7 / LUNAR MATERIALS AND PROCESSES

THE AVAILABILITY OF LOCAL RESOURCES constitutes a qualitative difference between a space station and a planetary base. All consumables and construction materials for expansion must be imported to a space station. Because of the great expense of Earth-to-Moon transportation, judicious use of planetary surface materials ought to reduce the cost of maintaining and enlarging a surface facility, in principle. The next generation of launch vehicles may well be designed to lower launch costs, but no concepts on the horizon will result in enough savings to favor importation of terrestrial materials in bulk over utilization of lunar ones whenever possible.

Papers in this section focus on the exploitation of surface materials and on processes that might be important in that enterprise. The opening paper by Haskin is a thoughtful essay on general guidelines for developing lunar resources, bringing to bear his considerable expertise in lunar geochemistry. He identifies "those raw materials for use in manufacture that can most readily be obtained from lunar materials as we know them," always choosing the most conservative scenarios. Since the first step in processing lunar materials has to be some form of mining, Podnieks and Roepke outline research necessary for understanding lunar mining technology, drawing on their experience at the Bureau of Mines supporting Project Apollo. Agosto presents laboratory data on a beneficiation technique for the important lunar mineral ilmenite. The proposed electrostatic separation of the mineral from the bulk soil exemplifies the adaptation of technologies to the lunar environment.

Three papers from the Los Alamos National Laboratory also explore unusual technologies and material properties for lunar utilization. Rowley and Neudecker suggest a universal but power intensive technique for the many types of drilling, coring, and tunneling operations that can be envisioned on the lunar surface. Meek *et al.*, present results of testing microwave heating of lunar soil to extract implanted gases or to form ceramic materials by sintering and melting. Blacic shows that the anhydrous nature of the lunar environment is not all bad news. Silicates show a significant increase in strength in the absence of water; glasses, in particular, show an increase in tensile strength of an order of magnitude, making glass a prime candidate for structural uses.

Testing any of these ideas on actual lunar soils is difficult. The Apollo samples are allocated to scientific investigators only after extensive review of proposals. Final aliquots are usually in milligram quantities. Allton *et al.*, discuss the issue of simulants and explore the possibility that certain small portions of the collection with limited scientific value might be made available for critical testing in future programs.

Many processes in terrestrial manufacturing that are taken for granted must be reexamined at a fundamental level for application on the Moon. Pettit tries to picture what a lunar distillation column looks like. The parameters for this perfectly common process in chemical engineering have been developed over the years largely by trial and error in the terrestrial setting. An analysis of the lunar version must be theoretical and poses an interesting problem in the physics of the important processes taking place in the column. In a similar vein, Lewis looks at the design parameters of lunar machine tools. Such problems make interesting exercises for students because the basic assumptions behind the physics and engineering must be disinterred from the technical literature.

TOWARD A SPARTAN SCENARIO FOR USE OF LUNAR MATERIALS

Larry A. Haskin

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, MO 63130

Many lunar materials have been proposed as raw materials for space manufacture. Only those that are abundant and extractable by relatively simple means may be feasible for use. These include mare and highland soils and very abundant rock types. Even the restricted set of materials and extraction processes considered can yield a good variety of raw materials.

INTRODUCTION

Visionaries seeking to show in general terms how our space environment can be used to our benefit have every justification for assuming the usefulness of the chemical elements available on the Moon or on other bodies in the solar system. Those proposing more specific uses of extraterrestrial materials should feel obliged to learn in detail the nature of the materials as found and to determine whether their strategies for use are reasonably based on material availability and probable economy of manufacture. In particular, it falls to the chemist, the chemical engineer, and the metallurgist to test the technological feasibility of individual stages of grander scenarios for product development from space resources.

If lunar ores and conditions resembled those on Earth, it would be straightforward to transplant terrestrial technology to the Moon's surface. Since they do not, it is necessary to consider whether it is better to try to adapt terrestrial technology to the Moon's very different conditions or to devise fresh technologies appropriate to them. This debate may continue for some time, as little research has been done so far to enable choices to be made. The best techniques for converting lunar materials to useful products may not even have been thought of or recognized yet, as we have little direct experience in coping with the space and lunar environments. We still tend to view most extraterrestrial conditions as obstacles and have not learned to react intuitively to them as the advantages that, for many purposes, they will surely be. At the very least, we owe it to ourselves to determine, at the laboratory bench scale, the basic characteristics of all the extraction and manufacturing processes we can conceive of during the next several years before choices must be made on whether to employ lunar matter for use in space and, if so, how.

Some proposed scenarios for manufacture seem to be based on misunderstanding of the nature of the starting materials or to demand for their execution outlandish layouts of factories, prepared reagents, and energy. It is better to use lunar materials instead of terrestrial ones only if there is significant gain in economy or time by doing so. There is, nevertheless, reason to be confident that the combination of those products that can be produced relatively simply from lunar materials for use in space will prove to be economical, will accelerate the growth of space activities, and will enrich human welfare and experience.

The purpose of the discussion below is to identify those raw materials for use in manufacture that can most readily be obtained from lunar materials as we know them. Availability of lunar materials has been considered by others (*e.g.*, Williams and Jadwick, 1980; Williams and Hubbard, 1981; Arnold and Duke, 1977; Arnold, 1984). Information on the nature of the materials found on the Moon is summarized by Taylor (1975) and the details are found in the many volumes of the Proceedings of the Lunar and Planetary Science Conferences. The state of lunar exploration is incomplete, and there is reason to believe that concentrated ores may exist for elements that must now be regarded as rare or dispersed. The discussion here, however, describes minimum possibilities, based on the notion of making do with the least feasible amounts of separation and processing.

This ground rule will not necessarily lead to the most likely scenarios for space manufacture using indigenous materials. Utilization of lunar resources is complicated sufficiently just by the difficulties of transportation and living that any such manufacture is necessarily somewhat complex, and the best methods may need to be very complex to be economical. There nevertheless seems to be merit in asking what is most easily available. Besides, there is a certain satisfaction in imagining oneself to be a lunar homesteader trying to adapt to the Moon's environment with as few fancy tools and as little dependence on support from home as possible. As seen below, it appears that a substantial range of materials can be obtained with minimal separation and that scenarios based on the simplest technologies are not severely restrictive.

GROUND RULES

For this discussion, we limit ourselves to the most abundant materials observed at lunar sites visited by the Apollo missions. Excluded from consideration are less abundant materials already known, conceivable exotic ores, and hoped-for polar water. Materials are to be used directly for manufacture in "as found" condition or high-graded or separated by only the simplest means.

Although manufacturing processes are not considered here, corresponding constraints can be defined for them. For example, manufactured products should be used on the Moon or in space, not on Earth; however, any complex components would be imported. Steps in manufacture would have to be few, easy, and reliable.

These constraints, in turn, can be accompanied by ground rules for use of lunar products. Materials used in space will be those available and adequate, not necessarily those traditionally used, envisioned, or preferred on technical grounds for a given application. The quality of materials used will not necessarily match those of similar materials produced on Earth; sizes and quantities needed must be adjusted accordingly. Assembly and application of products of space manufacture must be simple and rapid and tolerances relatively loose.

TOOLS

The tools necessary to carry out any significant production of raw materials for manufacture cannot be regarded as simple, but merely as relatively simple. One item will have to be dirt-moving equipment, necessary for habitat excavation, as well as for transporting feedstocks to smelting or manufacturing sites and removing waste products and, perhaps, the products themselves. It is assumed that all processes, from gathering and production of raw materials through manufacture and assembly, will be substantially automated. Equipment probably will be tended, mainly from remote stations nearby. Equipment should be designed to allow straightforward repair, optimization to actual encountered conditions, and innovative adaptation by the operator to new feedstocks and conditions.

Electrical power, at least one megawatt, will have to be available for any significant processing or manufacturing activity. Initially, this probably will need to be nuclear power, although eventually solar power should be exploited to the fullest extent. Through the use of concentrating mirrors, solar power should be available at the outset for heating of materials to high enough temperatures to melt or even distill them.

LUNAR SURFACE CONDITIONS

The lunar surface is a source of high and unavoidable vacuum, both an inconvenience and a potential aid to manufacture. The acceleration of gravity is only one sixth that of Earth, which makes strengths of materials less of a problem for lifting and supporting, although not for withstanding changes in momentum. Also, the microgravity of orbiting factories can be used for processing lunar material, where appropriate. Half the time, the lunar surface is bathed in sunlight, without uncertainties from clouds; each day and night is about 328 hours long. Surface temperatures range from roughly -170°C in the shade to +120°C in direct sunlight. There is no medium for heat exchange as on Earth where abundant water and air are available, so waste heat must be dissipated by radiators. Sunlight is available nearly full time in orbit, and lunar bases at polar locations might also achieve full-time use of solar energy. The lunar surface abounds in fine dust, a convenient form of rock for some uses but a potentially serious problem for operation of equipment and for personnel comfort and health.

READILY AVAILABLE MATERIALS

Unprocessed Regolith

The material most readily available is unprocessed lunar soil (McKay, 1984). This consists mainly of fine rock flour (Papike, 1984), produced by past impacts of meteorites on the atmosphereless lunar surface. Some of the particles have been melted during impact and are present as glassy agglutinates. As encountered, this rock flour contains fragments ranging in size from clay to boulders. The minimum high-grading would consist of sieving out the larger fragments. Soils at mare sites are made mainly from crushed lunar basalt, similar in nature to common terrestrial basalt but drier and chemically more reduced. Fragments in mare soils are rich in the minerals plagioclase feldspar and pyroxene with ilmenite an important minor component. These minerals are not mainly present as separate grains, but are joined together as rock fragments or mixed and partly melted to make glassy agglutinates. From an elemental point of view, these soils are rich in oxygen (41%) and silicon (19%) (as are all known lunar soils), and in iron (13%), magnesium (6%), and, relatively, titanium, (up to 6%). Soils derived from highland rocks have lower abundances of iron and magnesium, but tend to be rich in aluminum (14%) and calcium (11%).

These elements do not occur in elemental form but in combination with oxygen. Their compositions are usually reported in terms of idealized oxides based on the probable oxidation state in the rock. It must be recognized that the concentrations as given are not intended to imply the presence of the oxides as such; the elements and their shares of oxygen are present as solid solutions, *i.e.*, as the minerals, mainly silicates, from which the rocks are made.

Most soils in mare regions appear to contain significant quantities of highland rocks, probably because many mare deposits are rather shallow and have allowed craters of intermediate size to penetrate into their highlands substrates. Soils distant from maria seem to have rather small percentages of mare components. Mixed soils, found mainly near mare-highland boundaries, have intermediate compositions.

In addition to the soils there are rocks. While perhaps not in as convenient a form to use as the already pulverized soils, they offer the possibility of more concentrated sources for some elements. Some rocks found on the Moon's surface are nearly monomineralic. These include anorthosite (nearly pure plagioclase feldspar, a calcium aluminosilicate) and dunite (nearly pure olivine, an iron-magnesium orthosilicate solid solution). Similarly, certain mare basalts are richer in titanium than are the soils derived from them. Not enough is known about the highlands to determine whether any monomineralic rock is present in sufficient abundance to serve as a convenient source of ore. Dunite fragments are rare at Apollo sites. Anorthosite fragments are abundant at the Apollo 16 site and were found also at the Apollo 15 site as isolated pieces in the regolith or as large clasts in breccia boulders. Breccias are rocks composed of broken fragments of prior rocks, compressed together to produced mixed rocks. Breccias are overwhelmingly the most common type of rock collected in the lunar highlands. Other rock types fairly common as clasts in breccias from the highlands are troctolite (olivine-plagioclase rocks) and norite (pyroxene-plagioclase rocks). Remotely sensed infrared spectra indicate that the central peaks of some large craters may be principally olivine and of other craters principally plagioclase (*e.g.*, C. Pieters, personal communication, 1984). This is unconfirmed by sampling since no such sites were visited by the Apollo or Luna missions. However, the soil at the station 11 site, Apollo 16, is highly enriched in anorthosite. By far the most common compositions observed by infrared remote sensing are those corresponding to norite, the same compositions that are typical of bulk or average samples of highland breccias (B. Hawke, personal communication, 1985)

Minimally Processed Regolith

There is some metallic iron, commonly about a tenth of a percent, in lunar soils. It is mainly present as fragments from meteorites that broke apart during crater-forming explosions and became mechanically mixed with lunar rock debris. It consists of alloys of iron that contain up to several percent nickel and some cobalt. This metal can be high graded by simply drawing a magnet through the soil. Pure metal will not be obtained, however, because many fragments are incorporated into agglutinates, which are glassy shards produced by melting of soil during meteorite impacts. Also, there are small amounts of indigenous metallic iron in lunar igneous rocks, a reflection of Moon's dearth of free oxygen. When bits of such rocks are incorporated into agglutinates, they contribute to their magnetism. A magnet gathers both magnetic agglutinates and metal fragments, and further processing to obtain pure metal would have to be done.

Within most lunar soils at least a few percent of the fragments are grains of single minerals. The percentage can be fairly high when the rocks from which the soils derived were coarse grained (*e.g.*, anorthosites) so that even sizeable fragments can be essentially monomineralic. It is lower but not negligible in soils derived from finer grained rocks (*e.g.*, basalt), because soils tend to be so finely pulverized that many of their grains are monomineralic fragments. All grains do not become monomineralic, because the micrometeorite-driven processes of partial melting and agglomeration to produce agglutinates work against continued communition of soil grains. Electrostatic processing (Agosto, 1984) offers the possibility for separating some minerals (*e.g.*, ilmenite) in highly concentrated form, potentially useful for providing special feedstock. Residues from this processing are also available and will have properties different from those of the bulk soil. Since these residues must be handled anyway, it is desirable to find uses for them and to control their properties as much as possible to provide for good secondary products. Most separation processes produce several different fractionated materials.

Melting of common lunar silicates can produce a variety of glasses with different properties. These can be cast or drawn, and under water-free lunar conditions may have great tensile strengths (Blacic, 1984). Speculation on possible products (Steurer, 1984; Khalili, 1984) and their properties is beyond the scope of this discussion of raw materials; glasses are mentioned here because they can be produced by such simple processing.

MAXIMUM "ALLOWED" PROCESSING

Herein, we offer a few examples of processing methods we regard as the most complicated allowable for serious discussion in realistic planning for an initial Moon base. Any of these processes will require substantial engineering and equipment to carry out. Along with the products of interest, we call attention to the residues, which may themselves have application.

Thermal Release of Gases

The simplest scheme for production of gases involves heating of lunar soil to release trapped solar wind. The most abundant implanted elements that can be extracted in this way are hydrogen, helium, nitrogen, and carbon. Since concentrations of these elements are low (mainly 50–100 parts-per-million by weight), large volumes of soil must be heated for a reasonable yield. The elements are tightly bound within surfaces of soil grains; soils must be heated to temperatures of 700–1100°C to release them. Provided that the tonnages of fines can be handled adequately, useful amounts could be obtained. Some indigenous, relatively volatile elements such as sulfur, chlorine, and noble gases (mainly argon) are similarly abundant in some soils and could also be extracted by heating. The products of heating of materials from indigenous and solar-wind sources would include water, hydrogen sulfide, carbon monoxide and dioxide, ammonia, and hydrogen cyanide, among others. For efficient handling, these gases may require oxidation (with lunar derived oxygen) to produce three readily separable fractions: water, carbon dioxide, and nitrogen plus noble gases. The available quantities of entrapped solar wind are sufficiently high and the economies of complete propellant production on the Moon so appealing that production of hydrogen deserves serious consideration (Carter, 1984; Friedlander, 1984; Rosenberg, 1984; Blanford *et al.*, 1984). The problem of heating large tonnages of lunar soil in a closed system to capture emitted gas has not received adequate consideration. The residue would be degassed lunar soil, or, if melted, glass.

Hydrogen Reduction of Ilmenite

The gaseous product that has received the most consideration so far is oxygen (*e.g.*, Rosenberg *et al.*, 1965; Driggers, 1976; Davis, 1983; Carroll *et al.*, 1983; Cutler, 1984a,b,c; Kibler *et al.*, 1984; Gibson and Knudsen, 1984; Waldron, 1984). Extraction of oxygen requires oxidation of that element from an oxide (*e.g.*, ilmenite) or from silicates (*e.g.*, mare basalt; separation of a pure silicate mineral does not seem necessary). The method receiving the most attention is one in which the water is electrolyzed and the hydrogen returned for further reaction (*e.g.*, Williams and Mullins, 1983). The ilmenite concentrate would have to be provided by highgrading of lunar soil as described in the previous section, and in that sense the "ilmenite process" is at least a two-stage process. The residue would be an intimate mixture of iron metal and unreduced iron oxide and titanium oxides, plus perhaps some silicate, depending on the purity of the ilmenite concentrate (Johnson and Volk, 1965). Electrolysis of molten silicate and other processes are also being considered for oxygen production (*e.g.*, Kesterke, 1971; Lindstrom and Haskin, 1979). None of the proposed processes is adequately understood yet at the laboratory bench scale.

Carbonyl Processing

The carbonyl process has been studied extensively, used industrially on Earth, and considered for use in space (*e.g.*, Lewis and Nozette, 1983; Lewis and Meinel, 1984). It should be relatively straightforward to use it to extract the metal concentrated magnetically from lunar soil and, in the same sense as the ilmenite process, would be part of at least a two-stage operation. Possibly, it could extract metal from unbeneficiated soil. The principal product would be high purity iron, and a secondary product would be high purity nickel. Cobalt and heavy noble metals will also be extracted. In such high purity, iron metal may attain remarkably high strength (Sastri, 1984). The residue would be mainly metal-free or at least metal-poor silicate. Carbonyl extraction of iron in the residue from hydrogen reduction of ilmenite has been demonstrated and required carbon dioxide pressures of 100–150 atmospheres and catalysts such as hydrogen sulfide for efficient separation (Vishnapuu *et al.*, 1973).

Electrolysis of Molten Silicate

Electrolysis of molten silicates to produce oxygen gas has the attraction that it requires, in principle, only sunlight for heat and electricity and lunar soil as its feedstock (*e.g.*, Lindstrom and Haskin, 1979). Experiments using simulated lunar basalt show that, while oxygen is being liberated at the anode, iron metal is simultaneously formed at the cathode, possibly as an alloy containing small amounts of chromium and manganese and with other impurities. Ilmenite-rich compositions yield iron metal alloyed with some titanium; titanium-poor compositions can yield iron alloyed with silicon. Since compositions of silicates can be significantly changed as a result of electrolysis, this method can leave residues with compositions different from those of indigenous lunar materials. It is perhaps not proper to regard the silicate residue as a residue, since the silicate melt might be the primary product of electrolysis.

Destructive Distillation

Solar furnaces are capable of producing very high temperatures. Some experiments have been carried out on meteoritic material (*e.g.*, King, 1982; Agosto and King, 1983), but no systematic study has been made on condensates or residues from the destructive distillation of simulated lunar silicates. The most refractory material formed probably would be calcium aluminate or, perhaps, calcium oxide. Extraction of gases, discussed above, is a relatively low-temperature form of destructive distillation of silicates. At higher temperatures, even perhaps during gas extraction, other useful substances such as alkali metal oxides might be concentrated by volatilization.

CONCLUSIONS

Unprocessed lunar soil can be used for radiation shielding both on the Moon and in space. Numerous glass products can be made, perhaps with special properties resulting from the dry lunar and space environment; these may become the principal structural materials for space. Iron and nickel can provide steel products, including electrical conductors. Ultra-pure iron may be as good as steel for many purposes. Oxygen and perhaps hydrogen gases can be produced for propellant and life support. This is a very good list of potential early raw materials for use on the Moon or in space. Much work still must be done to determine the conditions required for development of even simple procedures for obtaining and using these raw materials. The constraint of keeping things simple (relatively) does not seem to be an uncomfortably restrictive one.

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MINING FOR LUNAR BASE SUPPORT

E. R. Podnieks and W. W. Roepke

U.S. Department of the Interior, Bureau of Mines, Twin Cities Research Center,
5629 Minnehaha Avenue South, Minneapolis, MN 55417

Mining and excavation technologies must be developed for the establishment of lunar bases that are capable of operating under the severe conditions of the lunar environment. The mining technology research needs for establishing a permanent lunar base utilizing lunar resources are outlined and briefly discussed. These requirements range from initial exploration needs to those required for gradually reaching full lunar base autarky. The extraterrestrial mining and excavation needs indicate that a multidisciplinary research effort must be initiated early in the lunar base program to provide timely research results for the subsequent development stages.

INTRODUCTION

The lunar base program NASA is proposing (Duke *et al.*, 1985) will require substantial rock and soil mechanics and excavation research and development before any self-sufficient lunar base will support extraterrestrial colonization. This ultimate goal of a self-supporting lunar base may require development of unorthodox mining and mineral extraction technology. This technology must include the ability to efficiently construct or excavate shelters for people and equipment to minimize thermal, radiation, and meteorite hazards, and to establish life support systems using lunar resources. These activities will require a knowledge of the characteristics and properties of lunar regolith and rocks, mining and excavation methods applicable to the lunar environment, and extraction processes for recovery of necessary resources involving material handling and special mining or metallurgical methods. Emphasis will need to be placed on making maximum use of lunar materials recovered with methods requiring the least amount of machinery. The development of lunar basing technology will establish basic concepts useful in any extraterrestrial regime. A substantial amount of research was conducted during the Apollo program on basic physical, geological, and chemical properties using simulated lunar materials from the rock suite developed by the Bureau of Mines (Fogelson, 1968). Engineering properties were determined for simulated lunar materials by the Bureau and others, using the Bureau's rock suite. The Bureau's research was oriented toward identification and definition of specific mining-related materials problems in the lunar environment. The research program consisted of:

1. Basic property and fragmentation studies on the effect of the lunar environment on physical, strength, elastic, and thermophysical properties affecting fragmentation (Atkins and Peng, 1974; Bur and Hjelmstad, 1970; Carpenter, written communication, 1969; Griffin and Demou, 1972; Heins and Friz, 1967; Lindroth, 1974; Lindroth and Krawza, 1971; Podnieks and Chamberlain, 1970; Podnieks *et al.*, 1968; Roepke and Schultz, 1967; Roepke, 1969; Roepke and Peng, 1975; Thirumalai and Demou, 1970; Willard and Hjelmstad, 1971).

2. Studies of lunar drilling, blasting, and novel fragmentation methods (Hay and Watson, personal communication, 1974; Paone and Schmidt, 1968; Roepke, 1975; Schmidt, 1969; Schmidt, 1970; Woo *et al.*, 1967).
3. Research on handling and transportation of materials on the lunar surface (Crow and Bates, 1970; Johnson *et al.*, 1973; Nicholson and Pariseau, 1971; Pariseau and Nicholson, 1972).
4. Lunar mineral processing studies (Fogelson *et al.*, written communication, 1972; Fraas, 1970; Haas and Khalafalla, 1968; Kesterke, 1969; Khalafalla and Haas, 1970).

Although Apollo lunar landing results have not demonstrated serious friction and wear problems, this is considered by Bureau of Mines researchers to be due to localized lubrication in the immediate activity area by offgassing from equipment and astronaut space suits. The actual level of friction problems to be expected is best illustrated by the problems experienced with the lunar surface drill. Although core samples were obtained from the Apollo 15 site, the drill was never fully successful and never worked as easily as expected in loose regolith (J. Bensko, personal communication, 1971). No deep core samples could be obtained (Baldwin, 1972). Rock and soil properties can be quite different in a pure pristine lunar environment, as earlier Bureau of Mines work has indicated (Atkins and Peng, 1974; Lindroth, 1974; Podnieks and Chamberlain, 1970; Thirumalai and Demou, 1970). Results have shown that in uncontaminated hard vacuum the surface friction and strength of rocks are higher than in a terrestrial environment. This may be due to greater adhesive (cohesive) forces from higher surface energies and/or due to lack of more than monolayer coverage of water vapor. Adhesion on rock and tool surfaces soaked in ultrahigh vacuum to the point of minimal offgassing will create a problem with chip formation, removal, and clogging during any drilling process (Paone and Schmidt, 1968; Schmidt, 1969; Woo *et al.*, 1967). An example of dust adhesion to space suits and tools used by the astronauts can be seen in Apollo 16 mission photographs.

Previous Bureau of Mines research in the tribology area (Roepke and Schultz, 1967; Roepke, 1969) with mineral-mineral and metal-mineral pairs using materials from the simulated rock suite (Fogelson, 1968) has shown that friction increases substantially in ultrahigh vacuum approaching the pristine lunar conditions. Even assuming that the surfaces still had at least a monolayer coverage of oxides and water vapor, the increase in friction ranged from 1.5 times to over 60 times. Since the lunar surface may consist of totally degassed pristine material, and since extended operations will permit extensive offgassing of equipment, the results suggest that an extremely high friction coefficient will be encountered during excavation and mining operations unless technology is established to minimize this friction.

Associated with the Bureau's work on friction, drilling experiments in ultrahigh vacuum were conducted with a drill designed for gas-free operation using polyimide bearings and gears impregnated with silver and tungsten disulfide. Laboratory results indicated that drilling operations can be performed in ultrahigh vacuum without the use of sealed bearings or any special lubricants (Roepke, 1975), but the earlier friction test results suggest that introduction of some gassy lubricant may be necessary for extended equipment use on the Moon.

Research on the use of explosives in vacuum was conducted by the Bureau of Mines to investigate the effects on explosive properties, including the blast wave pressure profiles (Hay and Watson, personal communication, 1974), and to perform small scale field cratering experiments in several simulated lunar material deposits to obtain indications of blasting effectiveness on the lunar surface. The preliminary results indicated that explosives and explosive components are available that can withstand the lunar environment without deterioration. The behavior of fragments from an explosion can be treated similarly to that in terrestrial explosions and should not present any problems, although lack of air currents and lower gravity will influence ejecta.

Substantial research was also directed toward developing novel methods of fragmentation involving mining equipment that minimizes moving parts. Work using electrothermal techniques for fragmenting simulated lunar rocks has shown some promising results (Thirumalai and Demou, 1970). Laser technology may also be useful for rock fragmentation purposes (Lindroth, 1974; Lindroth and Krawza, 1971).

Additional tests also were conducted using a simulated lunar soil to establish the range of cohesiveness and shear characteristics (Johnson *et al.*, 1975) for near pristine materials. The size distribution of lunar soil recovered by Apollo 11 was used to develop simulated lunar materials for these tests using tholeiitic basalt. A knowledge of shear strength of soils in the outgassed pristine condition will be essential to all materials handling problems. The Bureau results suggested that compacted particulate materials will require greater energy input to induce flow in any materials handling situation, and this potential problem will be exacerbated by the low gravity condition. Although the Apollo results did not indicate any problems with lunar soils, the conditions were similar to those discussed earlier on friction between surfaces. The soils handled were not necessarily pristine and no flow characteristics were considered. If they are handled by equipment fully outgassed due to long soak time in lunar vacuum, and if the soils are handled in quantity, the increase in energy needed to induce and maintain flow may become a factor to be considered.

Although prior work has indicated that electrowinning of oxygen from silicate rocks is feasible, further studies are needed to establish the practical application for the lunar environment (Kesterke, 1969). Similar findings were obtained by using reduction of silicates with carbon (Haas and Khalafalla, 1968), of raw soil by fluorine, and ilmenite by hydrogen (Fogelson *et al.*, 1972). These methods are not novel *per se*, but would be novel when used for obtaining oxygen in the lunar environment, since it will involve a transport of these catalysts to the Moon and their preservation by recycling.

The Bureau research effort during the Apollo years produced a variety of findings both in mining and resource extraction that provided ample proof of the need for a multidisciplinary mining systems development effort. Rock behavior is different in the lunar environment than on Earth; consequently, novel mining technologies may be required. The development of a lunar drill, a relatively simple device compared to the equipment necessary for extended base support, illustrated this point very well. Research and development of suitable mining technology will be in the critical path to establish shelters and maximize use of lunar resources for support of the lunar base.

LUNAR MINING NEEDS

Specific areas of research effort associated with lunar excavation and mining activities in support of lunar base activation must include both basic and applied research as well as prototype engineering development. An understanding of the materials being handled as well as environmental effects on both materials and mining equipment requires a systematic multidisciplinary approach.

The ultra high vacuum and the broad temperature range of the lunar surface will create a severe and restrictive working environment. Although much research was done during the Apollo period on materials properties, additional research is needed to specifically identify the problem areas of mining and handling the regolith materials and any hard rock substrata. From the mining perspective, it will be required that, at least initially, surface friction, strength, and thermal and dynamic (shock) rock properties need to be further investigated over the range of conditions expected to exist during lunar mining or excavation operations. The effects of a low pressure, low gravity environment on the failure mechanisms and on rock fragmentation products such as chips, flyrock, and dust must be established.

Knowledge of environmental effects on mining equipment and the operators will also be essential. Friction and wear of moving machine components may be a major equipment problem. Novel designs that minimize moving parts or that utilize solar or unconventional energy sources may be necessary.

ROCK MECHANICS RESEARCH

The early rock mechanics research in the Apollo program was conducted using a suite of 13 simulated lunar rocks selected by the Bureau of Mines (Fogelson, 1968) based on chemical analysis of the lunar surface by Surveyor V data. These were tested for basic behavior and properties such as fracture characteristics, strength, deformation, and friction (Atkins and Peng, 1974; Bur and Hjelmstad, 1970; Carpenter, written communication, 1969; Griffin and Demou, 1972; Heins and Friz, 1967; Lindroth, 1974; Lindroth and Krawza, 1971; Podnieks and Chamberlain, 1970; Podnieks *et al.*, 1968; Roepke and Schultz, 1967; Roepke, 1969; Roepke and Peng, 1975; Thirumalai and Demou, 1970; Willard and Hjelmstad, 1971) in a simulated lunar environment. These early preliminary studies need to be followed up with both real and simulated lunar rocks in order to extend the data base on materials properties needed for developmental research of the lunar base. A two-step approach is needed to further these studies: (1) determination of material behavior under simulated lunar environment in terrestrial facilities, and (2) using an orbiting space laboratory for long term degassing of materials and equipment to provide more realistic verification testing of drilling or other equipment. The results will provide the basic input needed to develop methods of excavation and construction of lunar shelters, and for mining processes providing life support or recovery of lunar resources.

ROCK FRAGMENTATION RESEARCH

The rock mechanics research should provide an extensive basis for research on the various engineering aspects of rock fragmentation in a lunar environment. Since previous lunar excursions have indicated a plethora of large boulders it seems very likely that fragmentation methods will be required to handle them and subsurface rock formations. More research is needed to help in identifying suitable fragmentation methods by using a methodology to classify lunar rock masses in terms of engineering parameters, rock strength and deformational properties, chemical and petrofabric descriptions, and index properties.

With any rock fragmentation or handling of regolith, dust is generated. It is important to determine dust generation characteristics for different methods of fragmentation and dispersion effects, as related to visibility, operator safety, and equipment use. The effects of low gravity and lack of surface winds must be considered on flyrock dispersion and airborne dwell time of dust clouds.

Use of explosives has been one of the primary methods of fragmentation in the terrestrial environment due to its relative simplicity and efficiency. Since minimal use of mechanical equipment is needed, explosives may be a good fragmentation method on the lunar surface. Initial work on blasting in vacuum has been done, but more fundamental knowledge of blasting in the lunar environment is needed to evaluate its feasibility, safety, and efficiency on the lunar surface.

Other fragmentation techniques already being studied by the Bureau include use of lasers, microwaves, and induction heating. These thermal systems cause the various minerals in the rock to heat at different rates dependent on their thermal conductivity, thus causing differential expansion and fragmentation.

MATERIALS HANDLING

Materials handling involves the removal of the regolith material, the fragmented rocks, and the transport from the site. Methods must be developed for effectively removing cuttings from drill holes during exploration or mining operation. Since there may be a synergism between the machine characteristics and the drilling media, the research must be done with specific design concepts adapted to the lunar environment.

Since materials handling is involved in a broad area of mining and excavation processes, the research needs to cover a variety of aspects.

EQUIPMENT DEVELOPMENT

One of the major problem areas associated with any exploration, excavation, or mining is the development of suitable equipment. The development of lunar-based excavation or mining equipment will require a major emphasis on tribology using designs that control friction and wear without hydrocarbon lubricants. It is unlikely that it will be possible to directly utilize terrestrial mine equipment designs or any direct extrapolation of them for application at a lunar base. Extensive revision of conventional technology or innovative new methods and designs will be required. Complete systems and design analysis will be required to identify and evaluate every step of the mining process in respect to the lunar base requirements. This analysis will identify equipment design needs and the necessary operating steps.

Human factors analysis will also play an important role, since it will be an essential part of developing a fully functional mining system in a lunar environment. The lunar miners are expected to be engineers and scientists who must become fully familiar and experienced with details of mining techniques unique to the lunar application. The special problems associated with mining in the lunar environment will amplify the many problems that any new operators will face. For these reasons, the system must be carefully designed for safety, ease of operation, and to satisfy the functional and operator needs while performing excavation or mining operations.

CONCLUSIONS

The Bureau of Mines past research with NASA on lunar resource utilization within the Apollo program has established a good foundation for more advanced and specific research efforts. The results indicate that on the lunar surface, mining or excavating must be performed using technology that is significantly different from terrestrial methodology. By developing a technology for lunar mining and excavating, a major step will be made toward further expansion of this concept to other planets or bodies in the solar system. The required technology will evolve from research results obtained on: (1) material properties, (2) environmental effects on these properties, (3) various energy mechanisms capable of fragmenting and removing material, and (4) relationships that govern the interaction of the mining and excavation mechanisms with lunar materials under specific environmental conditions.

Based on the conditions found on the surface of the Moon, the major excavation and materials handling will be in the regolith zone consisting of particulates and fine grained or blocky materials. However, the lunar surface also has large surface boulders and, by inference, large underground obstructions that must be fragmented. These tasks present an area of unknowns where research must provide answers generating engineering knowledge for the development of a lunar excavating, mining, and processing technology. The mining technology for extraterrestrial use most likely cannot be a simple adaptation of existing terrestrial methods, but will require novel approaches governed by the knowledge of the constraints of the lunar environment.

If the initial establishment of a lunar base is to occur in the first decade of the next century, it is essential that early research be undertaken in mining technology as part of the overall program effort. It will also be essential to do timely prototype development and testing of proposed lunar mining equipment. Past experience has shown that development of even the simplest exploration/mining tools for the lower gravity, gas-free lunar environment can be a lengthy effort.

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ELECTROSTATIC CONCENTRATION OF LUNAR SOIL MINERALS

William N. Agosto

Lunar Industries, P.O. Box 590004, Houston, TX 77259-0004

Estimates of the magnetic susceptibility of lunar ilmenite indicate that electrostatic separation may be preferable to magnetic separation as a beneficiation technique for concentration of the mineral in lunar soil. Single-pass electrostatic separations of terrestrial ilmenite from a lunar soil simulant in the 0.15–0.09 mm size range on a slide-type separator yielded higher grades in air or nitrogen (89 and 90 wt %, respectively) than in vacuum (78 wt %) due to the effects of air resistance, charging of the feed by gas ions, and the absence of vibratory feed in the vacuum runs. Single-pass concentrations on a 0.09–0.15 mm fraction of Apollo 11 soil 10084,853 increased the lunar ilmenite grade from 7 wt % to 51 wt % in dry nitrogen with the ferromagnetic agglutinates removed and to 29 wt % in vacuum (10^{-5} torr) with all agglutinates present. If all ilmenite-bearing soil phases are included, one-pass grades of lunar ilmenite increase to the mid 60s for the N_2 runs and to the mid 30s for the vacuum run. Soil ilmenite behaved like a conductor or semi-conductor and the agglutinates like non-conductors in all lunar runs. This behavior suggests that ilmenite grades and recoveries in the high 90s can be expected from comparable mare soil fractions with fully liberated ilmenite using multistage-multipass electrostatic concentrators of commercial design. However, redesign of the separator geometry is required for optimal performance in vacuum.

INTRODUCTION

Numerous authors (Andrews and Snow, 1981; Waldron and Criswell, 1982; Davis, 1983) have projected substantial economic advantages for lunar oxygen production as a major fuel and gas resource in extended space industrial operations. Several systems studies of lunar oxygen production (Davis, 1983; Gibson and Knudsen, 1985) have referenced a process utilizing ilmenite, the most abundant oxide in the returned lunar samples. Lunar ilmenite consists of 47 wt % FeO and 53 wt % TiO_2 stoichiometrically and is most heavily concentrated in the maria (McKay and Williams, 1979). Williams and Mullins (1983) have demonstrated the feasibility of oxygen extraction from terrestrial ilmenite by hydrogen reduction of the FeO component.

The paramagnetic properties of ilmenite at ordinary temperatures suggest magnetic separation as a method for concentrating it from mare soil. Accordingly, the magnetic susceptibility of lunar ilmenite was estimated in a 0.09–0.15 mm split of Apollo 11 soil 10084 using a Franz model L1 magnetic separator at the NASA/Johnson Space Center (JSC). The susceptibility was approximately 76×10^{-6} cgs mass units, similar to synthetic stoichiometric terrestrial ilmenite but orders of magnitude below that of natural terrestrial ilmenite, which averages $26{,}800 \times 10^{-6}$ cgs mass units (Carmichael, 1982). The low lunar ilmenite susceptibility probably reflects the virtual absence of Fe^{3+} compared with terrestrial varieties.

The susceptibility determination was made on the soil split after the high susceptibility agglutinates (approximately 75% of total sample agglutinates by microscopic count) were removed using a permanent magnet with a strength of approximately 1500 gauss. When the balance of the sample was run on the Franz separator, all paramagnetic splits that contained ilmenite also contained comparable abundances of agglutinates that had not been removed by the magnet. It was concluded that the lunar ilmenite may be difficult to separate magnetically from the population of soil agglutinates with comparable susceptibilities. Therefore, the alternate technique of electrostatic concentration of lunar soil ilmenite has been studied, and experimental results using electrostatic separators are reported here. The separators are based on industrial designs and were fabricated by Lockheed Engineering and Management Services Co. at NASA/JSC.

MINERAL ELECTROSTATIC SEPARATION

The primary commercial application of mineral electrostatic beneficiation is in processing beach sands and alluvial deposits for titanium minerals. All of the heavy mineral beach sand plants in Australia, and most in the United States (Florida), use electrostatic methods to separate rutile and ilmenite from zircon and monazite (Fraas, 1962; Kelly and Spottiswood, 1982). The most common electrostatic separator designs use a drum or slide configuration. In both designs, a high intensity electric field (several kV/cm) is established by a high voltage electrode spaced a few cm from the grounded drum or slide. Many separators use an additional ionizing electrode above the field electrode to charge the mineral feed with air ions and electrons before it enters the accelerating field (Fraas, 1962; Carpenter, 1970; Moore, 1973). The slide design (Figs. 1 and 2) was used for these experiments because its performance was superior to the drum design for small samples (0.1–5.0 g) (Agosto, 1983) and because it is simpler to operate in vacuum.

Minerals falling through the separating field commonly acquire charge by one or some combination of the following mechanisms: (1) Electrostatic induction; (2) Contact charging; (3) Ionic charging.

Electrostatic induction occurs primarily in conducting and semi-conducting grains which, because they are grounded by the slide, acquire charge opposite in polarity to the field electrode and are pulled toward it. As a result, conductor and semi-conductor particles preferentially report to the conductor bin or bins farthest from the foot of the slide.

Contact charging occurs when a material with a lower electronic work function gives up electrons and becomes positively charged by contact with a higher work function material. Since the rate of charging and discharging is an exponential function of the particle surface conductivity (Kelly and Spottiswood, 1982; Inculet, 1982), conductors lose excess charge rapidly on the slide. Given time to acquire sufficient contact charge, non-conductors tend to retain the charge and move toward the electrode of opposite polarity. Grains that acquire insufficient charge fall into the non-conductor bin or bins at the foot of the slide.

Mineral charging also occurs in the separator due to gas ion and electron bombardment generated by the ambient electric field. This mechanism was not introduced intentionally in these experiments, but evidence for the presence of ionic charging was noted in separation runs made in dry nitrogen.

The charging behavior of terrestrial varieties of the most common mare soil minerals (anorthite, ilmenite, olivine, pyroxene) in four size ranges <0.5 mm has been studied in slide-type electrostatic separators (Agosto, 1983). Ilmenite electrostatic concentration in air for soil-analog size fractions below 0.09 mm was found to be substantially poorer than in the larger size fractions. The reduced performance resulted from partial clumping of fines on the slide as well as billowing and dispersal of the falling fines, which were substantially retarded by the air. Virtually every investigator has reported these effects for particles under 0.075 mm (Fraas, 1962; Carta *et al.*, 1964; Carpenter, 1970; Inculet, 1979; Kelly and Spottiswood, 1982). Since mean grain size for most lunar soils is under 0.1 mm, it appeared that vacuum operation of the separator might improve performance by eliminating the disruptive effects of air resistance on the flow of fines.

ILMENITE ELECTROSTATIC CONCENTRATION IN LUNAR SOIL SIMULANTS

Lunar soil simulants were prepared from mixtures of comminuted terrestrial anorthite (An_{90}), ilmenite (Quebec), olivine (Fo_{90}), and augite pyroxene ($Wo_{50}En_{33}$) in the weight ratio 4:1:1:4, respectively. Two size ranges (0.09–0.15 mm and 0.15–0.25 mm) were tested in air, and one size range (0.09–0.15 mm) was tested in nitrogen and in a vacuum of approximately 10^{-5} torr. Samples were weighed in quantities of 1–5 g and were washed and boiled in isopropyl alcohol until the supernatant fluid appeared clear. Prior to separation, all samples were dried, first on filter paper and then in glass receptacles in an air oven at 120°-130°C overnight.

Ilmenite electrostatic separation grades and recoveries from the simulants are reported in each of three ambients: air at one atmosphere; dry nitrogen at about one torr positive pressure; and in vacuum at 10^{-5} (±20%) torr. In all cases, grade is defined to be the cumulative concentration (wt %) of ilmenite in the conductor bins; recovery is the wt % of total sample ilmenite reporting to those bins. Ilmenite concentration was determined in each bin by microscopic count. The wt % of ilmenite was then calculated by weighing the contents of each bin and assuming that the ilmenite fraction had a density ratio of 1.5 relative to the balance of the simulant sample.

Samples were maintained at 100°-200°C in the separator prior to and during separation by heating both the vibratory feed hopper and the grounded slide to drive off adsorbed feed moisture and to enhance the conductivity of the ilmenite. Feed heating is a common practice in commercial electrostatic mineral separation operations (Fraas, 1962; Kelly and Spottiswood, 1982). Feed rate was approximately 6 g/min, and feed size ranged from a maximum of a few grams in the bench top runs in air to a few hundred milligrams in the nitrogen and vacuum runs.

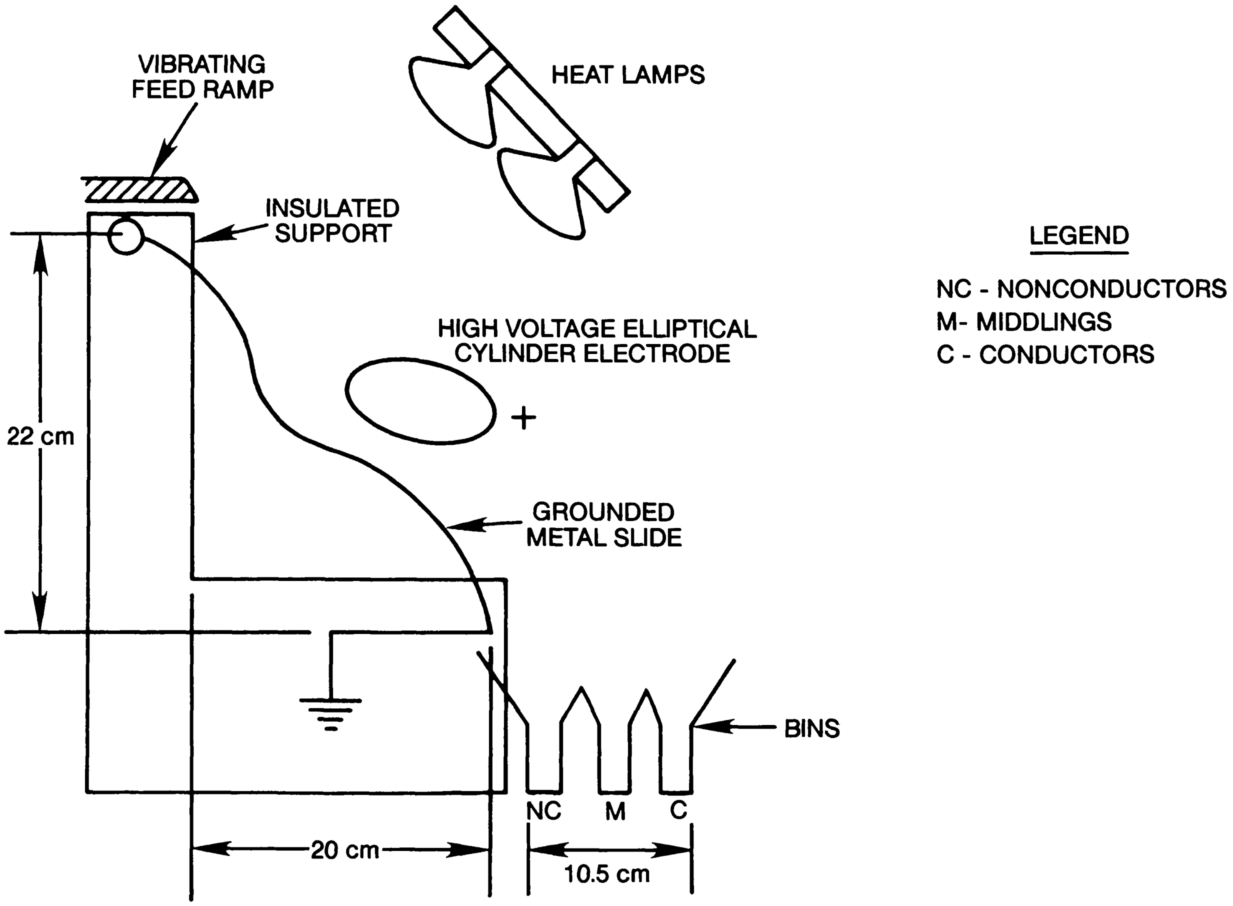

Figure 1. Mineral electrostatic separator: bench top slide configuration.

Maximum electric field strength was nominally +5 kV/cm DC but ranged between +2.5 and +7 kV/cm. Positive field electrode polarity was used throughout to make the ilmenite induced charge additive to the negative ilmenite contact charge on the aluminum slide (Agosto, 1984).

Four runs of ilmenite electrostatic concentration from simulants were made in air in a bench top apparatus (Fig. 1) where the feed hopper and slide were heated with infrared lamps. Separates were collected in three bins each 3.5 cm wide with bin 3 being the only conductor bin in the bench top setup. The feed size range was 0.15–0.25 mm.

Three other simulant runs in air and all simulant runs in N_2 and in vacuum were made in the slide configuration designed to fit the vacuum system (Figs. 2 and 3). The feed size range was 0.09–0.15 mm. The hopper and slide were resistance heated, and separates were collected in 7 bins each 2 cm wide. (The number of bins was increased to improve separates resolution for subsequent vacuum runs.) High concentrations of ilmenite reported to bins 2 through 7. Mean grade for all runs in air after one pass was 89±6 wt % (up from a mean ilmenite starting concentration of 8.8 wt %), and recovery was 51±9 wt %.

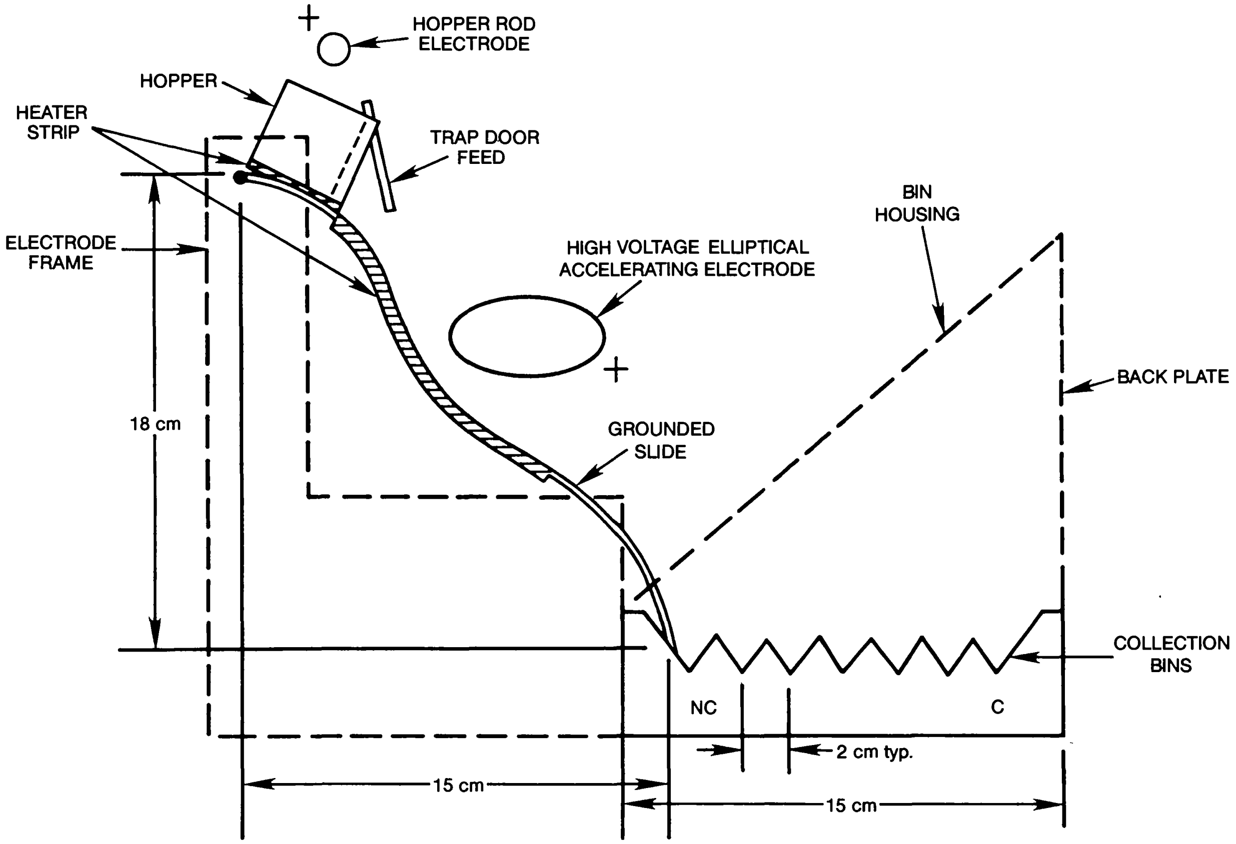

Figure 2. Mineral electrostatic separator: vacuum slide configuration.

For the nitrogen runs, the seven-bin collector was used in a glove box at a positive nitrogen pressure of about one torr. Ilmenite concentration data after one pass were collected in seven runs for four-component simulants in the 0.09-0.15 mm size range. High concentrations of ilmenite reported to bins 2 through 7. Mean grade after one pass was 90±7 wt % (up from 7.9 wt %), and recovery was 67±5 wt % for all runs in nitrogen.

For ilmenite electrostatic concentration in vacuum, the apparatus (Figs. 2 and 3) was scaled to fit a bell jar of approximately 70 liters volume. A trap door hopper was used instead of the the vibratory feed to reduce grain bounce and consequent random feed dispersal from the hopper mouth. Grain rebound is especially high in vacuum because both air resistance and sound energy radiation are greatly reduced (Fraas, 1970). A rod-shaped electrode was set above the hopper in an attempt to charge the feed sample by electrostatic induction prior to separation.

After exhausting the bell jar to 10^{-5} torr and heating the sample and slide to approximately 150°C, high voltage (15 kV) was applied to the hopper and the accelerating electrodes in parallel to obtain a field strength of approximately 3 kV/cm in the hopper for 10 minutes before separation. The trap door was then opened to drop the sample onto the slide and into the separating field of approximately 5 kV/cm. Material moved farther toward the back bins than in the air and nitrogen runs, and ilmenite concentrated

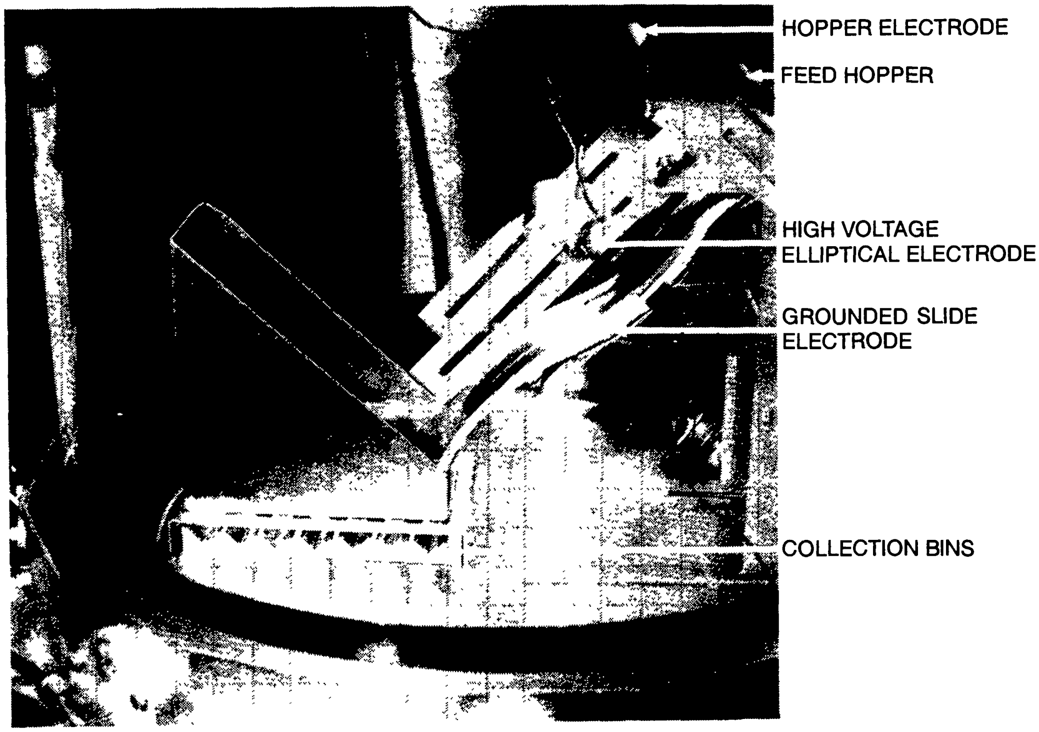

Figure 3. Mineral electrostatic separator slide configuration in vacuum bell jar.

in bins 5, 6, and 7. More material fell outside the bin system as well. Grades of twelve single-pass runs in vacuum were calculated from the cumulative ilmenite concentration in bins 5, 6, and 7. Two recoveries were calculated: R_1, which excludes material that fell outside the bins, and R_O, which includes that material. The mean ilmenite grade after one pass of all the vacuum runs was 78±7 wt % (up from 9.8 wt %); $R_1 = 56\pm8$ wt % and $R_O = 49\pm8$ wt %.

LUNAR ILMENITE ELECTROSTATIC CONCENTRATION

Table 1 lists lunar ilmenite grade and recovery data of four electrostatic concentration runs on a 0.09-0.15 mm sample of Apollo 11 soil 10084,853. Three of the runs were in dry nitrogen and one in vacuum. The lunar runs in nitrogen were made with the same apparatus and procedure as the simulant nitrogen runs. Similarly, the lunar vacuum run replicated the procedures of the simulant vacuum runs. Lunar ilmenite wt % was also calculated as in the simulant runs.

About 50 vol % of the sample were agglutinates before the first run, and the starting ilmenite content was about 10 wt %. The first nitrogen run in the table and the vacuum run were made without prior removal of agglutinates. However, before the other two nitrogen runs (#2 and #3), the ferromagnetic agglutinates were removed with a permanent magnet of approximately 1500 gauss. The ferromagnetic agglutinates comprised approximately 75 vol % of total sample agglutinates by microscopic count.

Table 1. Lunar Soil Ilmenite Electrostatic Concentration (One Pass)

Apollo 11 Soil Sample 10084, 853
(grain size: 0.09–0.15 mm; sample charging time: 10 min.)

Run Number	Ambient	Starting Ilmenite Concentration (weight percent)	Sample Feed Temperature (°C)	Maximum Electrostatic Field Strength (kV/cm)	Ilmenite Grade (weight percent)	Ilmenite Recovery (weight percent)	Conductor Bins
1	Dry nitrogen	10	173	4.7	45	24	2-7
2a*	Dry nitrogen	7.3	—	3.0	51	48	2-7
2b†	Dry nitrogen	7.3	—	3.0	66	50	2-7
3a	Dry nitrogen	7.3	193	5.0	51	35	2-7
3b	Dry nitrogen	7.3	193	5.0	62	36	2-7
4a	Vacuum 1.5×10^{-5} torr	7.0	154	5.0	29	55	6,7,Tr**
4b	1.5×10^{-5} torr	70	154	5.0	37	60	6,7,Tr

* a excludes ilmenite bearing glass and polyphase components.
† b includes ilmenite bearing glass and polyphase components.
** Tr is the catch tray beyond the 7th bin.

Tables 2 and 3 give lunar soil component distributions among the seven collection bins after one pass of electrostatic concentration for the first nitrogen run (#1) and the vacuum run (#4), respectively, with all agglutinates present in both cases. Components microscopically discriminated and confirmed by SEM-EDS analysis were: agglutinate, anorthite, glass, ilmenite, polyphase, and olivine/pyroxene. Olivine and pyroxene counts were lumped together. The polyphase component consisted of lithic fragments that were about half ilmenite, and about half the dark glass grains had ilmenite compositions. The

Table 2. Lunar Soil Ilmenite Electrostatic Concentration in Dry Nitrogen

Soil Component Distribution After One Pass (Run #1, Table 1)

Site	Weight/ Site (mg)	Aggl	An	Glass	Il	Poly	Px/Ol	Ot	Wt% Il	Wt Il (mg)
		(Modal Percent)								
Bin #1	61.2	31	11	11	5	18	22	1	7.3	4.5
2	2.4	11	1	14	24	30	17	3	32	0.8
3	1.1	11	-	9	40	27	14	-	50	0.6
4	0.4	-	-	-	82	14	4	-	87	0.3
5	<0.1	8	-	-	75	17	-	-	81	0.1
6	<0.1	-	-	-	100	-	-	-	100	
7	<0.1	-	-	-	100	-	-	-	100	
S+H+E	11.6	55	9	6	8	10	11	1	11	1.3
Tr	1.0	58	2	3	6	17	13	-	8.7	0.1
Total	77.7									7.7

Aggl-agglutinate; An—anorthite; E—field electrode; H—feed hopper; Il—ilmenite; Ot—other, Two of these grains were metal spherules; Poly—polyphase; Px/Ol—pyroxene/olivine, combined counts; S—grounded slide; Tr—catch tray under bins

Table 3. Lunar Soil Electrostatic Concentration in Vacuum (1.5×10^{-5} torr)

		Soil Component Distribution After One Pass (Run #4, Table 1)							
Site	Weight/ Site (mg)	Aggl	An	Glass	Il	Poly	Px/Ol	Wt% Il	Wt Il (mg)
		(Modal Percent)							
Bin #1	16.6	75	4	3	3	6	8	4.4	0.7
2	26.8	71	4	3	2	2	17	3.0	0.8
3	8.0	60	4	4	2	4	26	3.0	0.2
4	3.3	56	6	4	5	3	26	7.3	0.2
5	1.8	58	7	3	10	6	16	14.3	0.3
6	1.9	45	4	3	18	13	17	25.0	0.5
7	3.5	35	4	2	20	15	25	27.0	0.9
S+H+E	0.4	46	26	1	3	1	19	4.4	-
Tr	3.6	33	5	1	25	7	29	33.0	1.2
Total	65.9								4.8

Aggl-agglutinate; An—anorthite; E—field electrode; H—feed hopper; Il—ilmenite; Poly—polyphase; Px/Ol—pyroxene/olivine, combined counts; S—grounded slide; Tr—catch tray under bins

discrepancy in glass, polyphase, and agglutinate counts between Tables 2 and 3 resulted from a confusion among those components when counting run #1.

In the first nitrogen run, with all the agglutinates present, approximately 12 wt % of the sample coated the field electrode and about 3 wt % clung to the slide and hopper that together comprise the electrical ground. By contrast, in a vacuum run that also contained all the agglutinates, only 0.5 wt % of the sample clung to the slide, hopper, and field electrode combined. In both cases, half this material was agglutinates. Nitrogen ion and electron charging of the agglutinate-rich sample of the first run probably account for the differences.

Lunar ilmenite behaved like a semi-conductor in all the runs. Although it reached 100% concentration in bins 6 and 7 of the first nitrogen run (Table 2) and 80 and 90 wt % in the other nitrogen runs, only a few grains (<1 wt % of the sample) appeared there. In the vacuum run, by contrast, about 14 wt % of the sample reported to bins 6 & 7 and beyond (into the catch tray) but only at a combined ilmenite grade of 29 wt % (up from 7 wt %). Recovery for the vacuum run was 55 wt % (Tables 1 and 3). Mean ilmenite grades and recoveries were not calculated for the lunar sample runs because of the small number of runs and their differing conditions. However, the identical grade (51 wt %) for runs #2a and #3a under the same conditions suggests reproducibility. Adjusted grades and recoveries that include half the glass and polyphase fractions in the conductor bins to reflect their ilmenite contributions are also reported for runs 2, 3, and 4 in Table 1. After adjustment, the grade of the vacuum run increases from 29-37 wt %, and runs #2 and #3 in nitrogen increase from 51 wt % to the mid 60s. The calculation was not done for run #1 because of uncertainty in the glass and polyphase counts.

Agglutinates behaved like non-conductors in all the lunar runs regardless of whether or not the ferromagnetic agglutinates were removed. Over 90% of sample agglutinates reported to the non-conductor bin or bins and the electrodes combined, and about 5% were spread over the remaining bins (Tables 2 and 3).

DISCUSSION

Significant one-pass concentrations of ilmenite were obtained in all the runs from the average eleven-fold increase for the simulant runs in nitrogen (7.9–90 wt %) to a four-fold increase in the lunar soil run in vacuum (7.0–29 wt %). Grades in nitrogen and air were significantly better than in vacuum probably for the following reasons:

1. Gas ionization products contributed to feed charging in air and nitrogen.

2. The absence of vibratory sample feed in vacuum may have reduced the efficiency of mineral contact and induction charging compared with the atmospheric runs.

3. Partial density segregation of ilmenite occurred as the feed fell in gas at atmospheric pressure.

4. Feed transit time in the separating field was greater in air and nitrogen than in vacuum because of air resistance.

5. The ilmenite concentration in the seventh bin of the vacuum runs was reduced due to two effects.

    a. The horizontal component of acceleration imparted to feed grains by the slide (see Fig. 4) transported a few percent of the feed to the far bins in vacuum at zero electric field and led to a dilution of ilmenite separates reporting to the conductor bins with the field on. By contrast, none of the feed was transported mechanically to the far bins in air or in nitrogen at zero field.

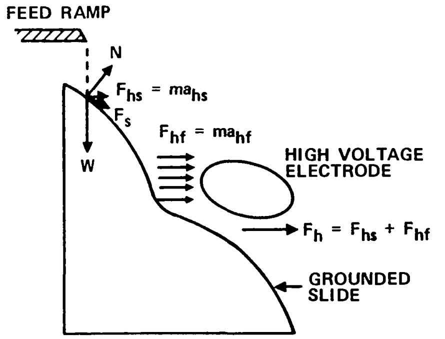

Figure 4. Force diagram of mineral grain on slide.

LEGEND

a_{hf} – HORIZONTAL COMPONENT OF GRAIN ACCELERATION DUE TO ELECTRIC FIELD
a_{hs} – HORIZONTAL COMPONENT OF GRAIN ACCELERATION DUE TO SLIDE
F_h – HORIZONTAL FORCE ON GRAIN
F_{hf} – HORIZONTAL FORCE ON GRAIN DUE TO ELECTRIC FIELD
F_{hs} – HORIZONTAL FORCE ON GRAIN DUE TO SLIDE
F_s – FORCE ON GRAIN PARALLEL TO SLIDE
m – MASS OF GRAIN
N – FORCE ON GRAIN PERPENDICULAR TO SLIDE
W – WEIGHT OF GRAIN

b. A back plate behind the seventh bin, for containment of material within the bin system (see Fig. 2), tended to deflect material striking it toward the seventh bin. As a consequence, more material was collected in the seventh than the fifth and sixth bins in the vacuum runs. That also may have contributed to dilution of the ilmenite concentrate and suggests that a more extended bin system might result in better grades on the slide apparatus in vacuum.

Recovery in the vacuum lunar soil run was higher than in the lunar sample runs in nitrogen and is in part due to the larger sample fraction that reached the conductor bins in vacuum. In the simulant runs, higher recoveries also tended to be associated with lower grades. Mean bin recovery (R_1) of the simulant runs in vacuum lies between the recoveries in air and nitrogen and probably reflects performance variability due to grain bounce within and outside the bin system in vacuum.

CONCLUSIONS

Significant concentrations of lunar soil ilmenite from 7.3–51 wt % have been obtained in one pass of an Apollo 11 soil sample through a slide-type electrostatic separator in nitrogen after the ferromagnetic agglutinates had been removed with a permanent magnet. Ilmenite was concentrated in the same sample and in a similar apparatus (Figs. 2 and 4) from 7.0–29 wt % after one pass in vacuum with all the agglutinates present. Lunar soil ilmenite recovery was 55 wt % in the vacuum run and lower in nitrogen (ranging from 24–48 wt % in three separate runs).

It should be emphasized that the lower limit of the grain sizes tested in this study was 0.09 mm. Mineral electrostatic separation of fines in vacuum has not yet been investigated, presumably because there has been no terrestrial commercial application. However, Carta *et al.* (1964) reported improved one-pass grades and recoveries of a graphite ore (7.7% carbon) concentrated in air at reduced pressure (120 torr) compared with concentration at one atmosphere in two commercial drum electrostatic separators. Grades and recoveries were doubled in some cases even for grain size ranges less than 0.075 mm. Carta *et al.* attributed the improvement to several factors: (1) enhanced ionization charging of the feed due to enhanced corona current at the lower gas pressure, (2) improved contact of feed and grounded electrode (the drum), (3) increased uniformity of grain trajectories in all size ranges, and (4) reduced agglomeration of fines and dusting of the coarser grains with fines. Factors 2 through 4 are likely to be even more enhanced in vacuum. For that reason, mineral electrostatic separation of fines in vacuum is an important follow-up investigation to this study, especially for lunar field applications.

Electrostatic separators offer the advantages of low power consumption and mass and efficient high voltage generation in a vacuum environment such as the lunar surface. However, existing separator designs are intended for atmospheric operation and take advantage, either by design or by accident, of atmospheric effects that enhance separation performance for grain sizes >0.1 mm such as (1) mineral feed charging by air ionization in the separating field, (2) partial density segregation of mineral grains falling through air in the feed path of the separator, or (3) increased feed transit time in the separating field due to air resistance. Existing designs with minor modifications would probably work very well in a gas environment established on the Moon, but major modifications are required for efficient vacuum operation.

Multistage electrostatic separation systems like those used in all commercial electrostatic mineral concentrators should raise grades and recoveries to 90%+ levels (*e.g.*, Kelly and Spottiswood, 1982), provided the soil ilmenite is sufficiently liberated. Even without additional liberation, lunar soil ilmenite grades in the size range tested could reach the high 70s because combined glass and polyphase soil components that reported along with ilmenite to the conductor bins and beyond were comparable to ilmenite in abundance (Table 3) and are about half ilmenite in composition. Agglutinates are the major component of ilmenite bearing mare soils (Papike *et al.*, 1982), and their divergent electrical behavior to ilmenite is an indication that the two components are separable electrostatically. This work suggests that the best sequence for concentrating lunar soil ilmenite would be magnetic extraction of the ferromagnetic agglutinates followed by electrostatic concentration of ilmenite in the non-ferromagnetic soil fraction.

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IN-SITU ROCK MELTING APPLIED TO LUNAR BASE CONSTRUCTION AND FOR EXPLORATION DRILLING AND CORING ON THE MOON

John C. Rowley[1] and Joseph W. Neudecker[2]

Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545
[1]Geology and Geochemistry Group, Earth and Space Sciences Division, MS D462
[2]Analysis and Testing Group, Design Engineering Division, MS C931

An excavation technology based upon melting of rock and soil has been extensively developed at the prototype hardware and conceptual design levels for terrestrial conditions. Laboratory and field tests of rock melting penetration have conclusively indicated that this excavation method is insensitive to rock soil types, and conditions. Especially significant is the ability to form in-place glass linings or casings on the walls of boreholes, tunnels, and shafts. These factors indicate the unique potential for *in situ* construction of primary lunar base facilities. Drilling and coring equipment for resource exploration on the Moon can also be devised that is largely automated and remotely operated. It is also very likely that lunar melt glasses will have changed mechanical properties when formed in anhydrous and hard vacuum conditions. Rock melting experiments and prototype hardware designs for lunar rock melting excavation applications are suggested.

INTRODUCTION

The Los Alamos National Laboratory conducted a research and development project in excavation technology from 1960 to 1976 (Armstrong *et al.*, 1962; Hanold, 1973b, 1977; Smith, 1971). The project subsequently developed the potential advantages of a rock and soil melting excavation process for lunar applications (Rowley and Neudecker, 1980). Field and laboratory demonstrations of prototype rock and soil melting penetrator systems under terrestrial conditions have illustrated the unique features of this technology that may have application to lunar base facilities construction and exploration drilling and coring on the Moon. These basic features are detailed here. (1) The melting method is relatively insensitive to rock or soil types or conditions; (2) the technique can be automated for remote and untended operation; (3) the melting penetrators create a formed-in-place rock-glass structural lining (casing) for boreholes, tunnels, or shafts; (4) selective formation of debris (or "cuttings") as glass wool or glass pellets is possible; and (5) electrical energy is used for resistive heaters for the melting penetrators, although direct heating by nuclear power is possible for larger equipment. These results were obtained with soil and rock samples at terrestrial ambient conditions of moisture and partial pressures of oxygen.

It is anticipated that vacuum conditions and essentially zero moisture content of the lunar soils and rocks should have significantly reduced thermal diffusivity relative to terrestrial counterparts. Therefore, reduced heat losses could be expected for lunar applications. The absence of moisture and oxygen should reduce the corrosion rate of the refractory metal penetrators. The most important parameter in the rock and soil penetration process of excavation is the viscosity of the soils and rocks. This property for lunar soils and basalts, as reported in the literature (MacKenzie and Claridge, 1980), appears to be within the same range as terrestrial materials of roughly the same composition. In any event, tests and experiments at vacuum condition could be performed in order to extend and optimize the penetrator designs perfected in the previous Los Alamos work to lunar soils and rocks.

This paper summarizes the results of the previous Los Alamos research and development project with emphasis on those concepts: laboratory test hardware, field tests, and equipment designs as related to lunar uses. After recording what is known, the discussion turns to concepts and hardware that might be used for lunar base facility excavation and construction, especially primary structures. In addition, the potential for borehole and shaft "drilling" applications and for exploration core holes on the Moon is reviewed.

The final section deals with suggested research and development activities that could extend and optimize the rock and soil melting technology and hardware to lunar conditions. As indicated, these efforts would focus on a few basic experiments to determine lunar rock and soil melt properties at hard vacuum and anhydrous conditions; an effort to develop preliminary equipment design for projected needed lunar construction and drilling tasks; and most importantly, a study performed to evaluate the structural properties of lunar glasses (LG). In this latter area, we would like to strongly support the ideas of Blacic (1985) that suggest the LG may have very desirable structural properties. This prospect should be especially pursued because the advantages of formed-in-place linings or casings could be enhanced considerably.

The original work at Los Alamos termed the terrestrial excavation devices for soil and rock melting "the Subterrene." Perhaps for lunar applications a more appropriate term would be "Subselene."

PREVIOUS RESULTS

In the course of the previous Los Alamos subterrene research and development project, many different terrestrial soil and rock samples were melted under laboratory conditions to assess the performance of rock melting penetrator designs. Tables 1–3 illustrate the range of samples investigated, melting behavior, crush strengths, and two basalt compositions. The compositions of the two basalts recorded in Table 3 are especially relevant because of the close similarity to those cited by Blacic (1985) as the "average" for the lunar regolith. Boreholes were melted in an extremely wide variety of samples, both wet and dry: soils, sands, clays, shales, gravels, tuffs, basalts, and granites (Table 1). In all these experiments the melting penetrators formed competent glass walls on the borehole wall (Fig. 1a) or a separable, free-standing glass structure (Fig. 1b).

In the course of the research project several detailed evaluations were made of formed-in-place glass linings. One example is the Bandelier tuff rock-melt glass (Roedder, 1980)

Table 1. Typical Rock Melting Behavior

Material	Melting Temperatures, K Start	Complete	Remarks
Bandelier Tuff	—	1750	Melt viscosity increased as quartz crystals were consumed.
Jemez basalt-1*	—	1570	Melts uniformly with some gas evolution.
Jemez basalt-2†	—	1510	
Dresser basalt	—	1570	
Charcoal granite**	—	1670	Dark phase melted first and then proceeded to consume the matrix.
Westerly granite	—	1760	
Sioux quartzite	—	1760	
Tennessee pink marble	—	—	Heated to 2270 K without melting; some decomposition.
Shale, Santa Fe County, New Mexico	1470	1560	Discrete phase melting accompanied by gas evolution. Viscosity increased as more material melted.
Caliche, Santa Fe County, New Mexico	1570	1850	
Green River Shale, Cuba, New Mexico	1550	1600	
Concrete	1620	1700	Localized melting. Less gas evolution than from shales or caliche.

†Started with rock fragments—1 to 3 mm

*Started with powder <1 mm

**Also called St. Cloud gray granodiorite

Table 2. Typical Crush Strength of Rocks and Rock Glasses

Item	Material	Average Crush Strength, MPa	Number of Specimens
1	Jemez basalt	44	10
2	Jemez basalt-glass*	108	4
3	Bandelier tuff	2.8	3
4	Bandelier tuff-glass from 51-mm-diam-hole wall		
	Axial	55	5
	Tangential	36	2
5	Bandelier tuff-glass from 114-mm-diam-hole wall		
	Axial (2.3 Mg/m^3)	126	4
	Axial (2.2 Mg/m^3)	110	3
	Radial (2.3 Mg/m^3)	115	3
	Tangential (2.3 Mg/m^3)	132	3

*Uniform glass prepared by Corning Glass Works

Table 3. Typical Chemical Compositions of Rocks and Rock Glasses

Constituents	Composition, wt %			
	Dresser Basalt	Dresser Basalt-Glass	Jemez Basalt	Jemez Basalt-Glass
SiO_2	48.2	49.52	50.01	50.09
Al_2O_3	16.13	15.54	16.82	16.81
Fe_2O_3	7.65	8.19	2.83	4.38
FeO	5.41	4.68	7.60	6.53
MgO	6.25	6.50	6.70	6.69
CaO	8.69	10.05	9.62	9.68
Na_2O	2.54	2.47	3.94	3.40
K_2O	0.96	0.97	0.97	0.94
H_2O	0.38	0.004	0.14	0.003
TiO_2	1.45	1.66	1.38	1.46
P_2O_5	0.16	—	—	—
CO_2	0.048	0.003	0.02	0.003
B_2O_3	—	—	—	—
MnO	—	0.18	0.15	0.15

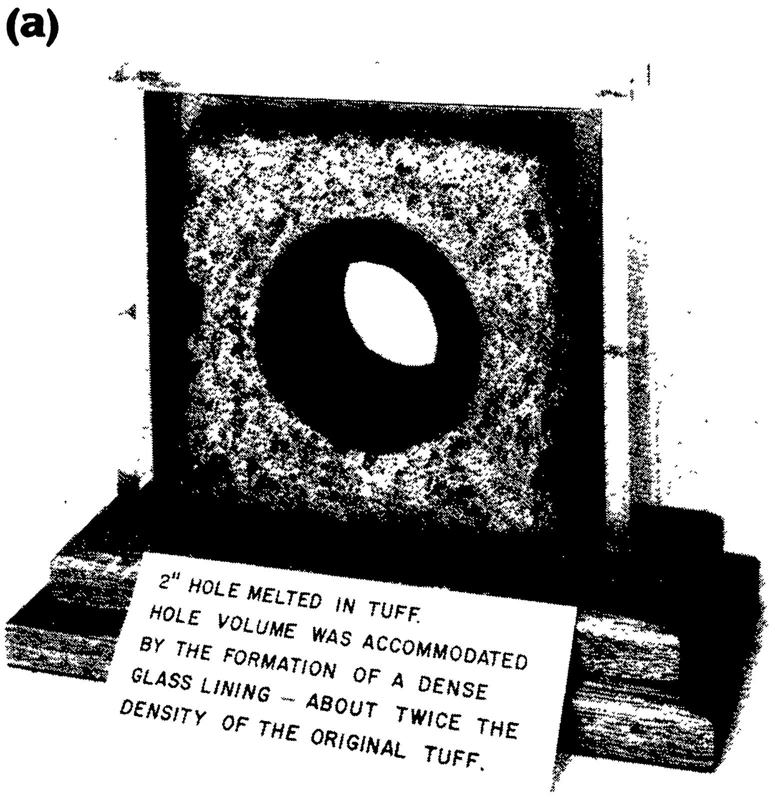


Figure 1. Typical glass-lined holes: (a) Cross section of glass-lined hole (51-mm-diameter) melted in tuff rock; (b) Exterior view of glass-lined hole melted in loose soil and rock.

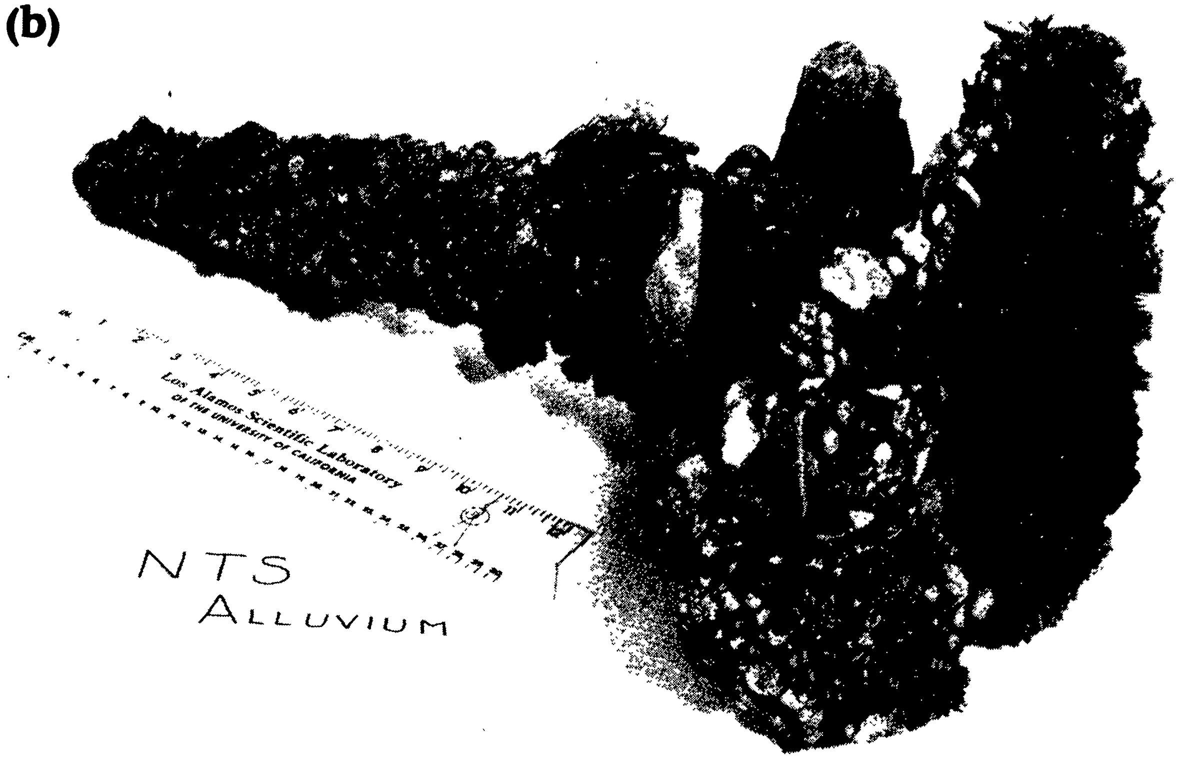


Figure 1. Typical glass-lined holes: (a) Cross section of glass-lined hole (51-mm-diameter) melted in tuff rock; (b) Exterior view of glass-lined hole melted in loose soil and rock.

where the properties of the glass-lining material were glass as summarized in Table 4. The study concludes that "the glass-lined hole formed by the penetrator is much more competent than an unlined hole and presents the possibility of engineering applications." The tuff-derived glass structures are somewhat less homogeneous than the glassy, basaltic melt glasses. Several reports on rock-melts, glass linings, and subterrene structures and the formation process were prepared by Nelson *et al.* (1975) and Krupka (1973, 1974).

The most basic conclusions reached from the laboratory research efforts were these. (1) Formed-in-place glass linings could be practically formed through proper handling, forming, and thermal processing (chilling) of the soil and rock melts (Lundberg, 1975; Stanton, 1974), and because these methods applied to all soils and rocks tested, a single penetrator design could be effectively used for virtually all natural terrestrial materials. (2) The melting process is quite insensitive to rapid variations in rock or soil types, void space, water content, or competence of the rocks or soils, and it is especially effective in consolidating "mixed ground" (*i.e.*, gravels or soils with rocks and cobbles). (3) A very uniform and precisely dimensioned borehole could be produced. (4) A high-temperature electric heater technology was perfected that used efficient low-voltage direct current resistance heaters (Armstrong, 1974; Krupka, 1972; Stark and Krupka, 1973). (5) Heat losses to the surrounding rocks or soils were low and predictable (Murphy and Gido, 1973; Cort, 1973; McFarland, 1974). (6) Low mass loss from the refractory metal penetrator

Table 4. Properties of Tuff and Tuff-Glass

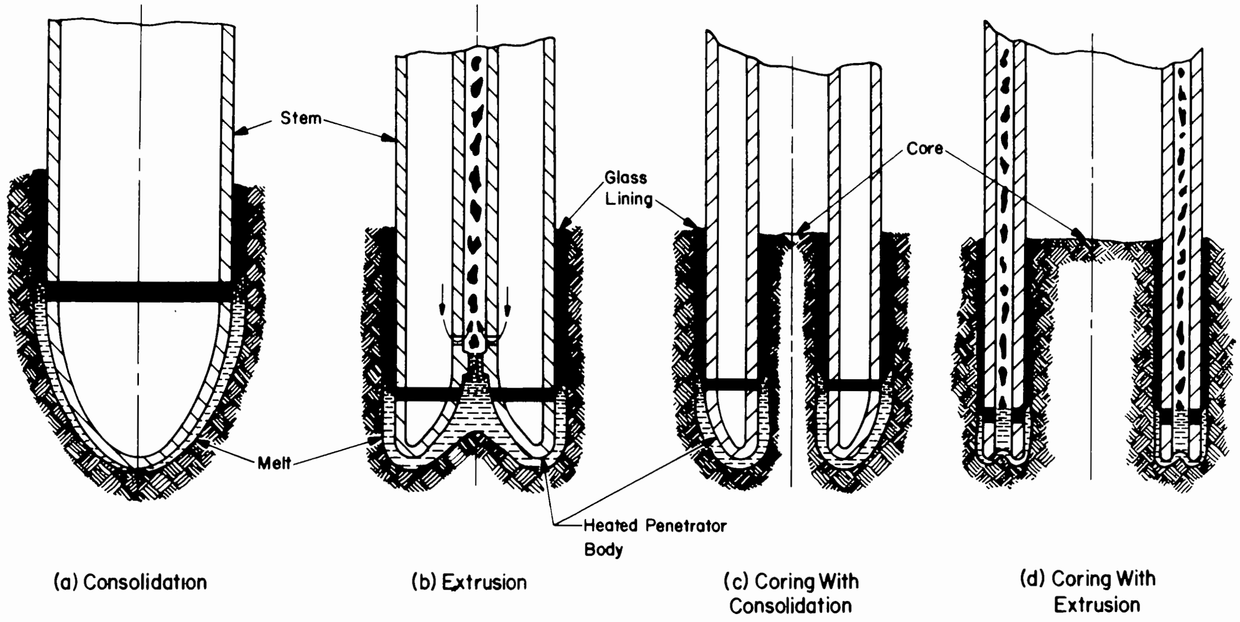
Property	Tuff*	Tuff Glass†
Density (Mg/m^3)	1.40	2.23
Grain Density (Mg/m^3)	2.54	2.40
Permeability (md)		
(a) No Confining Pressure	>100	2 to 5
(b) 50 MPa Confining pressure	—	0.1 to 0.3
Compressive Strength (MPa)	~4	~50
Moduli Average		
(a) No Confining Pressure		
E (GPa)	—	7
υ	—	0.3
G (GPa)	—	2.6
(b) 50 MPa Confining Pressure		
E (GPa)	—	55
υ	—	0.2
G (GPa)	—	7.0
Tensile Strength (MPa)	~1	~1

*A soft, friable, highly porous (41–45%) material.
†Grain size ~2 mm.

would lead to long equipment life (Stark and Krupka, 1975). Lastly, (7) materials, design methods, fabrication techniques, and analytical procedures were available to systematically construct and predict penetrator performance that scaled with size.

The subterrene project included a wide range of penetrator configurations (Fig. 2). The depicted shapes include nearly all concepts of hole making by melting. Figure 2a illustrates a "consolidating" penetrator (Neudecker, 1973) used in higher porosity materials; all the rock melted during formation of the hole will be densified, forming the glass lining. No debris removal is required. An alternate configuration for a melting penetrator, shown in Fig. 2b, is termed an "extruder" (Neudecker *et al.*, 1973). Pass-through port(s) allow the melt to flow back through the penetrator head into a device that chills the melt and forms "debris" (or "cuttings" or "muck," depending upon whether drilling or tunneling are considered). These solids can easily be formed as glass pellets, rods, or a glass wool-like material (Fig. 3). The core-consolidating mode of operation is shown in Fig. 2c, and cores with a glass encasement are possible (Murphy *et al.*, 1976). The final configuraton in Fig. 2d was not fabricated, but the knowledge and methods are all in hand to design and construct a kerf melting, coring extruding penetrator. This configuration might be the conceptual design for a large size tunneler. The cross section of the hole (tunnel) could be any (non-circular) geometry.

The project also developed and prepared the analytical tools (Lawton, 1974a,b) needed to perform design analyses and trade studies of the several excavation processes, *i.e.*, drilling and tunneling. These computer methods can be directly used to design soil and rock melting penetrators for lunar base application and exploring the Moon's subsurface structure and resources.



(a) Consolidation (b) Extrusion (c) Coring With Consolidation (d) Coring With Extrusion

Figure 2. Schematic cross sections of different rock melting penetrators. (a) Consolidation of porous rock and soils, no debris produced. (b) Extruding of glass fiber or pellets to remove material in more dense materials. (c) A coring-consolidating configuration with glass-lined hole and core. (d) An extruding-coring combination mode of hole formation.

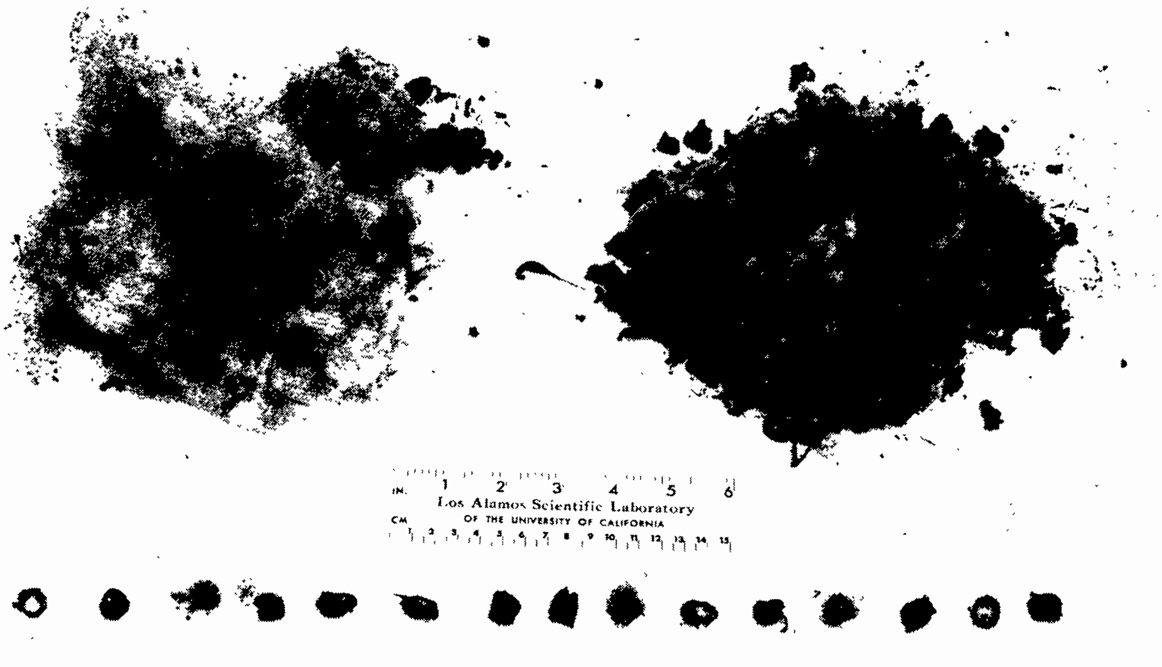


Figure 3. Typical debris or cuttings formed by extruder-type rock melting penetrators, glass pellets, and wool.

POTENTIAL APPLICATIONS ON THE MOON

It would be a straightforward process to develop design concepts and system designs for rock and soil melting in the lunar environment. Sensitivity, trade-off, and cost analyses can be performed as they were for geothermal well drilling (Altseimer, 1976) and tunneling equipment and operations, based on melting as the hole-making technology. The principal thrust would be to design glass-lined or stabilized openings, *i.e.*, to make structures or boreholes with in-place LG structural linings or casings. This would reduce the dependence on materials transported to or refined and fabricated on the Moon. To illustrate these concepts, two areas of excavation technology are outlined here: construction of subsurface primary structures, *i.e.*, tunnels or rooms, and drilling and coring.

The requirements for fairly deep burial as solar flare protection indicate that a tunneling procedure, in contrast to trenching and back-covering, may be more efficient. If the primary structural member of the tunnel walls can be formed-in-place LG, then a significant further advantage is achieved. If the LG surface can be sealed by continuous, direct vapor sputtering with a coating of metal (perhaps iron), then an airtight (or low leak rate) barrier may also be formed.

Figure 4 is a tunneler design (Hanold, 1973a; Altseimer, 1973) for loose soils or unconsolidated ground, and this design could be used on the Moon to produce such glass-lined tunnels in the regolith. The power source could be electric cables or a self-contained nuclear reactor. Such equipment will have only a few moving parts, chiefly

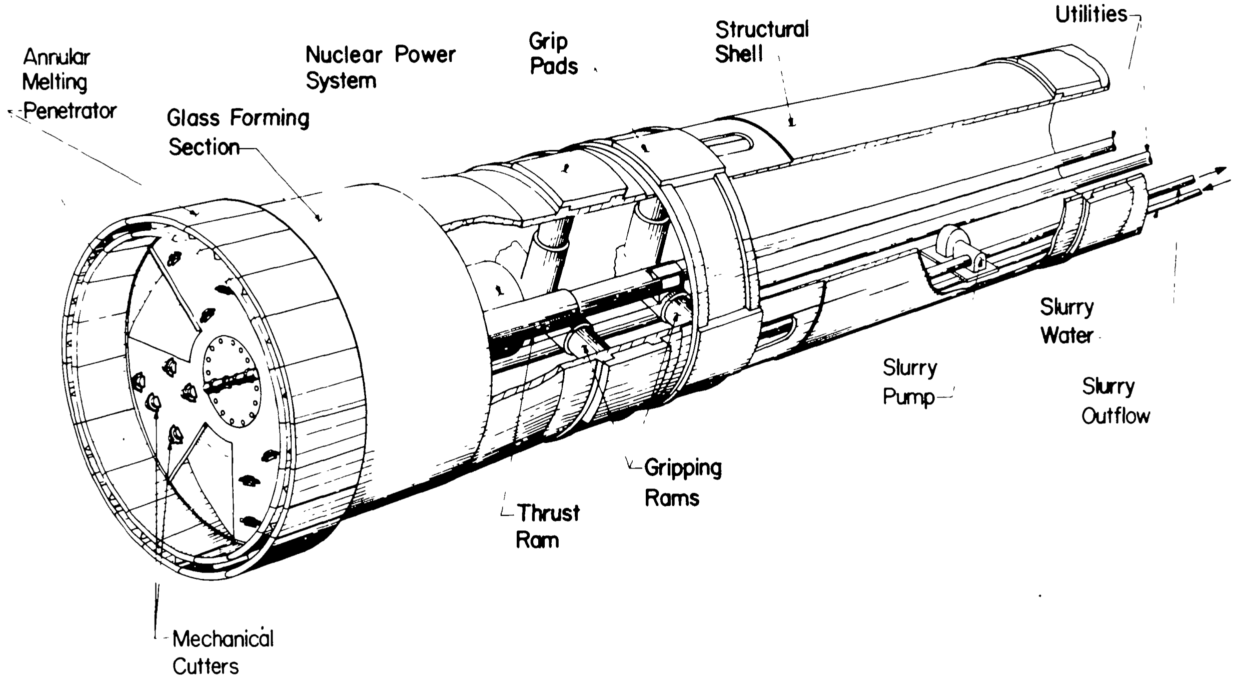


Figure 4. Large tunneler conceptual design for lunar base subsurface facilities construction. Glass lining is formed in place in the lunar regolith.

in the muck-handling system. Bulkheads of LG and LG fiber composites would provide extensive spaces for habitation, fabrication facilities, storage, and laboratories. A second concept for surface construction is illustrated in Fig. 5. A mound of regolith is prepared, and then a supporting LG "roof" is formed with a portable subselene system (shown schematically). The interior would then be excavated to form a room for use as a warehouse, vehicle storage, or large equipment housing, *etc.* The roof shape would be designed to support the overburden loads as well as side and edge reactions. A prototype of such a structure was built in the fashion described (Fig. 6), and though crude in appearance, it is quite adequate to support the overburden loading. Other applications are sketched in Fig. 5, such as horizontal holes (Sims, 1973) for utility installation.

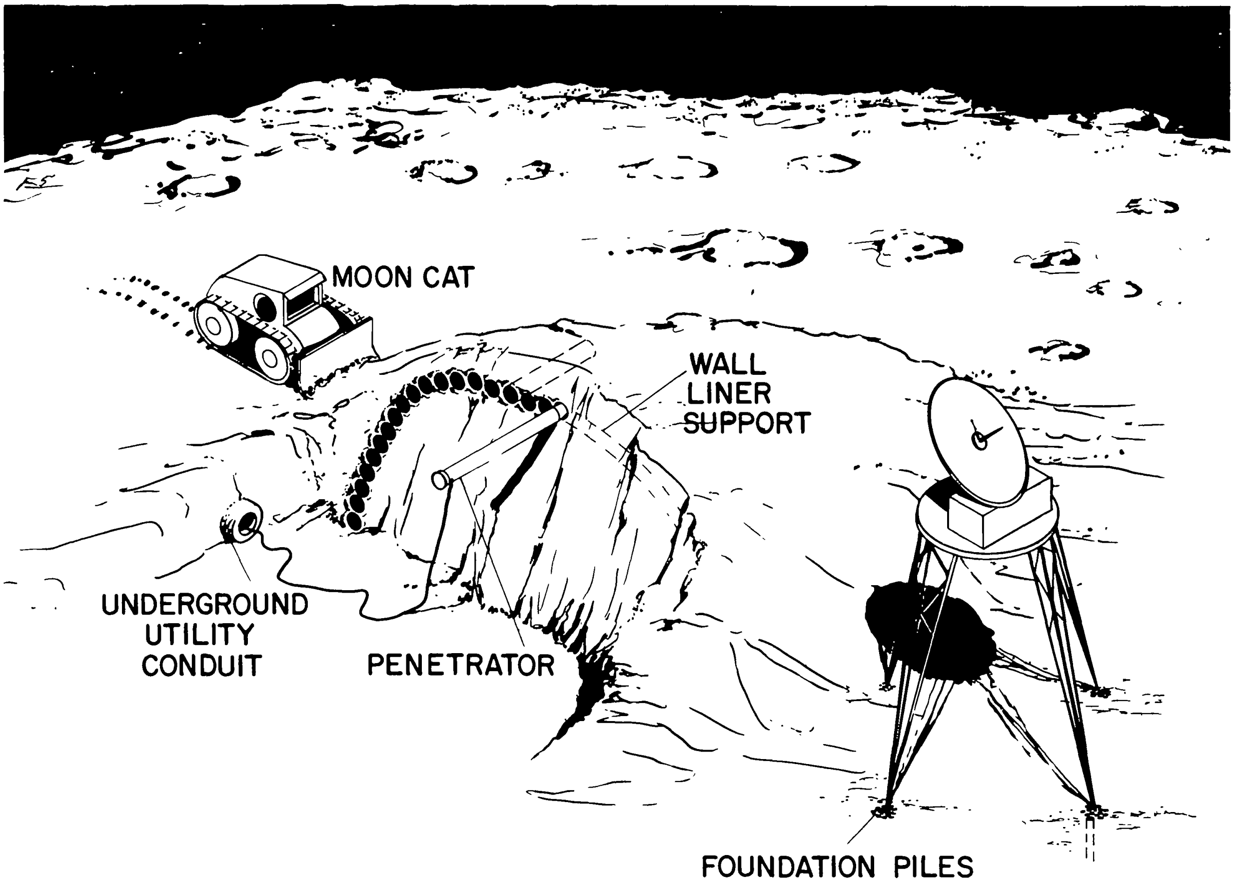


Figure 5. Conceptual sketches of possible applications of rock and soil melting for lunar base facility construction using melted-in-place glass lining.

A second area of application of lunar rock and soil melting is drilling equipment that could be adapted for lunar conditions, such as borehole or shaft drilling and coring applied to exploration (Fig. 7). It appears that vertical-hole-melting systems could be readily designed for use on the Moon, and the potential exists for essentially self-contained, remotely operated drill rig equipment (Altseimer, 1973). These possibilities result from

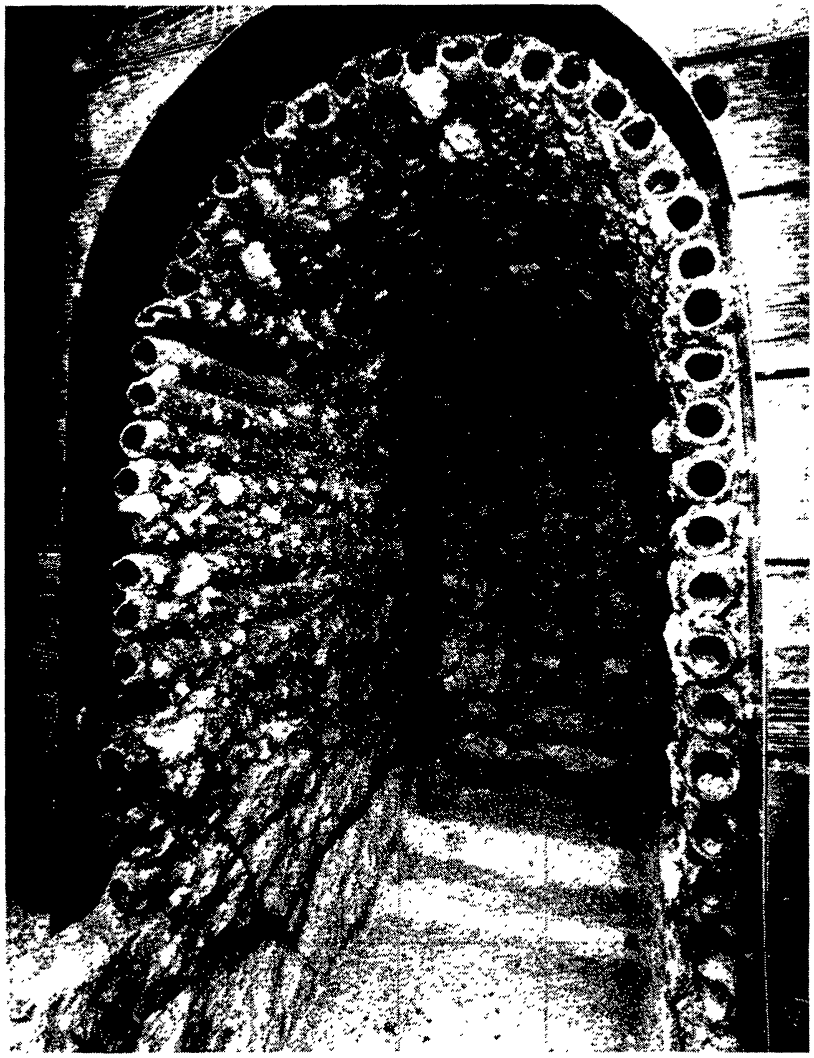


Figure 6. Photograph of prototype melted-in-place structure. Dimensions are 2 by 1 m at the opening, and 2 m deep. Interior rock and soil excavated after melting construction of arch and walls.

the automation potential of the melting methods and insensibility to subsurface conditions. An additional, inherent problem will be closed debris handling and separation systems.

A horizontal coring tool (Neudecker, 1974), termed a "geoprospector," has been devised for use on Earth. It is a mini-tunneler that is self-propelled, is remotely guided, and produces a continuous core. Such a device might be useful to explore along a proposed tunnel route.

RESEARCH ISSUES

Most of the basic concepts and methods to design subselene systems are available. However, a few areas of investigation are recommended if such equipment is to be developed. The tasks are primarily activities needed to extend or optimize the results available for terrestrial conditions to lunar environments. The recommended activities are as follows:

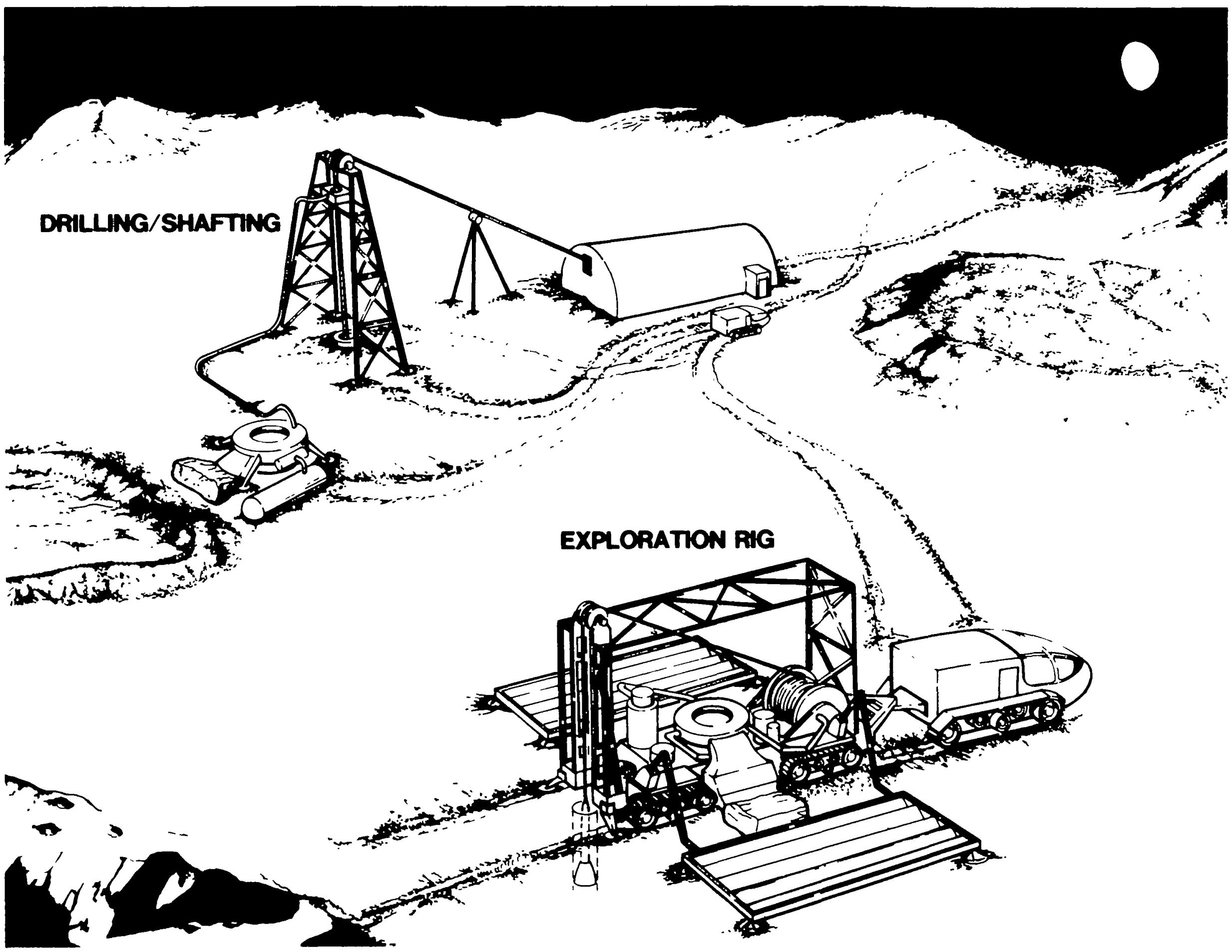


Figure 7. Conceptual sketch of automatic, remotely operated drilling/coring and shafting equipment for exploration of the Moon.

(a) Measure lunar rock and soil melt properties such as viscosity, conductivity, and melting data for hard vacuum and anhydrous conditions simulating lunar conditions.

(b) Determine corrosion rates of penetrator material in lunar conditions by testing refractory metals in lunar rock melts under hard vacuum and very low moisture contents.

(c) Conduct conceptual prototype design, sensitivity, operation, and cost studies of lunar subselene hardware and equipment for both construction and drilling/coring functions.

(d) Produce subcomponents for the most promising reference designs and conduct laboratory and field tests. Automation and remote operation schemes should be explored.

(e) Create designs for debris-handling systems for drilling and coring applications; the approach should provide for a closed circulation of debris-handling fluids and a loss-free debris/fluid separator.

Power source designs and requirements would be an important element in such studies.

In addition, the very important aspect (outlined by Blacic, 1985) of determining the potential for very high strength LG should be investigated. The potential exists for obtaining even more efficient structures from melted-in-place lunar base structures and casings for boreholes or core holes.

SUMMARY

A major advancement in excavation technology that already exists appears to be ideally suited to lunar base facility construction chores for primary structures. Rock and soil melting technology is simple, and the basic hole-making process has no subsurface moving parts. A lunar glass structural lining or support can be formed in the melt chilling process. Tunneling machines based upon soil melting technology have been designed and could be extended and adapted to lunar use with modest effort. Another promising area of application is drilling, coring, and shafting. Here the benefits of remote and automated operations are potentially available. These uses will require some further development of debris-handling techniques and closed fluid and cooling systems.

The potential for direct use of glass derived from lunar materials for primary structures, linings, casings, and the like would reduce Earth-lift mass requirements, should reduce import costs from Earth significantly, and should require much less commitment and use of lunar-based structural materials refinement and fabrication facilities.

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MICROWAVE PROCESSING OF LUNAR MATERIALS: POTENTIAL APPLICATIONS

Thomas T. Meek[1], David T. Vaniman[2], Franklin H. Cocks[3], Robin A. Wright[4]

[1] Materials Science and Technology Division, Los Alamos National Laboratory,
Los Alamos, NM 87545
[2] Earth and Space Science Division, Los Alamos National Laboratory, Los Alamos, NM 87545
[3] Department of Mechanical Engineering and Materials Science, Duke University,
Durham, NC 27706
[4] Department of Engineering Mechanics, Columbia University, New York, NY 10027

The microwave processing of lunar materials holds promise for the production of water, oxygen, primary metals, or ceramic materials. Extra high frequency microwaves (EHF), between 100 and 500 gigahertz (GHz), have the potential for selective coupling to specific atomic species and a concomitant low energy requirement for the extraction of specific materials, such as oxygen, from lunar materials. The coupling of ultra high frequency (UHF) (*e.g.*, 2.45 GHz) microwave frequencies to hydrogen-oxygen bonds might enable the preferential and low energy cost removal (as H_2O) of implanted protons from the sun or of adsorbed water that might be found in lunar dust in permanently shadowed polar areas. Microwave melting and selective phase melting of lunar materials could also be used either in the preparation of ceramic materials with simplified geometries (*e.g.*, bricks) and with custom-tailored microstructures, or for the direct preparation of hermetic walls in underground structures. Speculatively, the preparation of photovoltaic devices based on lunar materials, especially ilmenite, may be a potential use of microwave processing on the Moon. Preliminary experiments on UHF melting of a terrestrial basalt and of an ilmenite-rich terrestrial rock show that microwave processing is feasible, particularly in ilmenite-bearing rock types.

INTRODUCTION

Many different suggestions have been made with regard to the potential use of lunar materials in space as well as in lunar applications. In broad terms, these applications may be classified as involving either structural uses or raw material supply. In either case it generally is true that thermal processing will be needed for most of these potential applications. For such heating the use of both ultra high frequency (UHF) 2.45 GHz microwaves as well as extra high frequency (EHF) microwaves between 100 and 500 GHz would appear to have very special advantages over other heating methods, as, for example, the use of focused sunlight. Some specific advantages of microwave heating are the following: a potential savings in processing energy for certain applications of at least an order of magnitude; the development, in particular geometries, of tailored microstructures; and the possibility of selectively heating only desired phases in rocks composed of many different minerals. Additionally, the use of microwave energy to process lunar materials offers the prospect of designing a continuous flow from the raw material to the finished product in a self-contained process. For example, large rocks could be fractured by coupling to particular phases that possess relatively large thermal expansion coefficients. Once fractured, the rocks could be melted and separated into other raw materials or used directly for fabrication into simple but useful geometries, *e.g.*, bricks. Moreover, if sufficiently high temperatures can be obtained, it would be possible to decompose lunar materials substantially into their constituent elements without the need for any chemical feedstocks or further electrochemical processing.

In the following section we discuss first the principle features of microwave heating of ceramic or mineral materials before proceeding to a specific discussion of the application of this method to lunar substances and the presentation of specific examples of microwave-melted terrestrial rocks and ceramic materials.

Microwave Processing

Microwave processing of ceramics can be accomplished in two ways: first, by using UHF radiation to couple radio-frequency energy to defects, impurities, and H-O bonds, and second, by coupling directly to the oxide lattice with EHF radiation. Depending on the composition of the lunar material, either or both of these radiation bands may be used. Additionally, lunar materials have been bombarded for geologic times by high energy photons and particles and as a result contain a high density of fossil radiation damage (Eddy *et al.*, 1980; McDougall *et al.*, 1971). It is quite possible that these radiation-induced defects will couple strongly to UHF radiation.

As an example of ceramic processing by microwaves, Fig. 1 shows the typical geometry of ceramic-glass-ceramic junctions fabricated using UHF radiation. Region II is the seal, while regions I and III are alumina substrates. Figure 2 shows a greatly magnified view of the same junction fabricated using conventional heating. Region I is the alumina substrate, and region II is the glass seal. Note the very different microstructures that are produced. The microwave fabricated geometry is diffusion-bonded, while the conventionally heated geometry is held together by surface wetting only. The energy required to form the geometry

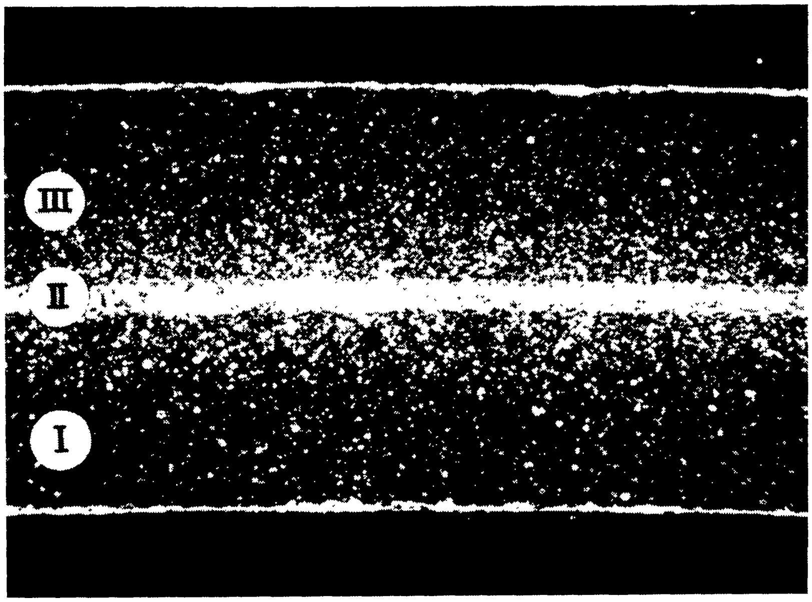

Figure 1. Microwave-formed seal between alumina substrates. (75X)

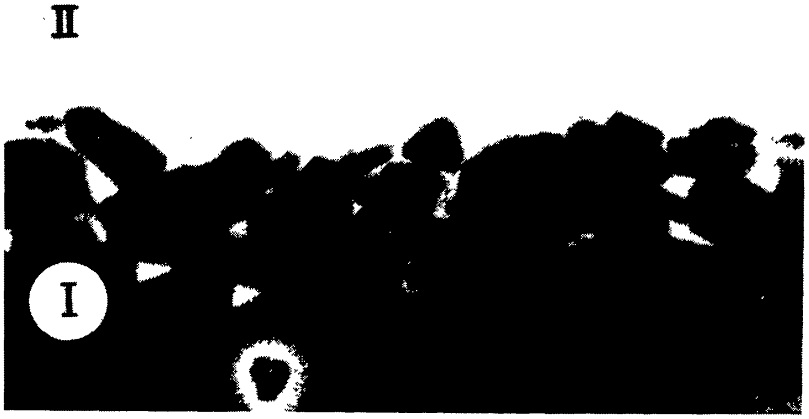

Figure 2. Conventional seal (interface along alumina substrate). (2000X)

of Fig. 1 was approximately 100 times less than that shown in Fig. 2, while the time required to complete the bonding shown in Fig. 1 was approximately 200 times less than that of Fig. 2. Microwave heating rates of up to approximately 80% of the fusion temperature have reached 32,000°C/hour. A rapid heating rate for a conventional heating cycle would be between 20° and 50°C per hour. The different microstructures evident when using microwave heating are due to high-temperature chemical reactions that occur so rapidly that the composition of the phases formed is not affected by the loss of reactants by evaporation.

Self-limiting temperatures have been observed in microwave heating. In Fig. 1, region II is the reacted interface between the alumina substrates and contains a fine grained region that is $ZrO-Al_2O_3$ (the small dark bands within the broader white band region between the alumina substrates.) The white band is a lead alumino silicate glass. Time-temperature data for this seal showed an initial rapid heating rate followed by a period when the maximum temperature of 1000°C was attained for about 45 minutes. After this time period temperature began to decrease with the microwave power still at the maximum setting. It is thought that temperature decreases due to the formation of phases with higher dielectric constant, and the time-temperature data may reflect high temperature reactions that resulted in the formation of these phases. It thus appears possible that the use of EHF radiation will enable selective coupling to be achieved by tuning to particular phases in the materials that have high coupling characteristics. In any case, it is evident that microwave heating can be used to heat ceramic materials with extreme rapidity and with very low power consumption, compared to conventional ceramic processing techniques.

Potential Applications

It is well known that UHF microwaves at 2.45 GHz couple strongly to water and that the lunar materials that have been examined to date appear to lack any water. The possibility exists, however, that some moisture may occur in permanently shadowed lunar polar regions (Watson *et al.*, 1961; Urey, 1967; Werner *et al.*, 1967), and a lunar polar-orbiting mission may be designed to detect such moisture by reflected radar or by other methods. Presumably polar moisture would be of an adsorbed nature and would not be actual ice. Assuming a water content of 10 ppm, heating an entire quantity of rock from −100°C to +100°C would require more than 10,000 times as much energy as that needed to heat the water alone. Neglecting the energy cost of the required material handling, and assuming both the coupling of 2.45 GHz to water and the generation of these microwaves to be 50% efficient or better, approximately 7 l of water could be obtained in 24 h from the power produced by 10 m^2 of solar cells having 10% efficiency. However, material handling costs would in fact be much smaller if the fossil hydrogen (and concomitant oxygen) were removed by a portable microwave unit and the resulting water vapor collected as ice after recondensation on a cold collecting plate.

It is also important to note that 40% by weight of lunar soil is, typically, oxygen (Mason and Melson, 1970). The extraction of this oxygen by microwave heating would be of enormous utility in the long-term support of any lunar base. The energy cost per unit weight of oxygen would be expected to be much greater than that for the extraction of water, due to the relatively high energy associated with metal-oxygen bonds. Such energies can be obtained with focused sunlight as well as by using microwave heating techniques (*i.e.,* by direct EHF coupling to the appropriate metal-oxygen bonds of a mineral lattice). It is also possible, however, that microwave heating might only be needed to reach temperatures high enough to cause melting, after which decomposition to produce both oxygen and metallics could be achieved by means of electrochemical decomposition of the molten rock. Focused sunlight methods of melting or decomposition could, of course, be usable only during the lunar day, whereas microwave melting, if powered from a nuclear source, would be continuously operable. As has been mentioned, it is to be expected that either UHF or EHF microwaves may preferentially couple to and selectively affect particular phases. In the making of brick-like materials in which only a small fraction of either crystalline or glassy phases need be liquified, such selective coupling could be expected to both lower the total energy requirement and aid in the development of tailored microstructures.

It is also possible to speculate that useful photovoltaic properties might be achievable using selected lunar minerals together with appropriate processing. The photovoltaic properties of elemental and compound semiconductors are of course well known. It is less widely known, however, that many minerals may also show certain semiconducting properties. In particular, mineral defect semiconductors can show well-defined, optical band gaps. The band gap of synthetic ilmenite has been measured to be 2.58 eV, for example. From band gap considerations alone, therefore, the theoretical efficiency of solar cells based on such ilmenite could be as high as 11% (Loferski, 1956). The very poor transport properties of such defect semiconductors would make it very unlikely that this level of efficiency could be reached. Nevertheless, the possibility of producing photovoltaic devices of low efficiency, but also low cost, using native lunar materials deserves mention. In such a process, the use of microwave heating with its possibility of coupling to selective phases could have useful advantages.

As an application of the foregoing concepts, UHF heating with 2.45 GHz microwaves has been utilized to produce brick-like materials using both a terrestrial basalt and an ilmenite-rich terrestrial rock. The basalt was not selected at random but was chosen because of its similarity in many components to lunar low-titanium olivine basalts, as shown in Table 1. This analogy is, of course, imperfect because of the considerably lower Fe and Cr contents and higher water, Na, K, and P content that is common to most terrestrial basalts in comparison to lunar mare basalts. The ilmenite-rich rock was a Norwegian sample consisting of about 75% ilmenite with hematite exsolution, and a matrix of plagioclase with minor pyroxenes, pyrite, pleonaste spinel, biotite, and olivine. Since ilmenite is a defect semiconductor, its resistivity is relatively low (on the order of hundreds of ohm-cm) and it couples strongly to the UHF microwave field. It has been found in this present work that a mixture of 10 wt % of the ilmenite-rich rock and 90 wt % of the Techado Mountain basalt can be melted successfully with 2.45 GHz fields, whereas the Techado Mountain basalt will not melt by itself. The ilmenite acts, in this case, as a coupling agent and the resulting temperature rise is sufficient to cause the basalt to couple to this field also. These admixtures have also been melted using normal resistance furnaces. Inasmuch as the temperatures produced during microwave melting could only be measured by optical means, it is not certain what temperatures were reached in the center of the melt. The surface of the basalt/ilmenite melt, however, was found to reach approximately 1200°C.

Table 1. Similarities and Differences Between the Techado Mountain Basalt and Lunar Low-Ti Olivine Basalts

	Techado Mt. New Mexico	Average Apollo 12 Olivine Basalt	Average Apollo 15 Olivine Basalt
SiO_2	44.3	44.3	45.0
TiO_2	3.18	2.65	2.41
Al_2O_3	10.8	8.0	8.8
†FeO	12.0	21.1	22.4
MnO	0.18	0.28	0.30
CaO	10.1	8.6	9.8
Na_2O	2.10	0.22	0.28
K_2O	1.74	0.06	0.05
P_2O_5	0.88	0.08	0.08
Cr_2O_3	0.05	0.63	0.57

Data for the average Apollo 12 and Apollo 15 olivine basalts are from Papike *et al.* (1976).

*Alkaline basalt from Techado Mountain, New Mexico, normalized to 100% water-free composition for comparative purposes (sample contains 2.1% H_2O).

†Essentially all iron occurs as FeO(Fe^{+2}) in lunar basalts; Fe^{+3} also occurs in terrestrial basalts, but the Techado Mountain sample is reported as FeO only for comparative purposes.

Using a standard resistance furnace, the ilmenite rock was melted, then cooled at approximately the same rate as that used for the microwave melted material (air-quenching). Figures 3 and 4 show the microstructures found in each case. As may be

Figure 3. Resistance-furnace melt of ilmenite-rich Norwegian sample (Wards ilmenite 46W4115). Globular ilmenite and lesser amounts of globular hematite in silicate glass matrix. Long dimension of photograph is 1.1 mm.

seen, there appear to be dramatic structural differences between these two melts. The mineralogical examination of the normally melted material (Fig. 3) shows that it is dominated by a globular admixture of 75% ilmenite (without hematite lamellae) and 15% hematite, in a glassy silicate matrix. Titanomagnetite occurs, but is very rare (less than 1%). In contrast, the microwave melted material (Fig. 4) contains abundant (15%) cruciform or dendritic titomagnetite, along with anhedral to subhedral ilmenite (60%, also without hematite lamellae) in a silicate matrix. Hematite is rare (~1%). It is still unknown to what extent these differences are due to microwave versus normal melting and to what extent

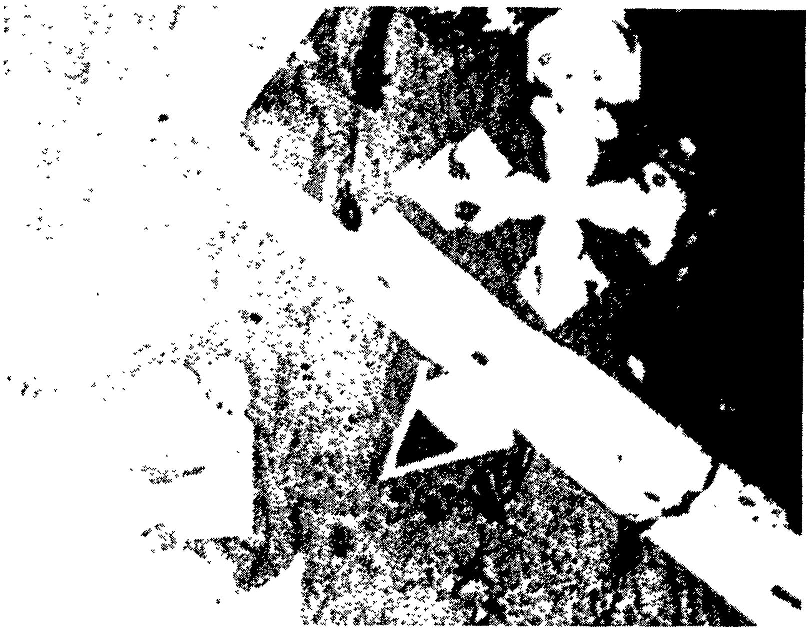

Figure 4. Microwave melt of ilmenite-rich Norwegian sample (Ward's ilmenite 46W4115). Cruciform titanomagnetite, laths of ilmenite, and one of the rare hematites (lower left corner) are shown. Long dimension of photograph is 0.2 mm.

the increased oxidation of the mormally melted sample is due to slower heating and cooling while exposed to atmosphere. However, considerable differences between microwave and normal furnace-melted material might be expected, based on the differential selective coupling of the different phases present in these melts. In the present case, both normal melting and microwave melting produced a brick-like material that would clearly have utility as a structural material, particularly if produced *in situ* along tunnel walls.

Additionally, microwave melting could be used as a means of dust consolidation. In this case, outright melting would probably not be required because dust particle agglomeration via sintering could be expected to occur at temperatures well below melting. Of course, during such treatment any fossil hydrogen would be expected to be driven off with the concomitant production of water that could be collected via the use of cold collecting surfaces. Such heating of the entire mass of dust, by means of EHF microwaves, would consume far more energy than the selective coupling to the H-O bond by 2.45 GHz microwaves. In this way, however, the two-fold purpose of dust agglomeration and water production would be achieved in a single operation.

CONCLUSION

Microwave heating appears to have several potential applications in the processing of lunar materials. The ability of selected microwave frequencies to couple to specific bonds appears to be especially valuable, particularly in the selective removal of fossil solar hydrogen, possibly as water, from lunar soils.

In certain applications, dense, impermeable materials will be required, whereas in others (as for example, in extralunar radiation shielding applications), only a solid brick-like mass, whether or not gas-permeable, will be needed. In either case, it will certainly be true that the ability of microwave processing to interact selectively with one or more specific mineralogic constituents will be of immense help in preparing ceramic bodies with specific structural properties from lunar materials. Furthermore, the ability to heat, melt, or otherwise process lunar materials with a minimum expenditure in both energy and time are extremely valuable characteristics. From these considerations, it appears that the use of microwave heating for the processing of lunar and other materials has unique and important benefits.

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MECHANICAL PROPERTIES OF LUNAR MATERIALS UNDER ANHYDROUS, HARD VACUUM CONDITIONS: APPLICATIONS OF LUNAR GLASS STRUCTURAL COMPONENTS

James D. Blacic

Los Alamos National Laboratory, Geophysics Group, Division of Earth and Space Sciences, MS C335, Los Alamos, NM 87545

Lunar materials and derivatives such as glass may possess very high tensile strengths compared to equivalent materials on Earth because of the absence of hydrolytic weakening processes on the Moon and in the hard vacuum of free space. Hydrolysis of Si-O bonds at crack tips or dislocations reduces the strength of silicates by about an order of magnitude in Earth environments. However, lunar materials are extremely anhydrous, and hydrolytic weakening will be suppressed in free space. Thus, the geomechanical properties of the Moon and engineering properties of lunar silicate materials in space environments will be very different than equivalent materials under Earth conditions, where the action of water cannot be conveniently avoided. Possible substitution of lunar glass for structural metals in a variety of space engineering applications enhances the economic utilization of the Moon.

INTRODUCTION

The intent of this paper is to consider the effects of the environmental conditions of the Moon and free space on the mechanical properties of lunar rocks and materials derived from them. Mechanical properties of silicate materials are very different in the anhydrous, hard vacuum conditions of space compared to Earth due to the virtual absence of hydrolytic weakening processes there. The implications of this realization will be very important in the interpretation of geophysical measurements in investigating the structure of the Moon, in exploitation of lunar materials for construction of a lunar base, and in eventual space industrialization and habitation.

After documenting what is currently known about these environmental effects, I concentrate on the implications of "anhydrous strengthening" of an easily formed structural material derived from lunar regolith, namely, lunar glass. Although the importance of lunar-derived glass has been known for some time (Phinney *et al.*, 1977), the full implications of the potentially very great strength of lunar glass in the vacuum environment are not widely realized. In detailing some applications of lunar glass structural components, I support a philosophy that requires maximal utilization of common lunar materials with minimal processing before end use. It has become clear that large-scale exploitation of space is limited by the cost of Earth-lift of materials. Therefore, it is essential that every possible means be taken to utilize indigenous materials from the Moon and, eventually, the asteroids. In doing so, we should not fight the *in situ* environmental conditions (*e.g.*, low gravity, vacuum), or try to wedge Earth-derived processes into conditions for which they are not adapted; rather, we should attempt to take advantage of that which is given in new ways. It is in this sense that lunar glass can play a central role in easing full-scale entry into the new frontier of space.

HYDROLYTIC WEAKENING PROCESSES IN SILICATES

It has been known for some time that the fracture strength of brittle amorphous and crystalline silicates is determined in Earth environments by the damage state of surfaces and, most especially, the corrosive action of water in extending microcracks (Charles, 1958; Scholz, 1972). For example, the moisture sensitivity of glass is well known. Merely touching freshly formed glass rods will drastically reduce their tensile strengths, and less than one percent of the theoretical tensile strength of glass is normally realized in industrial practice (LaCourse, 1972). Similarly, the plastic strengths of crystalline silicates (*e.g.*, quartz and olivine) at elevated temperatures and pressures are strongly affected because trace amounts of water aid dislocation motion (Griggs,1967; Blacic, 1972). In both instances, the weakening mechanism is believed to involve the hydrolyzation of Si-O bonds (Griggs, 1967; Blacic and Christie, 1984; Charles, 1959; Michalske and Freiman, 1982). A schematic representation of one proposed mechanism is shown in Fig. 1 (Blacic and Christie, 1984). The great inherent strength of silicates is due to the strength of the network-forming silicon-oxygen bonds. However, it appears that the polar water molecule can easily hydrolyze these linking bridges by replacing the strong Si-O bond with a hydrogen-bonded bridge that is an order of magnitude weaker. This hydrolyzation can occur along dislocations, thereby increasing the mobility of dislocation kinks, or at highly stressed microcrack tips resulting in a lower applied stress to propagate the cracks. In both cases, the net result is a large weakening of the material when even very small amounts of water are present.

Whatever its detailed nature, the hydrolytic weakening mechanism is demonstrably a thermally activated rate process. Thus, the time- and temperature-dependent mechanical properties of silicates (brittle and plastic creep, static fatigue, subcritical crack growth) are dominated by moisture effects (Charles, 1958; Scholz, 1972; Blacic and Christie, 1984). As might be expected, these hydrolytic weakening processes are an important factor in such diverse areas as solid earth mechanics, geotechnology (drilling and mining), materials science (glass and ceramic technology), communications (fiber optics), national defense (high energy laser optics), and others, since, on Earth, it is practically impossible to avoid the presence of some water in the fabrication or use of materials, be they natural or synthetic. However, the case may be much different on the Moon and in free space.

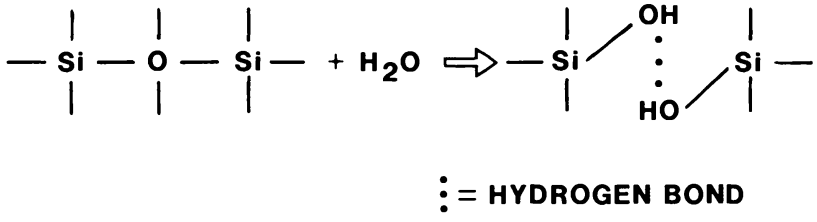

Figure 1. Schematic representation of the Si-O bond hydrolyzation reaction.

ANHYDROUS STRENGTHENING ON THE MOON

Although there is still hope that we may find some water preserved in the permanently shaded regions of the lunar poles (Arnold, 1979), a striking feature of all lunar materials examined so far is their almost total lack of water (Williams and Jadwick, 1980). The very small amount of water that is observed to evolve from heated lunar samples is likely due to either oxidation of solar wind-implanted hydrogen, present at about the 100 ppm level (Williams and Jadwick, 1980), or is the result of Earth contamination (Carrier *et al.*, 1973). There is no unequivocal evidence of native water in any lunar sample returned to date. This fact suggests that, in the hard vacuum of space, silicates derived from the Moon will not, if we can avoid contaminating them, exhibit the water-induced weakening that is so ubiquitous on Earth. In other words, lunar silicates may possess very high strengths due to an "anhydrous strengthening" effect relative to our common experience on Earth. This possibility has numerous implications for space industrialization, some of which are explored below.

There is some supporting laboratory evidence for the anhydrous strengthening phenomenon in lunar or lunar-simulant materials. The compressive strength of a mare-like simulant rock (basaltic intrusive) has been shown to increase by about a factor of two when samples are degassed and tested in a moderate laboratory vacuum compared to tests in 100% humid air (Mizutani *et al.*, 1977). Subcritical crack velocity measurements in a lunar analogue glass demonstrate many orders of magnitude reduction in crack velocity with decreasing partial pressure of water (Soga *et al.*, 1979). This suggests that static fatigue processes will be strongly suppressed or absent in lunar materials in a vacuum environment. Several investigators have found that very small amounts of water strongly affect the dissipation of vibratory energy (Q^{-1}) in lunar and terrestrial rocks (Pandit and Tozer, 1970; Tittmann *et al.*, 1980). These attenuation mechanisms are likely the result of the hydrolysis of crack surfaces with consequent reduction of surface energy in a manner similar to that shown in Fig. 1. The soil mechanics properties of Apollo samples and simulants have been shown to be strongly affected by atmospheric moisture contaminants in moderate and ultra high vacuum experiments (Carrier *et al.*, 1973; Johnson *et al.*, 1973). These latter results suggest that well-consolidated lunar regolith may be substantially stronger than similar materials on Earth with important implications for energy requirements for handling of lunar materials.

There are many additional examples, too numerous to document here, of research on the effects of water on the mechanical properties of terrestrial silicate materials. The main conclusion to be gained from all this work is that water, even in trace amounts, is all-important in explaining the great reduction in strength of silicates. However, in order to get a quantitative estimate of the possible increase in strength of lunar materials relative to their Earth counterparts, it is instructive to examine in some detail the elegant results of F. M. Ernsberger (1969) on glass.

In Ernsberger's experiments, etched glass rods are heated and deformed to produce entrapped bubbles in the form of oblate spheroids. The bubbles concentrate stress at the point of maximum curvature of the bubble-glass interface in a calculable way. In

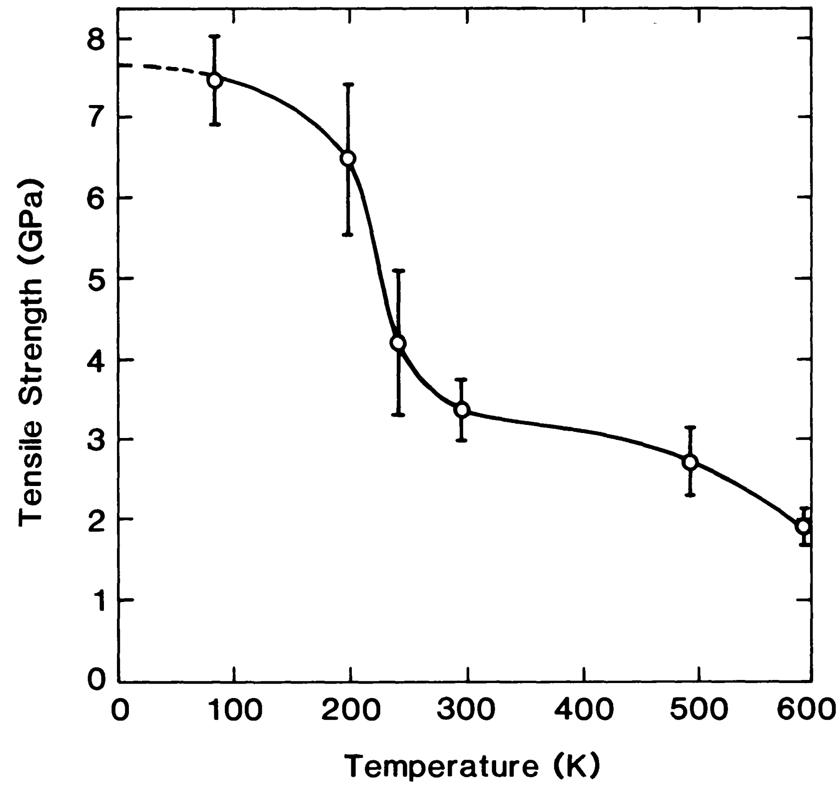

Figure 2. Tensile strength of Kimble R6 soda-lime glass in a relatively anhydrous environment as a function of temperature (Ernsberger, 1969).

addition, if care is taken, failure always occurs at the flaw-free bubble surface where the atmosphere is constant and relatively anhydrous. Using this technique, Ernsberger was the first to achieve controlled compressive failure of glass by shear fracture or densification. Scatter in tensile strength measurements was reduced compared to normal test methods; results are shown in Fig. 2 for soda-lime glass. The temperature dependence of strength shown in Fig. 2 is believed to be due to solid-state diffusion of weakening elements to the stress concentration, possibly sodium but more likely residual water dissolved in the glass. At reduced temperatures, the weakening element is immobilized and strength increases. The important aspect of this work, confirmed by other investigators for other glass compositions, is that the strength is about an order of magnitude higher in an anhydrous environment than it is for the same glass tested in a normal humidity atmosphere. This gives some idea of what might be expected for a lunar glass used in vacuum, although it probably represents only a minimum strength estimate because of the extremely anhydrous nature of lunar materials and the hard vacuum of space.

SOME POSSIBLE APPLICATIONS

Table 1 compares the mechanical properties of some structural metals likely to be produced from lunar regolith with estimates for lunar glass. Common soda-lime glass under Earth conditions is also listed for comparison. The range of tensile strength estimated for lunar glass is believed to be conservative, as discussed above, but even if only the low end of the range can be achieved, then one can see that lunar glass is very competitive

Table 1. Mechanical Properties of Lunar-Derived Materials

	T (GPa/10^6psi)	ρ	E (GPa/10^6psi)	T/ρ (GPa/10^6psi)	E/ρ (GPa/10^6psi)
Aluminum	0.17/0.02	2.7	70/10.2	0.06/0.009	25.9/3.76
Magnesium	0.20/0.03	1.7	45/6.5	0.12/0.017	26.5/3.84
Iron	0.28/0.04	7.9	196/28.4	0.04/0.006	24.8/3.60
Titanium	2.3/0.33	4.6	119/17.3	0.50/0.073	25.9/3.76
Alloy Steel	2.3/0.33	8.2	224/32	0.28/0.041	27.3/3.90
Soda-lime Glass (Earth Environment)	0.007/0.01	2.5	68/9.9	0.003/0.004	27.2/3.95
Lunar Glass (Space Environment)	0.007/0.01-3.0/0.44 or greater?	2.8	100/14.5?	0.003/0.004-1.07/0.16	35.7/5.19?

T = ultimate tensile strength
ρ = specific gravity
E = Young's modulus

with—if not superior to—the metals obtainable from lunar materials with considerably more processing effort.

How can lunar glass be utilized? One obvious way is in the form of glass fibers in tensile stress situations. Although lunar glass will be very strong, it will still be a very brittle material, and therefore it makes sense to distribute the load over many small elements whenever possible. Thus, lunar glass fiber cloths (Criswell, 1977) and multiply stranded cords and cables should see wide application in a lunar base and large space structures such as solar power satellites (SPS). However, lunar glass fibers should always be coated with a metal such as Fe, Al, or Mg to protect the glass from inadvertant or purposeful exposure to water vapor. Otherwise, a highly stressed glass component might fail catastrophically due to water-induced stress corrosion. The metal coating could easily be incorporated into the production process and would also serve the desirable purpose of protecting the fibers from mechanical damage during production handling or use. This is commonly done in terrestrial fiber glass production in the form of organic sizing coatings.

Figure 3 schematically shows the elements I believe will be required in a lunar or space-based glass fiber production plant. I have assumed that sufficient electrical energy will be available [alternatively, direct solar melting could be used (Ho and Sobon, 1979)] and that there will be at least some minimal beneficiation of the feedstock. No lunar or space-based processing plant should be without some means of capturing the rare but highly valuable volatile elements in the lunar regolith. We also suggest in the figure that the relatively new Pochet-type furnace (Loewenstein, 1973) be investigated for use in lunar glass production because of the advantage it would seem to have in weight over traditional furnaces.

For applications requiring flexural, compressive, or mixed loadings such as for bulkheads in a habitat, or beams and columns in an SPS, fiber glass composites would be advantageous. Of the many types of composite materials seeing increasing terrestrial

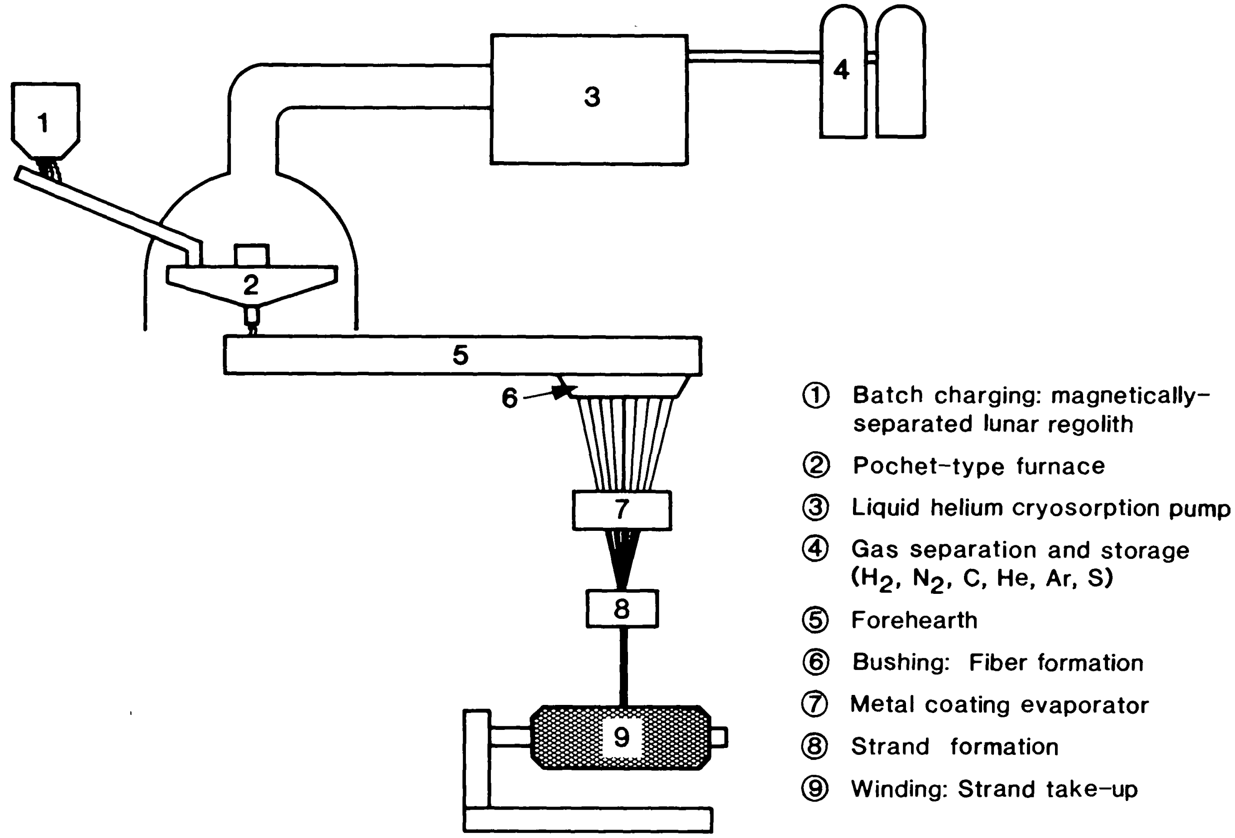

Figure 3. Elements of a lunar-base glass fiber and gas recovery plant.

usage, two would be especially attractive for space applications: metal matrix and ceramic matrix composites. Gas-tight metal matrix composites such as graphite-aluminum are now widely used in aerospace applications. If we follow the philosophy of minimal processing of lunar materials before end use, then lunar glass fiber (LG)-Fe matrix composites should be developed since native iron will be available from regolith beneficiation for fiber coating in any case. The lunar vacuum would make the diffusion bonding and liquid metal infiltration techniques (Davis and Bradstreet, 1970) of composite production advantageous. This lunar glass-metal matrix composite should be very useful in lunar base habitat construction. If a lighter weight composite is wanted (for example, for SPS applications), then silica fiber-Mg composites could be produced when a more sophisticated lunar processing capability becomes available.

Ceramic matrix composites offer some special advantages in certain applications. Large space structures such as antennas and support structures of an SPS are sensitive to the potentially large thermal strains associated with periodic eclipses. Table 2 lists thermal expansion coefficients for some structural materials. Note that glass generally has lower thermal expansivity than common structural metals, and also that some compositions derivable from abundant lunar materials (e.g., titanium silicate glass) exhibit extremely low thermal expansion. If one were willing to import from Earth small amounts

Table 2. Thermal Expansion

	$\Delta L/L$ (10^{-6} °C^{-1})
Aluminum	24.0
Magnesium	25.0
Titanium	8.5
Iron	12.0
Steel	12.0
Invar	1.2
E-Glass	4.8
Corning #7971 Titanium Silicate Glass	0.03

of graphite fiber (which has a negative thermal expansivity), then composites having zero thermal expansion could be produced (Browning, 1982). Ceramic matrix composites exhibit one other desirable property. If the reinforcement fibers do not chemically bond to the ceramic matrix, but instead are held dominantly by frictional forces, then the composite exhibits an enhanced ductility and residual strength beyond the yield point to relatively large strains and is notch insensitive in a manner similar to metals (A. Evans, personal communication, 1984). Thus, I envision a composite in which Fe-coated LG fibers are imbedded in a lunar glass matrix. Such a material may have very desirable structural properties and may represent the best structural material that can be formed entirely from the most common lunar materials with the least amount of processing.

Finally, I would like to support the suggestion of Rowley and Neudecker (1984) that lunar habitats be formed by melting in-place, glass-lined tunnels using the "subterrene" (perhaps in the present context, as they note, better termed "subselene") technology. If the glass-lined tunnels were sputter-coated with a metal to protect the glass from water vapor, and if the LG fiber composites were used for bulkheads, etc., then extensive lunar habitats with more than adequate radiation shielding from the largest solar flare storms could be produced from 100% lunar materials. No doubt engineers and architects will find many more uses than we have thought of for a lightweight structural material with several hundred thousand psi tensile strength.

RESEARCH NEEDS

Most of what I have advocated concerning the possible high strength of lunar materials in hard vacuum environments has been based on research of terrestrial silicates under terrestrial or, at best, poorly simulated space conditions. Ultimately, our contentions must be proved at full-scale using actual lunar materials under *in situ* conditions. A lunar-based materials testing laboratory would seem necessary for this and should be an early, high priority lunar base facility. Until reoccupation of the Moon, however, much can be learned, and perhaps our basic contentions can be proved by experiments using lunar simulants formed and tested under ultra high vacuum laboratory conditions on Earth. This approach would seem initially preferable to LEO shuttle experiments because of the relatively poor vacuum environment of the shuttle resulting from the normally low orbits achieved and, perhaps more importantly, outgassing of the vehicle itself. Perhaps the free flying or tethered experimental platforms proposed in conjunction with the space station will improve this situation and will be needed to evaluate the effects of extended exposure to radiation and micrometeoroid fluxes, but for now ultra high vacuum experiments in Earth laboratories appear most appropriate. Most urgently needed are basic mechanical properties such as tensile and compressive strengths, fracture toughness, and thermal properties. With these results in hand, investigation of potential composite materials can proceed followed by bench top and proto-type engineering of the manufacturing facilities that will be required. Also, research and evaluation of the "subselene" approach to lunar habitat formation should proceed because of the advantages it would seem to have over imported structures.

SUMMARY

Although the apparent absence of water on the lunar surface makes it difficult to do many of the things we would like on the Moon, in at least one respect it may be a blessing. It appears that the anhydrous, hard vacuum environment and the inherently dry nature of lunar regolith materials down to the ppb level make possible the use of lunar glass for structural applications that would be impossible on Earth. In view of the fact that the initial cost of large-scale industralization and scientific exploitation of the space environment is dominated by Earth-lift requirements, the possible extensive use of lunar glass structural materials in a wide variety of applications offers promise of very large savings in Earth export expenses and thereby enhances the economics of utilizing the Moon. From a purely scientific point of view, it is likely that the anhydrous strengthening phenomenon will have numerous implications for a wide range of geological and other scientific investigations on the Moon in which mechanical properties play an important role.

Acknowledgments. *I would like to acknowledge helpful discussions with J. Clemens, R. Dick, E. Mathez, M. Rovetta, J. Rowley, and T. Shankland.*

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GUIDE TO USING LUNAR SOIL AND SIMULANTS FOR EXPERIMENTATION

J. H. Allton, C. Galindo Jr., and L. A. Watts

Northrop Services, Inc., P.O. Box 34416, Houston, TX 77234

The vision of a lunar base has stimulated experimentation needed for the planning and construction of lunar vehicles, habitats, and factories. The following discussion is a guide to facilitate the design and interpretation of technology experiments on lunar soil and lunar soil simulants. Lunar soil, once it is taken from the Moon for study in the laboratory, may not represent true *in situ* lunar conditions. The proposed simulated soils are different from genuine lunar soils in several important respects, mostly due to the effects of micrometeorites and solar wind on the Moon. However, these proposed simulants do replicate the lunar soil grain size distribution, gross mineralogy, and general chemical composition and are useful for studies of these properties. There are several reserves of lunar material that are suitable for tests requiring genuine lunar soil.

INTRODUCTION

Past studies have concentrated on unlocking scientific secrets of lunar soil. Extracts of scientific studies on chemistry and petrography of the 163 individual soils and an extensive bibliography are found in *Handbook of Lunar Soils* (Morris *et al.*, 1983). A review of lunar soil petrography is given by Heiken (1975). Although lunar soil chemistry is fairly well known, engineering properties and industrial reactions are not as well studied.

Mechanics and thermal information on *in situ* soil conditions was gathered by early researchers from television, surface photography, and measurements using a penetrometer and heat flow probe. Observations on the lunar surface include the Apollo lunar module descent engine blowing dust, depths of footprints on crater rims, the rover throwing dirt in the "grand prix," drilling, trenching, scooping, and raking. *In situ* properties are most relevant to the use of lunar soil for tunneling, heaping, and excavating, and as a substrate for buildings and vehicles. The properties of interest are the *in situ* bulk density and porosity. For surface activities similar to those conducted on the Apollo missions, these properties are probably known well enough.

Other properties, intrinsic to the soil grains, become important for those experiments where lunar soil is an active ingredient in a process. These properties include composition, rock form (crystalline, glassy), grain size, grain shape, grain strength, grain surface reactivity, dielectric constant, and magnetic susceptibility. Present interest includes experiments for extracting oxygen from the soil, melting or chemically reacting the soil for use as structural material, and growing organisms on the soil.

BRIEF DESCRIPTION OF LUNAR SOIL

Lunar soil can be described in familiar terrestrial terms as well-graded silty sands or sandy silts with an average particle size by weight between 0.040 and 0.130 mm (Carrier *et al.,* 1973). The density of *in situ* bulk lunar soil, as determined from large diameter core tube samples, is typically 1.4 to 1.9 g/cm^3. The bulk density increases with depth, and below 10–20 cm the soil is often at higher density than is required to support the overburden in lunar gravity (Carrier *et al.*, 1973). Spheres, angular shards, and fragile, reentrant, vesicular grains are among the diverse shapes found in most lunar soils. The most abundant particles composing the soil are igneous or breccia lithic grains, mineral grains, glass fragments, and the unique lunar agglutinates. Major lunar minerals are pyroxenes, anorthite, ilmenite, and olivine. Compositionally, the lunar soils fall into two broad groups: the highlands soils, which developed on anorthositic bedrock, and the mare soils, which developed on basaltic bedrock. The mare soils can be further subclassified as to high or low titanium content. Highlands soils are relatively enriched in aluminum and calcium, while mare soils are relatively enriched in iron, magnesium, and titanium. Average major element chemistry of these three types is given in Table 1.

Table 1. Major Element Chemical Composition of Lunar Soils and Soil Simulants

	Lunar Highlands Soils* (%)	Lunar Low Titanium Mare Soils† (%)	Lunar High Titanium Mare Soils§ (%)	Hawaiian Basalt** (%)	High Titanium Mare Simulant‡ (%)
SiO_2	45.0	46.4	42.0	46.4	41.7
TiO_2	0.5	2.7	7.5	2.4	7.5
Al_2O_3	27.2	13.5	13.9	14.2	12.8
Fe_2O_3	-	-	-	4.1	3.7
FeO	5.2	15.5	15.7	8.9	12.8
MgO	5.7	9.7	7.9	9.5	8.5
CaO	15.7	10.5	12.0	10.3	9.2
Total	99.3	98.3	99.0	95.8	96.2

*Average composition of Apollo 16 soils compiled from *Handbook of Lunar Soils* (Morris, 1983).
†Average composition of Apollo 12 soils from Taylor (1975), p. 62.
§Average composition of Apollo 11 soils from Taylor (1975), p. 62.
**Composition of Hawaiian basalt HAW-11 from *Basaltic Volcanism on the Terrestrial Planets,* p. 166.
‡Calculated composition from recipe in Table 2. Iron in ilmenite as FeO.

CHANGES IN SOIL FROM MOON TO LABORATORY

Soil cannot be removed from the surface of the Moon without altering at least some of the *in situ* characteristics such as bulk density and stratigraphy. The least physically disturbing way of sampling the lunar soil was with the large diameter core tubes used

Table 2. Changes in Soil from Moon to Lab

	Conditions	Changes
Moon	Impact-derived particle packing High vacuum	
Curatorial Facility	Dry nitrogen	Loss of original packing Adsorb water (minor)
Laboratory	Laboratory atmosphere	Adsorb water (major) Oxidation

on Apollo 15, 16, and 17 (Carrier *et al.*, 1971). Soil undergoes still further changes in the experimenter's laboratory (Table 2). On the lunar surface soil particles reside in a hard vacuum, free of water molecules and other atmospheric gases. The packing of particles is affected by continual meteorite bombardment. The dominant effect of this pounding is to pack the soil more tightly, although occasionally soil particles on the surface are ejected and then settle to a less dense configuration on crater rims (Carrier, 1973).

In the lunar sample curatorial facility, "pristine" samples are stored and handled only under dry nitrogen. Even so, small amounts of water and other gases are probably adsorbed on the highly reactive surfaces of lunar soil grains. The soil grains have lost their original packing during excavation, transit to Earth, and laboratory handling.

Furthermore, the ambient atmosphere of the experimenter's laboratory, with its relatively high water vapor and oxygen content, causes much more water to be adsorbed on the grain surfaces and some oxidation to occur. For example, the abundant metallic iron in lunar soil rusts easily.

SOME CRITICAL DIFFERENCES BETWEEN SIMULANTS AND LUNAR SOIL

Solar radiation and meteorite impacts, large and small, alter soil grains in ways that are difficult to duplicate on Earth. Also, lunar minerals are compositionally different, on a minor scale, due to the lack of volatile elements and reduced amounts of oxygen when the minerals were formed. Some of these unique lunar characteristics can be reproduced in very small quantities of simulant in experimental guns, charged particle beams, or furnaces. However, it is not practical to make usable quantities of simulants by these methods. Since simulants will probably be made using crushed, naturally-occurring minerals, they will be different from true lunar soil in several ways (Table 3).

Agglutinates, Iron Metal

Since the Moon has no atmosphere, very small meteorites impact the soil at high velocity, melting and shocking the rocky soil grains. Evidence of an impact on a 1 mm

Table 3. How Successful is a Simulant?

Can Simulate	Difficult to Simulate
Grain size distribution	Agglutinate glass with dispersed metal, grain shape
Gross mineral composition	Solar wind nuclei implantation
	Shock effects (grain strength)
General chemical composition	Mineral chemistry (reduced elements, no hydration)

diameter glass sphere taken from lunar soil is shown in Fig. 1. The splatters of glass from many repetitions of such micrometeorite impacts can glue tiny grains together in convoluted structures called agglutinates (Fig. 2). Iron metal blebs of 10 nm diameter are distributed throughout the agglutinatic glass, making the glass magnetic. Agglutinates can make up over 50% of a mature lunar soil. This gluing together of smaller grains into larger ones is part of two competing processes, for impacts also break down soil grains into smaller ones.

Solar Wind

Because the Moon does not have a global magnetic field, high velocity nuclei from the solar wind impinge directly on small soil grains. These nuclei, of which hydrogen and helium are the most common, become implanted in the outer few angstroms of soil grains, creating an amorphous layer. In mature soils this solar wind hydrogen can exceed 100 ppm.

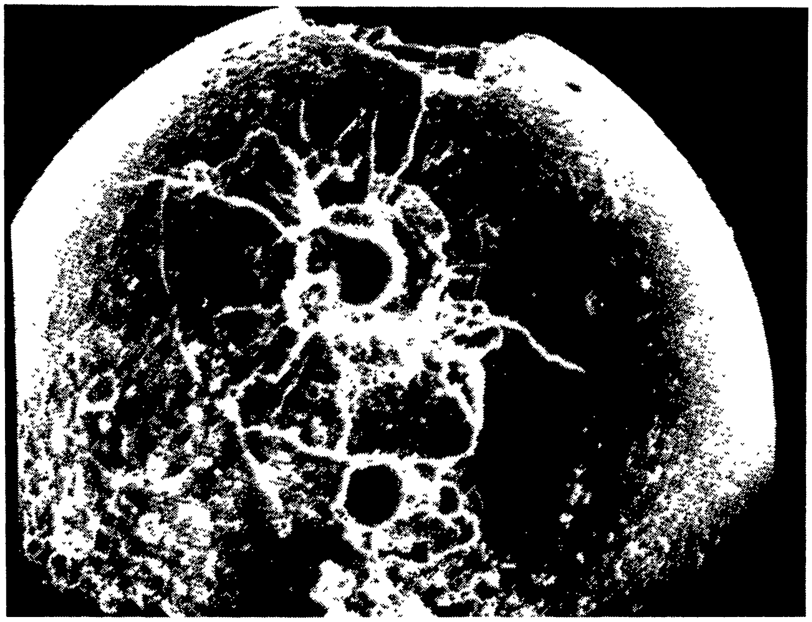

Figure 1. One millimeter diameter lunar glass sphere with micrometeorite impact pit. Photo courtesy of D. S. McKay (S-71-48106).

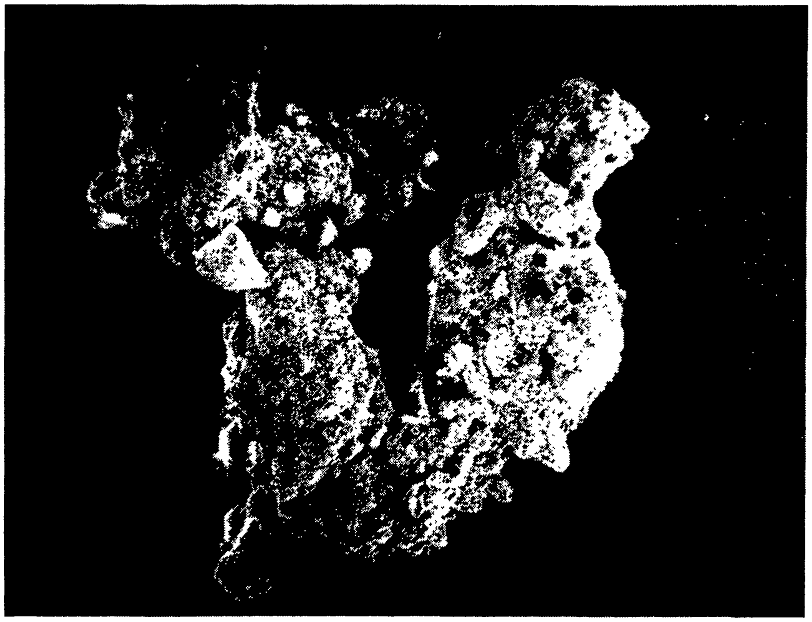

Figure 2. One millimeter diameter agglutinate. Photo courtesy of D. S. McKay (S-71-24575).

Shock Effects

The shock effects of meteorite impacts are commonly retained in lunar soil grains. Impacts fracture and weaken the mineral grains found in the lunar soil.

Mineral Chemistry

The major lunar minerals (anorthite, pyroxene, ilmenite, olivine) are similar in gross aspects to their terrestrial counterparts. However, the lunar minerals do not contain bound water in the crystal structure and have not been altered by hydration reactions on grain boundaries. Due to extremely low oxygen fugacities at the time of crystallization, several elements in lunar minerals are found in a more reduced state. Combined iron is almost totally ferrous iron, and iron metal may be found in interstitial phases and dispersed in glass. Titanium and chromium occur in the more reduced valence states of +3 and +2, respectively. Lunar ilmenite does not contain hematite as many terrestrial ilmenites do.

LUNAR FINES AS EXPERIMENTAL SAMPLES

Lunar samples are allocated very sparingly, and investigators are encouraged to work on the smallest possible samples. For example, scientific investigators typically determine major element chemistry from only 50 mg of material. Since engineering and industrial studies often require much larger sample size, experimenters must, when possible, scale down their experiments and make use of simulants.

Any lunar samples that may be available for technology studies will probably come from the residue of fines left in the Apollo collection bags. Early missions collected fewer, but larger, soil samples, On later missions, samples were smaller, more carefully chosen to sample different phenomena, and placed in individual bags.

Table 4. Grams of Sample Bag Residues from Apollo Missions

Apollo 11	55 g
Apollo 12	–
Apollo 14	225 g
Apollo 15	335 g
Apollo 16	1808 g
Apollo 17	3525 g
Total	5948 g

The residue of fine material remaining in the rock and soil sample bags (about 5 kg total) could be pooled and homogenized for each mission except Apollo 12 (Table 4). This would result in a mixture of fines, representing an average chemical composition for each site of large enough size to serve as a standardized sample. However, these samples would not be representative of a true soil since rock dust would be admixed. Soil maturity (degree of exposure to micrometeorites and solar wind), as determined by fine-grained metallic iron content (Morris, 1978), would give a general indication of proportion of soil to rock dust. Investigators concerned with agglutinate, metal, and solar wind content could then make adjustments for under-representation of these components in the pooled fines.

As a standard sample, these pooled fines would be of known composition, grain size distribution, and maturity. This would be advantageous for comparisons among experiments. Use of these bag residues would be an efficient use of the Apollo collection, since their mixed origin makes them less valuable scientifically.

SIMULANTS FOR EXPERIMENTS

Since the properties to be simulated and degree of fidelity required are different for laboratory experimentation than for testing equipment and structures, simulants for these two uses are discussed separately. In general, simulants for laboratory experimentation require greater fidelity to chemical and mineral composition, in addition to grain size distribution. In creating simulants, costs must be weighed against benefits of increasing fidelity to lunar soil. The approach described below is a "middle-of-the-road" effort, when compared to the low cost extreme of using the nearest sand or crushed rock and the high cost extreme of creating micrometeorite impacts and solar wind implantations one by one in experimental guns and ion beams. Simulating the lunar soil for laboratory experimentation is approached from three aspects: soil grain size distribution, soil particle type distribution, and particle chemistry.

Grain Size Distribution

Grain size distribution curves have been compiled that encompass most Apollo soils (Carrier *et al.*, 1973). The grain size distribution of simulants should be created with the fewest sieve sizes that adequately characterize the grain size distribution curve and yet are practical to use. Thus, simulant composition should be defined as 90% finer than

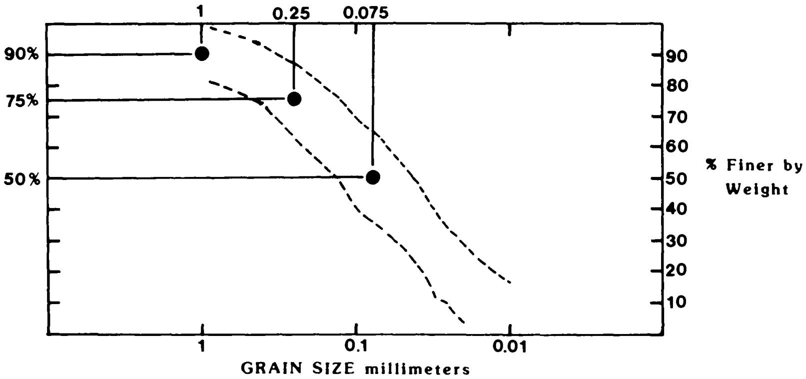

Figure 3. Grain size distribution curves encompassing most Apollo soils. Plot and data adapted from Carrier et al. (1973). Percent finer by weight at sieve sizes 1.0, 0.25, and 0.075 mm are used to define simulant characteristics.

1 mm, 75% finer than 0.250 mm, and 50% finer than 0.075 mm (Fig. 3). The distribution curve is not precisely simulated below 0.075 mm, because it is impractical to sieve large volumes of rock below this limit. Therefore, it is important to calibrate the pulverizing process in the small size range.

Particle Type Distribution

Nearly all particles comprising the lunar soil are lithic (chiefly breccia and poikilitic rocks in the highlands and breccia and basalt in the maria), mineral or glass fragments or agglutinates. The simulation is simplified by using crushed basalt or minerals to substitute for the lithic and mineral fragments and by using crushed glass to substitute for glass fragments and agglutinates. Although lunar particle type distribution varies with maturity of the soil, source rock type, and particle size, both mature highlands and mature mare soils can be approximated with a mineral or rock to glass ratio of 1:1 for sieve fraction <0.250 mm and a ratio of 3:1 for sieve fraction >0.250 mm. [These proportions were calculated from data for sample 60010 given in McKay *et al.* (1977) and from data for sample 71016 given in Heiken and McKay (1974).]

A Highlands Simulant

The target chemical composition for the highlands simulant is the average of Apollo 16 soils as given in Table 1. Normative calculations (Chayes and Metais, 1964), based only on Si, Al, Fe, Mg, and Ca indicate that a 3:1 weight ratio of anorthite ($CaAl_2Si_2O_8$) to pyroxenes (of mixed composition) would approximate this chemical composition. Adding pyroxenes raises both the iron and magnesium content.

Unaltered anorthite is not common on Earth. The least altered anorthite crystals can be found associated with frothy glass near some andesitic volcanoes, such as Miakejima near Tokyo. Anorthite also is found mixed with other minerals in andesitic areas and as anorthosite rock in layered intrusions, of which the Stillwater complex in Montana is an example.

The orthopyroxene bronzite is a close practical substitute for the norm-calculated pyroxene ratios of hypersthene (orthopyroxene) to diopside (clinopyroxene) of 6:1.

Glass of the highlands composition given in Table 1 can be made by Corning Glass Company by the dri-gauge method (Minkin *et al.*, 1976).

In summary, a highlands simulant can be made by combining crushed anorthite, pyroxene, and synthetic glass in proportions based on grain size, lithic or glassy character, and chemistry. A sample recipe of this type is given in Table 5.

A High Titanium Mare Simulant

The target chemical composition for the high titanium mare simulant is the Apollo 11 soil average given in Table 1. The lithic and mineral component can be approximated by terrestrial basalts plus ilmenite. HAW-11 (Basaltic Volcanism Study Project, 1981), whose chemical composition is also given in Table 1, is an example of a suitable basalt. Combining this basalt with ilmenite ($FeTiO_3$) in a 9:1 proportion raises the titanium content of the mixture to that of the Apollo 11 soil. The resulting mixture also improves the calculated fit to Si, Fe, and Mg percentages of the Apollo soil (Table 1).

Glass of high titanium mare composition can also be made from melting oxides. Naturally occurring, basaltic-composition volcanic glass, such as is found in Hawaii could be used, but probably will not have a titanium concentration as great as the high titanium mare soils.

In summary, a high titanium mare simulant can be made by combining crushed Hawaiian basalt HAW-11, ilmenite, and synthetic glass in proportions based on grain size, lithic or glassy character, and chemistry. A sample recipe of this type is given in Table 5.

SIMULANTS FOR TESTING EQUIPMENT AND STRUCTURES

Important parameters to simulate for testing equipment and structures include bulk density and porosity. Grains of correct size distribution and specific gravity are needed,

Table 5. Recipes for Lunar Soil Simulants

	Sample Highlands Simulant: Anorthite to Pyroxene Ratio 3:1*			
	<0.075 mm	0.075 to 0.25 mm	0.25 to 1.0 mm	>1.0 mm
Anorthite	18.8	9.4	8.4	5.6
Pyroxene	6.2	3.1	2.8	1.9
Glass	25.0	12.5	3.8	2.5
	Sample High Titanium Mare Simulant: Basalt to Ilmenite Ratio 9:1*			
	<0.075 mm	0.075 to 0.25 mm	0.25 to 1.0 mm	>1.0 mm
Basalt	22.5	11.3	10.1	6.8
Ilmenite	2.5	1.2	1.1	0.7
Glass	25.0	12.5	3.8	2.5

*To make 100 g of simulant, mix components by grams indicated in table.

The same grain size fractions and lithic to glass ratios were used for both simulants: >1 mm =0.10; 0.25-1 mm =0.15; 0.075-0.25 mm =0.25; <0.075 mm =0.50 (total = 1.00). The lithic to glass ratio for >0.25 mm =3:1 and for <0.25 mm =1:1.

so chemistry and mineralogy are less important. Also, since much larger quantities of simulant are needed (tons), crushing and grinding of a single component, usually basalt, on commercial size equipment would be used. Nearly 2500 kg of a basalt simulant was fabricated and characterized for testing the lunar rover (Mitchell and Houston, 1970; Green and Melzer, 1971). Crushed basalt also has been used for lunar resource utilization studies (Steurer, 1982).

The importance of packing the simulant properly after grinding is illustrated in the testing of the Apollo lunar surface drill by Martin Marietta. The simulant, used during design of the drill, was packed to a lesser density than was actually encountered on Apollo 15. The surprisingly dense soil at Hadley Rille made the drilling effort more difficult than expected. The density of the entire Apollo 15 drill sample was 1.75 g/cm^3, but the deepest section was 1.93 g/cm^3 (Carrier, 1974). Therefore, in preparation for subsequent drill testing, engineers recompacted the simulant to the densities encountered at Hadley Rille. The difficult task of achieving this high density for crushed vesicular glass and lithic particles was accomplished using electric tampers to compress each shallow layer (3-6 inches thick) as it was added to the test bed (Britton, personal communication, 1985).

CONCLUSIONS

When planning experiments for activities to take place on the Moon, investigators should remember the following.

1. Lunar soil in the laboratory does not accurately represent lunar *in situ* conditions. The Apollo soils have lost their original particle packing and have adsorbed volatiles.
2. Simulants can be made by ordinary means that reproduce specific properties of lunar soil such as grain size distribution, gross mineral composition, or general chemical composition.
3. Certain lunar soil characteristics are difficult to duplicate in simulants. These include agglutinates with their convoluted shapes and iron metal, implanted solar wind nuclei, impact shock effects on grains, and minerals with reduced elements.
4. A very small amount of lunar soil will be available for experimentation. Investigators should scale down their experiments and use simulant whenever possible.

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FRACTIONAL DISTILLATION IN A LUNAR ENVIRONMENT

Donald R. Pettit

Los Alamos National Laboratory, MS P952, Los Alamos, NM 87545

The establishment of a permanent lunar base will undoubtedly employ distillation operations as a routine practice. Reclamation of vital fluids along with products from chemical processes will lend itself to fractional distillation. The lunar environment, with reduced gravity and pressure, will dictate design modifications and offer some pleasant advantages. Column area will increase to maintain the same flow rates as Earth-based counterparts. Plate efficiencies can increase, allowing shorter columns. Thermal insulation will be facilitated by the lunar atmosphere, as well as low pressure "vacuum" distillation.

INTRODUCTION

With the development of a reliable space transport system, extraterrestrial engineering is becoming a respectable field of endeavor. The detailed engineering for maintaining a space station or lunar base, along with possible manufacturing processes, presents a challenge for scientists and engineers.

The establishment of a permanent lunar base will employ separation techniques as part of routine necessity. Recycling precious body fluids, in addition to solvents and products of chemical manufacture, could lend itself to fractional distillation. The lunar environment, with reduced gravity and pressure, will offer some unique possibilities for clever designs with a concurrent struggle to overcome the hardships.

Why use an age-old process like distillation when there are many "space age" separation techniques (such as membrane technology)? Distillation uses simple, hearty equipment that operates in a dependable manner, equipment that is not easily damaged if operation is in error. Many of the construction materials could ultimately be derived from lunar sources, saving the transportation costs of Earth-based goods. Most important, distillation uses heat energy as the main driving force for separation.

On the Moon, shaft and electrical energy will be at a premium. Whether from solar, combustion, or nuclear sources, heat energy will be more abundant and more efficiently obtained than shaft or electrical energy. In the allocation of such a valuable commodity, it makes good sense to employ processes that utilize heat directly, saving the shaft and electrical energy for those processes that cannot be driven any other way. Waste heat from ongoing processes may be of a quality suitable for driving distillation, thus realizing further economy.

The lunar environment will offer some unique advantages for distillation processes. Vacuum distillation will be possible due to the cryogenic temperatures available on the Moon. With vacuum distillation lower heat loads are realized with cleaner separations and with the possiblity of breaking azeotrope systems. With a radiation barrier the distillation columns will be essentially enclosed in a giant "thermos bottle," realizing very low heat losses, so the energy injected into the processes will be used efficiently for driving the separation. The constant nature of the lunar atmosphere will facilitate the process control, resulting in consistent product output and quality. In contrast, heat loss from Earth-based columns is of major concern, especially coupled with changing weather patterns that complicate the process control.

Fractional distillation is a mature engineering field backed with years of experimentation that resulted in practical design. The approach taken here is to utilize this existing knowledge, coupled with dimensional analysis and scaling arguments, to modify the design of Earth-based columns for lunar operation.

BACKGROUND IN DISTILLATION EQUIPMENT

The anatomy of a fractional distillation process is shown in Fig. 1. The heart of the unit consists of the fractionating column, basically a tall vertical pipe where the liquid and vapor experience intimate contact and where mass transfer between phases is effective, thus achieving component separation. At the bottom of the column is the reboiler, a vat of boiling liquid from which the vapors flow upward into the bottom of the column while the condensed liquid emanating from the column flows downward into the reboiler. The heat for driving the separation is injected into the reboiler.

At the top of the column is an overhead condenser that converts the enriched vapor effluent into a liquid, rejecting heat into the environment. A portion of this liquid is tapped off as head product, the balance being returned to the top of the column as reflux. The ratio of the amount of liquid returned to the amount tapped off is called the reflux ratio and is an important quantity in the design of a distillation process.

Most distillation processes are designed to operate on a continuous basis, unlike the familiar connotations of a moonshiner's batch still for making "white lightning." A continuous feed is introduced into the column at the point where the concentration of components in the feed matches that in the column. The enriched head product is continuously withdrawn from the top while depleted bottoms are continuously removed from the reboiler.

The design of what goes inside the column to achieve the intimate contact between vapor and liquid is somewhat of an art as well as a science. The column can be filled with plates, each having a standing pool of liquid that vapors bubble through, giving discrete or stage-wise contact. The column can be packed with irregular objects, providing continuous contact between the liquid trickling down and vapor percolating up. Presently, the most popular column design uses plates, with future trends leaning towards packed columns. This paper will deal with plate-type columns, with packed columns being the subject of another study.

There are many types of plate designs, with sieve tray plates being the most common. The sieve tray plate will be considered here initially, with the scaling arguments derived being general for most types of plate columns. Figure 2*a* shows a cross section of a

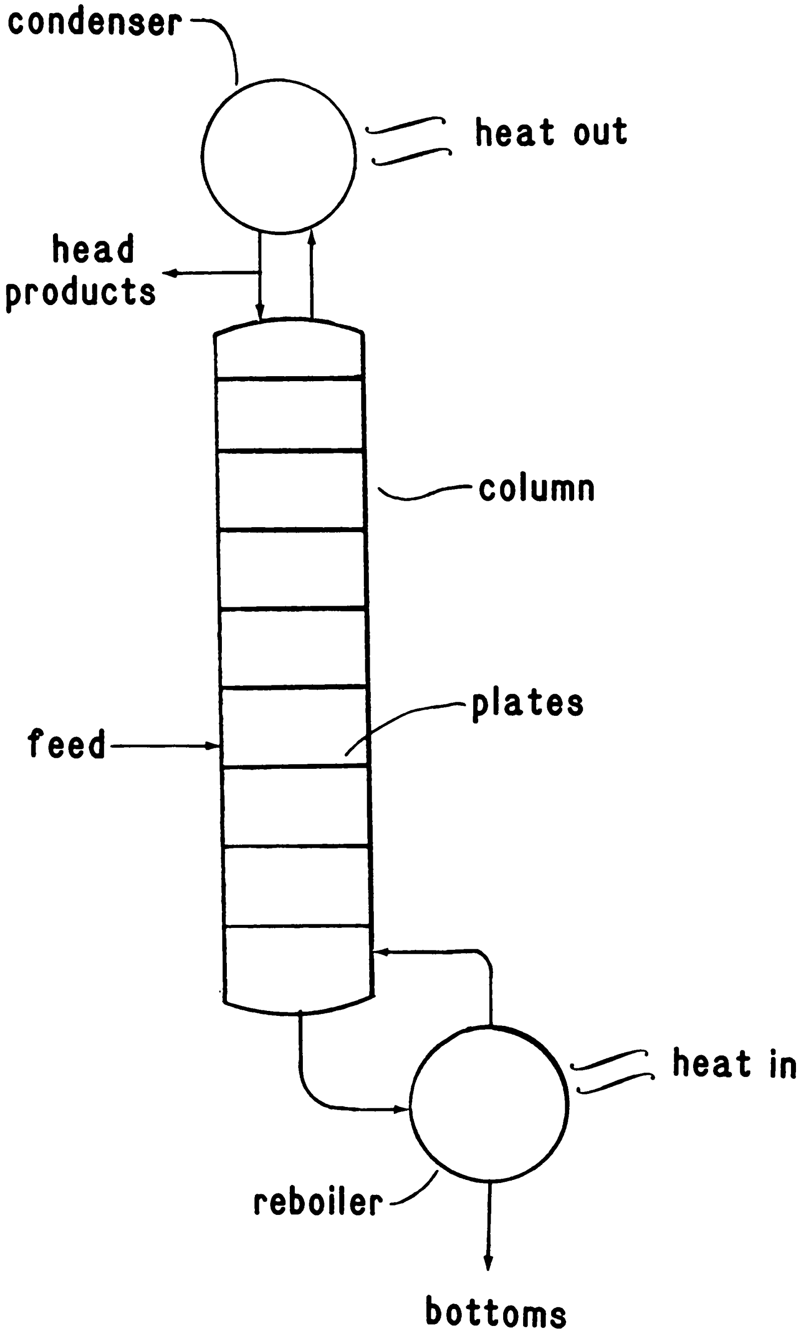

Figure. 1. Schematic of a basic fractional distillation process.

portion of a column containing a sieve tray plate, while Fig. 2*b* shows the top view. A pool of liquid, usually 10–20 cm deep, stands on top of a perforated plate with holes ranging from 4–15 mm in diameter. The liquid is kept from weeping through the holes by a steady stream of vapor pushing upward, emanating from the liquid on the plate immediately below. The vapor, with intimate contact, bubbles through the pool of liquid and thereby condenses. The heat released upon condensing vaporizes a corresponding amount of liquid, which pushes upwards as vapor to bubble through the next higher

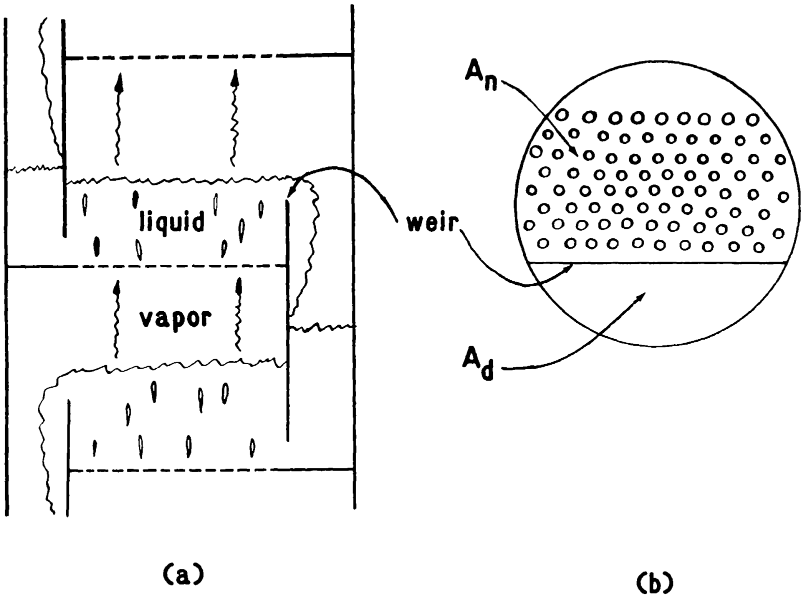

Figure 2. (a) Cross section of a column with sieve tray plates; (b) top view of a sieve tray plate.

plate. Insulation is critical in the operation, because the energy for vaporizing the liquid on a plate comes from the condensing vapors; any heat loss hinders this interplay.

The liquid level is maintained by a lip or weir, over which the liquid can splash and flow down a passage called a downer to the next lower plate. A liquid seal is provided so the vapors cannot flow "up the downer" and are forced to percolate through the sieve tray holes. The weir usually cuts some chord length of the column cross section, separating the downer area A_d, from the net area of the sieve tray, A_n (A_n is based on the sieve tray area, not the hole area), as seen in Fig. 2*b*.

To achieve a given head product purity, thermodynamics will dictate the ideal number of plates, assuming equilibrium is reached. A plate efficiency, E, is used to determine the number of real plates from this ideal case. Plate spacing is usually between 30–50 cm, so column height is then specified. Typical industrial columns may range from 1/2–2 m in diameter, 5–50 m high.

LUNAR MODIFICATIONS

Dimensional analysis and scaling arguments can be used to modify Earth-based columns for use on the Moon. The prime consideration is the reduction of gravity to one-sixth of that found on the Earth. Gravity-driven buoyant forces are responsible for moving the two-phase fluid system and will affect A_n, A_d, and E. Vapor-liquid thermodynamics will remain the same between the Earth and the Moon so that the number of ideal plates needed for a given separation will remain constant. Hydraulic similarity between Earth-based plates and Moon-based ones should be maintained through dimensional analysis so that the column operation will remain consistent with Earth-bound operations.

In the design of a distillation column, the feed rate and desired component separation are given; column pressure, temperature, number of ideal plates, and reflux ratio are then specified from a blend of thermodynamic and economic arguments. With these parameters fixed, the internal flow rates of vapor and liquid are also known. The column diameter is dictated by the A_n and A_d required to handle these internal flows, and the height is specified by the number of real plates calculated from the ideal number and E.

The net column area A_n is correlated to the internal volumetric gas (vapor) flow rate Q_G. The gas velocity V_F is defined as Q_G/A_n and is given by Treybal (1980) as

$$V_F = C_F\sqrt{\frac{\rho_L - \rho_G}{\rho_G}} \tag{1}$$

where ρ_L and ρ_G are the liquid and gas phase densities and C_F is the flooding coefficient, a constant determined from the details of plate geometry.

Equation (1) has no theoretical derivation; it is based on empirical correlation of experimental data for the prevention of droplet entrainment in the rising vapor. Realizing that such criterion is based on a balance of forces experienced by the droplets, it is recognized that the $(\rho_L - \rho_G)/\rho_G$ term in (1) is due to gravity-driven buoyant force between the liquid droplet and the gas. The density term must be multiplied by g, the acceleration due to gravity, in order to render the quantity into a proper buoyant force, which would certainly result if a theoretical derivation of (1) could be undertaken. Since (1) is developed empirically from Earth-based data, the acceleration due to gravity, which is not considered a separate parameter, would be buried in the flooding coefficient by the mechanics of the correlation process. It is not expected to find the gravitational acceleration anywhere in the equation. Therefore, the effect of gravity must enter in the flooding coefficient, resulting in V_F being proportional to $\sqrt{g}$.

The terminal velocity of a bubble in liquid (or a droplet in gas) has a well-known solution (Bird *et al.*, 1960) and can be used to reinforce the arguments applied (1), realizing that such analysis is an oversimplification of the actual flooding process. Considering a sperical-shaped bubble

$$F_d = \frac{\pi \rho_L V_B^2 d^2 \theta}{8} \tag{2}$$

will be the drag force F_d, where V_B is the bubble velocity, d is the diameter, and θ is the drag coefficient. The buoyancy force F_b will be as follows

$$F_b = \frac{(\rho_L - \rho_G)\, g \pi d^3}{6} \tag{3}$$

Equating the drag force to buoyant force and solving for the bubble velocity gives

$$V_B = \sqrt{\frac{4\ dg}{3\theta}\left(\frac{\rho_L - \rho_G}{\rho_L}\right)} \tag{4}$$

For Reynold's numbers greater than 10, which applies to the flow regimes found in plate-type columns, the drag coefficient is constant.

This balance is essentially the same for a droplet falling in gas, except that the density term is $(\rho_L - \rho_G)/\rho_G$ because the drag force in (2) is based on the external flow of the medium around a sphere. When applied to a falling droplet, (4) is remarkably similar in form to (1). For the onset of flooding, the gas velocity V_F must be of the order of the droplet velocity, which yields V_F proportional to $\sqrt{g}$ the same as the result deduced from the empirical correlation in (1). Substituting Q_G/A_n for V_F and solving for A_n gives the proportion

$$A_n \propto \frac{Q_G}{\sqrt{g}} \tag{5}$$

For the specified feed, reflux ratio, and column pressure, Q_G will be essentially the same between the Earth and the Moon, so the net area ratio will scale as

$$\frac{A_n|_M}{A_n|_E} = \sqrt{\frac{g_E}{g_M}} \tag{6}$$

where the subscripts E and M differentiate between the Earth and the Moon.

The scaling of downer area A_d will be dictated by the effects of gravitational forces on liquid flowing downwards in a closed conduit. Considering laminar flow in a vertical pipe, the liquid flow rate Q_L can be expressed (Bird *et al.*, 1960) as

$$Q_L = \frac{(\pi R^2)^2\ \rho_L g}{\pi 8 \mu_L} \tag{7}$$

where R is the radius and μ_L is the liquid viscosity. In general, for a closed conduit, Q_L will be proportional to gA_d^2. For a fixed volume of liquid flow, A_d will be as follows

$$A_d \propto \frac{1}{\sqrt{g}} \tag{8}$$

which gives the scaling ratio

$$\frac{A_d|_M}{A_d|_E} = \sqrt{\frac{g_E}{g_M}} \tag{9}$$

From (6) and (9), the lunar values of A_n and A_d increase by a factor of 2.45 in order to compensate for the one-sixth lunar gravity. For an earthly column 1 m in diameter, the corresponding lunar column would be 1.6 m.

The formation of bubbles with their corresponding interfacial surface area and rising velocity are the most important hydraulic concerns that affect plate efficiency. On a real plate, bubble-liquid interactions are complex. A simplified approach will be used to evaluate the major role of gravitational forces where single bubbles are rising in a body of liquid.

Assuming each plate is well mixed, the efficiency can be expressed as the proportion (Treybal, 1980)

$$E \propto 1 - e^{-k_L ah/V_B} \tag{10}$$

where E is called the Murphree plate efficiency, k_L is the bubble mass transfer coefficient base on the liquid phase, V_B is the bubble velocity, a is the total interfacial surface area, and h is the plate liquid depth. Equation (10) yields the ratio

$$\frac{\ell n\,(1 - E)|_M}{\ell n\,(1 - E)|_E} = \left(\frac{a_M}{a_E}\right)\left(\frac{h_M}{h_E}\right)\left(\frac{k_L|_M}{k_L|_E}\right)\left(\frac{V_B|_E}{V_B|_M}\right) \tag{11}$$

Based on penetration theory, k_L for a rising bubble is equal to (Treybal, 1980)

$$k_L = \left(\frac{D_{ab}}{\pi t}\right)^{1/2} \tag{12}$$

where D_{ab} is the diffusion coefficient and t is a fluid packet-bubble contact time. The contact time will be proportional to bubble diameter divided by bubble velocity, which gives

$$k_L \propto \left(\frac{V_B}{d}\right)^{1/2} \tag{13}$$

The diffusion coefficient is independent of gravity, thus being dropped as an argument. Equation (13) yields the mass transfer coefficient ratio

$$\frac{k_L|_M}{k_L|_E} = \left(\frac{d_E}{d_M}\right)^{1/2}\left(\frac{V_B|_M}{V_B|_E}\right)^{1/2} \tag{14}$$

which combined with (11) gives

$$\frac{\ell n\,(1 - E)|_M}{\ell n\,(1 - E)|_E} = \left(\frac{a_M}{a_E}\right)\left(\frac{h_M}{h_E}\right)\left(\frac{d_E}{d_M}\right)^{1/2}\left(\frac{V_B|_E}{V_B|_M}\right)^{1/2} \tag{15}$$

The rising velocity of a bubble has already been evaluated in (4) and is proportional to $\sqrt{dg}$.

The ratio of bubble velocity between the Earth and the Moon will be as follows

$$\frac{V_B|_M}{V_B|_E} = \sqrt{\left(\frac{g_M}{g_E}\right)\left(\frac{d_M}{d_E}\right)} \tag{16}$$

where the bubble diameter ratio has been included as a possible adjustable parameter.

Consider a bubble forming from gas percolating upwards through a plate hole into a body of liquid. It is important to determine the dependence of bubble mass (hence surface area) to hole diameter and the acceleration due to gravity coupled with the governing fluid properties. In the flow regime for bubble formation typically found on plates, surface tension has the dominating effect with the dependence of fluid viscosity being small. Using the Buckingham Pi method of dimensional analysis, the dimensionless pi group that arises is as follows

$$\pi = \frac{Mg}{\sigma D} \tag{17}$$

where M is the bubble mass, σ is the vapor-liquid surface tension, and D is the plate hole diameter. In order to assure hydraulic similarity, this dimensionless group is held constant between the Earth and the Moon, giving

$$\left.\frac{Mg}{\sigma D}\right|_E = \left.\frac{Mg}{\sigma D}\right|_M \tag{18}$$

There are several possibilities for juggling the parameters described in (15), (16), and (18) in order to scale the plates and determine their efficiencies.

Case I. Constant Bubble Mass

The most likely choice is to maintain constant bubble mass between the Earth and the Moon, which will assure the same bubble diameter and interfacial surface area for mass transfer. The velocity ratio from (16) will then be the following:

$$\frac{V_B|_M}{V_B|_E} = \left(\frac{g_M}{g_E}\right)^{1/2} \tag{19}$$

and

$$\frac{\ell n\,(1-E)|_M}{\ell n\,(1-E)|_E} = \left(\frac{h_M}{h_E}\right)\left(\frac{g_E}{g_M}\right)^{1/4} \tag{20}$$

will be the plate efficiency.

The bubble velocity will be 41% less than that on the Earth due to the one-sixth gravity on the Moon. For the same liquid depth on the plates the contact time will be longer, thus increasing the efficiency and requiring fewer plates for a given separation and a corresponding reduction in column height. The liquid depth could be reduced on lunar plates to maintain the same efficiency, so the number of plates would remain unchanged with plate spacing being reduced. From consideration of plate maintenance and column operation the standard spacings are the most practical, so liquid depth should be kept the same, realizing a shorter column from the increased efficiency. For constant liquid depth, Table 1 shows typical Earth plate efficiencies and their corresponding lunar efficiencies given by (20), which are enhanced by an average of 25%.

Table 1. Earth and Lunar Plate Efficiencies for Constant Bubble Mass and Liquid Depth

$E\|_E$	$E\|_M$
0.4	0.55
0.5	0.66
0.6	0.76
0.7	0.85
0.8	0.92

If bubble mass is to remain the same, (18) can be used to determine the hole diameter in the lunar plates, yielding

$$\frac{D_M}{D_E} = \frac{g_M}{g_E} \tag{21}$$

According to (21), the plate hole diameter for equal bubble masses will have to be six times smaller on the Moon; instead of holes 4–15 mm in diameter, the corresponding lunar perforations will be 0.67–2.5 mm. The pressure drop caused by the smaller holes could possibly increase, preventing the column from operating under vacuum conditions. From Treybal (1980), the pressure drop due to the perforated plate P, is proportional to

$$P \propto \frac{V_h^2}{g} \tag{22}$$

where V_h is the gas velocity through the holes. For holes placed on the corners of equilateral triangles and for equivalent hole diameter to pitch ratios, the increased value of A_n can increase the available hole area, decreasing the gas hole velocity. This can result in a pressure drop on the same order as Earth-based plates. In some instances it may be impossible to specify the smaller holes needed for constant bubble mass without dramatically increasing the pressure drop, making Case I an impractical approach.

Case II. Constant Plate Hole Diameter

For pressure drop consideration, the hole diameter in the plates will remain the same between the Earth and the Moon. From (18) the bubble mass ratio will then be as follows

$$\frac{M_M}{M_E} = \frac{g_E}{g_M} \tag{23}$$

which corresponds to lunar bubbles with six times the mass of earthly ones.

It follows from (23) that

$$\frac{d_M}{d_E} = \left(\frac{g_E}{g_M}\right)^{1/3} \tag{24}$$

is the bubble diameter ratio. The interfacial surface area can be approximated by the area of a single bubble times the number of bubbles. For a fixed Q_G, the number of bubbles, N, will scale inversely with the bubble mass

$$\frac{N_M}{N_E} = \frac{g_M}{g_E} \tag{25}$$

which gives an interfacial surface area ratio of

$$\frac{a_M}{a_E} = \left(\frac{d_M}{d_E}\right)^2 \left(\frac{N_M}{N_E}\right) = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{26}$$

Using (16) and (24), it follows that

$$\frac{V_B\big|_M}{V_B\big|_E} = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{27}$$

will be the bubble velocity ratio.

For constant hole diameter, the lunar plates will produce bubbles with 1.8× the diameter and 55% of the rising velocity and interfacial surface area. Combining (15), (24), (26), and (27) gives

$$\frac{\ell n\,(1 - E)\big|_M}{\ell n\,(1 - E)\big|_E} = \left(\frac{g_M}{g_E}\right)^{1/3} \tag{28}$$

for constant liquid depth. Table 2 shows the lunar plate efficiencies given by (28). The efficiencies decrease by an average of 34%, primarily the result of a significant decrease in the surface area due to the larger bubble diameter.

Table 2. Earth and Lunar Plate Efficiencies for Constant Plate Hole Diameter and Liquid Depth

$E\big\|_E$	$E\big\|_M$
0.4	0.25
0.5	0.32
0.6	0.40
0.7	0.48
0.8	0.59

Case III. Constant Bubble Velocity

Another scaling criterion would be to maintain constant bubble velocity between the Earth and the Moon. From (16), the lunar bubble diameter would have to be 6× larger, which corresponds to a bubble with 216× the mass. Equation (18) dictates a lunar plate hole 36× larger, which does not yield a practical engineering design.

THE LUNAR ENVIRONMENT

The lunar atmosphere has a pressure of 10^{-12} torr, which for most considerations is a total vacuum. One would initially think the way to maintain a vacuum distillation process is to utilize the lunar atmosphere as a giant sink, but there are several reasons why this cannot be done. Purging materials into the lunar atmosphere would be a dreadful waste of resources; these materials, especially organics, will be too valuable to lose even a few percent. The void of the lunar atmosphere itself is also a valuable resource (it is noteworthy to point out that the absence of anything can be a resource). Many scientific investigations can capitalize on the combination of a gravitational setting with a vacuum environment, and the scientific value of a lunar base would significantly decrease if this atmosphere were to be contaminated.

Vacuum distillation will be maintained through the use of the cryogenic temperatures available on the Moon. Temperatures as low as 59 K can be obtained through radiation into space. The column pressure is specified by the lowest temperature available in the overhead condenser; in a lunar environment this will correspond to as low a column pressure as desired. Even "fixed gases" like oxygen, nitrogen, and carbon dioxide can be condensed, eliminating the need for vacuum pumps. The extra cost for vacuum distillation will be in the capital equipment needed to handle the radiation heat loads.

An example of a lunar distillation process would be the production of ethanol from fermentation of organic wastes. The column pressure would be maintained so the fermenter functions as a reboiler, where the alcohol is continuously boiled off at a temperature for optimum yeast growth. The azeotrope could be broken under the low pressure so absolute alcohol would be produced. A two-stage overhead condenser would first remove the condensable vapors, with a second-stage cryogenic condenser that condenses the carbon dioxide (as a solid) and any other fixed gases.

SUMMARY

The establishment of a permanent lunar base will offer some interesting possibilities for the design of distillation processes. The lunar environment will make possible convenient vacuum distillation and will facilitate column insulation. For a lunar column, the net plate and downer areas will increase by a factor of 2.45. The lunar plate efficiencies will either increase by about 25% (for constant bubble mass) or decrease by 34% (for constant hole diameter), the choice depending on the imposed engineering constraints.

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LUNAR MACHINING

William Lewis

Electrical and Computer Engineering Department, Clemson University, Clemson, SC 29634-0915

Chip-making machine tools have traditionally been used to shape iron. Regolith is several tenths percent iron nodules by mass, which could be melted by solar process heat, then cast. Chip-making machine tools may well be used to further shape these castings. Little serious consideration has been given to machine tool design within a lunar context, however. This is a first survey of the problems and opportunities of lunar machining. A conceptual framework for machine tool design is given, then applied assuming lunar operations. It is concluded that there will be a need for small machines operating in shirtsleeve environments, that larger machines will have to be outside in vacuum because they require large, rigid foundations that can sink vibration, and that productivity will be extremely important due to very high labor costs.

Serious consideration is being given to the establishment of a lunar base during the first half of the next century (von Puttkamer, 1976; Duke, 1984). Whether a scientific, industrial, or growth rationale is selected, machine tools will almost certainly be used at the base site. Machine tools may first be used in repair and maintenance of the base itself. Later, more machines might be brought in as support for construction of scientific instruments, construction of industrial plants, construction of more habitats, and manufacture of capital goods.

It is of some intellectual and practical interest to consider the design challenges that must be answered before machine tools can be used in a lunar environment. This short paper will content itself with identifying design challenges and opportunities. Ways of meeting them will be treated only briefly.

KINDS OF MACHINE TOOLS CONSIDERED

Many promising means have been proposed for production of industrially useful raw materials in the lunar environment. The basic physics of the environment are well described in *Advanced Automation for Space Missions* (Freitas and Gilbreath, 1982). Several specific processes have since been proposed, including vitrification of lunar soil (Meek et al., 1984), production of glass fiber cables (Steurer, 1984), production of metal powder (Criswell, 1983), and the carbonyl process (Steigerwald, 1984; Lewis and Meinel, 1983). Fabrication of these raw materials has received less attention, although high technology methods have been discussed, such as David Criswell's work concerning powder metallurgy technology (Criswell, 1983) and an intersecting beam method of mold fabrication coupled with powder metallurgy suggested by David Brin (personal communication, 1984; Schwerzel *et al.*, 1984).

Lunar soil is several tenths of a percent iron spheroids that can be magnetically separated from regolith (Arnold, 1984). Iron may also be a by-product of lunar oxygen production (Cutler, 1984a,b). Furthermore, chip-making machine technology is reliable, simple, and mature. It was the critical manufacturing technology of the Industrial Revolution 200 years ago. It is thus a prime candidate for use under the primitive conditions that will characterize early lunar industry (Cutler, personal communication, 1984).

This paper will consider adaptation of chip-making machines to the lunar environment. It will emphasize adapting the lathe and the milling machine, which may encompass most significant challenges. Iron mining, extraction, and casting are beyond the scope of this paper.

PRINCIPAL DESIGN FACTORS OF MACHINE TOOLS

On Earth, the principal machine tool design factors may be thought of as precision, power, and economy (Doyle, 1961). These are apt to remain the principal factors on the lunar surface. Precision depends on avoidance of inaccuracy in construction, deflection under static or dynamic load, wear, and thermal expansion.

Inaccuracy in construction is avoided through careful control of factory environment and operations, use of precision machine tools, and careful inspection after each stage of manufacturing.

Deflection is minimized by rigidity and properly chosen natural frequency. Deflection can be caused by static loading, due to workpiece and frame weight, and also by dynamic loading, usually caused by eccentric rotation of a mass. Of the two, dynamic loading is usually the greater challenge, as it can cause large amplitude vibration if it is at the natural frequency of the machine tool's frame.

Static deflection is often minimized by massive iron alloy frames, which, for larger machine tools, are coupled to massive concrete foundations.

As a rule of thumb, dynamic deflection can be minimized by a combination of rigidity, low mass, and damping that gives the machine tool frame a natural frequency at least $\sqrt{2}$ (4 is better) times that of the highest exciting force frequency. Alternatively, a combination of rigidity, high mass, and damping can give the frame a natural frequency less than $1/\sqrt{2}$ (1/4 is better) that of the lowest frequency exciting force frequency (Tobias, 1965). However, the spectrum of the exciting force depends largely on the angular velocity of the eccentric mass, which varies during machining. Exciting force frequencies from 0–4000 Hz are commonly encountered during machine start-up and operations (the higher frequencies come from impact loads or gears), and an exciting force spectrum can have several peaks. The frame's natural frequency can also change with machine configuration.

On Earth, an industrial machine tool is rigidly attached to a massive, rigid foundation. If this is not possible, it is attached to a vibration isolation system. This drastically reduces the machine's natural frequency. Typically, one tries to put the natural frequency of the isolation system as far as practical from the nearest peak in the exciting force spectrum characteristic of normal operation and relies on damping to soak up noise and transient resonances during start-up. If the isolation system needs augmenting, dynamic deflection of the machine tool can be reduced by vibration dampers (Tobias, 1965) that dissipate vibrational energy most effectively over some narrow frequency range.

Wear of precision-located sliding way surfaces is reduced by hardened steel ways, by dirt shields, and sometimes by plastic inserts in which chips become embedded before they can damage the ways. Avoiding wear of precision-located shafts may involve a pressurized lubrication system or roller bearings. Should wear occur, it could make the precision surface curved, or could worsen fit and introduce motion hysteresis in the force vs. motion curve. It is difficult for a control system to compensate for either of these. Wear also promotes chatter and vibration with consequent degradation of workpiece surface finish and possible fracturing of the cutting insert. Should significant wear occur, the worn surfaces must either be restored or the machine must be discarded.

Thermal expansion is avoided by not exposing the machine tool to direct sunlight and keeping ambient air at a constant temperature. Of these two, shielding from sunlight is the more important, because local heating can distort the frame. Constant ambient temperature becomes important for precise work such as metering nozzle fabrication.

Power is provided by electric, hydraulic, or pneumatic drives. Conventional drives are bulky and frequently cannot be connected directly to the load. Mechanical energy must be conveyed from drive to load by mechanical elements. For rotary motion, gears and belts are commonly used. For linear motion, the pinion and rack, the screw and nut, and the crank are commonly used. All of these mechanical elements add flexibility, stick slip, and, frequently, force vs. motion hysteresis. Such effects are minimized only by maintenance of very small tolerances, which make these elements difficult to produce, hence expensive.

Economy of operation involves proper operating controls, provisions for safety, and facilities for changing jobs. Operating controls have tended to become increasingly automatic, so that for some systems of machine tools no direct labor is required, only monitoring. Safety features also have tended to involve automatic operation. Job changeover is a surprisingly important part of machine economy. The machine produced nothing during changeovers, so changeover time must be minimized. Contemporary practice favors use of pallets, downloading NC programs, and various shop floor control methods. General purpose machines tend to change over more rapidly than special purpose machines, accept a wider range of work, and are idle less. Conversely, they cannot be made as rigid as special purpose machines, and hence they remove metal more slowly.

Economy in construction and maintenance may involve the use of standardized component parts, such as the base, headstock, or saddle. These can be combined at times in novel ways to produce a special purpose machine tool.

This is summarized in Table 1, Primary Challenges.

ADDITIONAL DESIGN FACTORS FOR THE LUNAR SURFACE

Precision, power, and economy will be just as important on the lunar surface as they are on Earth but may be designed into the tools differently. Let us first consider the unique characteristics of the lunar operating environment.

Pressure Vessels

A large machine tool must generally be fixed to a massive foundation that provides rigidity and couples vibration to the soil. Such large tools cannot be simply bolted to

Table 1. Primary Challenges

Precision:
  - Vibration (grounding, or isolation and damping)
  - "Unsagging" in reduced gravity
  - Wear (in vacuum operation)
  - Thermal environment

Power:
  - Heat dissipation
  - Energy source (beyond scope of this paper)

Economy:
  - Labor requirements
  - Transportation costs from Earth

a pressure vessel. They would distort under load, lose accuracy, and shake the entire vessel. These effects are especially pronounced at low cutting speeds, which generate high cutting forces at low frequency. The cutting forces can be reduced by use of lubricating cutting fluid or a modified cutting tool geometry (Trent, 1977).

Smaller machine tools do not require rigid foundations. Resilient supports can be placed directly between the machine tool and the shop floor if the exciting forces are small in comparison with the machine tools' weight and if the machine tool frame is sufficiently rigid. In most cases, these supports need not even be fixed to the floor, since hardly any dynamic force is developed at the point of support (Makhult, 1977).

If the natural freqencies of the pressure vessel can be determined, vibrational dampers tuned to these frequencies can be added. Practical dampers frequently use rubber for the spring/dashpot. Effectiveness depends on many factors, including the natural frequencies of the machine tool, the spectrum of the exciting force, and the range of movement tolerable in the damper (Tobias, 1965).

Environment within the vessel is affected by debris from the machine tool. This includes vapor and droplets of cutting fluid, ozone and heat from electric motors, chips and chip fragments, lubricant vapors, and the many other things that make a machine shop a messy environment, wherever it may be. High accuracy operations require constant air temperature. This should be part of the base thermal control system's design criteria.

Vacuum

If a machine tool is operated in vacuum, heat dissipation by convection cannot occur. Heat dissipation by conduction and radiation is typically less efficient than convective cooling. Most of the waste heat from chip formation stays in the chip and thus will probably not be a serious problem (Trent, 1977). Heat dissipation from power and control units could be a challenge. Finally, exposure to direct sunlight could cause significant local heating and thermally warp the frame.

Vacuum operation could also create unoxidized free surfaces, particularly during chip formation. If the surface freshly uncovered during chip formation is not exposed to an oxidizing agent, chip-tool relations are changed. Edward Trent (1977) observed substantial increases in chip thickness and in cutting force when machining iron at atmospheric pressures below 0.001 mbar, apparently due to a substantially increased area of contact between chip and tool. Introduction of air, even at very low pressure, eliminated this effect. Trent suggested that unoxidized free surfaces seize against the cutting tool more strongly than do oxidized surfaces.

Wear at exposed bearing surfaces could lead to vacuum welding and rapid failure. Contamination by lunar dust is an additional environmental hazard. On the other hand, deliberate creation of precision unoxidized free surfaces in conjunction with locator pins/ holes could permit use of vacuum welding in construction of structures.

Gravitational Field

Reduced weight in the weaker lunar gravitational field will reduce frame self loading and will reduce the resulting sag to 1/6 of its Earth value (assuming elastic deformation and superposition). If a complex geometry superimposes several strains, a significant loss of accuracy may result. Machining forces are fairly small [several tens or hundreds of Kgf or lbf, several thousand N (Trent, 1977)] compared to workpiece weight, which is at most comparable to frame weight. Wayne R. Moore, a machine tool designer and fabricator, has put together a very interesting book (Moore, 1970) on machine tool accuracy. He emphasizes the importance of inspecting and correcting high precision machines under expected conditions of use and the importance of appreciating droop caused by cantilevering. Reduction of frame self loading could cause precision linear surfaces machined into the top of cantilevered frame members to curve upward into a ski jump shape. This could be significant for large or very high precision machine tools.

Workpiece weight will also be reduced. The primary effect may simply be to ease loading and unloading, since fixturing and not workpiece weight holds the workpiece to the work table. However, an eccentrically mounted, massive, and rapidly rotating workpiece could conceivably throw itself and an unsecured machine tool off its foundation in 1/6 g.

Reduced acceleration of freely falling bodies in lunar gravity will affect dispersion patterns of debris leaving the machine tool. Chip and cutting fluid dispersion would be increased. More seriously, rotating parts released through latch failure would travel further or would hit overhead surfaces at greater velocity than on Earth.

Transportation Costs

Transportation costs to the lunar surface are thought to be in the range of $3,000 to $15,000 per kilogram (Duke, 1984). While not directly affecting precision or power, these costs will have a strong influence on machine tool design. One could design very light and compact machine tools, or design heavy machine tools and fabricate the most massive components from lunar materials on the lunar surface.

Transportation costs will determine labor costs. People must be transported to the lunar base, and until controlled ecological life support system (CELSS) technology is developed and applied, their food must be brought up from Earth as well. The labor pool will accordingly be small. An initial base complement of something less than 20, and perhaps as few as 2, seems plausible. Support facilities will be less developed than those on Earth, including both recreation and training facilities. Additionally, work in a vacuum will involve either pressure suits or teleoperators, both of which reduce effectiveness. Work inside pressure vessels could be hampered by limited area and volume. The net result could be a small, expensive, but not very productive work force. Automation, teleoperation from Earth, and attention to habitat design could increase work force fitness.

Transportation costs will also determine material supply costs. Spare parts from Earth will be expensive, as will consumables such as cutting inserts, cutting fluid, and lubricants. Importation of an adequate inventory may well be deferred indefinitely. In the worst case, one could combine highly expensive repairs with long waits for spare parts. Proper attention to inventory requirements during planning will be essential.

Lunar design challenges are described in Table 2.

Table 2. Recommendations

Vibration:
- Operate smaller machines inside pressure vessel and isolate/damp vibration.
- Operate large machines in vacuum and sink vibration into massive foundation.

Unsagging:
- Correction if necessary at the lunar base.

Wear (in vacuum):
- Avoid vacuum welding.
- Avoid lunar grit contamination.

Thermal environment:
- Avoid sunlight in vacuum operation.
- Keep air temperature constant for high precision work in pressure vessels.
- Alternately, fabricate machine tools from zero coefficient of expansion composite material.

Power:
- Consider heat dissipation in base thermal budget and in machine design.

Economy:
- Automate or teleoperate material handling, setup, and operation to minimize labor requirements.
- Minimize transport cost by designing light machine tools *or* fabricating some machine tool elements at the lunar base.

DISCUSSION

The design challenges for a lunar base suggest that there will be two classes of machining: light duty machining inside and heavy duty machining outside. Light duty machining will be needed for base maintenance. Fortunately, inside, light duty machining requires only the design of a light duty, vibration isolated/damped, general purpose, but productive and accurate machine tool. Heavy duty machine tools pose more of a design challenge. They must operate in vacuum, require minimal oversight, and involve minimal haulage costs from Earth.

Technology Mix

The design challenges listed above are not those of Earth; consequently, we can expect a different technology mix. In the early days, the lunar machine tool will be entirely Earth-made and will combine low mass, reliability, versatility, and high productivity with high purchase price and a limited work volume. It may employ conventional technology within these limits, or may employ unusually high levels of automation, composite material, and unusually high power, high torque electric motors. The design goal would be to maximize productivity and minimize mass and shipping bulk.

From the second generation on, machines could be made partly on the Moon and partly on Earth. The economic issues here are more complex than may at first be apparent. Goldberg and Criswell (1981) have considered the general case. For the specific case of machine tools, the "make/buy" decision on the Moon will primarily involve the number of hours required to make an item, the marginal cost of these hours, the mass and geometry of the item to be made, the marginal cost of shipping this mass and geometry, and (as a secondary consideration) the salary of the people doing the work and the cost of the item if bought. Ordinarily, these discussions would be dominated by the primary considerations; one would choose the cheaper of marginal labor and marginal shipping. If assembly is feasible, one would expect massive parts to be made on the Moon [a 37 kW, 127-cm swing lathe masses about 21,400 kg (Doyle, 1961), most of which is frame] and precision parts, electronics, software, motors, and other goods whose manufacture requires extensive industrial plant, to be brought from Earth. The lunar machine tool may thus, in the medium range, be a mix of sophisticated, low mass components brought from Earth and very crude, but high mass components made at the lunar base.

Drivers

Over time, one can say that the technology mix will be driven first by labor costs, then by shipping costs from Earth, and eventually by material import costs. These different drivers will give rise to a mix of sophisticated and crude technologies that, however inappropriate they would be on Earth, will be quite functional on the Moon.

Side Effects

Lunar machine tools will generate seismic waves and will emit gases and vapors. These effects would not materially add to those of a moderate-sized (20-person) lunar base with supply rockets, construction equipment, and mining operations. A small, vibration isolated machine tool should have few or no significant side effects if kept in a pressure vessel.

SUMMARY OF RECOMMENDATIONS

The lunar environment poses unique, but partially predictable, challenges in machine tool design. The primary initial challenge appears to be the design of a light duty, small table, ultralight, ultrareliable, ultraversatile, vibration isolated, vibration damping, numerically controlled machine tool to be operated in a shirtsleeve environment for base maintenance. It might machine parts of up to 1 foot (30 cm) in longest dimension. This machine will be needed soon after the establishment of a permanently manned base.

A second challenge appears to be the design of a large, light, ultrareliable, numerically controlled lathe to be operated on a massive foundation in a vacuum. It might have a 30-inch (76-cm) throw, 7 feet (2 m) between centers and require 25 kW. Operation of this machine must be automated to the maximum extent possible. Consideration should be given to artificial intelligence, robotics, teleoperation from the lunar base, and teleoperation from Earth. If several are installed, attention should be given to material-handling between machines.

The large lathe could machine massive frames for small rolling mills, supports for solar furnaces, and frames for unpressurized but radiation-shielded work areas. It could machine and polish large iron mirrors for a solar furnace. It could, in conjunction with the light duty machine tool, make most elements of crude, but effective, machine tools. Much of the mass in lunar industry would be in such elements.

Table 3 describes a starter kit that could address the first two challenges.

Table 3. Starter Kit

- First, introduce a small, light duty, versatile machine tool for use inside base for maintenance and repair.
- After base is well established, introduce a large, heavy duty machine tool for use in vacuum, to machine large structural elements.
- Machine iron castings to make frames for mining equipment, machines, solar mirrors, machine tools, and other massive capital goods. This will require both the small and large machines above. Import fittings from Earth, assemble on Moon.
- Benefit is greatest for more massive frames and smaller assembly and machining times.

The final foreseeable challenge is expansion. Processes will become less crude and the range of available materials higher as the economy grows. This will mark the emergence of a self-sustaining lunar economy using lunar materials, a springboard to a true lunar industry and a true lunar society.

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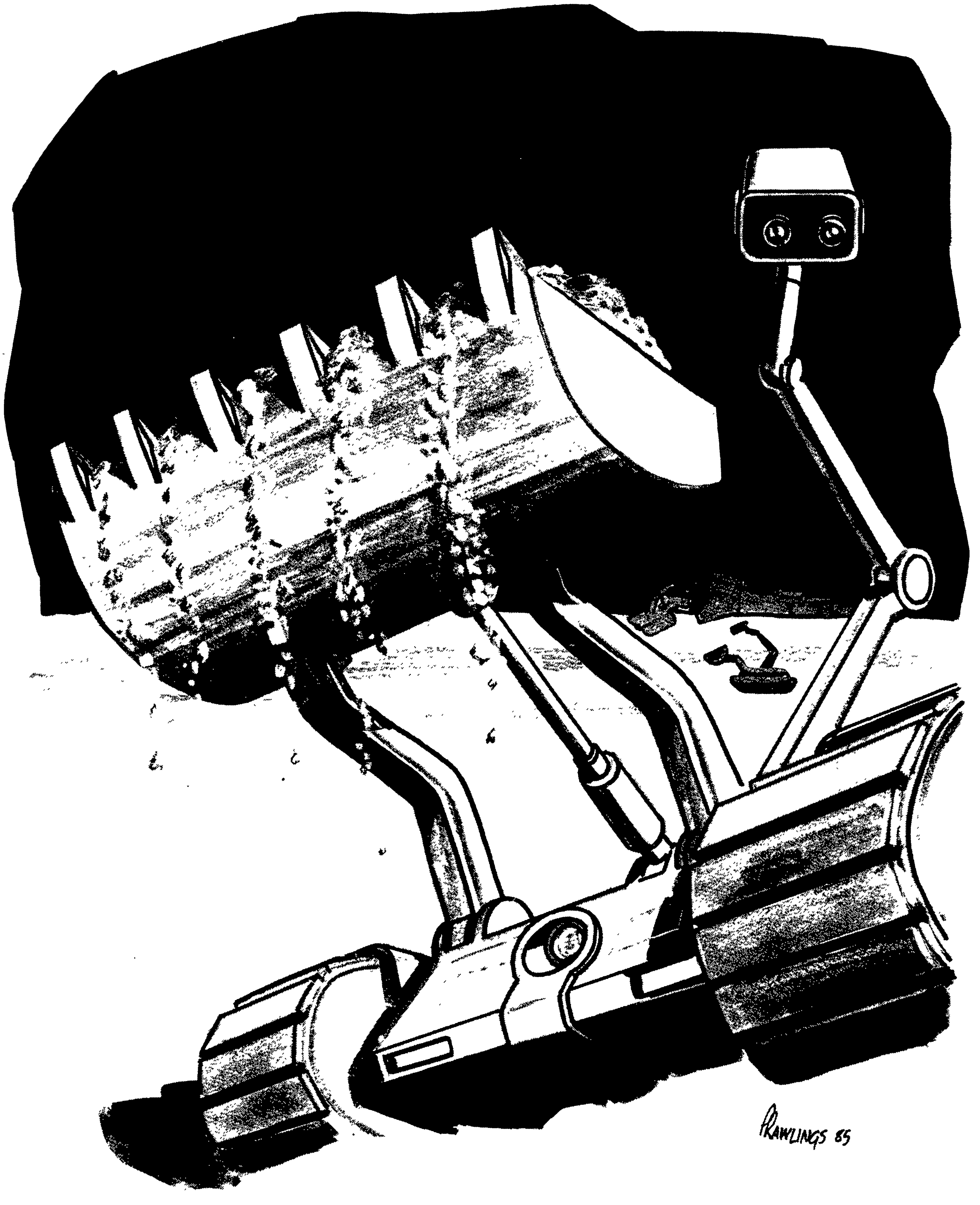
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