying air and water.

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Appendix A: Microwave Heating of Lunar Materials

Thomas T. Meek

Introduction

Microwave heating of nonmetallic inorganic material has been of interest for many years. Von Hippel in the late 1940s and early 1950s investigated how microwave radiation up to 10 GHz couples to various insulator materials. Perhaps the most work has been done by Wayne Tinga at the University of Edmonton (Alberta, Canada). Most of the work to date has been done at the two frequency bands allowed in industrial use (0.915 GHz and 2.45 GHz). However, some work has recently been carried out at 28 GHz* and 60 GHz (Meek et al. 1986). At Los Alamos National Laboratory, the work has centered about the fabrication of useful engineering components.

Table A-1 lists some materials that have been thermally processed using microwave energy and some products that have been fabricated at both 2.45 GHz and 60 GHz.

*Personal communication with H. D. Kimrey, Fusion Energy Division, Oak Ridge National Laboratory.

TABLE A-1. *Some Starting Materials Heated by Microwave Energy at Los Alamos and Resultant Products*

Material	Product	Processing temperature, °C	Frequency, GHz
Owens-Illinois (OI)– 1756C glass	Ceramic-glass seal	462	2.45
OI—0038 glass	Ceramic-glass seal	735	2.45
1613 glass**	Ceramic-glass seal	1450	2.45
Alkali basalt	Sintered material	1200	2.45
Al_2O_3	Sintered material	1300–1900	2.45, 60
ZrO_2	Sintered material	1300–1900	2.45, 60
Ilmenite	Sintered material	1350	2.45
Apollo 11 regolith	Sintered material	1100	60
SiC whisker-Al_2O_3	Composite material	1300–1900	2.45, 60

**High-temperature glass made at Los Alamos.

Using microwave energy to process lunar material offers a new, potentially very efficient way of heating these types of materials. Not only can lunar material be heated with less energy than that required by conventional methods, but the heating is accomplished more uniformly and in much less time (Meek et al. 1985).

Discussion

Many oxide materials are transparent to microwave energy at 2.45 GHz and 0.915 GHz. Oxides that possess impurities, such as mobile ions or mobile defects, that enhance their electrical conductivity will, however, couple to electromagnetic radiation in this frequency range. Heating will be primarily electronic.

For example, beta alumina contains by weight 11 percent sodium, thus enabling it to couple efficiently to 2.45 GHz microwave radiation. Beta alumina, when placed in a 2.45 GHz microwave field of 400 watts power can be heated from room temperature to its sintering temperature (1850 °C) in just a few seconds (Berteand and Badot 1976). Materials such as cuprous oxide (Cu_2O), zinc oxide (ZnO), and zirconium dioxide (ZrO_2) will also couple efficiently because they are defect-controlled semiconductors. To heat traditional oxide materials, such as alpha alumina, we incorporate materials that do couple to 2.45 GHz radiation, such as aluminum nitrate. These materials cause the oxide to heat to a few 100 degrees Celsius, after which the oxide will couple because its ability to absorb electromagnetic energy (its loss tangent) has increased sufficiently.

It is known that most lunar regolith, down to a depth of 3 meters, contains at least 10^6 imperfections per cubic centimeter from cosmic rays, solar flares, and the solar wind (see fig. A-1). The defects introduced into this soil over millions of years' exposure to these high-energy particles should increase the loss tangent of this material and allow it to be heated in a microwave field without the use of coupling agents. Terrestrial alkali basalt shows only weak coupling initially; however, when the intensity of the electric field is increased, this material heats rapidly. Recently we demonstrated the ability to heat ilmenite to its melting temperature using 2.45 GHz microwave energy. Since ilmenite is present in abundance on the lunar surface in mare regions, it could act as a coupling agent to allow the initial heating of those lunar materials that may not couple at ambient temperature.

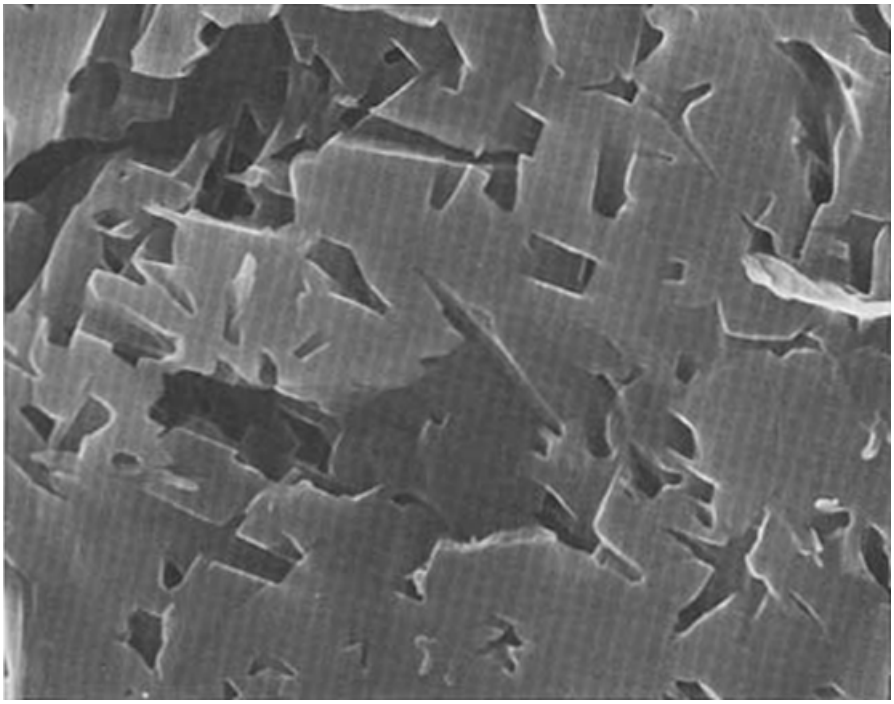

Figure A-1

Tracks of Cosmic Ray Particles and Solar Flare Particles in a Plagioclase Crystal

The plagioclase crystal structure has been severely damaged where these high-energy particles have penetrated into the crystal. Etching of the crystal with NaOH has preferentially removed the damaged material, leaving elongated, rectangular holes or tracks. Such track damage is common in many lunar regolith crystals.

Table A-2 shows observed heating rates for some of the materials thermally processed using 2.45 GHz and 60 GHz microwave energy. If the proper electric field intensity (E) or magnetic field intensity (H) is used, rapid heating of lunar materials will also occur. The following expression (Püschner 1966) shows the relationship between the approximate heating rate and the applied electric field intensity for the heating of an insulator material.

$$\dot{T} = \frac{8 \times 10^{-12} f E^2 k' \tan \delta}{\rho C_p}$$

where $\dot{T}$ = heating rate in degrees Celsius per minute
f = frequency in hertz
E = electric field intensity in volts/cm
k' = dielectric constant of the material
$\tan \delta$ = loss tangent of the material
ρ = density of the material
C_p = heat capacity of the material

Because heating on the Moon will occur in a vacuum, where much greater electric field intensities can be used, materials that would not couple on Earth may be heated

very easily and quickly.

TABLE A-2. *Heating Rates Observed for Different Insulator Materials Heated at 2.45 GHz and 60 GHz*

Material	Observed heating rate, °C per hour	Frequency, GHz
1613 glass	33 000	2.45
OI-0038 glass	20 000	2.45
OI-1756C glass	12 000	2.45
Aluminum oxide	18 000	60

Recommendations

Much work remains to fully characterize some of the phenomena observed to date with microwave-heated oxide and composite materials. For example, diffusion should be modeled, reaction kinetics should be studied, and sintering kinetics should be better understood.

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Appendix B: Properties and Uses of Concrete

Gene Corley

Properties of Concrete

Concretes that can now be formed have properties which may make them valuable for lunar or space construction. These properties include high compressive strength, good flexural strength (when reinforced), and favorable responses to temperature extremes (even increased strength at low temperatures). These and other properties of concrete are described in T. D. Lin's contribution to this report ("Concrete: Potential Material for Space Station").

Higher quality cements and products may become possible. Among other possibilities is manufacture of "zero-macro-defect" concrete products. When manufactured on Earth, these materials have the potential for developing a tensile strength of 15 000 psi [103 megapascals (MN/m^2)] and a compressive strength of 30 000 psi (207 MN/m^2). Although they are made at relatively low temperatures and pressures, they have properties similar to those of some ceramics.

Other properties of concrete that make its application attractive are good radiation absorption and stability at high temperature. Porosity and permeability may be a problem, necessitating the addition of impermeable coatings in some applications.

Fabrication Techniques

Procedures common on Earth can be used to fabricate structural products. The following techniques are possible:

1. Casting
2. Curing at ordinary temperatures or autoclaving
3. Shotcreting with glass fiber reinforcements

Of the techniques available, autoclaving appears most attractive for "high strength" products. This can be done by placing molded concrete units in a pressure vessel painted black on one side. Curing can be accomplished within a few hours. All free water can be recaptured for reuse. Autoclaving will accelerate the cure and produce concretes that contain less combined water than products cured at low temperatures and have greater volume stability upon drying, which are advantages in the space environment. Slag-type silicate-based hydraulic cements are well suited to autoclaving, because the high temperatures accelerate the hydration reactions.

Shotcreting can be used to construct large monolithic structures. Pressure vessels, structured shapes, floor slabs, and wall panels can be fabricated with the use of glass fiber reinforcements. Molds made of inflated membranes can be used

for large enclosures. As in the case of autoclaving, free moisture can be recaptured.

For some applications, such as patching or grouting, where conditions make special curing impossible, a relatively quick-setting cement might be needed. Portland cements are not well suited to such applications, but phosphate cements could be developed to meet such needs. Sulfur cements, which do not require water, have been suggested, but they have poorer properties than hydraulic cements. Special composition cements are a topic worthy of further research.

On the Moon, buildings made of concrete and sheltered by a soil covering can be used as space for living, manufacturing, and storage. The amount of energy used in concrete construction can be low, and the level of worker skill does not need to be high for good results.

As concrete processing technology using appropriate lunar materials develops, concrete may find application in Earth orbit for construction of large structures (see T. D. Lin's paper). Concrete materials such as aggregate, cement, and oxygen from the Moon and hydrogen from Earth can be transported and, in advanced scenarios, at competitive transportation costs. Where large masses of material are desired, concrete has the advantage over unprocessed or sintered material in that it can be cast into compartmented but monolithic structures of high strength, using lightweight forms (e.g., inflated impermeable membranes). Indeed, the versatility of concrete for construction on Earth may be matched in space.

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
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David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
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Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
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Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickell	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
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T. D. Lin	Construction Technology Laboratories
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Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. “Buzz” Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel L. Cruz	Jet Propulsion Laboratory
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Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Harnmerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P. Kerwin	NASA Johnson Space Center
Joseph P. Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
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Harrison H. “Jack” Schmitt	Consultant
Richard Schubert	NASA Headquarters
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Martin Spence	Shimizu Construction Company
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