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Report of Workshop on Methodology for Evaluating Potential Lunar Resource Sites

Richard J. Williams and
Norman Hubbard

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ATTENDEES

James Burke
Jet Propulsion Laboratory

David Carrier
Bromwell Engineering

David R. Criswell
Lunar and Planetary Institute

Everett K. Gibson, Jr.
NASA Johnson Space Center

James R. Grote
University of Miami

Norman Hubbard
NASA Johnson Space Center

Michail T. Hyson
California Institute of Technology

James J. Jadwick
Lockheed Electronics Company

David L. Kuck
Geological and Mining Consultant

Thomas R. McGetchin
Lunar and Planetary Institute

Wendell Mendell
NASA Johnson Space Center

Richard R. Richard
NASA Johnson Space Center

David H. Scott
U.S. Geological Survey

David W. Strangway
University of Toronto

Robert D. Waldron
Lunar and Planetary Institute

Richard J. Williams
NASA Johnson Space Center

Stan H. Zisk
Haystock Observatory

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Although it may be several decades before we actually utilize lunar resources in space activities, the lead times to develop and implement such utilization will also require several decades, and thus it is pertinent to examine the technical requirements for utilization now. The evaluation of potential sites where lunar resources might be mined and processed is an essential step in a program of resource utilization.

The complexity of the evaluation process - and, as a consequence, the complexity of research and development efforts to develop the tools that would be used to perform the evaluation - depends on the type of resource desired and the location of the site. The one factor common to all scenarios is a requirement for accurate topographic data. For the Apollo landing sites, these data already exist in usable form; for sites under the groundtracks of the later Apollo missions, the data exist but need to be reduced to usable form; for other sites, adequate data sets do not exist.

The chemical and mineralogical specificity with which the desired resource must be known is strongly dependent on the processes used to convert that resource to useful products. Geochemical and geophysical instrumentation now exists that, at least in the laboratory, can perform the required characterizations. The major problem appears to be developing automated and semi-automated systems that can collect and process the required data and make "intelligent" decisions based on those data. This data-handling capacity needs to be combined with a higher degree of autonomous mobility than is currently available.

A prudent yet aggressive research and development program would include the development of physical and chemical lunar soil simulants; the production of a map of lunar resources covering all the areas of the Moon covered by Apollo photography and incorporating information from the many geological, geochemical, and geophysical data sets now available; the development of robotics systems with emphasis on increased autonomy of the system; and development of a processing technology so that a technologically reasonable choice of utilization scenario could be made.

INTRODUCTION

Lunar resources are expected to one day be important in man's expanding use of space. Although the utilization of lunar resources is not imminent, a careful examination of the many preliminary and enabling steps of this enterprise is appropriate now because the lead time for such utilization is long, perhaps as much as 30 years. One essential step is the evaluation of potential sites where lunar resources might be mined and processed. The thorough evaluation of some sites is an undertaking similar in scope and complexity to that required for an Apollo landing, whereas, for those sites at which Apollo landed, almost all the necessary data are presently available.

The goals of this workshop were (1) to determine the major features and requirements of the evaluation process, (2) to determine the major foreseeable factors that will determine and limit the methodology that can be applied, (3) to survey the current and anticipated state of analytical instrumentation and techniques and spacecraft capabilities, and (4) to identify the critical tasks that must be accomplished so that the tools will be available when needed. Some of the information assembled in this document will be of value to other NASA activities; e.g., the discussion of lunar rovers and the instrumentation that they might carry is especially relevant to considerations of in situ study of other planetary bodies. Hopefully, this document will be of value in two ways. First, it will describe the magnitude of the exploration phase of lunar resource utilization, given a variety of assumptions about the resource sought. Second, it will consider the research and development (R&D) items that were identified during the study and that are seriously suggested for implementation. These R&D tasks are the quintessence of this work. The workshop analysis examined five major topics - lunar resources, geological studies, geophysical studies, geochemical instrumentation, and robotics; these topics make up the body of this report.

The complexity of the exploration is a function of the type of resource and of the level of existing knowledge. The three distinct end-member-type resources are as follows.

1. Bulk soil is used with no beneficiation beyond simple size sorting and with no strong preference as to location or composition except, e.g., a choice between mare and highland sites.

2. A deliberate effort is made to optimize the resource site within the bounds of what is now known about the Moon; e.g., one might seek to exploit the highest titanium concentration observed from orbit or in samples returned by the Apollo missions or one might seek a concentration of a specific mineral.

3. A search is made beyond the zone of present knowledge and unique or exotic new resources are found; e.g., cold-trapped polar ice or other useful substances concentrated by geologic processes peculiar to the Moon.

In the first case, the initial goal would be to take an average lunar soil and submit it to physical and chemical processes, resulting in a useful range of products such as metals, silica, and oxygen. Little or no lunar exploration would be required.

In the second case, research would be conducted using existing samples and other data to define a best raw material. A process would then be designed to handle this material as "feedstock," and, finally, a site survey (using an orbiter and a surface rover) for the material would be made on the Moon to determine the best location for the process demonstration.

In the third case, several developments would be pursued in parallel. Theoretical studies would be intensified to assess the prospects for finding exotic resources and a search for rare or unusual things would be made through the entire existing collection of samples and data. A polar orbiter with a variety of remote-sensing instruments would be launched to survey the entire Moon and, depending on what was found, one or more rovers would be dispatched to confirm and map in detail the deposits of highly concentrated resources.

These three scenarios roughly span the various classes of quarry and mine development on Earth. The first resembles mere earth-moving for roads; the second resembles the mining of abundant materials, such as sand and gravel; and the third is analogous to the development of rare and concentrated resources, such as metal ores. In all three cases, the first major step is an Earth-based simulation of the processing to be carried out on the Moon. In the first and second scenarios, this Earth-based demonstration could be conducted using real lunar material, but it would probably be prudent to do much of the needed R&D using a prepared lunar material simulant made from Earth rocks. In the third scenario, the making of the simulant would itself be a research goal.

These three possible paths and the major R&D activities involved in each are summarized in table I. Specific R&D tasks within each of these major activities are described in other sections of this report.

This document originated as a draft prepared by James Burke, Roger Phillips, Norman Hubbard, David Scott, and Richard Williams. The draft was discussed, revised, and amended during a 4-day workshop held at the Lunar and Planetary Institute (LPI), November 14-17, 1978. The authors wish to express appreciation to Sue Wilson (Lyndon B. Johnson Space Center (JSC)) and to Carolyn Kohring and other LPI staff members who made the work easier by transcribing the many handwritten pages produced during the workshop.

Finally, considerable time could have been spent creating a smoothed overall presentation of the material developed during the workshop or sections could have been compiled that reflected points of view without any attempt at integration. Insofar as possible, an attempt has been made to pursue the first method rather than the second. Thus, several participants will find that their inputs have been absorbed into one or two sections of this document rather than standing alone. An effort has been made not to significantly alter any points of view in this process.

In compliance with NASA's publication policy, the original units of measure have been converted to the equivalent value in the Systéme International d'Unites (SI). As an aid to the reader, the SI units are written first and the original units are written parenthetically thereafter.

LUNAR RESOURCES

In order to perform work or conduct research in space, some manmade structures are needed. Structures up to the size of the Apollo spacecraft/Saturn IV-B launch vehicle combination are assembled on Earth and launched as a complete unit. Structures that are much larger could be launched in pieces and assembled in orbit. This procedure would allow Earth-based high-level technology to be used to produce and test a highly complex satellite at leisure in the relatively "kind" environment of the Earth's surface. Conversely, if very large structures of relatively low inherent complexity are to be constructed for either applied or research use, it may be desirable to use lunar materials in their construction. The primary reason for considering the use of lunar materials is the savings expected by using materials from the Moon rather than those brought from Earth. Theoretically, the energy required to go from the Moon to geosynchronous orbit is only 4.5 percent of that required to go there from the Earth's surface. Launch from the airless lunar surface might even be accomplished using motor-driven launch facilities (ref. 1).

The practicality of constructing large space structures using lunar materials requires the resolution of a number of complex technical and economic issues, as well as a better understanding of scenarios for the use of space. Most of these issues can be summarized as the following set of questions:

What are the materials needed for large-scale activities in space?
What lunar materials exist that can meet these needs?
What processes can convert these lunar materials into relevant products?
What are the economics of a system that can accomplish this?

It was impractical to evaluate all these issues during the workshop because the presently proposed scenarios range from visionary to very conservative and because the technical and economic issues can only be resolved by an iterative process that has only just begun. The course of action that results in the use of lunar materials for space construction should be determined from a very large range of possibilities and from the particular requirements of the space structure to be built. Only the first three questions posed above and only answers that are useful for addressing the issues affecting the exploration for lunar resources have been considered.

Material Needs of Large-Scale Space Activities

A wide variety of satellite systems has been proposed for the 1980 to 2000 time frame (table II). Although plans exist for all these systems, the best defined satellite system is the Satellite Power System (SPS) (refs. 4 and 5). Recent study results (ref. 3) have demonstrated that all scenarios that incorporate the SPS are dominated by its material needs and the materials that are needed to construct an SPS are mainly the same as those necessary to construct the other systems. Therefore, the SPS is used as a materials-need model.

Briefly, the SPS is a large photovoltaic array that converts solar radiation into microwaves for transmission to Earth and ultimate use as electrical power. Each of these satellites has a mass of nearly 97 000 megagrams (97 000 metric tons) and more than 100 satellites would be built over a 30-year period. Thus, this construction program needs nearly 10 000 000 megagrams (10 000 000 metric tons) of satellite-specific material.

The necessary materials include a wide range of substances but only a few are needed in large amounts. Glasses, fused silica, or silica with minor additives account for 30.3 percent of the amount needed; silicon, for 15.1 percent; aluminum, for 11.4 percent; and iron, for 5.7 percent (table III). By various substitutions (ref. 3), some of which are straightforward (e.g., substituting aluminum for copper in electrical conditions) and some of which are more complex (e.g., using foamed glass to replace graphite composite), the amounts needed may be changed somewhat; but the basic pattern remains. Silica, silicon, aluminum, and iron are needed in total quantities on the order of 7 000 000 megagrams (7 000 000 metric tons) for an SPS program.

It should be emphasized that, for the purposes of outlining the goals and difficulties of a lunar resource exploration program, the exact form of the structure to be built is irrelevant. The basic requirements, which appear in the SPS design, are expected to be universal: (1) a structural framework, essentially of aluminum, glass, or a composite; (2) a power system using photovoltaic cells and metals (heat engines may require additional consideration and might shift the balance of materials somewhat); and (3) a complex of high-technology machinery, probably of much smaller mass than the remainder of the structure and hence a candidate for partial or complete manufacture on Earth. The quantity and quality of material might vary drastically with different space construction scenarios, but the structural and electrical needs will be nearly invariant and could be met from the silicon, silica, aluminum, iron, and other materials available in the lunar soil.

Requirements also exist for oxygen (primarily for propulsion systems and secondarily for life support) and water (for cooling and for life support). However, recent studies (e.g., ref. 3) have indicated that, with the exception of oxygen for use in propulsion systems, these requirements are relatively minor. Oxygen should be a natural byproduct of metal recovery from silicates and oxides and thus is not considered explicitly as a resource. If an indigenous source of water were available, process design would be easier and the overall risk would be reduced. Water is thus considered to be a desirable but not a necessary resource.

Possible Lunar Resources

The manned and unmanned exploration of the Moon has revealed much about its internal structure and the distribution, composition, age, and origin of the principal lunar surface units. These revelations were startling in that all the pre-Apollo models of the Moon were incomplete in some essential way. Several recent reviews of lunar science and of the chemical, physical, and mineralogic properties of the lunar materials have been prepared (refs. 6, 7, and 8) and will not be repeated here.

With respect to lunar resources, the scientific discoveries have emphasized the important fundamental differences between the Moon and the Earth. The Earth has a vigorously convecting interior; its crust and uppermost mantle consist of rigid plates that move relative to one another at velocities of several centimeters each year. Terrestrial mineral and energy resources are concentrated by processes that occur at these plate boundaries and in nearly all cases water or other fluids play a fundamental role in the concentration processes. The Moon's interior is essentially dead; it has no evidence of either plate tectonics or water and thus finding terrestrial-type ore deposits on the Moon is not anticipated.

Known lunar resources are predominantly found in the Moon's major chemical and physical features. The basic geology of the Moon is that of a fundamental dichotomy between the dark-colored iron- and titanium-rich materials that fill the mare basins and the light-colored aluminum- and plagioclase-rich materials that comprise the lunar highlands (fig. 1). Throughout its history, the Moon has been subjected to bombardment by meteorites, which has reduced its surface to a ubiquitous layer of rubble and fine dust (called the regolith) that is everywhere a few meters deep. It is the regolith - and the rocks, minerals, and glasses of which it is composed - that contains the primary lunar resources from which the needed metals and glasses are to be obtained.

It must be emphasized that only a small portion of the Moon has been sampled at the nine Apollo and Luna sites (fig. 2) and only about 10 percent of the returned samples have been examined in detail. Consequently, surprises may yet appear; indeed, Earth-based telescopic studies (ref. 9) show that only one-third of the major lunar basalt types were sampled by an Apollo mission, and there are theoretical reasons to suspect that water ices may exist near the lunar poles (refs. 10 and 11).

Of the materials needed for large-scale satellite systems, the easiest to obtain will be the glasses, which can either be extracted from the regolith or formed by fusing the soil. Colorless glasses will predominate in the highlands. Silicon, chemically combined, is ubiquitous and occurs at nearly the same concentration at all sites. Aluminum is enriched at highland sites that contain concentrations of the mineral plagioclase ($CaAl_2Si_2O_8$). However, local variation in aluminum content (at the 10-kilometer scale) of as much as a factor of 2 (relative to magnesium) is known, and careful site selection would thus optimize the aluminum content by a significant factor. Iron and titanium are enriched at the mare sites, primarily because these sites contain concentrations of the mineral ilmenite ($FeTiO_3$); there are also sites that contain iron-enriched bulk compositions without high titanium (e.g., Luna 24).

In summary, it appears that the major needs for satellite construction can be met from lunar resources. In fact, on the basis of existing knowledge, sites can be selected that optimize access to one or more of the material needs with relative ease.

Exotic Resources

There are some exotic materials that, if present in the Moon, would greatly enhance the appeal of lunar resources and simplify their exploitation. Foremost among these are water and other volatiles. The possibility that water has been trapped in the cold traps associated with the permanently shadowed regions near the poles has been extensively discussed (ref. 11). Because of the special problems in the exploration and exploitation of these resources, they are discussed separately.

The volatiles carbon, hydrogen, nitrogen, and noble gases are generally derived from the solar wind, although some may also be derived from outgassing of the Moon and from meteorites that have impacted the Moon during its history. Volatiles from both sources tend to be most concentrated in the fine-grained soil fraction. Other volatiles, such as chlorine, fluorine, and sulfur, are known to be concentrated in the dark mantle material and in regions with orange soil (such as the Apollo 17 site).

Several trace elements, such as zinc, cadmium, indium, mercury, lead, germanium, and the halogens, which generally occur in surface materials in concentrations of 10 to 0.001 ppm, also readily undergo volatilization and migration on the lunar surface due to the heating and melting of soils by solar radiation and meteorite impacts. As a result, these elements are often found in considerably higher concentrations in areas shadowed by large rocks and on grain surfaces of the finest grain sizes of soils.

The concentration of indigenous water in lunar basalts is vanishingly small (<10 ppm) compared to that in terrestrial rocks and is generally difficult to distinguish from terrestrial contamination. Essentially all water found in lunar soils has been formed by the interaction of solar-wind hydrogen with oxygen-bearing silicates. Of all these possible exotic resources, hydrogen is the most interesting because it is essential to making water.

It now appears that there are three potential sources of hydrogen on the Moon: solar-wind hydrogen is implanted in soil grains; ice may exist in shadowed polar regions; and volatiles may still be trapped below the surface in volcanic areas. Of these three possibilities, the first is certain but the quantity of hydrogen is very small (approximately 0.33 cubic centimeter at standard temperature and pressure per gram of soil); the second seems theoretically quite likely (refs. 10 and 11) but no relevant measurements have yet been made; and the third is speculative and controversial. Prospecting methods are discussed here in two classes: (1) methods for developing the known solar-wind hydrogen resource and (2) methods for finding one or both of the other two resources if they exist and developing them if found.

Solar-wind hydrogen recovery.- Solar protons (and other solar products such as noble gas atoms) are found implanted in lunar soil particles, mostly within a few hundred angstroms of the grain surface, where they can be easily extracted by heating the soil to a few hundred degrees centigrade. The main problem is that a lot of material must be processed to get a small amount of hydrogen, perhaps 50 grams per ton; however, if this amount can be obtained as a byproduct of another process, it may be worthwhile to at least provide a makeup source for maintaining a recycled hydrogen supply on the Moon. This solar-wind hydrogen source is presumably available in all mature lunar soils, so it generates no special prospecting or survey needs. It may, however, generate a need for processing R&D; e.g., two ways of extracting the hydrogen are to transport the soil past a heat source or to transport a heat source (and a hydrogen collector) over the surface of the Moon.

Recovery of lunar polar ice.- Recovery of lunar polar ice presents a totally different problem because the existence of the resource is unproven. The most logical way to establish the existence of lunar polar ice is to orbit a polar orbiter with a gamma-ray spectrometer and neutron detectors (ref. 12). However, the cold-trapped ice could also be investigated by a surface rover - provided that this rover could operate in the dark and out of sight of the Earth.

To establish the existence of polar ice, the orbiter need have a surface resolution no better than tens of kilometers. Considerable integration time is required because of the low gamma-ray and neutron fluxes (ref. 12), but this is not a great problem because of the orbiter's repeated passage over the lunar poles.

Because practical ice mining may be limited to the top few meters of ice-laden soil (which may be beneath a dry overburden), vertical resolution in the data is not important; the intrinsic properties of the orbital gamma-ray measurement are such that it detects hydrogen to a depth of tens of centimeters. From a longer-range programmatic standpoint, it is desirable to determine whether the polar permafrost extends to kilometer depths. Onsite active seismic or electromagnetic soundings could determine this; however, for the initial resource explorations, this deeper ice prospecting is not essential.

"Anomalous" lunar hydrogen.- Because all current lunar data show the lunar crust to be generally very deficient in volatiles, the prospect of finding a hydrogen source, such as a trapped body of volcanic water, appears very remote. Nevertheless, there are some as-yet-unexplained phenomena that should be investigated, primarily for their intrinsic scientific interest but also as possible volatile-resource "long shots."

Some of these phenomena are found in the Marius Hills volcanic complex, the Aristarchus region (including the Prinz Rilles (fig. 3) with their strange collapse-like depressions), and the various apparently endogenic features (circumferential cracks, dark-halo craters, etc.) that appear around the margins of maria and large craters such as Alphonsus. A surface rover with gamma-ray, neutron, X-ray, electromagnetic-sounding, and seismic and magnetic sensors can investigate these anomalous regions, provided that its mobility is high enough to permit traversing the features of interest. The Apollo 15 astronauts stood on the brink of Hadley Rille (fig. 4), but they could not safely descend into it. To examine possibly endogenic collapse features, it will probably be necessary to get close to the source and also to drill as deeply as possible, at least with a soft-soil auger. The horizontal resolution of the rover measurements probably need be no better than tens of meters, and the vertical resolution on the depth to ice or other volatiles will probably be of the same order (except in the drill cores) because of the limitations of the instrumental technique. Whether such a mission can unequivocally detect an exploitable subsurface source of volcanic volatiles remains an unanswered question. Table IV presents a summary of the key issues involved in the exploration for these various types of lunar hydrogen.

Processes for Lunar Resource Use

To use a lunar resource in the construction of large space structures, it must be mined, the ore beneficiated and refined, and the refined products manufactured into usable items. For this study, the important consideration is whether the activities that need to be done to use a lunar resource place constraints on the exploration.

Manufacturing.- Manufacturing converts refined metals, chemicals, and gases into the products needed. The processes are varied and complex; however, they do not influence the type of exploration data that will be needed.

Refining.- The refining processes that could be used to convert ores into metals, glasses, chemicals, or gases for subsequent use fall into three broad categories: those that use primarily chemical means, those that use electrical means, and those that use thermal means. In fact, most processes are hybrid in that all three means are used. Several processes have been studied in some detail (e.g., refs. 13, 14, and 15). At the present level of knowledge, only the chemical, mineralogical, and physical states of the material appear to be essential. Apparently, neither minor nor trace elements affect any of the processes.

Beneficiation.- The process of winning the desired mineral or glass fraction from the mineral material is profoundly affected by the physical and mineralogical characteristics of the ore. Current interest has centered on electromagnetic and electrostatic techniques for beneficiation (refs. 15 and 16) because they are ideally suited to operation without a fluid medium. These techniques are highly empirical and must be adjusted in real time to produce the best results. They are strong candidates for the processes that must be tested directly on the lunar surface. Although these processes need development, there is nothing presently known that constrains exploration.

Mining.- The studies of lunar mining have focused on the regolith because of the ease with which it can be mined; however, some earlier researchers did consider hard-rock techniques that offer access to mineralogically simpler material. This primary difference profoundly influences exploration strategy and there is no unequivocal way to choose between them. However, current reasoning strongly favors regolith mining because it has been more throughly studied.

There are two basic concepts for regolith mining: one uses conveyors as an ore transport system (e.g., ref. 16) and the other uses trucks (e.g., ref. 15). In both systems, the single dominant factor determining the scale of the operation is the grade of the deposit. The higher the grade, the smaller the mine and transport system. It is essential that the mineralogy of the deposit be known for scaling these operations.

The topography of a candidate mine site must be known within a resolution of 10 meters for detailed planning of the mining operations. For a very long mass-driver (up to 40 kilometers) (ref. 1), topography would have to be known with a resolution of 1 meter. This higher resolution is required because a small change in elevation can make an enormous difference in the volume of cut and fill required. Photographic coverage of much of the equatorial belt (fig. 5) on the lunar surface is already available and could be used to construct such topographical maps.

Finally, most recent studies have suggested that the mining should be either automated or remotely controlled. In either case, it will be necessary to have intelligent machines that can avoid hazards such as craters and boulders. A previously determined mining plan is also necessary so that the cuts are made in material of consistent grade and buried hazards can be avoided. The site should be relatively free of boulders (less than 10 percent covered) so that mining plans do not become too complex. Table V presents the primary constraints developed from the evaluations of resource models.

GEOLOGICAL METHODS

This section has three major purposes: (1) to briefly describe the background and current state of geologic knowledge of the Moon as they relate to the evaluation of lunar resources, (2) to describe the geologic data that exist but that have not been systematically studied to improve our understanding of many areas on the Moon, and (3) to outline programs of study leading to the further evaluation and ultimate selection of lunar resource sites and to determine the level of effort required for this evaluation. A preliminary list of tentative resource sites is included as is a brief discussion of the more obvious steps that must be taken to make the current lunar data more suitable for use in preparing a list of potential lunar-resource sites.

Background and Status of Lunar Geologic Information

A systematic program of lunar geologic mapping from telescopic observations and photographs was begun during the early 1960's before the acquisition of high-resolution photographs from the Lunar Orbiters. The work was concluded more than 10 years later and represents the only comprehensive geologic coverage of the near side of the Moon. The 44 maps are at a scale of 1:1 000 000. During the course of the work, Lunar Orbiter photographs (primarily from Lunar Orbiter IV) became available and 27 maps were made using these high-resolution photographs. The quality of the maps is highly variable because it depended on both the data base available at the time of their construction and the experience of the individual cartographer. Many of these maps were revised and combined in a composite geologic map of the Moon at a scale of 1:5 000 000 (ref. 17).

Later, during the course of the Apollo missions to the Moon, large-scale (1:250 000 and greater) maps of localized areas (proposed Apollo sites) were made using high-resolution Lunar Orbiter I to III, Ranger, Surveyor, and, ultimately, Apollo metric and panoramic photographs. More recently, numerous specialized geologic maps and studies covering small parts of the Moon, mostly along the Apollo groundtracks, have been made for projects of topical interest. This work includes crater-frequency distribution diagrams for the estimation of ages of lunar surfaces and spectral-reflectance data and other remote-sensing information (Earth-based and from orbit) to determine soil composition, gravity and magnetic fields, topography, and many other characteristics of the Moon's surface and near-surface rocks.

The following types of photographs have been used or are available for lunar geologic studies and site evaluations.

1. Lunar Orbiter IV photographs provide the only complete coverage of the near side of the Moon. Resolution is approximately 100 meters. The average altitude of the spacecraft was 300 kilometers.

2. Lunar Orbiter I, II, and III photographs cover small equatorial areas and lunar Orbiter V photographs cover some potential landing sites and parts of the Moon's far side.

3. Handheld Hasselblad photographs from Apollo missions are available. The quality and resolution are variable but there are many excellent photographs.

4. Photographs from three Ranger and five Surveyor unmanned missions show a high resolution of small areas.

5. Apollo 15, 16, and 17 (J missions) metric (76-millimeter focal length) and panoramic (610-millimeter focal length) photographs are of excellent quality with precise orientation (metric), high resolution (panoramic), and overlap for stereo viewing. The coverage was limited to the central region of Moon but provided a wide range of lighting conditions.

6. Numerous Apollo handheld and bracket-mounted photographs from the lunar module and the lunar roving vehicle are available.

Photographs that contributed to the large-scale (1:1 000 000) geologic map series of the Moon's near side, in order of increasing observational data quality, are as follows.

Data used	No. of maps
Telescopic photographs and visual observations	17
Lunar Orbiter and telescopic photographs	23
Apollo metric and panoramic, Lunar Orbiter, and telescopic photographs	4
	44

Depending on model requirements of the operations, the geologic maps of the Moon presently available may not provide adequate information for the selection of lunar resources mining sites. Many of the maps do not show geologic and terrain units smaller than several kilometers in size and do not show some details of structure and materials possibly important to site selection, such as boulder fields, ejecta boundaries, secondary craters, etc. The relatively few maps of the equatorial region made from Apollo high-resolution photographs (from the mapping and panoramic cameras) cover very small areas. They do provide valuable information, however, on the characteristics of ejecta blankets, including boulder distributions and textural changes as distance from the crater rim crest increases. Also, most of the available geological maps show reliable relative age classifications of craters based on morphologic and superposition criteria; the maps clearly define young craters and their ejecta blankets as well as mare regions of contrasting albedo. Presumably, many of these blankets consist of light-matrix breccias having a relatively high plagioclase content, whereas the darker mare regions are high in iron and titanium.

Possible Lunar Mining Sites

In order to focus the geologic studies that aid in site selection, it is necessary to choose a resource model having the desired characteristics of mineral type, quantity of ore, and topography. The model selected for this discussion is based on plagioclase as the dominant ore mineral with an abundant source of iron and titanium nearby that could be mined as a joint operation. The location should be within $\pm 10^\circ$ of the lunar equator to permit efficient use of a mass-driver. This model is believed to be best satisfied by the ejecta blankets of fresh-appearing young craters having minimum diameters of approximately 10 kilometers and located on patches of dark (and relatively blue) mare material. Ten kilometers was somewhat arbitrarily selected as a lower limit because smaller craters may not exhume submare material except, of course, where the craters border or lie on highland rocks (as at the North Ray Crater, Apollo 16 site).

With this model in mind, available geologic maps of the lunar near side equatorial region were examined and 17 prime-candidate sites were selected (table VI). Table VI also lists six special craters that either are in regions of very dark mare or are known to have very anorthite-rich ejecta (North and South Ray). The craters listed in table VI are plotted in figure 5 along with the groundtracks from the later Apollo missions. Unfortunately, the groundtracks (and photographic footprints) do not include 13 of these prime sites. The remaining four, however, can be studied and mapped in more detail using Apollo data. Moreover, such studies might reveal additional areas of interest not recognized on the smaller-scale map reviews.

For craters on the Apollo groundtracks, the high-resolution metric, the panoramic, and possibly the on-ground photographs should provide detailed information on the extent of crater ejecta blankets, distribution of boulders by size and their abundance in crater rim materials, and perhaps details of topography useful in estimating ejecta thicknesses.

Apollo photographs might also provide some indication of mare regolith thickness changes in some small-crater floor morphologies that are possibly attributable to the depth of the regolith-bedrock interface. Mare thicknesses could be established, within limits, by measuring buried crater rims (refs. 18 and 19) and analyzing gravity data (refs. 20 and 21). Crater frequency-distribution studies and new techniques involving crater degradation rates would provide relative age estimates of the surfaces around the candidate sites; these data would be useful should regolith maturity be a factor in site selection.

Certainly, the additional amount of geologic information provided by the Apollo photography would enable highly detailed maps (1:25 000 scale and larger) to be made of several prospective resource sites. Also, the large amount of remote-sensing data from these missions would constitute an additional basis for the ultimate selection of one site over another, possibly by indicating the relative abundance of minerals and/or elements and their effect on ore quality.

As in many studies, unexpected developments may occur, especially as more detailed observations are made and information is obtained by new orbital or in situ investigations. Some of these developments may relate to small craters that have impacted mare basalt and whose ejecta blankets may be highly contaminated with basalt fragments - particularly in their outer reaches where the upper parts of the original target surfaces tend to be concentrated. These ejecta blankets may also contain highly heterogeneous mineral assemblages. It is conceivable, too, that the best and most readily obtainable sources for plagioclase may occur in massifs along or near large basin rings.

GEOPHYSICAL METHODS

Geophysics can enter into resource assessment in three distinct ways: discovery, volume evaluation, and remote determination of mechanical properties of the resource deposit. The last aspect is important in determining the mineability of a given deposit.

Discovery

The discovery of a given resource target by geophysical means requires a physical-property contrast between the target and the surrounding material. In the following discussion, for the most part, the ore minerals will be restricted to plagioclase and ilmenite. The physical properties of interest are seismic velocity, density, dielectric constant, electrical conductivity, magnetic susceptibility, remanent magnetization, and thermal conductivity.

Possible measurements that can be obtained from orbit are gravity, magnetic field, infrared, microwave emission, and active radar. With a single possible exception, orbital geophysics is not an effective tool for the discovery of plagioclase or ilmenite deposits; i.e., geophysical measurements are inferior to geochemical measurements in this regard.

Gravity measurements do not provide adequate spatial resolution and suffer from uniqueness of interpretation, far overshadowing the lower density that a high-grade anorthosite deposit might have relative to that in "normal" highlands.

Magnetic-field measurements at the scale of interest are dominated by local remanent fields. Correlation of these fields with chemical composition has not been established.

Thermal conductivity affects infrared and microwave emission, but variations are dominated by bulk density and not by composition. Similarly, dielectric constant variations are dominated by density.

Electrical conductivity, or equivalent loss tangent (tan δ), is more sensitive to ilmenite content than to density at frequencies greater than 100 kilohertz (ref. 22). At 450 megahertz, a regression fit was found to the Apollo 16 data of

$$\tan \delta = \left[(0.0015 \pm 0.0012) + (0.00009 \pm 0.00022)C\right] \rho$$

where C is the percent of ferrous oxide (FeO) + titanium oxide (TiO_2) and ρ is the density. Microwave radiometry and active radar are both sensitive to tan δ, but the former does not provide adequate spatial resolution from orbit for the current problem. Low reflectivity in Earth-based 70-centimeter wavelength data has been attributed to high TiO_2 content in the regolith (ref. 23). Such an interpretation assumes that a significant component of the radar backscatter arises from a regolith-bedrock interface or from subsurface rocks and that the presence of a high TiO_2 content attenuates the subsurface signal contribution. If this supposition is correct, then areas of thick regolith might be incorrectly interpreted as regions of high TiO_2. Nevertheless, the hypothesis may be valid and more laboratory measurements of tan δ as a function of frequency for various TiO_2 concentrations may be required. Additionally, further studies of the correlations between orbital and Earth-based geochemically derived TiO_2 abundances and radar results may be required.

Although dependent on the frequency or frequencies of selection, radar imagers and altimeters that could carry out appropriate measurements exist or are being planned for future missions. These instruments could potentially add the vertical dimension to high-ilmenite areas mapped by geochemical means.

On the surface, gravitational, magnetic, electrical, and seismic methods can be used in addition to direct measurements of heat flow. Physical property contrasts certainly exist for high-grade anorthosite relative to "normal" highlands. It is doubtful, however, whether these contrasts are detectable with standard geophysical approaches. In the regolith, most of the geophysically relevant properties are controlled by density and not by chemical composition.

Surface electrical methods are directly applicable to determining ilmenite content of the regolith, given that the loss tangent is proportional to the FeO + TiO_2 content. Caution must be exercised, however, in a modest ambiguity between the FeO + TiO_2 content and the density (ref. 24). The dielectric constant can apparently be used to remove this ambiguity. A number of different electrical prospecting techniques are applicable to the determination of regolith thickness and loss tangent. One technique, the surface electrical properties experiment (ref. 25), was used on the Apollo 17 mission to map variations of subsurface dielectric constant and loss tangent. The experiment consisted of field-strength measurements as a function of transmitter-receiver separation. The transmitter consisted of two orthogonal dipole antennas operating at 1, 2, 4, 8, 16, and 32 megahertz. The signals were received on the lunar rover with three orthogonal coils. The basic data set consisted of plots of field strength versus distance for several frequencies (ref. 24). At the Apollo 17 site, the surface electrical properties experiment mapped a regolith thickness of 7 ± 1 meter, a loss tangent of 0.008 ± 0.004, and a relative dielectric constant of 3.8 ± 0.2.

The surface electrical properties experiment represents a prototype lunar-rover technique for measuring regolith thickness and FeO + TiO_2 content.

Volume Evaluation

In a scenario for ilmenite or plagioclase exploration, the horizontal extent of the deposit is assumed to be delineated by geochemical means. Because of the ease of extraction, it is assumed the economic ore is confined to the regolith, on the order of 1 to 10 meters thick. Verification that the surface composition extends to the base of the regolith is ultimately provided by drilling and coring, with the possible exception of FeO + TiO_2 mapping by electrical methods, as discussed previously. If, however, it is assumed that the regolith is of uniform vertical composition at any point on the surface, then volume determination consists of determining the depth to the base of the regolith. Both seismic and electrical techniques may be used to map the base of the regolith layer.

One electrical technique has been discussed previously; others are possible for mapping the regolith base. One possibility is a high-frequency monostatic pulsed radar. Such a radar could operate in the low-gigahertz range with a bandwidth of approximately 100 megahertz to give approximately a 1-meter resolution. If the loss tangent is approximately 0.001 at this frequency, then this radar could receive signals at a depth of 20 meters with an attenuation of no more than 10 decibels.

Seismic refraction methods were quite successful during the Apollo 14, 16, and 17 missions in determining the thickness and velocity of the lunar regolith (ref. 26). The seismic refraction experiment consisted of a seismic energy source, a geophone array, and a recording system. On the Apollo 14 and 16 missions, the energy source was a squib-fired thumper. The explosive squib contained approximately 100 milligrams of explosive and generated seismic energy slightly less than that of a blasting cap (ref. 27). The squib was fired directly into a ground coupling plate, which distributed seismic energy over a wider area than did the squib alone.

The seismic refraction method is an obvious candidate to survey a target area for regolith volume and velocity. The latter property is important in mineability determinations. The key development item is a reusable seismic energy source. Further, the rover technology of picking up and laying geophone arrays will have to be developed.

Mineability

Mineability, as used here, is the ease by which, from a mechanical standpoint, regolith can be mined and processed. The most important aspect is that the regolith be relatively fine grained; i.e., free of large rocks. The task of geophysical exploration is to evaluate the quantity of rocky material in the regolith subsurface before drilling and to rate one target area over another in terms of mineability.

Two orbital techniques are sensitive to rocks in and on top of the regolith: infrared radiometry and active radar.

An infrared scanning radiometer was flown on the Apollo 17 mission (ref. 28) with a 2-kilometer resolution at 100-kilometer orbital altitude and a +2 K measurement accuracy. Thermal enhancements in nighttime temperatures mapped with this instrument are associated with the presence of rocks to a depth of a few tens of centimeters. According to Mendell and Low (ref. 29), "The intensity and duration of an anomaly in the lunar night are functions of the size distribution and the number density of the rock populations. Generally, the rocks must be larger than a decimeter to have a noticeable thermal effect." Mendell (ref. 30) states that a "mature regolith" can be defined in terms of an infrared emission having no thermal enhancement and that components of this mature regolith are at "a depth greater than a meter everywhere and no grain-size fraction larger than 10 cm."

Absence of material larger than 10 centimeters tens of centimeters from the surface does not guarantee this material would not exist to the base of any given regolith, particularly in view of lateral deposition caused by crater impact. Nevertheless, an orbital infrared survey could easily eliminate unmineable areas in terms of probable rock fraction. Mendell (ref. 30) is able to estimate the percentage of rock "outcrops" from the infrared data.

There should be no difficulty in improving the resolution and temperature sensitivity of the Apollo instrument, if required, for future orbital surveys.

Active radar provides a means of probing for subsurface rocks. Depolarized returns and off-axis polarized returns are sensitive to the volume distribution of rocks in the regolith. Schaber et al. (ref. 23) claim, for example, that centimeter radar is sensitive to 20-centimeter to 7-meter rocks that are buried no deeper than 20 meters. Areas of low radar return may indicate areas of low rock-distribution density or areas of high absorption due to an increased FeO + TiO_2 content, as discussed previously. Any radar technique that attempts to map subsurface rock distribution must calibrate out signal attenuation due to chemistry, such chemistry having been determined by orbital geochemical means. Further, a quantitative theory relating radar brightness to rock population must be substantiated.

Earth-based radar may not provide proper resolution to carry out the required survey. An orbital survey is properly carried out in terms of a calibrated polarized/depolarized side-looking imaging radar. Much of the capability for conducting this type experiment is being developed for the Venus Orbiting Imaging Radar (VOIR) mission.

Surface measurements to ascertain subsurface rock content center on reflection seismics and radar. Both experiments would be characterized by short pulses (wide bandwidth) and high timing accuracy and would determine the subsurface nature of rock distribution in terms of time delay and echo strength, operating in a surface traverse (mapping) mode. Both instruments require development.

In addition, velocities determined from refraction seismic experiments may be used to directly infer gross density of the regolith, a physical parameter that may directly relate to mineability and very indirectly to composition.

In summary, a large amount of new instrument development does not appear to be required to carry out the assessment of high-grade plagioclase and ilmenite deposits on the Moon. The largest issue may be the problem of packaging existing instruments into a remotely controlled rover capability. Two areas of potential instrument development are wide-band surface radars and wide-band reflection seismics.

GEOCHEMICAL INSTRUMENTS

Geochemical instruments provide elemental chemical analyses and analyses of the mineral composition and the mineral-to-glass ratio. These data may be used in various ways and at various points in the evaluation and extraction of lunar resources. Many of these data can be acquired using orbital instruments; however, instruments placed on the lunar surface will often differ in important ways from those used by or considered for unmanned planetary probes simply because more is known about the Moon and thus lunar resource questions can often be stated more precisely than general planetary questions. The instruments, therefore, can often concentrate on making superior measurements under a more restricted range of analytical situations. One can also anticipate that weight and power constraints will be relaxed, partly because of advances in technology and partly because any space program that uses lunar resources will probably be replete with rather massive spacecraft that have rather abundant sources of electrical power.

Better orbital instruments are expected because of the Apollo experience and improved technology, both in spacecraft technology and in instrument technology. In the context of resource-site evaluation, some of these instruments will need higher spatial resolution than current versions have and most of them should return data that are more interpretable than at present. This latter feature may be possible because the data will have a more direct link between variations in the measured signals and variations in the elemental and mineralogical compositions of the lunar surfaces or because this link is better understood. These instruments may not differ greatly from those used in the general planetary program.

The instruments for conducting chemical and mineralogical analyses on the lunar surface may differ substantially from those designed for general planetary use, especially those used later in the evaluation. The later stages of evaluation are expected to overlap the start of mining and extraction operations. During these operations, there will almost certainly be a requirement to monitor the composition of the feedstock before it is mined or as it enters the processing plant so that the operation of the plant can be adjusted. The analytical requirements of the latter stages of evaluation, and especially of the monitoring of the feedstock, are closer to those of a process-control situation than to those of planetary science. In any extraction process, analytical needs will emanate from process-control requirements. Although process control is not discussed in any length elsewhere in this document, it is mentioned here because it is expected to produce a much larger analytical task than the evaluation process and to share instrumentation with the latter stages of site evaluation. Process-control instruments are designed to measure a small number of informative variables in fixed analytical situations, in contrast to planetary science instruments, which are designed to measure a wide range of elemental and mineralogical abundances in an imprecisely anticipated situation.

Orbital Instruments

The remote-sensing instruments described and discussed here will be used on a spacecraft in lunar orbit. Earth-based remote-sensing instruments will have a minor role in evaluating potential resource sites because of their poor spatial resolution relative to the requirements and because of the limitations imposed by the Earth's atmosphere. Remote sensing from Earth-orbiting spacecraft may be more important because of the freedom from atmospheric interference. If a long-focal-length astronomical telescope in Earth orbit (a space telescope, for example) were used in site evaluation, the spatial resolution would be improved to something better than 1.0 kilometer and useful spectral reflectance data would be obtained if there had not been a previous lunar polar orbiter carrying a spectral reflectance experiment covering the same wavelength range. With this possible exception, the acquisition of additional remote-sensing data will be from lunar orbit because the spatial resolution required can only be obtained that way. For any resource site in near-equatorial or near-polar areas, orbiting instruments having high spatial resolution can be effectively used because of the high density of groundtracks that polar orbits provide in polar areas and that equatorial orbits provide in equatorial areas. The high density of groundtracks also allows a buildup of contiguous and overlapping coverage from narrow strips or small spots of high-resolution coverage, thus providing both high-resolution and wide-area coverage of a candidate site.

The geochemical instruments expected to be used on a lunar orbiter supporting the evaluation of resource sites are as follows.

1. X-ray fluorescence spectrometer

2. Reflectance spectrometer operating in the ultraviolet, visible, and infrared regions

3. Gamma-ray spectrometer

4. Neutron detectors

5. Alpha-particle spectrometer

6. Spectrometer operating in the thermal infrared regions

7. "Laser" spectrometer

An important feature of remote-sensing data for the Moon is that it is more interpretable than data for other planetary bodies because of the available lunar samples and the relative wealth of information about the Moon. Three techniques have already proven highly valuable in lunar studies: orbital X-ray fluorescence, orbital gamma-ray spectroscopy, and spectral reflectance spectroscopy. Building on this experience, all three techniques can provide greatly improved results when used on a future lunar orbiter, partly because the use of these techniques to study the Moon is better understood and partly because much better instruments can now be built.

Additional chemical data can be inferred from the limited set of elements that can be determined by remote-sensing methods because the interelement ratios in most lunar soils and series of rocks vary in a systematic fashion. This has been most recently shown by the use of pattern-recognition techniques. It has been shown (refs. 31 and 32) that, given the analysis of four or five selected elements for lunar materials, the concentration of the remaining elements can be predicted within a certainty of 10 to 20 percent of the element present for lunar materials. For example, measuring the concentrations of silicon, aluminum, iron, titanium, potassium, and uranium by remote methods permits one to predict the concentration of other elements that might be needed.

Instruments for Landed Spacecraft

Instruments for landed spacecraft will very probably base their measurements on the same physics as the remote-sensing instruments. The major operational difference will be that they will include sources of nuclear or electromagnetic radiation to illuminate the sample and induce the characteristic signals that are to be measured. The major result will be to provide higher-quality data for more elements and minerals.

The simplest way to use these instruments is to analyze the natural lunar surface. Various schemes to sample and prepare lunar material for analysis can be envisioned. Such schemes should meet two basic criteria: (1) they should provide a required improvement in the data, or (2) they should be required as a consequence of some necessary activity. The first criterion is closely related to the instrument chosen and will not be discussed further. The second criterion applies to a general situation that is expected to exist for important types of samples; e.g., samples that are obtained by drilling or digging into the lunar regolith.

All analytical instruments - sampling and sample-preparation devices - must meet one essential criterion; i.e., they must be able to produce multiple analyses without significant cross contamination or loss of precision or accuracy for the duration of rover operation, which is expected to be several months. A major environmental obstacle to the operation of these instruments on the lunar surface is the ubiquitous and "sticky" dust that tends to coat all exposed surfaces. This can lead to the severe degradation of optical surfaces and to the "blinding" of analytical instruments to changes in the samples.

The more probable candidate instruments for landed spacecraft are as follows.

1. X-ray spectrometer, using either X-ray fluorescence or alpha excitation of the characteristic X-radiation.

2. Gamma-ray spectrometer, either passive or with a neutron generator.

3. Alpha backscatter.

4. Spectral reflectance spectrometer using an artificial light source.

5. X-ray diffractometer, perhaps in a combined instrument that provides for both X-ray fluorescence and X-ray diffraction.

6. Possibly an instrument to analyze the gases released when lunar soil is heated. Mass sectrometers, gas chromatographs, or spectral-adsorption methods represent the major instrument types.

The quality of the X-ray and gamma-ray instruments will be much higher if silicon, lithium, and intrinsic germanium detectors can be used. The use of these detectors requires that they be cooled to approximately the temperature of liquid nitrogen. For the reasons stated previously, this is not expected to be a severe problem for a space program that uses lunar materials as industrial feedstocks.

Given the combined analytical capabilities of X-ray, neutron-gamma, and alpha backscatter methods (especially with the use of silicon, lithium, and intrinsic germanium detectors), it is almost certain that the concentrations of all chemical elements of interest can be measured with the required precision and accuracy using remotely controlled instruments. The successful operation of these instruments for the long times required will depend on the mating of analytical instrumentation to robotics.

AUTOMATED SYSTEMS

Automated systems will be needed for any program designed to use lunar resources. Some of the tools that will be needed for prospecting and early resource development on the Moon are considered in this section. Although these tools cannot all be described in detail without better definition of the tasks they will be needed for, enough knowledge already exists to list the main functions needed and - of particular importance for current planning - to describe preliminary R&D programs that should be started now.

Functional Requirements for Automated Lunar Prospecting and Resource Demonstration

Given information on local topography, average surface composition for some elements and minerals, and a relevant geological model of a target site some tens of kilometers in extent, the next need is mobile exploration on the surface. An ability to drill or dig below the surface would be highly desirable. The analytical instruments are presumed to have been chosen using site-specific criteria and knowledge of the feedstocks that are acceptable to subsequent extraction and/or manufacturing processes.

The general abilities that would be needed in almost any conceivable case and items that may or may not be needed are briefly discussed in the following paragraphs.

Mobility.- Mobility on the lunar surface is absolutely essential to prospecting and assaying. Limited mobility has, of course, already been demonstrated by the Lunokhods and manned Apollo rovers, and reasonably good knowledge of both the Moon and rover mechanisms exists as a basis for system design. A prospecting/assaying rover, however, must meet new requirements: (1) it must have essentially unlimited range and endurance; (2) as a necessary requirement for prospecting in high lunar latitudes, it must be able to operate, at least for limited times and distances, out of sight from Earth; and (3) since the rover's movement is essentially a service function, its obstacle-crossing, slope-negotiation, and crisis-extrication abilities should be as high as possible. An example might be the ability to go into and out of a typical lunar volcanic vent or a sinuous rille, which neither the Apollo rover nor the Lunokhod could safely achieve.

In situ material characterization.- Given the ability to move around, the next need is for observation systems to determine what is found. A rudimentary example is the Lunokhod X-ray spectrometer, which could measure the approximate concentrations of a few elements along the rover's path. A rich opportunity exists for research and development of more capable analytical instruments and data systems for this purpose. Until now, the few known applicable principles (alpha backscatter, X-ray fluorescence and diffractometry, gamma-ray spectrometry, reflectance spectroscopy, neutron activation, etc.) have been pursued only as possible scientific instruments, being developed in principle by individual experimenters in the hope of being selected for a flight mission. A more aggressive and integrated approach could be pursued at modest cost, using the existing scientific instrument development as a point of departure. An important functional requirement to be met would be to measure, along the rover's path, enough properties of the lunar surface so that decisions can be made whether to stay and investigate more thoroughly or to continue to the next scheduled halt. This requirement generates a need for compositional measurements of the regolith and for knowledge of the local geological and geophysical relationships, permitting the exercise of the same kinds of judgment that are applied in prospecting on Earth. In other words, the rover must have not only analytical instruments but also an imaging system. Because one of the most important resources may be in the permanently shadowed areas of the polar regions or because it may be desirable to operate during lunar twilight or night, lights should be seriously considered and may be essential. In view of the peculiar backscatter and shadowing properties of lunar soil, the source of illumination must not be too close to the camera. The characteristics of a lunar exploration rover and the functions that it should be capable of executing are summarized as follows.

Required functions and abilities:

1. Full operation during lunar days and partial operation during lunar nights

2. Remotely operable from Earth

3. Operation out of sight of Earth with at least partial autonomy

4. Adequate communications with Earth

5. Imaging systems with a metric capability

6. Navigation capability adequate for mine-site layout

7. Limited self-maintenance capability

8. Basic site-evaluation instruments and manipulative abilities

Minimal site evaluation requirements:

1. Determination of the mechanical properties of the soil, including packing characteristics, density, and stickiness

2. Determination of the presence and size distribution of boulders at the surface and at various depths up to 10 meters

3. Determination of the depth of the regolith, which determines the volume of the deposit to be mined

4. Determination of the rolling resistance of the soil, which, along with grade, affects the energy required for transport of ore to the processing plant

5. Acquisition of both surface and subsurface samples at many locations to determine the purity and homogeneity of the ore

6. Sample analysis to determine composition

7. Ability to deploy and retrieve instruments

Manipulation and analysis.- Having analyzed the lunar regolith in situ, there will very probably be a need to further characterize the material by directly sampling it and separating the various components. This might involve nothing more than simple sieving of soils with magnetic separation of iron particles. The samples might be fed into instruments that cannot analyze the regolith in situ, such as X-ray diffractometers, thermal extraction systems, etc. Many physical property measurements require direct manipulation of the regolith.

The field is wide open for R&D on remote analytical instrumentation applied to resource prospecting. A point of departure for this work is discussed in reference 33, the result of an inquiry several years ago in which various scientists were asked to define instrumentation requirements for automated, long-range lunar rovers. The minimal needs appear to be for placing and retrieving instruments and samples from the surface and for drilling or digging beneath the surface. A number of manipulators, arms, and other sample acquisition devices exist or have been designed that appear suitable for these tasks (refs. 34 and 35).

Basic rover configuration.- The rover must have superior terrain accommodation in order to avoid or surmount holes, boulders, and other obstacles. A six-wheeled articulated vehicle has been built and seems appropriate for the task (ref. 36).

The rover should have manipulators, metric-imaging systems, and lights. In view of the peculiar backscattering and shadowing properties of the lunar soil, provision must be made to place lights some distance from the camera. The rover will be powered by a solar-cell array and batteries. Radioisotope thermoelectric generator (RTG) power is not suitable, primarily because its gamma and neutron radiation will strongly interfere with the radiation-detecting instrumentation used in rock analysis.

Consideration should be given to making any site-exploration rover as adaptive as possible for future mining uses. Such uses could include the capacity for initial site preparation employing such functions as digging, loading, and moving at least limited quantities of soil. These functions could be undertaken by adding digging tools or blades to the rover or providing attachment points so that they could be added at later stages. By making a flexible site-exploration rover of this kind, transportation costs for additional vehicles would be reduced.

Further rover requirements may include the ability to explore for "exotic" minerals or concentrated ore deposits. The principal additions to the basic site-evaluation rover for these new functions would include the following.

1. Superior mobility and terrain accommodation with winch self-extrication devices, self-righting ability, and levered locomotion (walking) devices

2. Increased ability to operate at night or in shadows

3. Increased range/speeds

4. Great increase in autonomous operation and data storage ability

5. Lunar radio relay or orbital radio control

Automated Systems Summary

A site-evaluation rover could be made with modest advances of existing technology. Many of the basic functions, such as power, locomotion, imaging, manipulation, and human supervisory control, have been investigated (refs. 37 through 46).

However, careful study and analysis should continue because predictable advances in computers, software, and microelectronics will make any task involving automation progressively easier in the near future. Although current hardware is certainly adequate, a thousandfold increase in processing speed and a thousandfold decrease in size can be expected in the next 15 years. Even sooner, probably within the next 5 years, such commercial products as 16-bit single-chip computers with 32-bit addressing; single-chip 64-channel data acquisition systems; and single chips capable of Fast Fourier Transforms (FFT) and the Chirp Z-transform, among others, will be available. The large address space and word size will aid onboard data reduction, especially of images. An FFT chip will allow onboard edge enhancement and data compression of images now done on the ground. Many channeled data acquisition chips will allow the interrogation of many distributed instruments in a simple way. Finally, the integration of what are now considered separate subsystems onto single chips will decrease the number of connections and modules on the spacecraft, giving greater reliability.

These advances, which will occur independently of lunar-resource exploration programs, are highly significant because analytical techniques that might be rejected now because of their complexity may be easily within the capabilities of future spacecraft electronics.

RESEARCH AND DEVELOPMENT TASKS

For each of the general R&D activities shown in table I, the workshop group came up with specific tasks that could be started now so as to begin making serious progress toward the goals of evaluating and using lunar resources. These research efforts can be divided into three categories: (1) tasks that can be done using existing lunar samples and data to learn more about the Moon's resources, (2) technology tasks that can be done here on Earth to develop and demonstrate techniques needed for exploiting lunar resources, and (3) tasks, both scientific and technological, that can only be done near or on the Moon.

Needed efforts of the first category were outlined in a previous workshop (ref. 6, pp. 40-41). It was recognized that there is a feedback interaction between the processing method and what one must know about the feedstock; e.g., some methods are sensitive to impurities and some are not. Therefore, research on processing methods should proceed in parallel with research involving lunar samples and simulants.

A significant conclusion of the present workshop and other studies (ref. 15) is that some lunar resources can be extracted and converted to useful products without needing major new technology developments; e.g., using bulk lunar soil in its natural state for thermal and radiation shielding. Other possible resources, however, will require new technology; e.g., if buried polar ice is found, a method must be devised for digging or drilling down into it, extracting it (probably by heating), and then refreezing or otherwise storing it for future use - all in darkness and out of sight of the Earth.

If we wanted to start vigorously now to prepare for a wide range of possible futures, a long list of worthwhile technology-development tasks could be generated. However, it was the consensus of the workshop group that a more selective approach may be needed if anything useful is to be initiated in the near term. Therefore, in the following list, only those Earth-based technology tasks are outlined that are now considered to be (1) practical based on present knowledge, (2) of basic importance in using lunar resources, and (3) critical in the sense that the outcome may illuminate or even force future program decisions, depending on what is found in the as-yet-unexplored parts of the Moon. We have also attempted to list the tasks in a rough priority, placing scenario-independent tasks ahead of scenario-dependent ones; however, all the described tasks are considered essential if a serious effort is started to find and develop lunar resources, especially those of high grade.

1. Simulated lunar soil. A prerequisite for most of the processing-technique experiments is a raw material that simulates natural lunar soil. For some processes, only a rough simulant (e.g., ground basalt) may be needed; however, for others, a more accurate simulation will be required. For example, no natural Earth material duplicates the peculiar surface properties of lunar soil grains, and these can be important for both chemical and physical reasons. Should it prove extremely difficult to make

soils duplicating these properties, the use of small amounts of actual lunar soil should be considered.

2. Simple solar processor demonstration. Since solar-wind-implanted gases are easily released by moderate heating of lunar soils, it appears logical to try to extract these useful products even though, as pointed out elsewhere in this report, their quantity is quite small. The technological problem is whether it is more efficient to move a large amount of soil past a solar energy concentrator and gas collector or to move the concentrator and collector past the soil. Laboratory experiments using any of several available solar furnaces are feasible, provided that a suitable lunar soil or simulant can be used.

3. Further evaluation of lunar resource candidate sites using available data. Several sites and a large amount of existing data could be used to prepare a site evaluation. This effort could take the following form.

Mapping program	Time (man years)
Examine Apollo photographs within the equatorial zone to confirm five preliminary sites and/or to select more prospective locations	0.5
Construct detailed geologic maps of sites chosen using a map scale of 1:250 000 to 1:50 000	1.5
Combine geologic information with remote sensing, topographic data, etc., for final site selection	0.5
Make highly detailed geologic maps of (a) entire crater ejecta area including parts of adjacent mare (1:25 000 scale) and (b) map most prospective sector (30°?) of crater ejecta blanket showing boulder fields, ridges, secondary craters, and any other features affecting mining operations, volume of ore, etc.	0.5
Total effort (minimum)	3.0

Together with the studies outlined above but as a separate effort, a lunar resources map covering all the Apollo photography should be constructed. The map would incorporate photogeology interpretations, sample returns, geophysical and geochemical data, and meaningful correlations between these data sets. The map would delineate major lunar rock units such as maria, light plains (Cayley), highland rocks, and significant crater ejecta blankets. Emphasis would be placed on the various mineral and element assemblages and their boundaries, however, rather than on rock lithologies inferred from their morphologic expressions.

4. Robotics. In most of the scenarios considered, it will be necessary for some machines to move about on the lunar surface; to drill or dig into soils; and to collect, manipulate, and characterize samples. This need generates a set of R&D objectives for lunar rovers and their instrument/manipulator payloads as outlined earlier in this report. Much of the required technology is already being developed for other applications (refs. 47 and 48 give the most recent summary). Features unique to the lunar-resource applications are as follows.

a. Systems must survive and operate with essentially unlimited lifetime in the lunar environment (vacuum, long and large temperature cycles, and sticky dirt on everything).

b. Systems must be able to operate, at least for limited periods, in the dark and out of sight from Earth, perhaps with the aid of an orbital relay.

c. Close human supervision, at least while in direct view of Earth, is feasible and desirable, in contrast, for example, to rovers operating on Mars.

Earth-based experimental development of these rover principles can readily be carried out at modest cost and should be, so that the essential service functions of the rover are well-proved by the time they are needed on the Moon.

5. Processing technologies. The technology for developing process methods is listed after the previous items not because they are less important - on the contrary, they are central to all but the most elementary uses of lunar resources - but because, as pointed out earlier, scenario-independent items are being listed first and the processing R&D is somewhat scenario-dependent.

Typical processes are presented in references 13, 14, and 15. These conceptual cycles take in lunar soil and solar energy and put out aluminum and other metals, silica, and oxygen as products. Although there is no question of chemical practicality since very similar processes have been routinely used on Earth, a development of this process for use on the Moon would require new technology, beginning with the primary power source (presumably solar) and including all the needed machinery. Because of the high cost of bringing materials from Earth, it will be worthwhile to advance the technologies affecting the mass of the processing plant, its needed reagent makeup rate, and its operating lifetime. (The latter is important because a small plant operating for a long time can produce the same product stockpile as a larger plant working for a shorter time.)

Mineral-dressing equipment should be built and tested here on Earth on simulated lunar soils.

A pilot plant needs to be constructed using the above equipment and tested on simulated lunar soil. The pilot plant should have design changes incorporated and then be retested, first on the simulated materials and then on stored lunar soils. Once the equipment is working on Earth on lunar regolith, it will be ready to be transported to the Moon for testing on lunar soils.

6. Tasks that can only be done on the Moon. Though many of the essential questions can be answered by research on Earth, some of them can only be answered by observation of and operation on the Moon. The needed lunar research is again scenario-dependent. Regarding bulk soil, no further lunar reconnaissance is needed and the precursor missions, if any, would merely constitute a checkout. In the other assumed scenarios, precursor missions would be essential and would have two purposes: (1) to prospect for and assay optimal or new lunar resources and (2) to confirm, demonstrate, and evaluate the automated onsite functions needed for resource extraction and processing. The workshop group concludes that, in those instances where precursor missions are needed, they should be of three types:

a. Overhead survey by instrumented orbiters

b. Mobile surface exploration in one or more selected target regions

c. Automated small-scale processing demonstration with the intent not only to check out the required functions but also to begin building a product cache to be used by later missions

In the 1977 summer study of near-Earth resources (ref. 6), NASA's proposed scientific Lunar Polar Orbiter (LPO) (ref. 49) was examined as a candidate for the orbital resource survey and it was concluded that the mission would be well-suited to the purpose with no changes in its instrumentation and only minor changes in its operations. The LPO would make a complete map of lunar surface compositions for several elements and minerals on a scale of kilometers to tens of kilometers; it would also map relevant geophysical parameters including gravity, magnetism, and heat flow. If polar ice were present within a meter or so of the surface, the LPO would detect it by the cosmic-ray-excited gamma rays from hydrogen in the ice.

Assuming a prospective site was found in the orbital survey, the next logical step would be an automated surface-roving traverse with an analytical instrument/manipulator payload. This mission would provide the needed proof (ground truth) of the existence and extent of the resource and determine the recoverabiliy of the resources and associated problems (soil consistency, regolith depth, rock population, local topography, and thermal environment).

In principle, this rover could also carry a miniature automated process-demonstration plant. However, in the judgment of the workshop group, this would unduly complicate the mobile prospecting/assaying mission and should instead be the purpose of a subsequent automated lander. The automated process demonstrator should be designed to accept feedstock delivered by the rover (now operating in a service rather than a survey mode), but it should also be designed to collect local samples itself so as to avoid complete dependence on the rover.

The process demonstrator should convert a raw material and sunlight into separated and refined products, which should, after assay to determine the effectiveness of the processing, be saved for later use. If the processor was located near a lunar pole and produced water, this could be stored by simply allowing the products to freeze and placing them in a dark cold trap, thus alleviating any need for heavy storage tanks. Figure 6 is a composite of an artist's conceptions of several systems that might be used in such a scenario.

Another scenario requires that the mining, mineral beneficiation plant, and chemical recovery pilot plants be transported to the Moon for final testing on the equivalent of an Apollo 18 mission. Two men would be landed near one of the lunar poles. The command module would be in a polar orbit to survey and photograph the rest of the Moon. If the two men on the ground were to stay 2 weeks, a complete coverage of the lunar surface could be accomplished by the orbiter for those instruments that do not require sunlight.

The lander should carry down the pilot plant. The rover and part of the scientific package would be replaced by supplies and the pilot plant. The plant can be tested but a large exploration effort will be precluded. Even so, such a mission will be able to fulfill much of the coverage desired before plant-siting is accomplished. A polar area would be available for sampling for volatile materials.

CONCLUDING REMARKS

The workshop focused its attention on the implications for site evaluation of the various scenarios for the utilization of lunar resources. At the highest levels of abstraction, we have found that there are no technical limitations on our abilities to evaluate a site. However, there are R&D tasks that should be undertaken to increase the number of sites available for consideration, to increase the flexibility of operations, to decrease the technical risks associated with siting, and to reduce the number of options available to planners.

Consequently, we would recommend that resource maps be prepared for several sites using existing data, that automated systems be developed to obtain in situ physical and chemical data, and that R&D projects be conducted to test and quantify the mineral beneficiation and refining processes that have been proposed. Such activities would provide a firm base from which an actual program of utilization of lunar materials could be implemented.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, February 20, 1981
152-85-00-00-72

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TABLE I.- REQUIRED RESEARCH AND DEVELOPMENT FOR VARIOUS TYPES OF RESOURCES

Chronology	Use bulk average soil	Optimize within present knowledge	Seek new resources
Now	1. Design studies	1. Design studies	1. Lunar theoretical studies (e.g., refs. 1 and 2)
	2. Make simulant	2. Review samples and data, then make simulant	2. Thorough search of samples and data for hints of exotics
Near future	3. Run process demonstration on Earth	3. Run process demonstration on Earth	3. Simulate possible raw materials; e.g., permafrost
	4. Select lunar site	4. Evaluate Apollo sites, probably choose one, perhaps explore further with a rover	4. Run process experiments on Earth
Mid future			5. Survey entire Moon from orbit
			6. Select exploration site; explore with rover
	7. Run process demonstration on Moon	7. Run process demonstration on Moon	7. Run process demonstration on Moon
Commit to use lunar resource	8. Scale up	8. Revise if needed, then scale up	8. Design compatible systems to use product; continue (5) to build stockpile for future use
			9. Scale up
Operational	10. Refine process for efficiency and economy	10. Choose between staying at an Apollo site or moving to a better site	10. Fit (5) and (8) into a larger system; continue operating at "best" site known

TABLE II.- POSSIBLE SATELLITE PROGRAMS FOR 1980-2000 (REF. 3)

Satellite description	Mass, kg (ton)		Quantity 30 yr	Quantity estimate rationale	Total mass, kg (ton)	
Early public service platform (PSP-1): fire detection, meteorological, water level and fault movement, diplomatic hotlines, etc.	14 900	(14.9)	20	~1 each for major industrial nations plus regions containing compatible countries	298 000	(298)
Expanded public service platform (PSP-2): border surveillance, wrist radio, disaster communications, electronic mail, navigation, vehicle and package locator, etc.	133 200	(133.2)	10	Top 50 percent of industrial nations and regions using PSP-1	1 332 000	(1 332)
Nuclear fuel locator (CO-7)	1 400	(1.4)	80	4 per PSP-1 region	112 000	(112)
Rail anticollision system (CS-13)	1 400	(1.4)	60	3 per PSP-1 region	84 000	(84)
Global search and rescue (CC-1)	700	(.7)	20	Aerospace report	14 000	(14)
Coastal anticollision radar (CO-9)	909 100	(909.1)	30	2 per industrial coastline	27 273 000	(27 273)
Night illuminator[a] (CS-6)	45 500	(45.5)	150	70 percent of major cities	6 825 000	(6 825)
Power relay satellite[a] (CS-15)	272 000	(272.7)	100	Aerospace report	27 270 000	(27 270)
Total mass					63 208 000	(63 208)
Solar Power Satellite (SPS)	97 550 000	(97 550)			9 755 000 000	(9 755 000)

[a] Redundant if SPS is built.

TABLE III.- MAJOR MATERIALS REQUIREMENTS OF THE SPS
(REFS. 3 AND 5)

Mass, kg (ton)	Percent of total SPS mass	Earth baseline SPS material	Application
21 658 000 (21 658)	22.2	Borosilicate glass	Photovoltaic cell covers
14 775 000 (14 775)	15.1	Silicon	Solar cells
14 439 000 (14 439)	14.8	Fused silica glass	Photovoltaic cell substrate
6 208 000 (6 208)	6.4	Graphite composite	Primary structure for solar array
5 980 000 (5 980)	6.1	Copper wire	Klystron and dc-dc converter coils, power cables
5 257 000 (5 257)	5.4	Graphite composite	MPTS[a] waveguides
3 892 000 (3 892)	4.0	CRES[b] tubing	Heat pipe for klystron radiators
3 535 000 (3 535)	3.6	Aluminum sheet	Power transmission buses, array, and MPTS
2 749 000 (2 749)	2.8	Aluminum sheet	Klystron and dc-dc converter radiators
1 820 000 (1 820)	1.9	Copper (machine part)	Klystron solenoid cavity
1 758 000 (1 758)	1.8	Iron	Klystron solenoid and transformer for dc-dc converter
1 539 000 (1 539)	1.6	Copper sheet	Klystron collector radiators
1 524 000 (1 524)	1.6	CRES (machine part)	Klystron housing
1 456 000 (1 456)	1.5	Vacuum-deposited copper	Solar cell interconnects
1 210 000 (1 210)	1.2	Graphite composite	MPTS antenna
87 800 000 (87 800)	[c]90.0		

[a] Microwave power transmission system.
[b] Corrosion-resistant steel.
[c] 90 percent of total 97 550 000 kg (97 550 tons) Earth baseline SPS.

TABLE IV.- EXPLORATION FOR VOLATILES

Problem	Procedures
Implanted solar hydrogen	
Range of variation of hydrogen concentration and correlation with other measurables; e.g., grain size	Summarize existing lunar sample data; examine existing stored lunar samples.
Practical ways to capture hydrogen after its release from soil by moderate heating	Conduct laboratory experiments correlated with other (major-element) soil-processing R&D.
Ways to store the recovered hydrogen	Conduct design studies (e.g., make into water and freeze? or pump into tanks?) Several methods feasible; choice depends on program assumptions.
Polar cold-trapped hydrogen	
Is it there?	Conduct polar-orbit mission with gamma ray, neutron albedo, radar altimeter, and (possibly) gravity experiments.
If so, what is its concentration in the soil and how is it distributed with depth (at least to a few meters)?	Equip rover with gamma-ray, neutron, etc., detectors and possibly an auger or drill.
What is the ice composition (water, organics, etc.)?	Equip rover with instruments such as the nuclear magnetic resonance (NMR) spectrometer.
What are the processing-relevant physical properties of the permafrost (hardness, friability, thermal decomposition profile)?	Use modeling in Earth-based laboratory experiments after lunar ice detected by orbiter.

TABLE IV.- Concluded

Problem	Procedures
"Anomalous" lunar volatiles	
Do they exist?	A polar orbiter mission may give only a hint from geological/ geochemical/geophysical context or may directly detect hydrogen. A rover will answer the question unequivocally if - and only if - the hydrogen-bearing deposit is within some tens of meters of the surface; however, this is good enough for an early resource-recovery operation.
How are they trapped?	Deploy rover, followed by a digging or coring operation to "prove out" the deposit.
What is their composition?	Perform chemical analyses (e.g., gas chromatography/mass spectometry of samples brought up by auger).

TABLE V.- PRIMARY CONSTRAINTS FROM CIVIL, MINING, AND PROCESS ENGINEERING BASED ON RESOURCE MODEL EVALUATIONS

Resource model	Exploration requirements	Constraints	Spatial resolution	Vertical resolution
All resource scenarios	Topography		1 to 10 m	1 to 10 m
	Depth of regolith		--	>1 to 2 m
	Particle size		~1 m	--
Raw bulk soil	No additional chemical or mineralogical data are required for selecting a site to mine raw bulk lunar soil. The existing X-ray fluorescence data obtained from lunar orbit during Apollo 15 and 16 cover a large portion of the Moon at a 30-km resolution for the elements aluminum and magnesium, which is sufficient for mining raw soil. Sites outside the present X-ray fluorescence coverage can be evaluated by geologic inference, and subsurface chemistry can be assumed to be like that at the surface to a sufficient accuracy (±10 percent).	Chemistry	30 km	--
		Mineralogy	30 km	--
Blended bulk soil	Blended bulk soil is a special case of the raw bulk soil scenario. The purpose would be to maintain a reasonably constant ratio of aluminum to iron and to be able to vary the ratio within limits as required. To do this, orbital chemical data would have to be obtained at a resolution of 1 km.	Chemistry	1 km	--
Aluminum-rich soil	The existing X-ray fluorescence data are sufficient for evaluating the aluminum concentration of a candidate site if such a site lies within the relatively limited area of the Moon for which data are available. A special case of this resource type is the clear glass that may be required by some scenarios in addition to aluminum. To determine the concentration of clear glass, direct sampling of a candidate site would be required. For direct sampling, one sample per square kilometer of mine area would be required to define the ore body. X-ray fluorescence and X-ray diffraction would have to be performed remotely on the individual samples. The instruments would have to have a resolution and sensitivity similar to standard equipment on Earth.	Chemistry	30 km	--
		With clear glass	1 sample/km^2	
Iron-rich soil	The existing X-ray fluorescence data for aluminum are sufficient for evaluating a candidate site for enriched iron for sites within the present limits of coverage. This can be done by using the ferrous oxide (FeO)/aluminum oxide (Al_2O_3) variation known for lunar soils obtained by the Apollo and Luna missions.	Chemistry	30 km	--
Titanium-rich soil	The existing Earth-based reflectance spectroscopy data are sufficient to identify candidate mine sites that are probably rich in titanium. If it is desired to mine aluminum and titanium at the same site in two pits located no more than approximately 5 km apart, reflectance spectroscopy will have to be performed at 1 to 2 km resolution.	Chemistry	30 km	--
		With aluminum	1 to 2 km	--

TABLE VI.- PROVISIONAL LUNAR RESOURCE SITES

Crater	Diameter, km	Location	Comments
		Typical sites	
Sirsalis K	5	10°30' S, 57° W	
Damoiseau E	15	5° S, 58° W	
Lohrmann A	10	1° S, 62° 30' W	Near Orientale ejecta
Cavalerius	50	5° N, 67° W	Erastothenian
Reiner	30	7° N, 55° W	Erastothenian, mare domes nearby
Dionysius	15	3° N, 17°30' E	Moderately dark mare
Maskelyne B	10	2° N, 29° E	Dark halo crater, possibly volcanic
Flamsteed vicinity	25	4°30' S, 44° W	
Guericke C	10	11°30' S, 12° W	
Cauchy	10	9°30' N, 38.5° E	Near rilles with crater chains, possibly volcanic
Taruntius	60	5°30' N, 46° E	
Taruntius F	10	4° N, 40° E	
Copernicus (floor)	90	10° N, 20° W	Many dark halo craters, volcanic (?)
Hortensius	15	6°30' N, 28° W	Near volcanic (?) domes
Crater cluster, Torricelli H, I, J, K	3 to 7	3°30' S, 25° E	Border mare and highlands; highlands may be similar to those near North Ray Craters; very high anorthite possible
Gambart C	12	3°30' N, 12° W	
Gambart L	5	3° + N, 15° + W	

TABLE VI.- Concluded

Crater	Diameter, km	Location	Comments
Special craters			
North Ray	1	8° 30' S, 15° 30' E	No dark mare; very high anorthite content
South Ray	0.5	9° S, 15° 30' E	No dark mare; very high anorthite content
Sulpicius Gallus	10	19° 30' N, 12° E	Very dark mare
Menelaus	30	16° 30' N, 16° E	Very dark mare
Manilius	40	14° 30' N, 9° E	Very dark mare
Crater cluster	1 to 2	14° N, 0°	In or adjacent to highlands and very dark mare

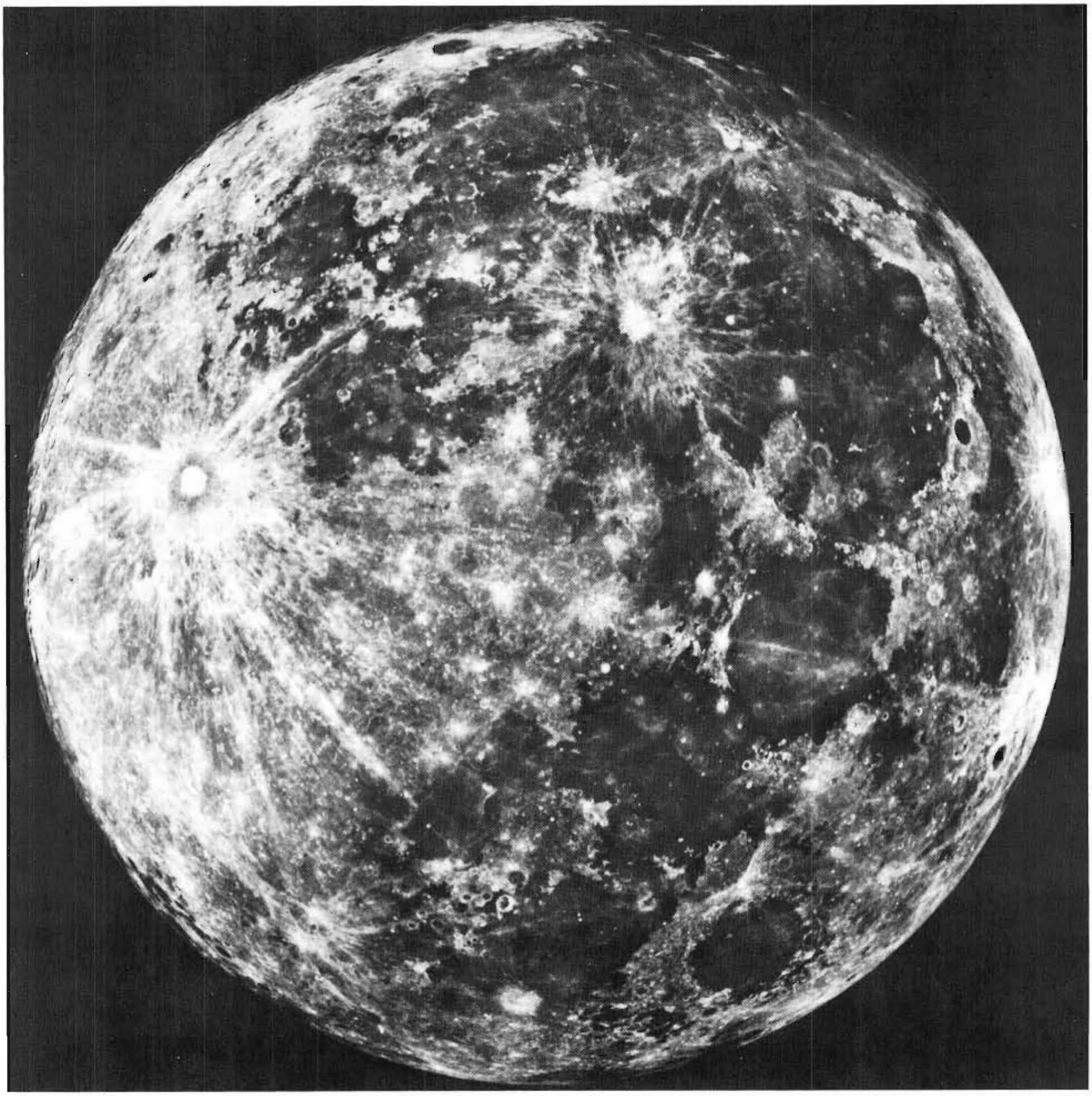


Figure 1.- The Lick Observatory L-4 composite photograph of the Moon. The lighting angle enhances the contrast between materials with different reflectivity (albedo). The difference between the light-colored lunar highlands, which are rich in plagioclase, and the darker mare is enhanced. This contrast represents actual differences in mineralogy and chemistry.

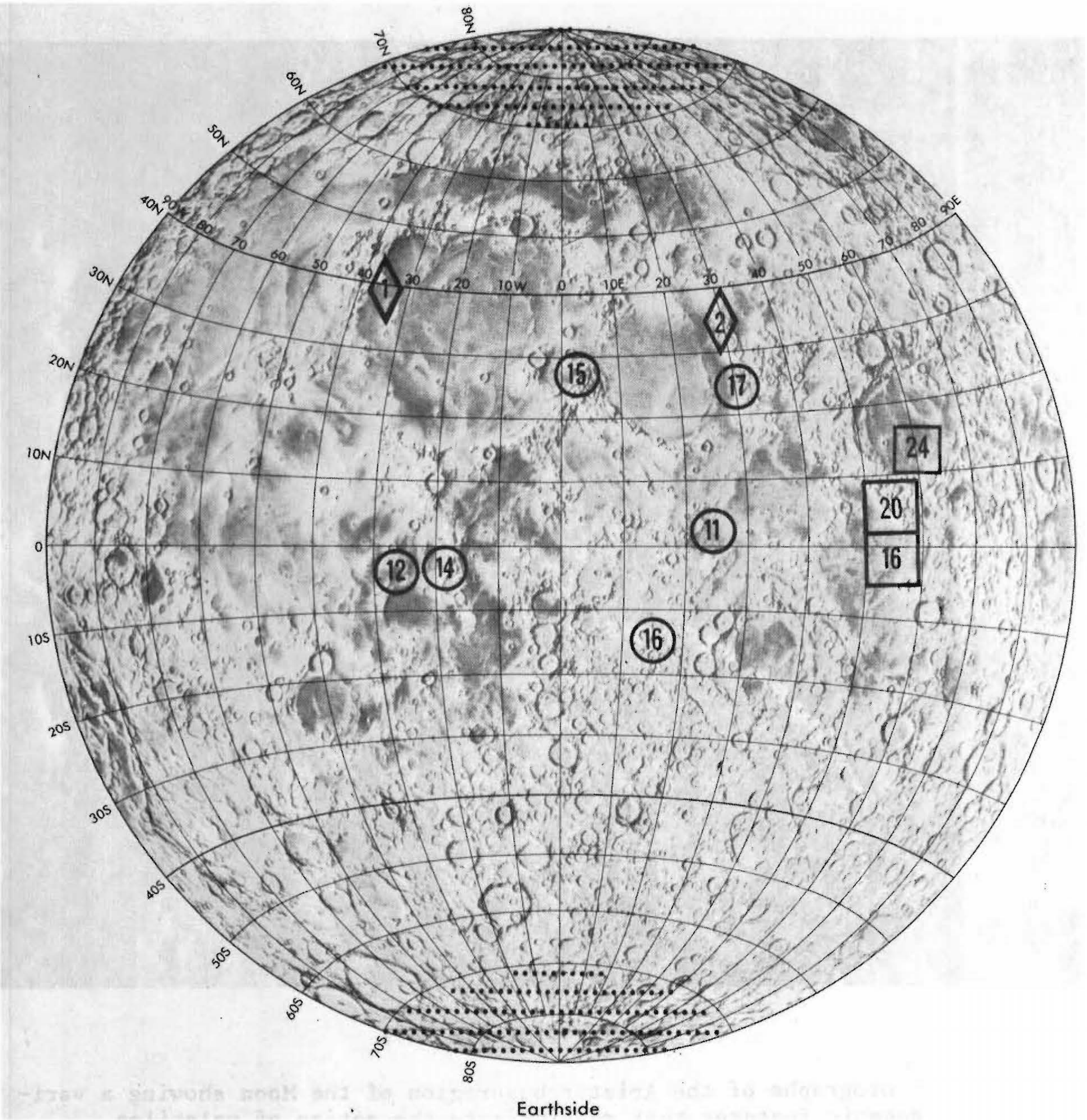
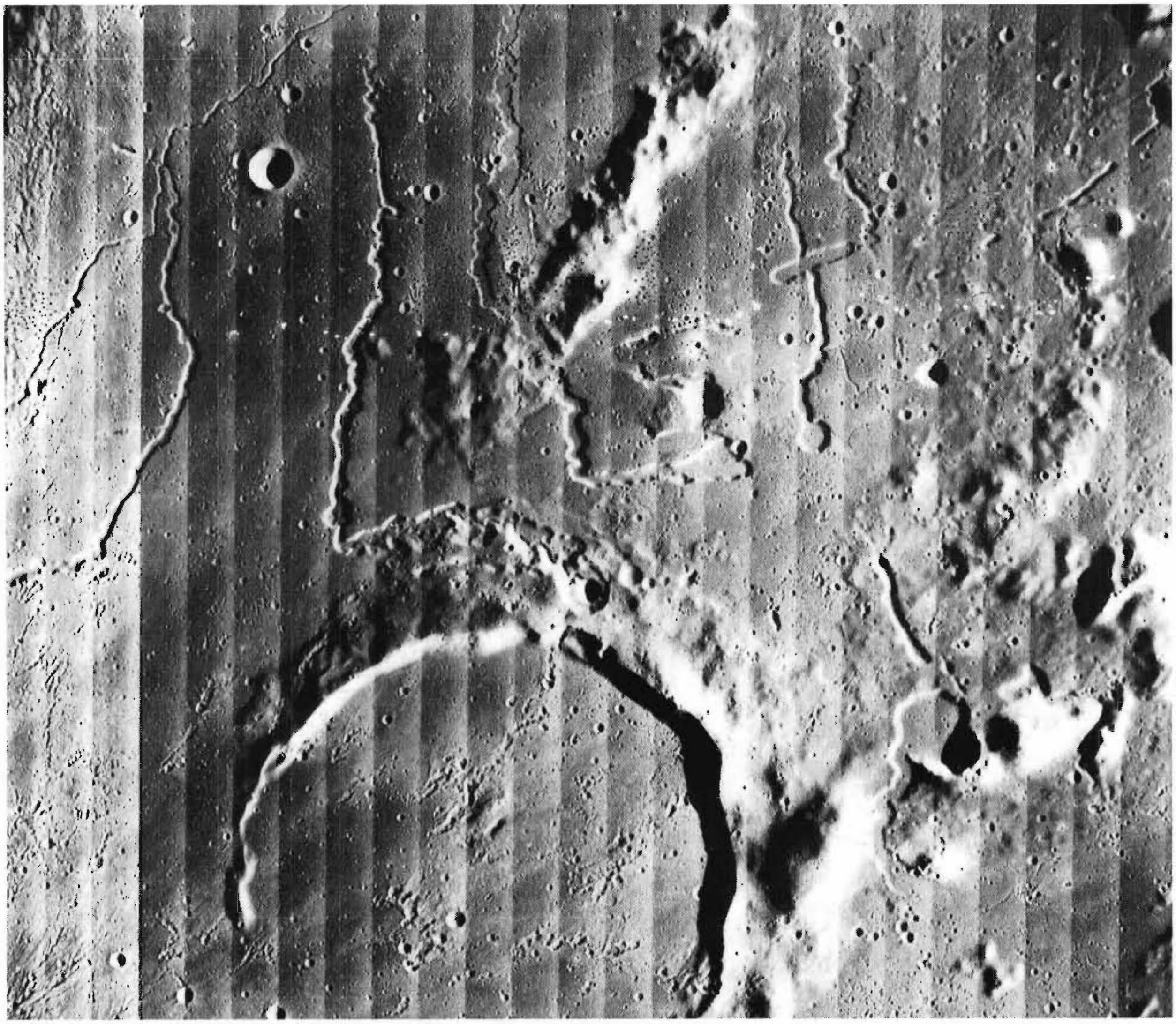
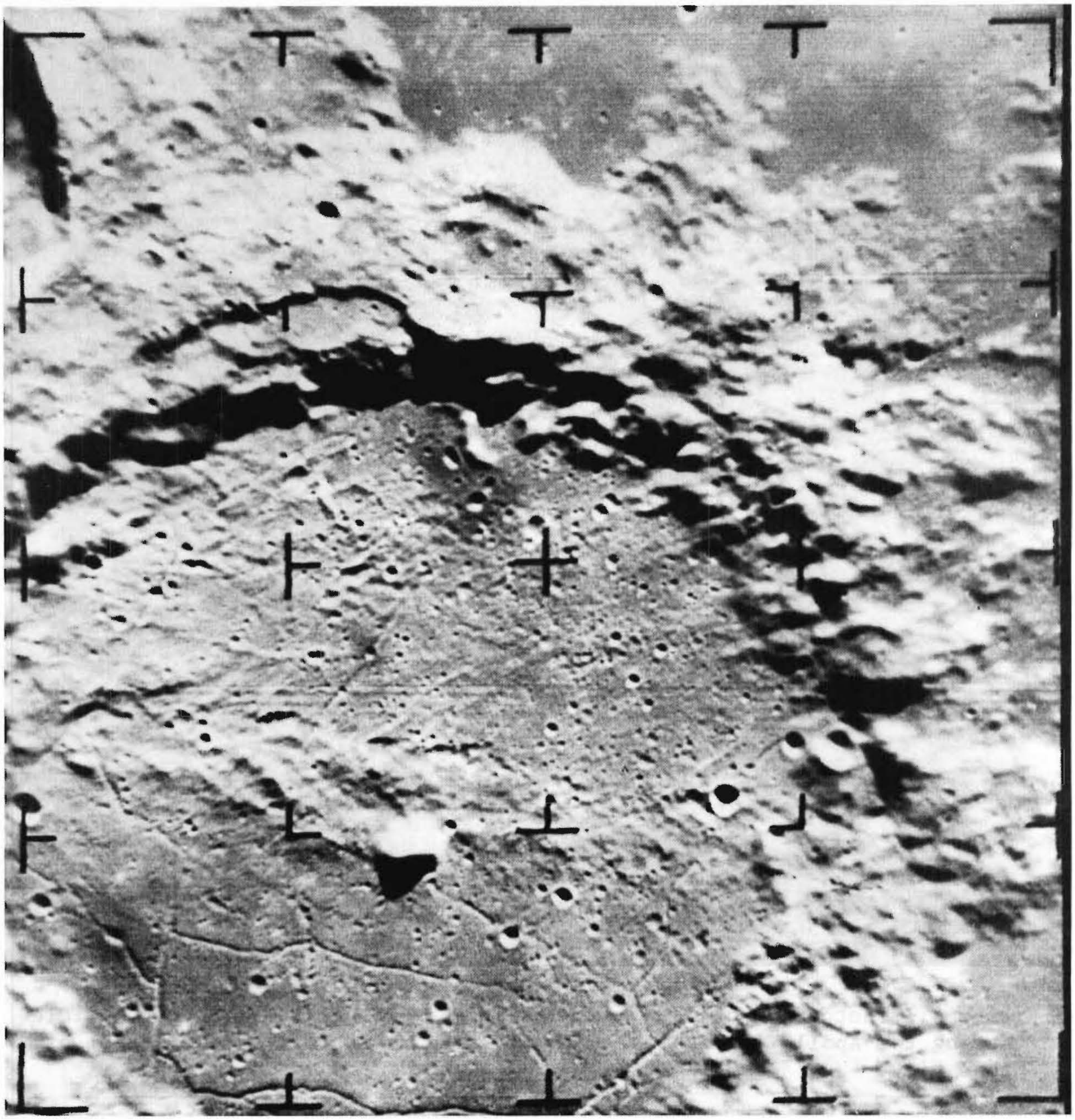


Figure 2.- Map showing location of the Apollo (circles), Luna (squares), and Lunokhod (diamonds) sites; numbers in the symbols are the mission numbers. The stippling near the poles indicates the approximate limits of permanently shadowed regions in which volatiles might be trapped.



(a) Ranger IX frame A47.

Figure 3.- Photographs of the Aristarchus region of the Moon showing a variety of endogenic features that may indicate the action of volatiles.



(b) Lunar Orbiter 5 frame M188 V46.

Figure 3.- Concluded.

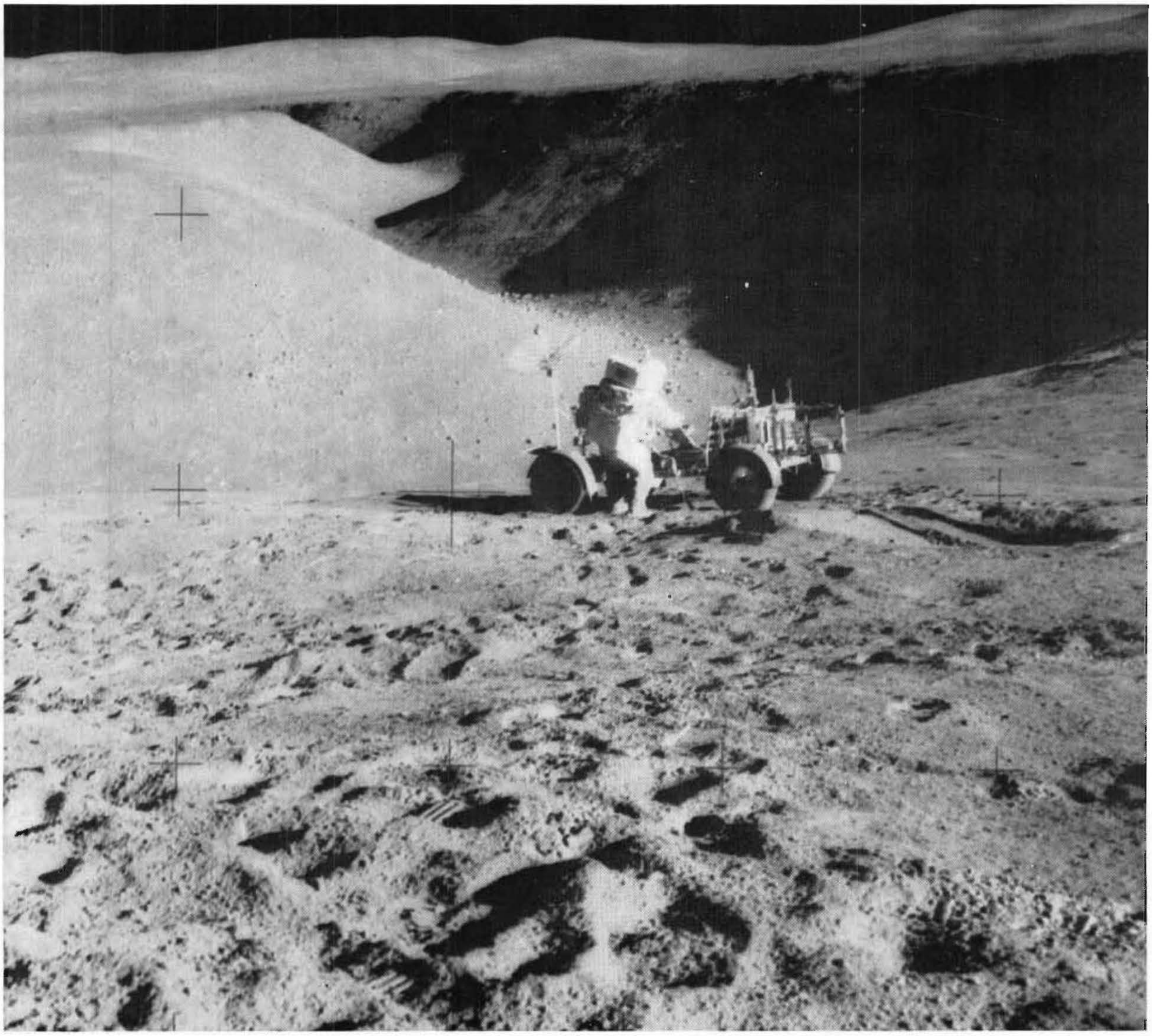


Figure 4.- Photograph of Astronaut David Scott at the lunar roving vehicle during the Apollo 15 mission. Hadley Rille is visible in the center of this view.

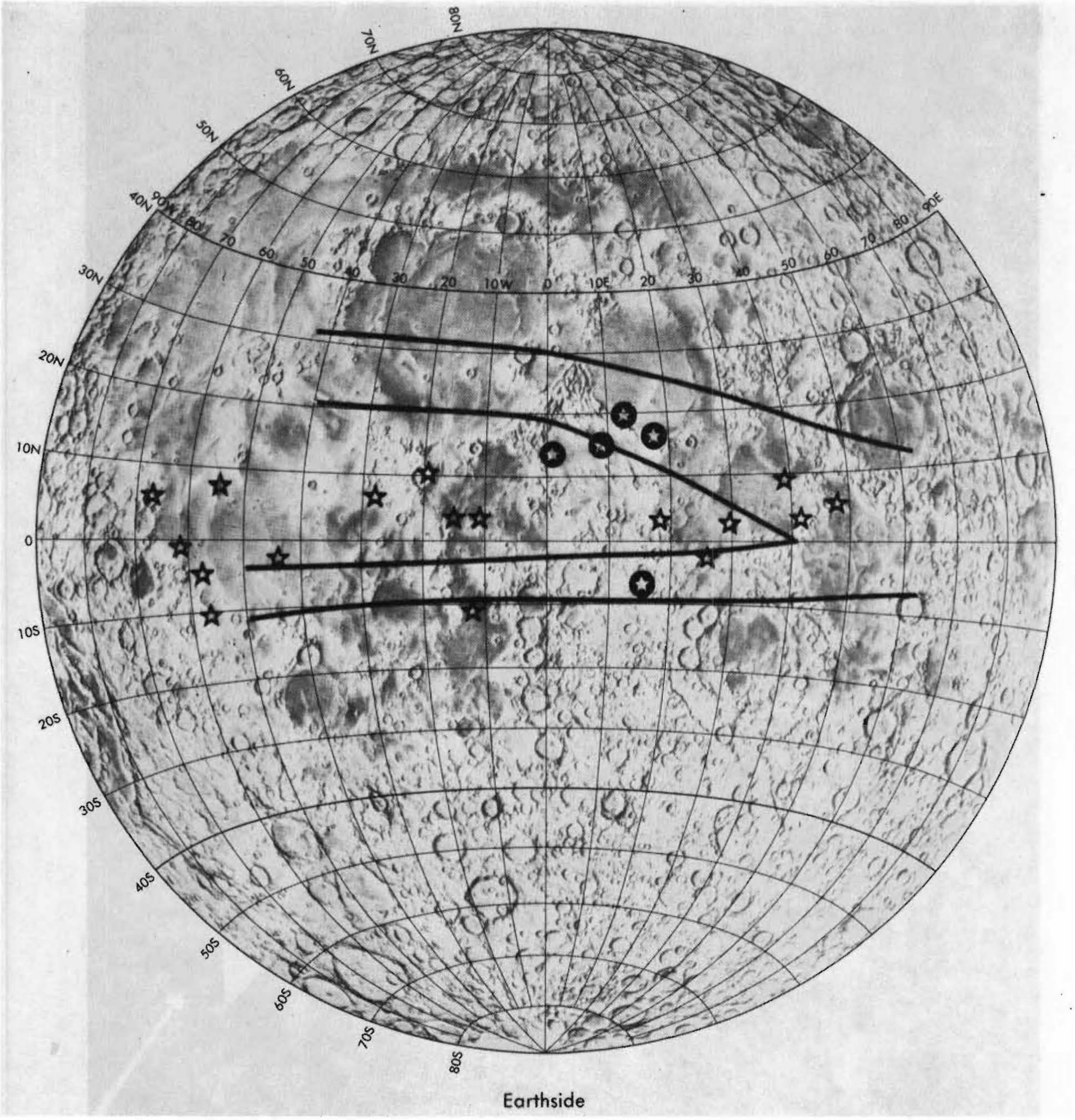
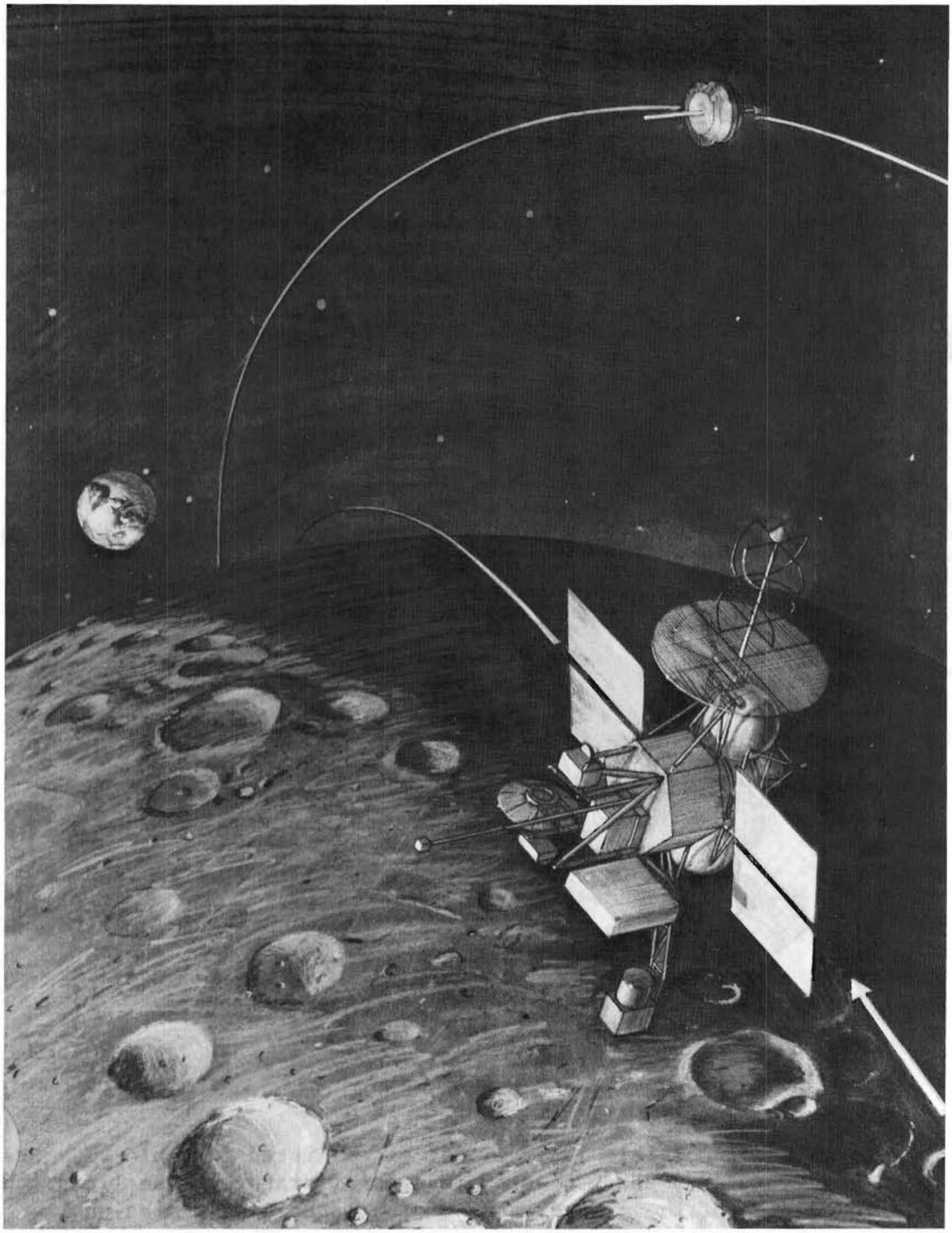


Figure 5.- Location of possible lunar mining sites listed in table VI. Stars are fresh young craters; starred dots are special craters. The lines indicate the boundaries of the groundtracks of the later Apollo missions.



(a) An orbiting spacecraft surveys the chemical, physical, and morphological properties of the Moon. The smaller satellite is a relay that beams information back to Earth when the orbiter is on the far side of the Moon.

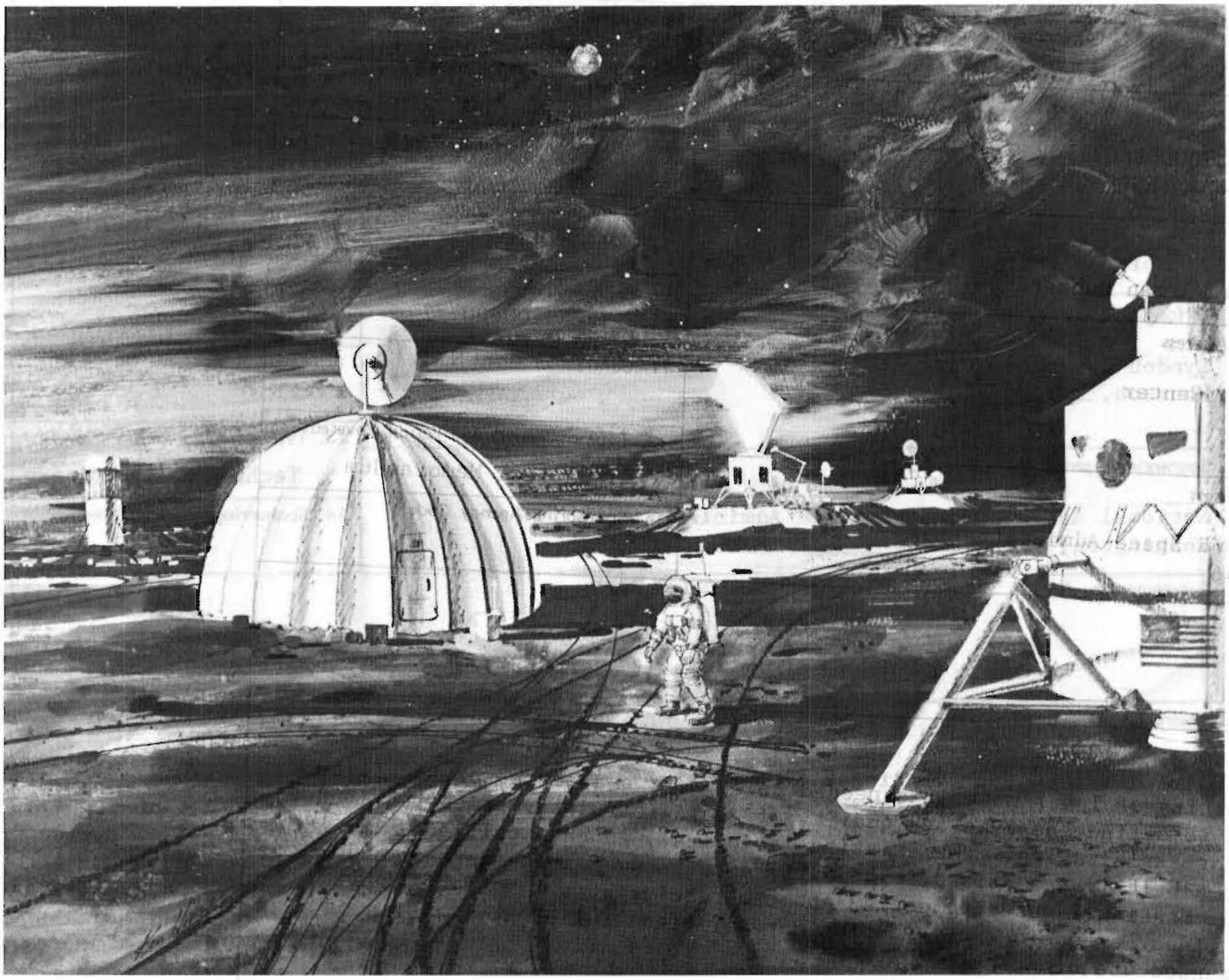
Figure 6.- Artist's conceptions of future lunar exploration and exploitation.

(b) A rover peers into a permanently shadowed area in search of volatiles.

Figure 6.- Continued.

(c) An automated processing station uses solar power to produce metals and gases from the lunar soil, which is gathered by the automated mining rovers.

Figure 6.- Continued.



(d) Man returns to the Moon and uses the inventory accumulated by his automated predecessors to build a base.

Figure 6.- Concluded.

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16. **Abstract**

The type and quantity of lunar materials needed to support a space power satellite program has been used to define the type and quality of geological information required to "certify" a site for exploitation. The existing geological, geochemical, and geophysical data have been briefly summarized. The difference between these data and the required data for exploitation is used to define program requirements. Most of these requirements involve linear extensions of existing capabilities, fuller utilization of existing data, or expanded use of automated systems.

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