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Summer Workshop on Near-Earth Resources

A Workshop held at
University of California at San Diego
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Summer Workshop on Near-Earth Resources

Edited by

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A Workshop sponsored by
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SUMMARY AND RECOMMENDATIONS

This subject, near-Earth resources, is something new. The first stage of activity in space could properly be called the Age of Discovery. Although some direct human benefits developed early, especially in telecommunications and weather observation, the main goal of mankind's efforts has been exploration of the unknown.

It is now possible that a discovery phase will be succeeded by a phase of utilization for human benefit. One example is a response to the energy crisis. Prof. G. K. O'Neill and his colleagues have been developing such a response in detail: the fabrication of solar power satellites from lunar or asteroidal materials. The group has used this proposal as a "point example" of the sort of enterprise that might involve the use of near-Earth resources on a large scale. There are other ideas, less well developed or yet unthought of, that may also involve the large-scale use of near-Earth resources. This report is general enough to include such possibilities. At the same time, it refers ideas to the solar power satellite proposals, where concreteness seems desirable.

Why not supply mankind's need for materials in space by sending them from the Earth as has been the practice so far? Earth's resources are at the bottom of a deep gravitational potential well. The energy requirement for transport into space is measured, qualitatively, by the square of the escape velocity, $(\Delta V_e)^2$ where ΔV_e for the Earth is 11 km/sec. By comparison, the lunar ΔV_e is 2.4 km/sec, so that the energy requirement to escape the lunar surface to free space is only a few percent of that for the Earth. As in most technical enterprises, the reality is more complex than this simple comparison shows. Very large multistage rockets are still needed to remove matter from the Earth's g-field, and these must accelerate their own much larger weight to high speed along with the payload. On the Moon, it appears that much simpler means, not using chemical rockets, may serve.

The near-Earth asteroids are a much less familiar, but equally promising, possibility. The best present estimates are that at least hundreds of objects larger than 1 km must pass through or near the orbit of the Earth. Of these, only about 40 have so far been found. Smaller, but still massive, objects must be much more numerous. These near-Earth asteroids probably hold a wider variety of useful materials than the surface layers of the moon. Their ΔV_e's are very small, but another significant ΔV is required to reach them from the Earth and to return material, because of the differences in orbit.

When will mankind be using these resources? This workshop group is not ready to attempt a definite answer to this question, which depends on many things that are not understood. However, the group has taken as a working assumption for purposes of this study that a significant level of production of transferrable (useful) material can occur on a time scale of 20 to 30 years -- say, by the year 2000. Some of the group believe this is probable. All of the group believe in the desirability of having this option, either because of energy needs or for reasons not now foreseeable.

What must be known first has been the main focus of the study. As these recommendations should show, this study does not attempt to evaluate the worth of the solar power satellite concept to meet the country's energy needs, or of other specific ideas. One fact is evident: If a program for use of near-Earth resources were needed tomorrow, not enough is known.

How long will it take to get the facts? The detailed answers to this and the previous question are provided in this report. The report tries to outline a program, for a period of 5 to 15 years, that will reach the desired point. This point is considered to be a state in which a senior governmental official, faced with a major proposal involving near-Earth resources, will have the minimum technical facts needed for an intelligent choice.

The interaction of resource-oriented research and "pure" research in this field deserves special emphasis. Most of the ground-based studies recommended, and the first generation of missions proposed, have a high yield of basic scientific knowledge, irrespective of any future applications. The resource concept might suggest some change in the order of priority in a program of scientific studies of the solar system. Its main effect will be to strengthen the case for that program, by affording a new reason for doing it.

No attempt has been made to make an engineering, economic, or social analysis. This group is not competent to do so. Rather, an attempt has been made to say what is necessary to learn about these resources: (1) where they are, (2) what they are, and (3) as far as possible, how they might be extracted and processed.

Previous lunar programs have provided extensive photographic coverage, detailed sample studies at nine near-side sites, local and regional geophysical information, and limited orbital maps of chemical composition. Telescopic observations continue to contribute knowledge. As a result, it is already known that lunar materials could be used for purposes such as thermal and radiation shielding.

Most of the data have been obtained only from equatorial regions. Although a first-order understanding of the Moon has been developed, many major geologic units and most apparently anomalous areas have not been sampled or chemically mapped from orbit.

The Lunar Polar Orbiter (LPO) will carry a complement of scientific instruments that will improve understanding of the Moon's evolution and the diversity of major rock types over nearly the entire lunar surface. These are necessary first steps in exploration for exploitable lunar resources. Subsequent resource exploration strategy will be based on what the LPO finds. This workshop group has reviewed the LPO and its individual experiments for their applicability to resource problems. The proposed payload is considered excellent for the explorative stage of resource evaluation, although some changes of emphasis may be desirable to optimize its usefulness.

A research and development program should be initiated to address key problems related to lunar resource definition and use. The data from this program, if available in the mid-1980's when LPO data become available and resource needs are better established, would allow prompt definition of the next explorative step.

This group therefore recommends the following:

1. The LPO should be flown as soon as possible with its present instrument complement, because further lunar resource exploration depends on LPO discoveries.

2. The resource survey aspects of the LPO should receive continued study to maximize its usefulness as a survey mission. Relatively simple modifications such as definition of extended mission capabilities may be important.

3. A research and technology effort should be initiated to provide a basis for lunar resource exploration beyond the LPO. Early starts of importance include (a) studies of lunar samples and data aimed at extending understanding of special lunar environments and rare materials, (b) studies of beneficiation and refinement processes for known varieties of lunar materials, and (c) conceptual studies of lunar resource prospecting techniques and missions.

4. The NASA Office of Aeronautics and Space Technology and Office of Space Flight initiatives in defining nonterrestrial material requirements should be supported.

Very much less is known about the Earth-approaching asteroids than is known about the Moon. The Moon has been studied with telescopes for centuries. It has been the object of numerous orbiting and surface missions. Samples have been returned. In contrast, the first Earth-crossing object was discovered in 1932, was promptly lost, and not seen again until 1973. Only in the last few years have these bodies been studied systematically, and only a very few have been investigated using the state-of-the-art remote-sensing techniques of planetary astronomy.

Therefore, much needs to be done before anyone will be in a position to evaluate the importance of these bodies in a program of space utilization. The following recommendations respresent the group's view concerning the scale of effort required if there is to be any chance of making such an evaluation within the next 10 to 15 years. Because so much new knowledge is needed, this level of effort would require a significant shift of priorities in the current program of planetary exploration. The group believes the recommended investigations have great scientific merit, quite apart from their contribution to a program of space utilization. However, the recommended program of spacecraft missions, including rendezvous, landing, and sample return, could easily unbalance a scientific program of planetary investigation. Therefore, they are recommended under the condition that, after appropriate consideration of the engineering, economic, and social issues involved, the NASA will decide to embark on a program of near-Earth resource evaluation. The justification of this program of missions would extend beyond their purely scientific priority.

In the area of asteroidal studies, the following actions are recommended:

1. Asteroid search

   a. Take immediate steps that will increase opportunities to search for near-Earth asteroids with large-field telescopes having apertures of 60 cm or larger.

   b. Support construction of a new 100- to 120-cm Schmidt camera, which would be dedicated to the search for near-Earth asteroids.

   c. Increase support of effort associated with the search for near-Earth asteroids from the present level of two full-time persons to at least four full-time persons and to at least six persons when a large dedicated Schmidt camera becomes available.

2. Physical and chemical studies of asteroids

   a. Expand the ground-based asteroid-observing program by developing new instruments useful to multiwavelength observations of very faint objects.

   b. Make available more large-aperture-telescope time to permit the characterization of newly discovered Earth-approaching and main-belt asteroids in terms of physical, chemical, and mineralogical properties.

3. Studies of meteoritic materials

   a. Make an evaluation of the extraction techniques needed to produce useful materials from meteoritic matter. Based on current knowledge, meteorites represent the best estimate of the type of material to be found on asteroidal surfaces.

   b. Further study the mechanical properties and chemical nature of meteorites to evaluate material-processing techniques.

4. Advanced studies

   Expand the current program of advanced studies for small bodies being conducted by the NASA Office of Aeronautics and Space Technology and the Office of Space Science to embrace important issues relevant to near-Earth asteroids as retrievable resources.

5. Flight missions

Define program of rendezvous and sample return to low ΔV asteroidal targets. The purpose of these missions will be to characterize the physical and chemical properties of these bodies to permit evaluation of their potential as natural resources. It is proposed that this program be a fiscal year 1980 new start leading to missions in the mid-1980's. These missions add a new dimension in planning for NASA and should have a broader base of support than the planetary exploration program within the Office of Space Science.

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INTRODUCTION

The idea for this workshop developed in the spring of 1977 in a series of discussions among the chairman and several individuals at NASA Headquarters and at the Lyndon B. Johnson Space Center (JSC). In particular, James Fletcher, then the NASA Administrator, expressed interest in a preliminary exploration of this area of study. The work of G. K. O'Neill and his associates, particularly in a series of summer studies at the NASA Ames Research Center, had developed interesting possibilities for the use of lunar and asteroidal resources for human benefit. The examination of what resources might exist and how they might be made available seemed to be timely and indeed necessary. The proposal for this summer workshop was a result.

The participants in the conference were experts in a wide range of fields, a mix of generalists and specialists, NASA employees and outsiders. Some attended at considerable personal inconvenience. Given that some important aspects had to be excluded to keep the subject at all within bounds, the authors believe experts (often the leading experts) in all the essential fields attended. A number of participants also took part in the NASA Ames summer study in June and July; they brought much useful material from that study. The workshop was not, however, able to have as much participation as was wished from branches of NASA outside the Office of Space Science. As the recommendations show, the topic is regarded as having important implications for many parts of the NASA.

The participants are listed at the end of this section and the program is contained in appendix A. The pace of mutual education was intense in the first days; its success can be measured by the results. The three major subcommittees formed on Tuesday (Resources, R. Williams, chairman; Lunar Materials, M. Duke, chairman; and Asteroidal Materials, G. Wetherill, chairman) have the main responsibility for the corresponding sections of this report. Attendees were free to move from one subcommittee to another as required. The recommendations were generated in the subcommittees after report outlines and some draft text had been produced. They were reviewed in plenary session on Friday. The summary report and recommendations were approved in a final plenary session Friday afternoon. They were presented to Thomas Young, Office of Space Science, and other NASA officials on Saturday morning.

The subject of the conference is an old dream of mankind. Its very interesting history is beyond the scope of this report; its immediacy is due to the advent of the Space Shuttle, which is designed to lower the cost of transportation to near-Earth orbit and to provide frequent and regular access to near-Earth space. A part of the economic justification of the Shuttle is the possibility of useful manufacturing or separation processess or, more generally, of prolonged and intensive human effort in space.

Even with the Shuttle, transport costs (in energy or money) of terrestrial materials to and from space remain very high. Although future sytstems can be expected to further reduce transport costs, costs will almost certainly remain high enough to encourage the search for alternative sources of raw materials.

The Earth's surface is at the bottom of a deep gravitational well, "at the base of a mountain 4000 miles high" in O'Neill's phrase. The escape velocity ΔV_e from the surface to free space is 11.2km/sec; from the Moon, it is only 2.4 km/sec. The required energy for escape from the Moon is $(2.4/11.2)^2$ or $\backsim$4.5 percent of that from the Earth. In practice, one must take into account the fact that multistage rockets are needed for Earth escape. The Shuttle mass at launch (including fuel) is 2 000 000 kg, and much of this must be accelerated to a considerable fraction of the (orbital) escape velocity. The payload mass actually carried into near-Earth orbit is only 30 000 kg. Thus, the energy efficiency is still very low.

On the Moon, simpler means are possible. The Apollo landing module used a one-stage rocket. Recent proposals have been planned around an electromagnetic "mass driver" for ejection, the energy efficiency of which (relative to electric energy used) is remarkably high. Direct energy costs for transport into near-Moon space can thus be lower by orders of magnitude than for the Earth. It should not be forgotten, however, that the capital cost of placing the mass driver, or any launching system, on the Moon must be high.

The escape velocity from asteroidal surfaces is very small and hence material from them is easily available in space at the location (and velocity) of the asteroid. To bring this material "home" to the region of the Earth, either in the form of a large coherent object or otherwise, requires a ΔV that depends on the asteroid's orbital elements and to some degree on the individual opportunity. Still, as will be shown, the overall ΔV may be very favorable. It is the fundamental gravitational advantage of lunar or asteroidal materials that makes them attractive.

When might these materials be put to use? On the first day of the meeting, estimates were given ranging from 15 to 100 years. No one knows, of course. Still, it may be worth pointing out that, when the Enterprise landed on the California desert during the meeting, less than 20 years had elapsed since Sputnik. Significant advances have been achieved during those two decades.

For working purposes, a planning target of 20 to 30 years was adopted to reach a significant level of utilization of near-Earth resources. This is far enough off that an orderly research and development program can prepare for it, if a start is made now. An urgent national priority could shorten this time scale somewhat; many factors could work to lengthen it.

The main concern of the present report is first steps. Most of the recommendations call for action, or at least for preliminary studies or commitments, in the next 2 fiscal years. Some of these actions can be completed quickly. The most important ones, whether for ground-based studies or missions, involve ongoing commitments for a period of years.

What would be the effect of delay? This group believes, of course, that the whole program should go forward together. If nothing is done for a year, the earliest date for use of these materials will be delayed a year more or less. In particular, delay will tend to freeze the present situation, in which lunar resources are likely to be developed first, not because they are inherently more useful (which is not known), but because so much less is known about the near-Earth asteroids.

The programs recommended for starting have natural time scales on the order of 5 to 10 years. The asteroidal mission programs could well require a somewhat longer period.

Certain specific possibilities for international cooperation are discussed in the body of the report; a more general comment seems appropriate here. A program of the sort recommended can be helped by cooperation with other countries engaged in space activities, and it is hoped that such possibilities can be actively encouraged. It may be, also, that joint endeavors in this area would make some contribution to international understanding.

Finally, a word is in order about the nature of this report. As stated, most of the report was written by most of the workshop participants in "real time" during the meeting itself. The editors took the view that an unpolished report completed quickly would be more useful than a scholarly product after some years. Hence, their activities have been confined to minimal efforts to improve readability and coherence. In general, the individual writers have not reviewed their sections after editing, which may cause some problems. With more time, the report and the summary report could have been made shorter. More time to work on the references would have been beneficial; however, the interested reader should be able to find his way into the literature from those given. Appendix B contains a glossary of useful terms that may be as new to the reader as they were to some members of the group.

The workshop could not have taken place at all, or have been so pleasant, without the work of a strong support staff at the University of California at San Diego. Florence Kirchner was responsible for the overall operation; Deanna Wilkes produced reams of comprehensible copy from a large number of different illegible handwritings; and Norman Fong prepared Vugraphs and slides and handled other problems as they arose. The authors wish to acknowledge their help.

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RESOURCES FROM SPACE

SPACE RESOURCE CONSIDERATIONS

In recent decades, civilization has become increasingly dependent on an ever-expanding use of resources and energy. The present "energy crisis" and potential "raw materials crisis" result from approaching the limits of availability of these resources at reasonable cost.

The cost of resources increasingly must include assessment of environmental factors, including long-term climatic effects, health hazards, quality-of-life aspects, and so on. This assessment requires that the total system from the mining of raw materials to the ultimate disposal of the products and wastes be considered. Limits on the rate of economic growth may stem from limits on availability of raw materials, energy, open spaces, secure storage environments, or a host of other considerations. Some of these limits may be removed by the use of space resources.

The resources of space include raw materials, energy, and special aspects of the space environment. The availability of energy and many aspects of the space environment are fairly well known. The scientific investigations of the Moon, asteroids, and meteorites have provided some tantalizing clues to raw materials that may be recoverable. The Apollo and Skylab experiences have begun to show man's capabilities to work in space near the Earth. The time appears to be ripe to consider how the potential space resources could be further investigated and used, and to what extent it may be practical and economical to use them.

To quantify the concepts for use of near-Earth material resources, it is important to model the potential uses for them. This report does not attempt to set forth such models. It is recognized that several classes of uses have been proposed, of which the solar power satellite (SPS) concept (refs. 1 and 2) is the best defined one that requires large amounts of materials. Figure 1 summarizes the material needs of one model for an SPS (ref. 3). This is not the only model for an SPS, but it illustrates the range and quantities of materials necessary to build the system.

It is likely that the first uses of near-Earth material resources will be associated with a specific project, such as an SPS. However, once begun, it is likely that a more diverse space industry could develop, which would expand the availability of materials and decrease their cost in space. To evaluate whether a complex industrial base could be supported with nonterrestrial material resources, Criswell (ref. 4) has used the concept of "demandite" to define materials requirements. Demandite (ref. 5) is a term that has been applied to the composition of the total nonrenewable resources used in the United States. Table I provides this distribution for 1968. The terrestrial "demandite" is dominated by the fuel component,

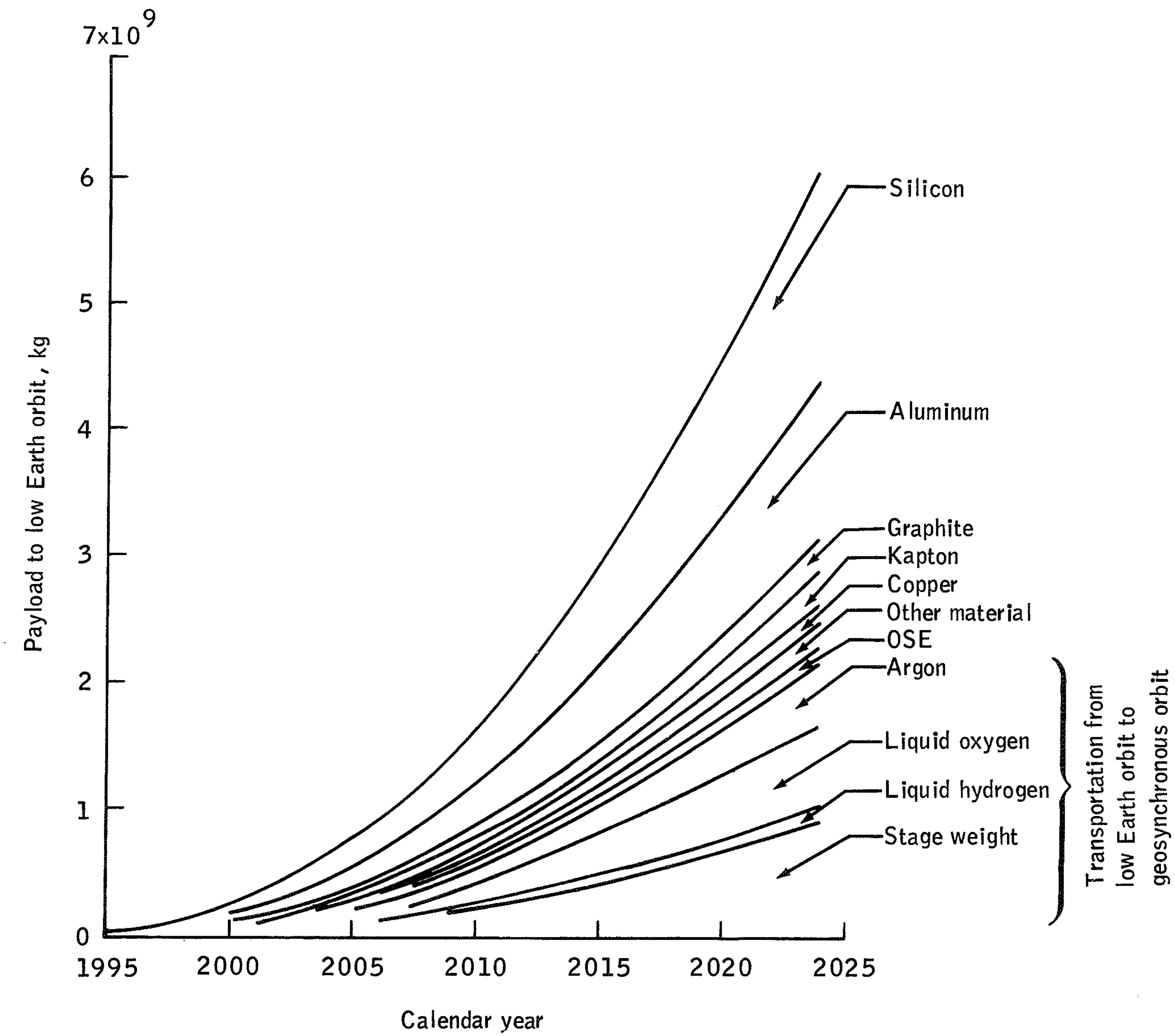

Figure 1.- Mass requirements for illustrative SPS Program.

TABLE I.- DEMANDITE[a]

(a) Molecular composition

Use	Weight fraction	Components	Molecular fraction
Fuel	0.46	Hydrocarbon (CH_2 to C_6H_{14})	0.8022
Building	.45	Silica (SiO_2)	.1115
		Calcium carbonate ($CaCO_3$)	.0453
Metals	.06	Iron	.0110
		Aluminum	.0011
		(b)	.0008
		Magnesium	.0004
		(c)	.0004
Agriculture	.01	Nitrogen	.0076
		Phosphorus	.0008
		Potassium	.0007
Others	.02	Oxygen	.0053
		Sodium	.0053
		Chlorine	.0053
		Carbon	.0023

(b) Molecular properties

Parameter	Value
Average molecular weight	23.9
Average recovery energy, kJ/kg (kWh/kg)	15 (0.57)
Average unit cost, cents/kg	1.4
Total quantity used, Mg/yr	3×10^9
Total value, $	42×10^9
Per capita mass consumption, Mg	15.4
Per capita energy consumption, MJ(kWh)	67 680 (18 800)
Per capita power consumption, kW	2.14

[a]Represents average nonrenewable resources used in the United States in 1968.

[b]Total of manganese, barium, chromium, fluorine, titanium, nickel, argon, tin, boron, bromine, and zirconium.

[c]Total of copper, zinc, and lead.

which clearly would be provided by other means in space. The nonfuel components of terrestrial demandite (for the same year) are recalculated in table II, in which they are compared to the composition of lunar soil from the Apollo 15 landing site. The comparison shows that more than 90 percent of the materials required for a complex industrial society are available from average lunar soil with little or no enrichment. By starting from comparisons of this type, it should be possible to begin to define substitutions that would make use of the most readily available lunar elements and to identify those elements that should be the targets for exploration because discovery of localized high concentrations would permit them to be mined profitably.

Most models currently being discussed for the use of near-Earth material resources involve their use in space. The economic return is usually presumed to be electrical energy, which can be transmitted efficiently from space. However, it also is possible that materials derived from space may be brought to the Earth in substantial quantities. Gaffey and McCord (ref. 6) have suggested that metallic asteroids might be returned to the vicinity of the Earth, where they would be processed and their metal (particularly nickel) formed into shapes that could be glided down to the Earth's surface. Transportation to any point on the Earth should cost approximately the same and could provide a secure, nonintrusive supply of materials to terrestrial industry.

In this report, the premise is adopted that large-scale use of nonterrestrial resources may be economically and socially desirable in the foreseeable future. In a general way, the types of materials involved are known and the pathways that must be followed to better define and use those materials can begin to be sought. It remains for others to establish the economic and social costs and benefits of their use. Nevertheless, the potential benefit of a program that would use near-Earth resources cannot be ignored.

The NASA would face many new challenges from involvement in these inherently large and complex activities. The motivations for explorative programs would grow to include economic goals, as well as scientific and political ones. Furthermore, NASA would become involved with the same decisions that the largest corporations in the world (up to 15 times larger than NASA) now face in projecting their own growth and future opportunities. Above all, the NASA would become directly linked to the time scales that affect society. The potential economic productivity of space development activities provides an incentive for early evaluation of the alternatives by the NASA, which is the source of experience in major space activities. This must be combined with the experience of industry to realize the myriad of specialized applications for a diverse space-based enterprise.

POTENTIAL RESOURCES IN SPACE - WHAT DOES EARTH EXPERIENCE PROVIDE?

In near-Earth space, two possible sources of raw materials exist: the asteroids and the Moon. Explorative programs can be launched in both directions. What are the targets?

TABLE II.- NONFUEL DEMANDITE COMPARED TO ELEMENTAL DISTRIBUTION FROM ONE MOON SITE

Element	Weight fractions		
	Nonfuel demandite	Apollo 15 mare (low titanium)	Enhancement required[a]
Silicon	0.2444	0.2158	1.13
Oxygen	.4547	.4130	1.10
Iron	.0479	.1535	.31
Aluminum	.0023	.0546	.042
Magnesium	.0017	.0681	.025
Copper, zinc, and lead	.0020	.000022	90.
(b)	.0030	.0189	.16
Calcium	.1417	.0696	2.0
Sodium	.0095	.0023	4.1
Sulfur	.0058	.0006	9.7
Potassium	.0021	.0008	2.6
Phosphorus	.0019	.0005	3.8
Chlorine	.0147	.0000076	1934.
Nitrogen	.0083	.00008	103.
Carbon	.0574	.000095	604.
Hydrogen[c]	.0025	.000070	350.
Total	0.9999	1.0000	

[a]Required to meet terrestrial demandite fractions.
[b]Manganese, titanium, chromium, barium, fluorine, nickel, argon, tin, bromine, zirconium, and boron.
[c]For use in plastics; does not include water.

At the present state of knowledge, it is possible to visualize five kinds of explorative targets that extend beyond simply providing material mass (e.g., for shielding).

1. Plagioclase "float cumulates" in anorthositic terrains on the Moon.

2. Magmatic oxide concentrations of the ferrous metals, including chromium.

3. Native metal concentrations of iron and nickel (especially in asteroids).

4. Collections of the "volatiles," chiefly water, carbon, nitrogen, and sulfur.

5. Lunar volcanic or fumarolic concentrations of base metals in compounds with sulfur and/or chlorine. These may be in complex glasses or similar compounds, in areas of most recent volcanic activity.

The first two types may be analogous to similar deposits on Earth. For the rest, no terrestrial analogs exist. Unanticipated types may, in fact, be numerous. Theoretical characterization of these is still a fascinating enterprise.

The Moon

Potential ores of aluminum, silicon, and oxygen.- Portions of the highland regolith are rich in anorthosites, a highly suitable raw material for extraction of aluminum, silicon, and oxygen. Anorthosites of the highest aluminum content will likely be delineated by the Lunar Polar Orbiter (LPO). If grades of 80 to 90 percent anorthosite could be found in otherwise desirable locations, it is unlikely that a superior mineral assemblage will be found in near-Earth space for those materials. Consequently, laboratory experiments on the extraction of aluminum, silicon, and oxygen from plagioclase can be begun immediately.

Potential ores for the ferrous metals iron, nickel, titanium, and chromium.- The currently known lunar sources for the ferrous metal elements are limited to disseminated granules of oxides in lunar soil or rock, which would have to be concentrated before refining. (Iron potentially could be recovered from silicates, as well.) For those metals, a higher grade resource would be beneficial. Oxide cumulates of chrome-rich spinel or ilmenite, naturally concentrated during magmatic processes, would also be useful, although the deep tilling of the regolith by impact may have obliterated most layering. Nevertheless, late mafic igneous activity could have escaped much of the bombardment, and mafic (and especially ultramafic) rocks of the mare should be observed closely for possible segregations.

In judging the probabilities for this type of explorative target, one must remember that, for a cumulate to form, not only must there be sufficient oxygen in the melt to generate the oxide phase, but crystallization of the heavy cumulate must occur before magma viscosity and crystallinity prevent gravity accumulation. Presumably the plagioclase accumulations in the highland anorthosites are "float" accumulations in the primitive crust, and, owing to the very low oxidation state of lunar rocks, it is difficult to be optimistic that corresponding oxide cumulates were formed at that time deeper in the lunar crust. Yet it should be noted that some of the oldest rocks on Earth, from the Greenland craton, include anorthosites with which are associated low-grade chrome cumulates (the Fiskenaesset deposits), which may be the oldest "ore" deposit of any kind on Earth.

Ilmenite ores on the Earth are nearly all mid-upper-Proterozoic (ages of 1.6 to 1.1 billion years), and the chromium-rich chromites of the Great Dyke and the Bushveldt are about 2.5 and 2.0 billion years, respectively. All commercial terrestrial oxide cumulates are thus later than the beginning of biogenic oxygenation of the Earth's surface environment, a situation that had no counterpart on the Moon.

Most other types of terrestrial ores are the result of interaction with water, either in igneous-volcanic or sedimentary processes. Some of the oldest terrestrial ores are in greenstone belts, believed to represent metamorphosed sediments. The earliest greenstone belt ores on Earth are in the Kaapvaal craton of South Africa, at about 3.4 billion years, but only the gold-quartz veins of the Barberton make commercial deposits, and these probably are metamorphic in origin. Even the oldest "granitic" migmatite and granites between greenstone volcanic belts are singularly devoid of mineralizations of any kind, except for those noncommercial chrome concentrations near the anorthosites of the Fiskenaesset area in Greenland. Subsequent interactions of volcanic rocks with near-surface water-rich zones have produced the hydrothermal ores that constitute the most productive metallic ore deposits on Earth.

Therefore, except for the possiblity of chromite associated with some of the special lunar mafic rocks of local distribution, or ilmenite in the deeper crustal zones beneath anorthosite, terrestrial ore deposits probably do not assist much in the definition of explorative targets on the Moon.

Water and volatiles.- It is theoretically possible that water and associated volatiles could be found on the Moon in permanently shaded regions near the poles. The LPO could be used to determine if such resources do indeed exist. Small quantities of hydrogen, carbon, and nitrogen derived from the solar wind also exist in the lunar soil but are not presently known to exist in high concentration.

Volcanic or fumarolic concentration.- The special cases of "green" and "orange" glasses, or sulfide or chloride exhalations in rifts, may represent concentrations of elements scarce in the general lunar regolith. They could comprise targets for surface exploration if the LPO detects substantial anomalies.

Near-Earth Asteroids

The near-Earth asteroids contain a variety of potentially useful materials, including metallic nickel-iron, silicates, hydrocarbons, and water. Asteroids range considerably in character, some apparently being siliceous, others carbonaceous, and so on. Insufficient data exist at present to make comparisons between the origins of terrestrial ore bodies and those of possible asteroidal "ores." It may be possible in the future to make such comparisons for the largest asteroids or for smaller objects that are fragments of preexisting larger bodies. On the other hand, resources on many asteroids may be formed by processes (accretionary) quite different from Earth or Moon processes. Meteorites, which are available in laboratories, are fragments of some small bodies in the solar system. They are certainly useful in both scientific and technical studies of asteroidal resources. However, they are surely not representative of the potential variety of those resources. Initial exploration for asteroidal resources, therefore, is at the stage of an inventory of types of bodies that are present.

DEVELOPMENT OF RESOURCES

Development Patterns for Terrestrial Resources

The process by which a resource prospect is developed into a producing facility evolves through three broad categories of activities. The first phase is exploration, which involves the elements of reconnaissance, specific target selection, and finally target testing and evaluation. (The proposed LPO mission should accomplish the first two of these elements for the Moon; it is noteworthy that the Apollo sites are in some respects completely through this stage.)

The second stage is development; detailed evaluation, pilot testing, financing, and construction are the primary activities during this phase. No nonterrestrial resource even approximates this stage of maturity. The final stage is actual ore production, the needs of which will be discussed.

Typical terrestrial time scales involve 3 to 10 years in exploration, 5 to 10 years in development, and up to 30 years from start to realization of ore production; although, in favorable and important projects, which use established technology, the process may be reduced to only 5 years. It is evident from the typical time scale for terrestrial development that the resource needs of the late 20th and early 21st centuries require activities beginning now.

Common Steps in Terrestrial Resource Development Projects

After exploration objectives (such as desirable types of conventional ore bodies and selection of regional target areas) have been adopted, the following steps are generally required before terrestrial resources can be placed into commercial production. Many of these same considerations and requirements may apply to the utilization of space resources if the materials requirements (e.g., for SPS) are defined as exploration objectives, and the lunar surface and near-Earth asteroids are identified as exploration target areas.

Exploration.- The usual time span for exploration is 3 to 10 years and involves the following.

1. Reconnaissance and multiple-target selection phase: Regional mapping and data compilation; airborne geophysics and remote sensing; geochemistry, geologic interpretation

2. Target selection: Identification and ground examination; preliminary detailed mapping, sampling, and assaying of most promising target areas

3. Detailed examination of target(s): Detailed mapping, systematic sampling and assaying of best target area; ground geophysics; detailed geochemistry, etc.

4. Target testing: Drilling and/or underground tunneling, trenching or pitting of prime area within best target area

5. Preliminary evaluation of results: Assuming successful discovery, preliminary calculation of potential reserves, and first consideration of feasibility of various options and schemes for exploitation; preliminary laboratory scale metallurgical tests

Development.- For development, the common time span is 5 to 10 years and includes the following.

1. Fill-in drilling, sampling and/or underground work to confirm reserve calculations and to provide bulk samples; extensive and systematic laboratory-scale metallurgical tests and rock mechanics studies for mining

2. Preliminary design of exploitation scheme including mining, metallurgical, transportation, power, water systems, and other infrastructure required; preliminary contacts with money lenders

3. Pilot scale testing of metallurgical processes using bulk samples

4. Environmental effect studies of exploitation scheme under consideration (applies only to resource development projects in U.S. and a few other developed countries)

5. In-depth feasibility study, including detailed costing, calculation of rates of return, and sensitivity studies to various market and economic variables; formulation of specific and detailed mining plans and flow sheets, etc.; obtaining bids from contractors

6. Financial arrangements, submitting feasibility study and economics studies to money lenders and obtaining commitments for financing

7. Updating feasibility study and financial studies and obtaining final bids from contractors

8. Detailed design and engineering; final planning; awarding contracts

9. Construction of mine, mine layout, plant, and other infrastructures

10. First production and break-in of plant; elimination of startup problems; establishment of efficient and profitable operations

Full-scale production of ore.- After exploration and development have been done, full-scale ore production can begin.

Resource Development in the Space Environment

The two primary candidates for consideration as sources for ores are the near-Earth asteroids and the Moon. These are airless, small bodies that exist in a peculiar environment relative to the Earth's. Of the many differences, the following known physical conditions are of extreme importance to materials processing. These environmental considerations are not necessarily negative factors, only unfamiliar ones.

1. The environment is a vacuum (1.333 pPa (10^{-14} torr)). Thus, encapsulation of vaporizable materials and life support systems is necessary. Any process that depends on a fluid medium (e.g., air) must be modified.

2. The gravitational forces are small. This may be an aid in handling massive loads, but it slows the rate at which bodies fall. Thus, active transport may replace passive transport.

3. Radiation is intense. Shielding of devices and personnel is required.

4. The lunar surface is dusty. Thus, bearings will have to be carefully sealed and cleaning facilities will be required. Dust may be present on asteroids. The dust is transported ballistically and may travel long distances.

5. Temperature variations can be large (e.g., 100 to 450 K on the Moon for a night/day cycle). Equipment must be capable of surviving such extremes, or provision for storage must be made.

6. The Moon and probably the asteroids are extremely dry. Thus, electrostatic migration of dust could be a problem.

7. The lunar day/night cycle is long (672 hr) except near the poles. Scheduling of work will have to account for this. Machinery may have to recover from long periods of idleness.

Four classes of processes must be applied to transform a resource into a usable product: mining, beneficiation, refining, and transporation. Until all these are demonstrated, the mineral resource is not an ore in a strict sense. On Earth, each process has associated with it many particular devices. The analogous devices and operations in the space environment will require special design and testing under realistic conditions before they can be used confidently in space.

Mining.- The basic procedures and techniques of mining must be established with reference to the properties of the particular ore body. If lunar mining primarily involves excavation of the regolith, the procedures will be quite different from those used if mining involves the excavation and crushing of rocks. The types of devices used (excavators, continuous miners, shovels, bottom loaders) depend largely on the type of material that will be mined and on the scale of the operations. If regolith is mined, crushing and grinding probably can be minimized, although sizing will be required unless the material can be used raw. However, if rocks are to be mined, jaw, gyratory, or cone crushers and rod and ball mills may be necessary. Machines and techniques that can be modified for lunar mining exist (refs. 7 and 8).

The mining procedures for asteroids are more difficult to define with any certainty because the physical definition of the target resource is not certain. It may range from essentially solid metal through normal hard silicates to rather friable mineral-rock-ice mixtures. The differences are quantitatively significant in that techniques designed to excavate silicates cannot be used to mine massive metals and vice versa. It is clear, however, that techniques do exist that can be matched to the type of deposit to be mined.

Beneficiation.- Beneficiation of the mined material may not be necessary if resources of sufficient grade can be found; e.g., nickel-iron asteroids or highly feldspathic rocks and soils. However, a generally prudent view is that such procedures should be developed. Beneficiation involves the concentration of the ore by separation of valuable minerals from tailings. These techniques are well developed terrestrially (ref. 9), but often depend upon the use or presence of fluids. Use of fluidless physical techniques should be given careful consideration for use in nonterrestrial beneficiation.[1] It should be emphasized that these processes are largely empirical in application and thus testing, at least at laboratory scale, with actual materials is essential. The returned lunar samples and meteorite materials may be sufficient for the preliminary testing of beneficiation. In both cases, scaling of laboratory phenomena to the bench and pilot scale cannot be assumed to be direct; however, preliminary scaling may be possible using simulants. Construction and operation of pilot facilities, probably at the actual mining site or at least in the space environment, are highly desirable. The effects of reduced gravitational fields on beneficiation will need to be established.

Beneficiation processes generally involve exploitation of the differences in physical property between minerals, and normally the separation must be preceded by grinding to free the desired particles, followed by sizing to standardize surface-to-mass ratios. This repeated handling is expensive and difficult to tune, even in ideal situations under terrestrial conditions. Such difficulties of control and monitoring will likely

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[1] Williams, R. J.; McKay, D. S.; Giles, D.; and Bunch, T. E.: The Mining and Beneficiation of Lunar Ores. Draft report from NASA Ames Space Settlements Summer Study, 1977.

be multiplied in space. Designers should recognize that a principle of "the less handling, the better" will apply. So, in space, as on Earth, the pressure will likely be to find better grade ore. There is no substitute for grade when applying conventional mining procedures.

Refining.- The refining of mined material is usually a chemical and metallurgical process, but for some classes of materials and uses refining may be simple or unnecessary; e.g., use of asteroidal nickel-iron as metal ore or regolith as shielding mass. Some of the most interesting uses, however, involve the conversion of oxides and silicates into metals. These processes, which use chemically complex natural materials, must be tested and proved on actual materials and close simulants at laboratory, bench, and pilot scale to establish the kinetic limitations. Again, the peculiarity of the space environment suggests that pilot testing under actual conditions will be valuable. The availability of returned lunar samples and the considerable chemical and petrologic literature on them suggests that laboratory verification of the proposed processes using simulants can be undertaken almost immediately. The cases for refining asteroidal materials are not as clearly established unless the meteorites provide sufficient analogs.

The bulk lunar regolith contains aluminum, silicon, iron, titanium, and oxygen in a mixture of silicate and oxide minerals. One possible method of extracting these elements for use in construction of space stations is by direct vaporization, using the Sun's energy, followed by some type of selective vapor deposition. Such a group of processes presents formidable problems in plant design and control, but it also minimizes handling of material between raw ore and reduced metal, while making use of the great energy resource of space -- the Sun. In one process, it might be possible to refine numerous important minor elements as well as the major ones. Research along these lines can be undertaken now on terrestrial materials to ascertain how feasible and competitive direct sublimation might be compared to other methods of producing the elements needed for construction and other purposes.

More conventional procedures of metal extraction must also be tested. The special conditions of operating in space impose major limitations, however, as well as certain advantages. For example, the profligate use of water for mineral separation procedures and refining is unlikely ever to be possible. However, processes such as the carbochlorination process[2] may benefit from the easy access to high vacuum.

Transportation.- The transporation of materials between the various processes described is an essential element of the system that converts a resource to an ore. Systems exist (ref. 8) that can be matched to the scale of operation desired; however, these must be designed to accommodate the special needs of the space environment.

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[2]Rao, D. B.; Choudary, U. V.; Erstfeld, T. E.; Williams, R. J.; and Chang, Y. A.: Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen. Draft report from NASA Ames Space Settlements Summer Study, 1977.

SUMMARY

Substantial lunar and asteroidal resources exist that are potentially useful for large-scale space manufacturing; e.g., an SPS. Systems and theoretical processes exist that might turn these resources into ores. The success of designing mining, beneficiation, refining, and transportation facilities will determine if these resources will become ores. Transportation systems are amenable to direct design studies with minimal access to actual samples; mining, beneficiation, and refining require testing using actual materials or carefully constructed simulants. The availability of returned lunar samples and the extensive data on lunar samples permit laboratory-scale testing to be begun immediately. Similarly, some testing of meteoritic material as asteroidal analogs could be done; however, the physical state of the asteroidal bodies is unknown, so mining and beneficiation studies appear to be premature.

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LUNAR RESOURCES

INTRODUCTION

Geology of the Moon: An Overview

The geology of the Moon provides the framework for any discussion of lunar resources. The surface of the Moon consists of two major physiographic units: the higher albedo (brighter) highlands and the lower albedo (darker) maria. Before the Apollo Program, little more could be said without serious debate, especially about the highlands. But the Apollo data permit a reasonably firm synthesis of the Moon's landforms, major rock types, interior, and to some extent its evolution. The bibliography provides further reading on the subjects discussed in this section.

Highlands.- The lunar highlands that have been sampled consist primarily of feldspar-rich (high aluminum) rocks that have been intensely brecciated and locally melted by intense impact cratering. Crystalline rocks are believed to have formed about 4.4 billion years ago by a mechanism of feldspar crystal flotation from an early outer molten layer, commonly called a "magma ocean."

The huge circular mare basins, such as that containing Mare Imbrium, are generally believed to have been formed 3.9 billion years ago by catastrophic impacts; 3.9-billion-year-old breccias consisting of fragments of earlier rock are widespread on the lunar highlands as a result of those impacts.

Maria.- The maria were formed by filling of the mare basins and other low areas by basaltic magma, starting about 3.8 billion years ago and continuing for about 700 million years. The rocks thus formed are a series of iron- and titanium-rich basalts. Remote-sensing data and sample analyses show that the mare compositions vary from place to place and that the magma compositions probably varied with time, perhaps reflecting derivation from progressively deeper source regions. The mare basalts are enriched in some elements (barium, strontium, rare earth elements, uranium) but generally are depleted in relatively volatile elements, in particular potassium, sodium, lead, and rubidium. All lunar crystalline rocks so far analyzed are completely without water.

The unusual composition, known by the acronym KREEP from its characteristic elements potassium (K), rare earth elements (REE), and phosphorus (P), warrants special mention, both for its scientific and resources implications. Orbital gamma ray data and sample analysis reveal that this material is concentrated around the Imbrium basin (fig. 2). KREEP was found to dominate the "mystery component" responsible for the apparent paradox that lunar soils seemed to have very old radiometric ages (4.4 to

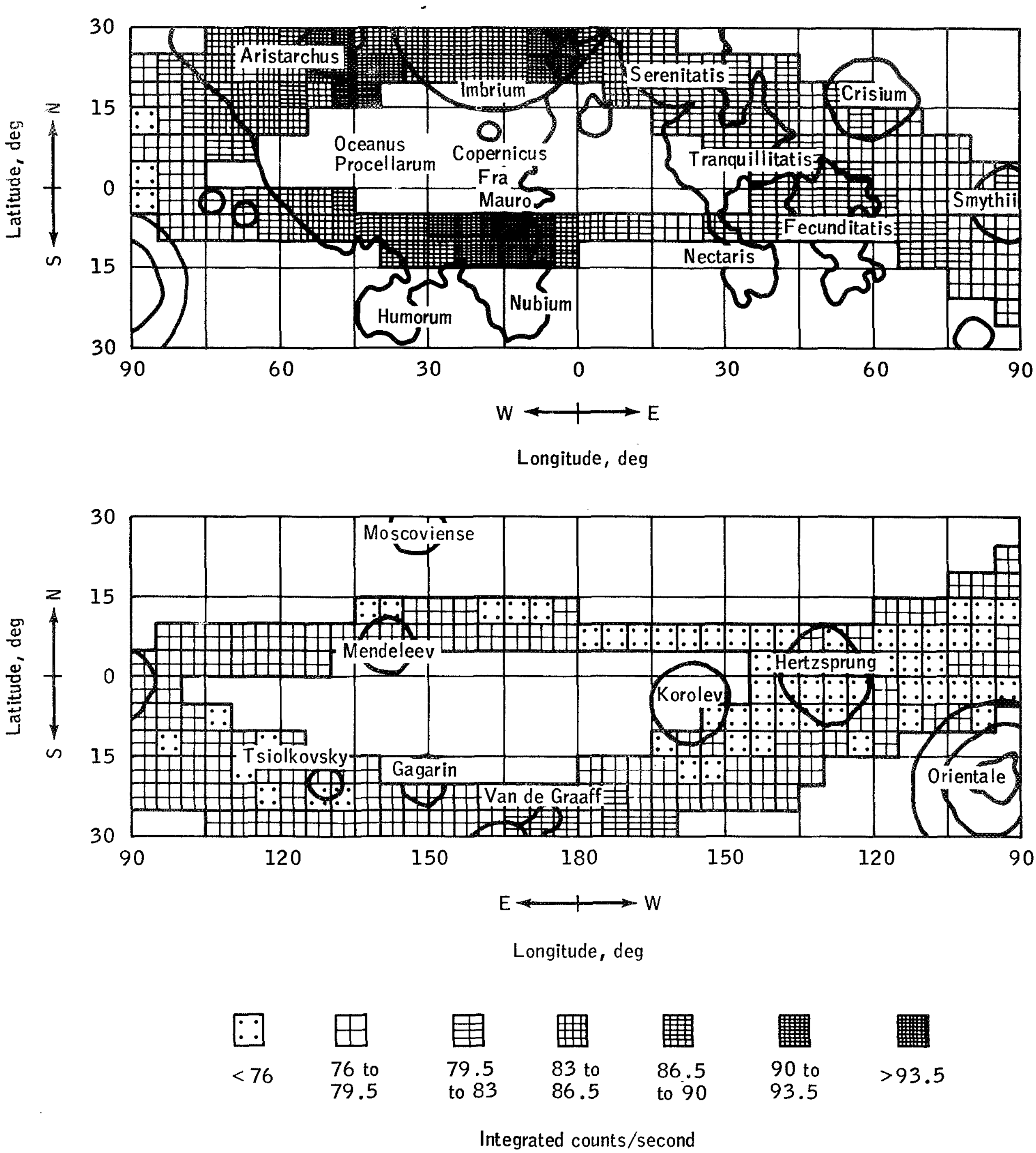

Figure 2.- Integrated intensities from K, Th, and U from the gamma-ray experiment (remote sensing).

4.6 billion years) regardless of the age or type of bedrock on which they lay. KREEP is enriched by a factor of 3 or more in potassium, uranium, rare earth elements, and phosphorus, relative to other lunar rocks. The high abundance of heat-producing radionuclides dictates that KREEP cannot be a major component of the Moon's interior, or the Moon would be too hot and still active volcanically. Its distribution around the Imbrium basin and occurrence in the samples suggest that it was formed deep in the Moon. Its apparently unique association with Mare Imbrium may imply large-scale asymmetry within the Moon, on a regional or global scale.

Interior of the Moon.- Seismic data from the emplaced Apollo lunar surface experiments packages (ALSEP's) indicate that the physical properties of the upper mantle are consistent with those of rocks consisting of magnesium-iron silicates. This is consistent with the petrology of mare basalts. The Moon is rigid and relatively cool to a depth of about 1000 km. However, a zone of attenuation of seismic waves exists below, which is commonly inferred to indicate a molten zone. The Moon presently has virtually no magnetic field although the lunar breccias and basalts evidently cooled in a weak magnetic field. The origin of this ancient field is unknown and remains a major problem, as does the existence or nonexistence of a core.

Lunar soil.- The surface of the maria is covered to a depth of 5 to 15 m by a fragmental soil (the regolith) produced by repeated impacts. The highlands, more heavily cratered, have a much deeper regolith. Most of the mare regolith is locally derived, but it contains a minor component of exotic fragments ballistically transported by impacts from distant areas. Vertical and horizontal mixing has been more extensive in the highlands. A minor part, about 1 percent, of the soil is of meteoritic origin. Because of the absence of an atmosphere, the Moon's surface is directly exposed to the solar wind; consequently, the soil contains a small proportion of hydrogen and other light elements from the Sun. Some degree of radiation damage is common to all surface samples.

Geologic evolution of the Moon.- The main features of the Moon's evolution are now believed to be understood; however, the three major theories of formation proposed before Apollo still compete. These include concurrent accretion with the Earth, fission of the proto-Earth, and post-accretion capture by the Earth. High temperatures, or the accretion process itself, produced a pervasive depletion in volatile elements.

Shortly after 4.6 billion years ago, the Moon developed an extensive crust of feldspar-rich rocks, which now constitutes the lunar highlands. This period was also marked by intense but declining impact cratering. About 3.9 billion years ago, a number of large impacts excavated the mare basins. These basins were filled, over the next 700 million years, with flows of basalt. By about 3 billion years ago, the vigorous igneous activity subsided with subsequent events being primarily external. Formation of the large ray craters, such as Copernicus, the numerous smaller ones, and the mare regolith belongs to this stage. Inferential evidence exists for minor volcanic activity in the postmare period, forming features such as the Marius domes and the rille-associated chain craters. A minority of investigators believes that lunar transient phenomena ("red spots" and anomalous brightenings) occur; if they do, it would suggest that a low level of outgassing may persist even now, but these observations are not understood, nor have any been repeated.

It is important to note that many fundamental questions about the Moon are yet to be answered. Comparison of remote-sensing data and hand-picked fragments from Apollo 17 cores have shown that several major basalt types are yet to be sampled in situ; in fact, only about half the major types are represented in Apollo and Luna samples. Man has yet to visit or sample the far side. The highlands are virtually unexplored. Because of Apollo latitude restrictions, the polar regions were not visited. A variety of unsampled surface features that may have importance in resource considerations warrants investigation, such as the dark halo craters (possible volcanoes with volatile material and/or deep-seated fragments); rilles of several types, orange soils described from orbit during Apollo 17 in Mare Serenitatis (possibly the site of young volcanism, with volatiles and fumarolic material); possibly volcanic domes (Marius Hills, Rumker Hills); young impact craters, and associated features such as Copernicus, including their rays (which may sample deep material).

Lunar Resources

The prime resources of the Moon will be found in the assemblage of rocks and minerals, which represent the end product of both internal and external geochemical and physical processes. The major crystalline rock types can be divided conveniently into mare and nonmare varieties, which have been explored in an initial way with lunar samples and Apollo orbital mapping. These rocks occur in a variety of broken and mixed forms as a result of lunar surface bombardment by meteorites. Breccias, which predominate in nonmare regions, are coarse mixtures of impact debris. In addition, the entire lunar surface is covered with a few meters of intensely comminuted "soil," which has mixed fragments of primary rocks and their fusion products with elements derived from solar radiation and meteorites. Minor rock types may occur locally within the major units of regional extent and in special environments, such as the vicinity of volcanic vents where volatile materials may be concentrated. The polar regions contain permanently shadowed cold traps where volatiles released at the surface, including water, may have been concentrated.

The mare regions cover 17 percent of the Moon's surface and consist primarily of basaltic volcanic rock that has spread as relatively thin, widespread flow units. The maria are relatively flat, topographically low, and not densely cratered. Thickness of the basalt filling is 0.5 to perhaps 10 km. Depending on age, the soil cover ranges from a few to 15 m. The principal minerals of mare basalts and the range of bulk compositions are given in tables III and IV. The basalts are fine grained; consequently, mineral fragments do not predominate except in fractions finer than 100 μm in the soil.

TABLE III.- PRINCIPAL MINERALS OF BASALTS

Mineral	Composition
Pyroxene	$(Ca,Mg,Fe)SiO_3$
Olivine	$(Mg,Fe)_2 SiO_4$
Plagioclase	$(Ca,Na)Al(Al,Si)_3 O_8$
Ilmenite	$FeTiO_3$
Tridymite, cristobalite	SiO_2

The basalts issued from volcanic vents that have not been identified. Locally, deposits of vitreous materials that apparently are equivalent to terrestrial volcanic ash have been found (Apollo 15 green glass; Apollo 17 orange glass). Whereas these materials have the bulk chemical composition of basalt, they also contain thin coatings of volatile-rich (sulfur, chlorine, zinc, and lead) materials, strongly enriched with respect to ordinary basalts. In orbital photography, possibly similar occurrences of colored materials in the region of Sulpicius Gallus and dark halo deposits in a variety of regions have been observed. Some of these were prime objectives for Apollo missions originally planned to follow Apollo 17.

The nonmare regions (highlands) are generally rugged (although extensive relatively low relief "plainsfilling" units (Cayley formation) exist) and are heavily cratered. They cover 83 percent of the Moon and apparently are very thick, ranging from 50 to 120 km in thickness. The altitude is variable but generally higher than the maria.

The composition of the nonmare regions is complex and highly variable (table V). The predominant crystalline rock types are from a suite of materials that have been termed the anorthosite-norite-troctolite suite. The principal rock-forming minerals are similar to those of mare basalts (table IV). Anorthosites are rich in mineral plagioclase; norites are plagioclase-pyroxene rocks, and troctolites plagioclase-olivine rocks. In detail, the mineral compositions are distinct from the mare basalts in that the pyroxenes and olivines have lower iron/magnesium ratios and the plagioclase contains less sodium. The oxide minerals such as ilmenite are rare. A sample of dunite, a 100 percent olivine rock, was collected by the Apollo 17 astronauts. Many of these rocks are coarse grained.

Several classes of possible primary rock types were observed in the lunar samples and have been inferred to exist in abundance on the basis of Apollo orbital data. These include the variety known as KREEP, enriched in potassium, rare earth elements, and phosphorus, and the so-called "low potassium Fra Mauro" composition found in samples from several missions.

TABLE IV.- MARIA BASALT COMPOSITION

Component	Abundance, percent, in -					
	Apollo 15 Ol. basalt	Apollo 12 Ol. basalt	Apollo 11 basalt	Apollo 17 basalt	Apollo 15 green glass[a]	Apollo 17 orange glass[a]
Silica (SiO_2)	44.2	45.6	40.5	37.6	45.6	38.8
Titanium dioxide (TiO_2)	2.26	2.90	10.5	12.1	.3	8.8
Aluminum oxide (Al_2O_3)	8.48	8.59	10.4	8.74	7.64	6.4
Ferrous oxide (FeO)	22.5	21.0	18.5	21.5	19.7	22.2
Magnesium oxide (MgO)	11.2	11.6	7.0	8.2	16.6	17.4
Calcium oxide (CaO)	9.5	9.4	11.6	10.3	8.7	7.7
Sodium oxide (Na_2O)	.24	.23	.4	.40	.12	.40
Potassium oxide (K_2O)	.03	.06	.09	.08	.02	.08
	Abundance, ppm					
Thorium	0.50	0.88	1.0	0.54	0.08	0.3
Zinc	1.8	$\sim$2	--	2	20	250
Cadmium	2.0	$\sim$2	--	2	50	320

[a]Most of the volatiles are concentrated on the surfaces of the glasses. Additional elements such as sulfur, lead, germanium, chlorine, bromine, fluorine, silver, gold, bismuth, antimony, arsenic, indium, sodium, and potassium are significantly enriched on the surfaces of the glasses.

TABLE V.- NONMARE PERCENTAGE COMPOSITIONS

Component	Anorthosite (15415)	KREEP basalt (15382)	Troctolite (76535)	Low-potassium Fra Mauro basalt[a]	Dunite (72415)
Silica (SiO_2)	44.1	52.4	42.9	46.6	39.9
Titanium dioxide (TiO_2)	.02	1.8	.05	1.3	.03
Aluminum oxide (Al_2O_3)	35.5	17.8	20.7	18.8	1.5
Ferrous oxide (FeO)	.2	8.6	5.0	9.7	11.3
Magnesium oxide (MgO)	.1	7.1	19.1	11.0	43.6
Calcium oxide (CaO)	19.7	9.9	11.4	11.6	1.1
Sodium oxide (Na_2O)	.3	1.0	.2	.37	<.02
Potassium oxide (K_2O)	<.01	.57	.03	.06 to .1	.05
Thorium[b]	.02	12	.16	.5 to .3	<.02

[a]Has variable MgO/FeO ratio and trace element composition.
[b]Parts per million.

These compositions cannot be identified with specific primary volcanic rocks but exist among the current lunar sample collection only as small fragments or as breccias. They are of importance because many trace elements are enriched in these relative to typical lunar basalt compositions.

The Moon's complement of volatile elements is apparently small; however, several sources, even if small, could have contributed to concentrations at the lunar surface. These include solar wind, meteorites, comets, and outgassing of the Moon (volcanism). The highly vesicular nature of many mare basalts indicates that gases were present during the volcanic episodes. Cold traps provided by permanently shadowed regions near the lunar poles may have attracted concentrations of these volatile elements or compounds. Small amounts of solar-wind-derived elements (hydrogen, carbon, nitrogen, noble gases such as argon, etc.) exist in the lunar soil and soil breccias (table VI).

A variety of minor minerals that contain otherwise rare elements (for the Moon) as major constituents has been observed in samples (table VII). These occur in quantities less than 1 percent of the total rock. No concentrations of these minerals have been discovered in samples studied to date, but localized concentrations may exist in special environments.

TABLE VI.- TYPICAL RANGES FOR VOLATILE ELEMENTS IN APOLLO 11 FINES, BRECCIA, AND BASALTS

Rock type	Hydrogen,[a] ppm	Carbon,[b] ppm	Nitrogen,[b] ppm	Argon-36,[c] 10^{-8} cm^3/g	Argon-40/Argon-36 ratio[b]
Fines	75	140 to 225	102 to 153	35 000	1.1
Breccia	120	137 to 230	125	42 000 to 100 000	2.1
Basalts	--	11 to 77	30 to 116	10 to 150	40 to 500

[a]From ref. 10.

[b]From ref. 11; carbon is originally as CH_4, CO.

[c]From ref. 12.

TABLE VII.- SOME ACCESSORY MINERALS OF LUNAR ROCKS

Mineral	Composition
Apatite	$Ca_5(PO_4)_3(F,Cl)$
Chromite	$FeCr_2O_4$
Native iron nickel	(Fe,Ni)
Tranquillityite	$Fe_8(Zr,Y)_2Ti_3Si_3O_{24}$
Troilite	FeS
Whitlockite	$Ca_9Mg(PO_4)_7$
Zirconolite	$CaZrTi_2O_7$

The principal known or potential resources of the Moon are listed in table VIII. Different resources are at different stages of identification or exploration. For example, the availability of materials for shielding, thermal insulation, or reaction mass is well established; sources of major metals require optimization of grade and physical properties before they can be regarded as reserves, hydrogen concentrations at the poles remain to be discovered, and a variety of minor elements may be locally concentrated but would require extensive exploration to be located.[3]

EXPLORATION OBJECTIVES

In a discussion of exploration objectives, a consideration of those materials that are available in bulk quantities is followed by consideration of those that may be present but will require intense and detailed exploration. The intent of this subsection is to define potential steps leading to discovery of mineable resources and to development of mining and beneficiation procedures.

[3]More information is available in the draft of the Handbook of Lunar Resources, to be published by JSC.

TABLE VIII.- TYPICAL LUNAR RESOURCE AVAILABILITY

Material	Representative uses	Source	Source material concentration	Beneficiation and processing considerations	Abundance and occurrence
Regolith, not chemically or mechanically separated	Reaction mass, radiation shielding, thermal shielding, spun glass, sintered building material	Regolith	100 percent of surface material	Handling of dust, excavating	Ubiquitous
Basalt, not chemically separated	Cast basalt for construction	Basaltic flows into maria	100 percent of subregolith and scattered fragments	Hard rock	Abundant in maria
Nonmetallics	Construction materials, special uses	Plagioclase and processing by-products	70 to 95 percent of highlands anorthositic rocks; 10 to 40 percent in mare basalts	Use anorthositic regolith or crush friable anorthosite; basalt is generally tough	Abundant in highlands
Al, Al_2O_3, Ca, CaO, Na, Na_2O, Si, SiO_2, O_2	Metals for construction, ceramics, solar cells, reactants for chemical processing, life support	Plagioclase	70 to 95 percent of highlands anorthositic rocks; 10 to 40 percent in mare basalts	Use anorthositic regolith or crush friable anorthosite; basalt is generally tough	Abundant in highlands
Fe, FeO, Ti, TiO_2, O_2	Metals, pigments, life support, special uses	Ilmenite	2 to 20 percent in mare basalt and mare regolith	Size separation of regolith to concentrate ilmenite	Abundant in maria
Mg, MgO, Fe, FeO, Si, SiO_2, O_2	Metals, ceramics, solar cells	Olivine	0 to 20 percent in mare basalt; 95 percent in dunite	Difficult to separate from basalt	Dunite is rare in sample collection, as breccia clasts
H_2, H_2O	Life support, fuels	Cold-trapped volatiles at lunar poles	Unknown	Significant technological development required	Occurrence has not been demonstrated
H_2, C, N	Life support, organics	Solar wind trapped in regolith and soil breccia and buried possibly in polar cold traps	100 ppm in mature regolith and soil breccia	Direct thermal extraction; concentration of ilmenite or <60-μm fraction enhances yield	Ubiquitous, but low grade
Zn, Pb, Cl, S, F, other volatile elements	Industrial materials	Surface deposits on volcanic spherules and regolith fines	5 to 100 ppm concentrated at surfaces; may be higher locally	Requires technique development for low-grade extraction	Two known sources; others possible
P, Zr, F, Cl, Y, Cr		Major components in accessory minerals in KREEP, basalts, etc.	Minerals present in abundance <1 percent of rock; elements are substantially lower in abundance; local concentrations are conceivable	Exceedingly difficult to concentrate from dispersed source	No known concentrations

Bulk Mass

The regolith is a ready source of mass in a crushed and powdered form. The exploration required is largely an evaluation of optimum sites with respect to handling procedures. It would appear that important required information is (1) the grain size distribution, (2) compaction properties, and (3) the local topography and thickness of the powdered layer and its vertical stratification.

The site location will largely be determined by factors other than grade of the reserves, such as optimum operating conditions for launch or thermal control. Information from the LPO would be useful in selecting sites insofar as the thermal/microwave experiments yield data on the regolith properties, and one would use the available high-resolution photography of the proposed landing site. One should expect, in addition, to use seismic and/or radar methods on the surface to map boulder distribution and regolith thickness at specific sites.

So that bulk mass can be excavated, packaged, and transported, the primary research endeavors that should be initiated in the near future are studying the packaging properties of powders in vacuum, improving understanding of models of the origin of the regolith using existing data, establishing procedures for dust control, and studying sintering properties of different soil types.

Major Materials

Considered specifically under the category of major materials are ilmenite and plagioclase for the production of iron, titanium, aluminum, and silicon. (Oxygen is a byproduct.) It is noted, in addition, that other major minerals, such as pyroxenes and olivines that contain significant amounts of iron, may be important.

Ilmenite.- Ilmenite is abundant on the lunar surface and is considered a source for iron and titanium. This mineral is concentrated in the mare regions of the Moon and two key questions need to be addressed. Where are the optimum concentrations in the regolith? What is the mineralogic affiliation affecting concepts for beneficiation? To pick a site, it is important to produce a map of ilmenite content over the lunar surface. This objective is achieved by the gamma-ray experiment and the optical experiments planned for the LPO. In this context, understanding the optical spectra associated with ilmenite in various assemblages must be furthered.

The specific site studies can be conducted in several ways. The surface should be studied using the available high-resolution photography and orbital data. Electromagnetic sounding techniques may be used to detect the particles of metallic material. A scheme to assay material taken from surface samples and from a series of 1-m-deep cores should be used. This assay, for example by rapid X-ray fluorescence analysis, would be conducted to locate optimal concentrations within the general landing site.

Extraction of ilmenite from its matrix material poses a number of varied challenges. Titanium is found in the complex mixture of regolith within isolated grains, in glass beads, in igneous rock fragments, and in breccia fragments. Beneficiation from each of these might be different. It is important to begin to assess this problem now, using available lunar samples and analogs and bearing in mind the lunar environment.

Plagioclase.- Plagioclase is one of the most widespread materials in the lunar crust and is considered a major potential source for aluminum and silicon. This material is readily detected by the gamma-ray and optical orbital experiments on the LPO. The LPO data will be important in assessing the distribution and purity of plagioclase in selecting target areas where the aluminum content is maximum. The questions to be addressed in the exploration of plagioclase are similar to those of ilmenite and relate to the concentration and the mineral assemblages.

Once this general site has been selected, using the LPO data and available high-resolution photography, a general site survey on the surface will be necessary, using geochemical and geophysical methods. Again, one can readily envision a system to conduct rapid assays of surface and core samples to provide a three-dimensional view of the distribution of the plagioclase and so specific optimum locations for excavation can be selected.

Obviously, the question of beneficiation on the lunar surface needs to be considered. Perhaps, for example, bedrock that has not been exposed to the mixing of the regolith could be located and used.

Rare Resources

The resources discussed so far are known to occur in large quantities on the lunar surface and three key questions exist. Where is an optimum location on the lunar surface (addressed by the LPO)? How can a specific site be characterized (requires surface operations of geophysical and geochemical methods)? What are the soil mechanical and mineralogic properties, so that optimum extraction and beneficiation processes can be developed?

Now considered is a category of materials that are not known to occur in quantities and that have either not been detected or have been detected only in small concentrations. For these substances, the key questions are more basic. Do significant concentrations occur? What are the most likely locations to search for these? What can one do to sense these from orbit? What site surveys can one do on the surface to increase the possibility of detecting these? Only at a later stage can procedures for exploiting these resources be considered.

Water at the poles.- The possibility has been extensively discussed that water has been trapped in the cold traps that would be associated with permanently shadowed regions near the poles (ref. 13). The LPO contains a gamma-ray experiment that will provide answers to the question of whether water is present. The infrared surface temperature experiment and topography from orbit may also contribute. If water is found, there are numerous important observations to be made to determine the nature and amount of the occurrences. If no water is found, the strategy of lunar exploration would follow quite a different course. Because no high-resolution photography of the poles exists, a high-latitude orbiting mission might be necessary to acquire high-resolution photography and/or radar (for dark regions) as a precursor for surface operations. The followup surface exploration could include many possibilities. Listed here are only a few that might be used for detailed site exploration: seismic mapping for ice (high velocity in low-velocity soil), neutron logging techniques either on the surface or in shallow bore holes, and chemical analyses of a wide variety of materials to detect the presence of water and related volatile species.

It is important to reexamine all available photography to see whether shadow maps can be constructed. It would be useful to examine the thermochemistry, kinetics, and physical properties of ice at very low temperatures as an aid to interpreting the observations.

Volatiles.- The volatiles carbon, hydrogen, nitrogen, and noble gases are generally solar-wind-derived and are correlated with the surfaces of grains. Some may also be derived from outgassing of the Moon and from meteorites. They tend therefore to be most concentrated in the fine-grained fractions. A strategy to exploit these volatiles needs to be focused on regions where they might be expected to occur in unusually high concentrations, such as in permanently shadowed areas. The LPO could contribute to this, largely in identifying and locating unusual sites. In addition to general distribution in the regolith, they may occur in association with materials such as chlorine, fluorine, and sulfur. Targets for these concentrations are dark mantle material, regions with orange soil, and possible vent regions. A detailed photogeologic catalog of these sites would be a useful product from LPO, together with a characterization of the chemistry and spectral reflectance properties. Low-orbit examination of such features would be useful. If sites outside presently available high-resolution photography are considered, additional site studies from an orbiter may be necessary before selecting a specific landing site.

No full assessment can be made, however, without eventual landing and sample analyses. Studies on the surface would consist of regional traverses to analyze the geological, geophysical, and geochemical setting of the feature under study and to use this as a guide to more detailed analyses of samples. An in-situ mass spectrometer would provide invaluable information as an extension to the Apollo 17 mass spectrometer study to evaluate volatiles in the tenuous lunar atmosphere.

In addition to traps in surface regolith layers, the possible presence of other traps should receive some thought. For example, various soil layers may exist at depths that might be tapped by deeper drilling.

Related studies that can be done now and should be encouraged include an expanded study of the distribution of volatiles in the present lunar sample collection. It is important to understand more thoroughly the migration of gases through soils in vacuum as well as the sticking and absorption properties as an aid to making models. The presently available orbital data should be examined much more carefully to see if anomalous chemical signatures are present.

Metallic deposits.- A key question to ask is whether rarer metals in useful concentrations exist in the regolith or in the bedrock below the regolith. It is evident that most terrestrial-type deposits could not exist on the Moon because of the lack of fluids for concentrating them. Magmatic segregations associated with crustal formation, basaltic activity, or fractionation from major impacts are, however, possible. To develop models, the process of metal concentration in dry magmas needs study. One might also focus on elemental associations with cadmium, zinc, lead, chlorine, and sulfur, which are volatile and might be useful indicators of metallic concentration. Attention should therefore be focused on the vents, dark mantle regions, and orange glass regions discussed. Because metallic iron occurs in the regolith at about the 0.5-percent level, some consideration should be given to techniques that could locate higher concentrations at various places. Again geophysical magnetic sounding methods on the surface will be useful.

A suitable strategy for exploration is difficult to devise at this time, because it is difficult to set criteria for site location. The regolith is known to be largely derived from the local bedrock and, because of extensive gardening, it is probably a relatively good sample of the bedrock beneath it. A detailed geochemical survey for a very wide range of elements done on the surface on a grid would be a useful first step in exploration for concentration of metals at the base of the bedrock. The electrical conductivity of metallic deposits is likely to be very high compared to the highly resistive surrounding regolith and dry rock; consequently such objects would be excellent targets for electromagnetic exploration.

It appears that the current tasks that need to be accelerated are largely those that extend knowledge of magmatic and exhalative ore deposits and mechanisms for their formation. Study is needed of transport mechanisms, which would be needed to form metal deposits in magma processes that were very dry and oxygen poor. Transport mechanisms at lower temperatures also need study for metals in which the carriers were volatiles other than water, perhaps including chlorine and sulfur. As future sites are occupied, available rapid analytical procedures and geophysical tools should be available. Together with limited drilling capability, perhaps to a depth of 20 m to get well into the bedrock, these tools would be of major importance for exploration for potential ores.

Beneficial Use of Lunar Environments

Many of the early objectives relate to determining what is on and in the Moon, and then how to use lunar materials in the presence of hazards and difficulties. However, another class of mission objectives exists, having to do with the beneficial use of lunar environments. For example, an important LPO objective is to ascertain whether or not the polar regions include elevated areas where the Sun is always visible. If such an area exists, it will be the place to put a heliostat for providing continuous solar energy to a base. The dark polar cold traps also constitute a beneficial environment, even if they contain no significant amounts of volatiles. For example, they can be used as sites for radiators continuously rejecting waste heat from base processes. Other dark sites could be used for cryogenic (e.g., superconducting) energy storage and other cryogenic operations such as infrared astronomy. With specific reference to the resource problem, these cold spots provide an ideal storage site for processed materials including purified water and other volatiles, avoiding the need for heavy, pressurized storage tanks. It is, therefore, an important objective in the surface-prospecting stage to evaluate quantitatively these potential environmental benefits by, for example, measuring the temperature, surface heat balance, and subsurface thermal properties in the cold traps. For processes in which high vacuum is the beneficial resource, it is an objective to evaluate the lunar surface environment for contamination by the small quantities of dust and gas that are known to exist in the lunar atmosphere within a few meters of the surface. This can be done by instruments similar to those of ALSEP, emplaced at the proposed process sites.

In a later stage of the program, other beneficial lunar environments may become important - for example, the radio quiet zone on the lunar far side. If mass driver launching requires a particular topographic profile, promising mass driver sites should be searched out. It will be a legitimate, if not primary, objective to evaluate such environments.

Geological Models

Models of two rather different types may be of use in exploration for lunar resources; namely, large-scale or global models and models seeking to explain local features or processes. The first includes the origin of the Moon, its thermal evolution, and such broad questions as the existence and conditions in a magma ocean commonly believed to have dominated early lunar history, and the broad-scale evolution of the crust by igneous and large impact processes. The second category of model is smaller in scale and seeks to explain specific features in terms of well-defined processes, such as the formation of the lunar regolith, crater formation by impact, and volcanic and plutonic processes.

It is likely that the global models will play an important indirect role in exploration for lunar resources. The plate tectonics model for the Earth has begun to help with the regional location of ore deposits by developing models, rather than in selecting specific targets. But global features of planets, observed and rationalized by models, need to be considered with care. One must remember that rare or unrecognized processes may concentrate material very effectively into local anomalies quite sufficient to exploit.

If local concentration mechanisms and processes can be recognized, sufficient data should be gathered to evaluate their importance and how they work. Quantitative models for these processes may prove of great value in assessing lunar resources because surface observations might be used to estimate conditions at depth and to direct the search at other similar sites.

It is noteworthy that much information supplied in a lunar resource assessment program would have great scientific worth, in the context of modeling lunar processes on all scales. Thus, if the LPO should discover a major new geological province, it might well be wise exploration strategy to study this region to shed further light on lunar models. Exploitation of this opportunity, however, will require a modest supporting research and technology (SR&T) program. It is probably reasonable to expect that, as on the Earth, this investment in knowledge would pay practical dividends.

MISSION, RESEARCH, AND TECHNOLOGY OBJECTIVES

Potential Missions

A series of missions would be required to complete the exploration-development-production phases for lunar resources. This subsection first defines some potential mission alternatives and then discusses the possible decision points.

Polar orbiter.- The first step in exploring lunar resource prospects is to examine the Moon's entire surface from orbit. The objectives of such a mission should be to characterize the surface, its topography, chemistry, minerals, and thermal and physical state; to determine the bulk properties to the extent feasible by measuring gravity, magnetism, and heat flow; and to identify especially favorable environments such as permanently sunlit and permanently shadowed polar sites, geologic province boundaries giving nearby access to a variety of useful minerals, regions with available water, and regions topographically suitable for base construction.

Knowledge of the surface properties is essential for many reasons; the most compelling one is that the next stage requires knowing where to go, because surface prospectors cannot cover the entire Moon.

Knowledge of the interior properties is essential to permit modeling of the processes that have produced the present crustal distribution of materials, so that confidence may be had in tying the synoptic orbital observations to local ground truth at the 11 Apollo and Luna (sample return and roving vehicle) landing sites.

Knowledge of special environments is important for planning the later program, because it may permit short-cut solutions to difficult problems and may alter research and development priorities.

These objectives can be met by a spacecraft in low, circular polar orbit with nadir-pointed, remote-sensing instrumentation including altimetry, infrared and microwave radiometry, magnetometry, visible and infrared spectrometry, gamma-ray and X-ray spectrometry, multispectral stereographic imaging and precision radio tracking. This is the payload tentatively selected on purely scientific grounds for an LPO[4], and it is also very well suited for the resource survey (table IX). Possible LPO extensions in support of a resource-use objective are described later in this section.

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[4]Mission Summary for Lunar Polar Orbiter, rev. A (JPL 660-41), Jet Propulsion Laboratory, Aug. 1977.

TABLE IX.- APPLICABILITY OF LPO EXPERIMENTS TO RESOURCE EVALUATION

Experiment	Applicability
Gamma ray	Chemical compositional variability on regional basis
X-Ray fluorescence	Chemical compositional variability on regional basis
Reflectance spectroscopy	Mineralogical variability and concentration
Heat flow/infrared mapping	Surface and near-surface texture (boulder distribution), thermal gradient in subsurface
Spectrostereographic imager	Imagery of selected areas; survey of polar regions complements several experiments; selenodesy net improvement
Magnetometer Electron reflection	(Not a survey tool for magnetic minerals) Age of surfaces (related to maturity of soil) and evidence of magnetic history and crustal evolution
Altimetry/gravity	Surface morphology; crustal thickness (relates to geochemical models), mascons, etc., on far side; selenodesy net improvement

Surface prospectors.- After the orbital survey and, of course, dependent upon its results, the next step is to select a promising region and explore it in detail. At this time, it appears that this can be done only by equipment on the surface. Engineering, cost, and time constraints suggest that at this stage in the program only one or a few of these local regions can be examined. The prospected region or regions will be small -- tens to hundreds of kilometers at the most. Therefore, a high premium exists on a sound choice of site based on the orbital data. Of course, a possibility exists that this choice will be obvious -- as would probably be the case if the orbiter found large polar permafrost deposits.

The objectives of an automated surface prospecting survey should be to characterize the surface and near-surface (few meters) materials in regard to their chemical, mineral, and physical properties for mining and processing; to determine detailed geologic setting, local topography, roughness, bearing strength, volatile content, and regolith depth to the degree required for planning base construction; and to measure significant environments such as the polar permanently lit and shadowed region temperatures, the gas and dust atmosphere within a few meters of the surface, and the cold-soil thermal properties (emissivity, diffusivity) relevant in the design of radiators, superconductors, and other base subsystems using shadowed regions as cryogenic environments.

These objectives can be met by an automated roving prospector carrying metric stereographic cameras (with lights for illuminating shadowed areas), instruments measuring tilt, distance traveled, etc., a subsurface radio sounder, closeup and microscopic imaging, instruments for subsurface ice detection (gamma ray, neutron spectrometry), and instruments for elemental and mineral analysis such as an alpha-proton X-ray backscatter device or an X-ray diffractometer/spectrometer. To sample subsurface materials, the mobile prospector should also carry a soil auger or coring tube capable of penetrating to a depth of 1 or 2 m.

Although no such rover or payload has been built in the United States, there have been many studies of these missions[5] (ref. 14) and the Soviets have operated two Lunokhod rovers on the Moon with imaging, X-ray, and other instruments. The shortest and most obvious route to achieving this phase of a lunar utilization program would be to mount advanced U.S. instruments on a Soviet machine -- if the U.S.S.R. would agree. This prospect is further discussed later in this section.

Because the region selected for prospecting may be polar, on the far side, or near the lunar limb, the machine must be able to operate while out of sight of Earth, with commands and data sent via a lunar communications satellite. The latter could be the LPO relay spacecraft or another orbiter launched with the prospector. If the latter choice is made, the possibility exists of instrumenting the orbiter for landing site certification (high-resolution imagery being the primary need) and using it in real time to decide where to land -- as was done by the Vikings on Mars. Although this is obviously feasible, it would add significantly to the cost of the prospecting mission. Other ways of obtaining the needed high-resolution imagery are discussed later in this section.

<u>Small-scale, automated resource recovery operation</u>.- Assuming success in the surface prospecting (i.e., a determination that usable resources are available in good quantity), the next step would be to establish a small automated processing plant. This would have two purposes: to demonstrate essential techniques under real lunar conditions and to begin stockpiling useful products. The detailed objectives at this stage cannot all be specified in advance of the orbital survey and surface prospecting, but they would include mining and size-sorting of lunar soil; separation or beneficiation of soils based on magnetic properties or simple chemical and physical affinities; conversion of solar energy into heat and electricity, and use of same for breaking down soil into its chemical constituents; recovery and (probably cryogenic) storage of volatiles; and refinement and stockpiling of materials to be used in constructing the early manned encampment: shielding metals, oxygen, water, and carbonaceous

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[5] A Study of Lunar Traverse Missions (JPL 760-26), Jet Propulsion Laboratory, 1968.

compounds if any. Because the fabrication capacities of an early base will be very limited, this stockpile may at first, except for volatiles and shielding, be only a minor adjunct to materials brought from Earth; but it is important as a pathfinder for later events.

These objectives can be achieved by a stationary lander, but a problem exists of assuring that the lander is placed exactly where it should be placed. Either the prospector should have a homing beacon to guide the lander in, or the lander should have limited mobility for relocating itself after landing.

Because no design for an automated processing plant has been developed, it is not now possible to specify the lander's functions and subsystems in detail. These would, however, surely include a solar-energy collector (photovoltaic panel, heliostat mirror, or both); a waste-heat rejection system (radiators and, if volatiles are found, a melter-vaporizer); mechanical soil-handling systems equivalent to conveyors and sieves, but perhaps differing in design because of the lunar environmental considerations; the chemical process hardware; and a system for transporting the products to their stockpile sites. (This could be the prospector operating as a transport.)

The intended throughput rate for this whole process would be small, perhaps a few kilograms per Earth day, but if it were started early enough, products could be accumulated sufficient for at least the make-up inventory in the first manned encampment.

Other alternate mission objectives.- It may not be prudent to go directly from the LPO to the surface prospecting phase. If the moderate-resolution imagery from the LPO indicates a landing area that is of great interest but is not covered in Apollo or other high-resolution imagery, there will be a lack of information for planning details of the prospecting surveys. If the LPO shows strong advantages for a polar site, imagery over much of the prospecting region will be nonexistent because of shadows. Therefore, another orbital mission may be required in specific support of the prospecting. As mentioned earlier, this could be contemporary with or part of the prospecting mission (analogous to Viking) but it would be better to have the orbital data available sooner. Because imagery in the polar-shadowed regions appears quite likely to be a requirement, this orbiter might carry a synthetic-aperture radar in preference to or in addition to cameras. Such a mission could be derived from the Seasat and Venus orbital imaging radar (VOIR) developments now in progress. Alternatively, if very anomalous regions are identified by the LPO, a sample return by automated means may prove prudent before a surface prospecting mission. The U.S.S.R. has performed sample-return missions; however, their sample selection capability consisted only of a single core sample up to 2 m deep.

Other sequences are possible. For example, it may be decided on the basis of the LPO data that the automated prospecting step is not needed and that the next visit to the lunar surface should be a manned expedition with the combined objectives of prospecting, establishing the automated processing demonstration plant, and returning samples of both raw and processed materials. This more ambitious and faster paced program could follow upon discovery by the LPO of a site with such obvious resource potential as to reduce significantly the risk in the next step.

Decision points and possible alternative paths.- Alternative paths in the development of objectives by phases will be dictated by the resource demand and what is learned at preceding steps. Because a further evolution of the requirements is certain to occur if studies of lunar resource utilization continue, a variety of potential objectives beyond the LPO must be considered.

Figure 3 shows schematically a developmental sequence of lunar exploration, with potential first-order decision-influencing observations. Except in the case that only undifferentiated lunar material attains very high value, further exploration is required. The LPO is perceived to be a key to the identification of the best areas to conduct that future exploration. Major programmatic decisions such as the need for an imaging radar mission, a high-resolution imaging mission, or the type of initial surface prospecting mission depend on the LPO data. The time scale for the major decisions will be determined by the needs for the resources; however, the mid-1980's is a logical time to expect a decision opportunity for utilization of lunar resources. In the mid-1980's, three major factors may converge to provide that opportunity: maturation of the Space Transporation System to a well-understood operating system with clearly defined growth potential, definition of national needs in terms of long-term solutions of energy and materials requirements, and availability of LPO data.

This workshop group, therefore, recommends that the LPO be flown as soon as possible with its present instrument complement, because further lunar resource exploration depends on the diversity revealed by the LPO.

The key to these decisions appears to be the LPO. Based on a general characterization of the chemical and mineralogical composition of the Moon's surface and a base of high-resolution spectral data, a detailed survey of the Moon for local anomalies that are potential sites for further prospecting will be possible.

Research and Technology Objectives

Initiation of a research and technology effort is recommended to provide a basis for lunar resource exploration beyond LPO. Early starts of importance include studies of lunar samples and data aimed at extending understanding of special lunar environments and rare materials, studies of beneficiation and refinement processes for known varieties of lunar materials, and conceptual studies of lunar resource prospecting techniques and missions.

Several factors affect the research and technology objectives of the lunar resources program. The most important of these is that, although the proposed program possesses high intrinsic scientific merit, it does not have science objectives as its only goal; that is, the proposed investigations are driven to obtain the science data and in some cases technology with the ultimate goal of reducing the risk involved in answering the question: Are nonterrestrial resources useful?

Year	Major program decisions	Data base
▲ 1978	Begin exploration	Sufficient for mass and shielding
▲ 1985	Go/no go for lunar resources intensive exploration	Sufficient for Fe, Ti, Ca, Al, and possibly specific resources; exploit unanticipated results and pursue SR&T
▲ 1990	Go/no go for lunar pilot plant	Sufficient to define reserves of some materials; perhaps some ores; explore unanticipated results with SR&T, define resource base for most materials
▲~2000	Go/no go lunar base	Further refinement of resource base and reserves; selection of best sites; explore unanticipated results

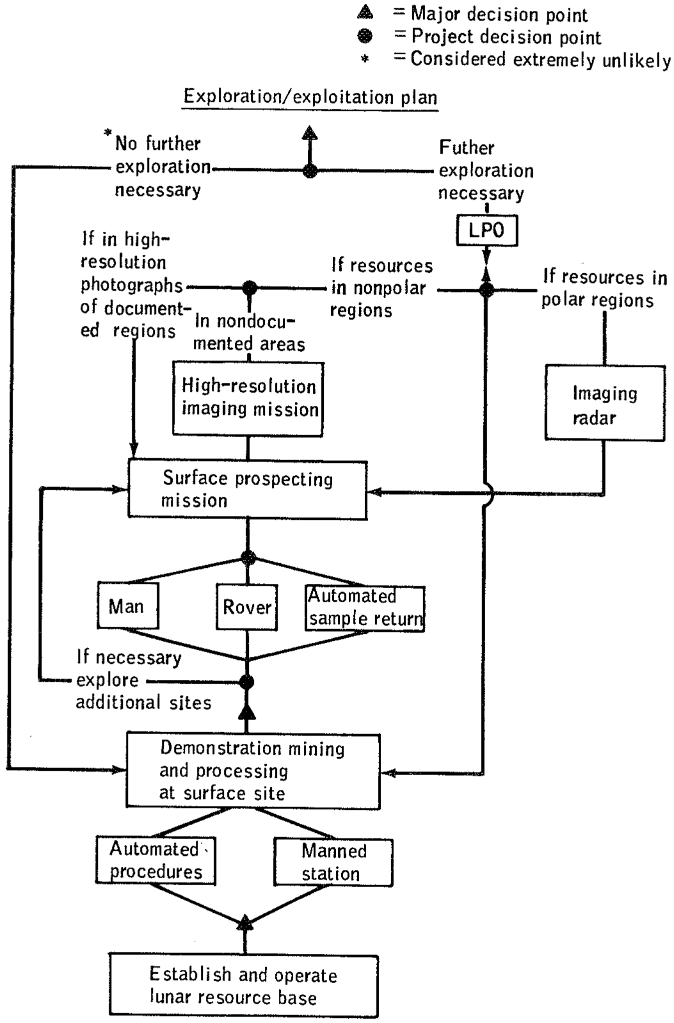

Figure 3.- Lunar resource exploration steps and decision points.

The very fact that this program can be framed illustrates two interesting facets of the discussion of lunar resources. The problems proposed are significant, illustrating the premise that not enough is yet known. On the other hand, the questions are detailed and specific, illustrating that previous lunar research has provided the information necessary to frame detailed research and technology proposals.

The research proposals are as follows.

1. Petrologic and chemical characterization of the ultrafine fraction of lunar soils. This fraction (<20μm) comprises 25 percent by weight of lunar soil; it may be the site of volatile concentrations. A knowledge of its properties is essential for beneficiation, for control of dust, and possible unusual concentrations of valuable trace and minor materials.

2. Volatiles in lunar materials. Volatiles may be concentrated in specific minerals and are enriched in smaller grain sized fractions. The potential sites of hydrogen concentration should be determined to evaluate the potential for extraction and concentration of this resource.

3. Physical properties of lunar minerals and powders, particularly electrostatic and magnetic properties. These are particularly relevant to questions of materials handling and beneficiation of lunar resources.

4. Beneficiation of lunar materials. A variety of techniques of separation -- elutriative, electrostatic, magnetic -- should be attempted at laboratory scale to determine the actual grade of potential lunar ores, taking into account the lunar environment.

5. The various schemes for refinement of lunar materials should be investigated at laboratory scale using simulants to expected ore concentrates to test the feasibility of the refinement schemes and determine the kinetics of reaction. In particular, the chlorocarbonization of anorthosite should be investigated immediately because it is certain that anorthosite or plagioclase is the prime potential lunar aluminum ore.

6. The proposed processes of refinement should be subjected to chemical engineering design studies particularly directed toward the problem of closing the chemical cycles.

7. The properties of ceramics, glasses, and fiber glasses, producible from lunar compositions, should be investigated to determine the effect of minor elements on the physical and chemical properties of these materials.

8. Studies to assess economic parameters of lunar resource utilization scenarios should be undertaken.

9. Simulants to lunar materials should be defined and developed where possible so that the beneficiation and refinement schemes can be carried to bench scale.

10. Development of prospecting techniques for use on the lunar surface should be started, particularly in situ chemical analysis for geochemical exploration and electromagnetic and seismic technique for regolith characterization and profiling. These should be ready for deployment as automated systems in the late 1980's.

11. Experimental and theoretical studies of lunar ore-forming processes. The primary candidate for such processes is the accumulation of chromites and ilmenites in magmatic systems. The behavior of chromium and titanium as a function of redox condition in fractionating bodies is not fully understood, and it is amenable to experimental study. Concentration of lead, zinc, etc., caused by sulfurs and chlorine transport, is a possible lunar ore-forming process; there are few analogous terrestrial processes (that is, sulfur and chlorine without water) and experimental study is needed.

12. Modeling studies should be encouraged, particularly the segregation of metallic and oxide phases in dry magmatic processes and by exhalation process as related to the experimentation already listed. Also general studies that seek to correlate chemical and physical properties of the Moon are essential because such models are necessary to understand the global distribution of resources.

13. Topical photogeologic mapping of interesting sites using existing imagery (for example, the distribution of permanently shadowed regions, of "red" deposits, and dark-haloed craters) should be performed before the LPO mission.

14. Earth-based spectrophotometric infrared mapping of the mentioned sites (except, of course, the shadowed regions) should be performed before the LPO mission.

A chart showing the approximate phasing of this program is presented in figure 4. It is important to note that these efforts can begin immediately with existing data, facilities, and samples and that no single element is very costly. The findings are essential if an orderly exploration, development, and production program is to proceed expeditiously and reasonably. A number of these projects will be most useful if performed before LPO data are returned, so that information from the LPO can be promptly and accurately interpreted.

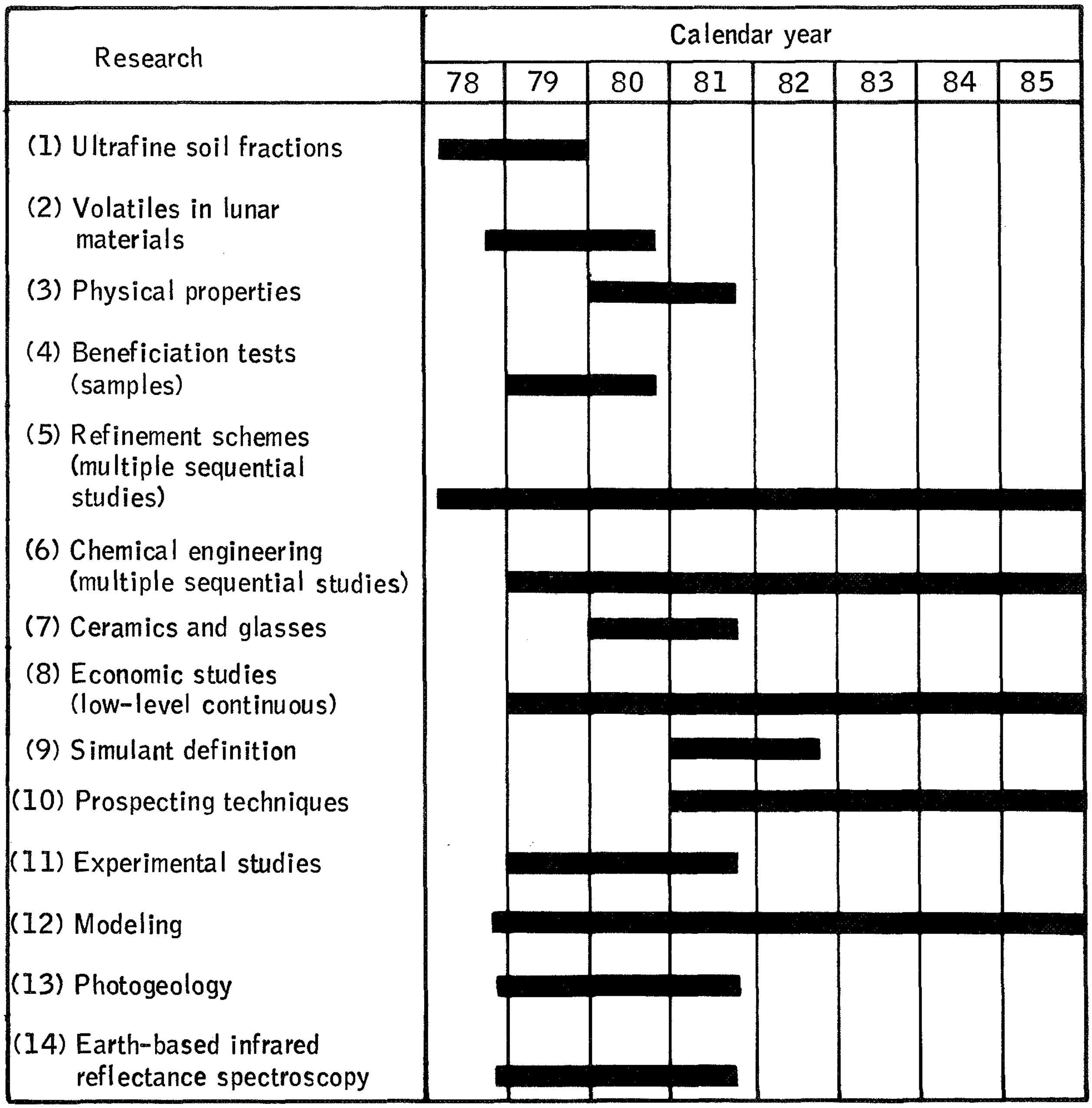

Figure 4.- Research and technology schedule.

EVALUATION OF CURRENT CONCEPTS AND PROGRAMS

Lunar Polar Orbiter in Resource Applications

The LPO mission as now conceived[4] will, in meeting its scientific objectives, also constitute the essential first step in any program for evaluating and using lunar resources. Table IX illustrates the applicability of the present LPO investigations to resource questions. In this subsection, possible extensions or modifications to the LPO are examined that could be considered to further enhance the resource-survey aspects of the mission.

A recommendation is made that the resource-survey aspects of the LPO should receive continued study to maximize its usefulness as a survey mission. Relatively simple modifications, such as definition of extended mission capabilities, may be important.

Possible operational modifications are (1) to perform orbital maneuvers to change eccentricity or inclination or altitude following nominal mission, to observe areas of special interest; this possibility could be enhanced by increasing fuel availability for orbit changes (i.e., larger tanks), (2) to observe potential volatile-rich "clouds" by using a reflection spectrometer as the spacecraft crosses the terminator (not now planned), and (3) provide rapid screening capability for LPO data to distinguish potential transient events for closer looks or extended mission opportunities (data-taking sequence might be optimized).

Additional experiments considered useful but not recommended include (1) an active radar to study regolith structure, (2) an alpha detector to study emissions of radon and polonium, (3) a neutron flux and energy detector to study vertical distribution of water in regolith, (4) a mass spectrometer to detect argon or other atmospheric gases that may be emitted episodically, and (5) an illuminator to view permanently shadowed region.

An additional capability considered useful but not recommended would be achieved by upgrading high orbiter (relay and science experiments) so that the high orbiter acts as a communications satellite for prospecting or explores libration points following extended mission.

Modified experiment operating sequences.- Because the LPO mission incorporates eight major investigations sharing a limited data link to Earth, there is, of course, a problem of time sharing and allocation among experiments. For example, in the base-line plan, reflectance spectrometry is active only when the nadir is well illuminated by sunlight. The spectrometer could (at some expense to other investigations in the base-line mission, or in an extended mission) also be programed to view the dark

[4]Mission Summary for Lunar Polar Orbiter, rev. A (JPL 660-41), Jet Propulsion Laboratory, Aug. 1977.

near the terminator, where it would have a chance of identifying lunar volatiles excited by sunlight. Although it is known from ALSEP data that there is dust above the surface at sunset, these phenomena are poorly understood. This reprograming of the spectrometry is but one example of the sort of operations sequence changes that might be considered in an LPO extended mission. Another example is the programing of spectrometry and imaging experiments to investigate regions of particular interest to resource problems.

Adaptive operations.- The base-line LPO mapping concept is not very adaptive, because routine operations are much less costly than adaptive ones. In an extended mission (or, conceivably, by a resource-use-stimulated augmentation of the base-line mission) more manpower could be allocated to operations, providing a capability for quick-look data screening and near-real-time response to interesting discoveries.

Extended-mission concept.- In previous automated deep-space missions, it has often proved worthwhile to consider extending the mission lifetime beyond the base-line plan and budget. For example, the Vikings at Mars, after successfully completing the planned activities, are now operating as an extended mission with modified objectives and reduced staffing, using funding provided separately from the original project budget. As long as the systems are originally designed to accept it (with sufficient gas supplies, etc.) this extended mission is practical and economical.

Orbit changes.- For the LPO, an obvious extended-mission prospect exists. After completing the planned 1-year mapping from a circular 100-km lunar orbit, the spacecraft will very likely still have enough onboard consumables to maneuver into other orbits and continue operating for many months. The reason is that the original propellant supply has to be large enough to offset a worst-case situation in terms of presently unknown lunar meridional gravitational perturbations to the orbit. If it is not necessary to offset the worst case, there will be propellant to spare.

One way to use this potential would be to maneuver the spacecraft into an eccentric orbit with pericynthion as low as permissible over some interesting feature, thus improving the resolution of the data there at the expense of lower resolution elsewhere. There is a class of stable, so-called "frozen" orbits, with pericynthion locations near the south pole, particularly well suited to this purpose.

Another way to use available propellants would be to change orbital inclination, but this is much more difficult to do. The LPO nominally is in an 85° retrograde orbit, missing the lunar poles by about 150 km, because higher inclination orbits are predicted to be too unstable for the basic mission. If a plane change all the way to 90° were desired, the spacecraft would need larger propellant tanks.

Additional investigations and instruments.- The studies that have been considered could be done with "just money"; i.e., without significantly affecting the base-line LPO design or mission. Larger changes, as mentioned briefly, are, of course, possible. However, it is emphatically the authors' view that the base-line mission as formulated at present is justified and should be flown as soon as possible. If introducing more experiments were to cause a delay of the LPO launch, these experiments should not be considered.

Upgrading LPO subsatellite.- The present LPO design incorporates a small, spinning subsatellite in high (∿4000 km) lunar orbit the only purpose of which is to relay gravity Doppler (e.g., mascon detection) data while the LPO is over the lunar far side out of sight of Earth. With additional funding, this high orbiter could be upgraded to include instrumentation, telemetry, guidance, and propulsion. After completing its mission in support of the LPO, the spacecraft could be used either as a communications satellite supporting prospecting on the lunar surface or (by maneuvering it out into a much higher orbit) as a libration-dynamics explorer. The former function is essential for prospecting out of sight of Earth, for example in the polar-shadowed regions, and the latter is essential for designing any systems dependent on the stability and guidance error properties of libration orbits.

One way to obtain this upgraded high satellite would be via international cooperation; some interest in such a project has already been shown, first by the United Kingdom and later by the European Space Agency. However, as in the case of adding instruments to the LPO, this prospect should be considered only if it can be made compatible with the present 1981 or 1982 launch scheduled for the LPO.

Examination of Existing Lunar Samples and Data From a Resource-Exploration Standpoint

A high-quality intensive scientific study of lunar samples is underway. The philosophy of that program has been to encourage the investigation of fundamental processes and properties of the Moon. A high degree of parallelism exists between the study of the lunar sample collection for resource evaluation and for scientific pursuits; however, it is likely that experiments required to verify aspects important to resource recovery would in some cases not be included under current program guidelines. Some examples of studies requiring lunar samples have already been discussed.

Many types of investigations of lunar samples should be pursued that bear either on exploration models or the extraction procedures, which also will provide fundamentally new scientific results. Examples of these studies include examination of volatile-rich coatings on glasses in addition to the green or orange glasses, the study of the mineralogy and chemistry of the ultrafine (<20 μm) fraction of the lunar soil, and distribution of hydrogen in soil particles.

The lunar samples are a precious scientific resource, but they may also be crucial in preparing to use lunar materials. Typical bench testing and pilot plant studies of beneficiation and extraction ultimately require samples of the actual material to be processed. On Earth, one would use the actual material at all stages of process verification. Because the available samples are limited, major scaling up may be successful only if more attention is paid to basic properties, such as electrostatic and magnetic properties or reactions of lunar materials with various gases, rather than if empirical approaches are simply taken.

The strategy that appears to be practical in terms of proper use and preservation of the sample collection is (1) to design experiments to explore the basic physical properties that would be important to processing of lunar materials and (2) to find or produce simulants from terrestrial materials for scaling up. Even so, eventual use of some lunar materials for process verification may be necessary.

The photographic collections from Ranger through Apollo constitute a rich source of data regarding potential resource sites, in addition to their continuing role in understanding lunar surface processes. Also, they are useful in assessing the state of surface materials, the environment of potential extraction operations in a civil or mining engineering sense. Existing imagery can serve as a useful guide in defining future requirements.

Photographic material is inventoried and available through the National Space Sciences Data Center (NSSDC) and a user-oriented photolibrary is housed and staffed at the Lunar Science Institute. The existing photographic collections should be systematically scanned, and potentially important sites and features cataloged and described. The global distribution of these features should be mapped and the implications considered both by experienced lunar scientists and resource exploration and exploitation specialists. During this process, an assessment of the utility of existing photography can be made and future requirements defined in terms of adequate geological descriptions of potential sites, formulation of alternative geological models, and anticipated future site engineering requirements - site development, facilities planning, and topographic maps for operation planning and resource assessment. These are among the activities listed in the research and development objectives under photogeology.

Use of Existing Spacecraft

One way to gain more rapid progress in the pathfinding stage would be to fly missions suited to the capabilities of existing spare spacecraft. For example, the Mariner Venus-Mercury spare (identical to Mariner 10) has been maintained in readiness for a possible "cloudsat" imaging mission in high Earth orbit, but it could instead be used for a lunar polar survey, a libration orbit tour, or an Earth-crossing asteroid flyby. Various other possibilities exist involving Viking orbiter spares, the Voyager proof test model, etc., but none of these has been specifically explored or proposed. As the definition of information needs advances, it will be well to keep such possibilities in mind, because missions of this type can be mounted at short notice. Mariner 5 was converted from a Mars-flyby design to a Venus craft and successfully launched to Venus in a period of 11 months.

Possibilities Involving Soviet Cooperation

If the United States were to start serious preparations toward evaluating and using extraterrestrial resources, cooperative ventures with the Soviets should be encouraged. The Soviet automated Luna program, the Earth-launched payloads of which have included sample returners, orbiters, and the two Lunokhod rovers, has scientific objectives emphasizing lunar environmental characteristics. If upgraded by the addition of advanced instrumentation and an ability to operate on the surface while occulted from Earth (with the aid of a lunar communications satellite), the Luna systems would provide an important early capability. Soviet large launch vehicles may also offer a useful heavy-lift capacity in later stages of the program. Although the prospects for quick agreement and fruitful collaboration are slight, the subject should be pursued.

Attention should be given to a current United Nations draft Moon treaty, which forbids removal of lunar materials by any state except for scientific purposes.

Program Coordination

It is manifestly evident that the potential effect of using near-Earth resources goes well beyond the sole interest of the Office of Space Science. A basic need to coordinate programs within the NASA and possibly with outside agencies is foreseen. The Office of Aeronautics and Space Technology has supported conceptual studies of applications of nonterrestrial resources, such as the Ames Summer Study of 1977. The workshop participants are aware also of interest in the Office of Space Flight.

As the scope of the program expands, these participants believe that further initiatives to bring these offices into a close working relation may well be required.

For the present, it is recommended that initiatives in defining nonterrestrial material requirements by both offices should be supported.

ENVIRONMENTAL CONSEQUENCES OF LUNAR RESOURCE EXPLORATION AND UTILIZATION ACTIVITIES

Manned operations are unlikely to proceed in completely closed environments; even automatic exploration activities will have some effect on the lunar environment. Release of experimental, industrial, or metabolic (human) waste may produce global effects.

Particularly because of the Moon's low surface gravity and lack of an appreciable atmosphere, the consequences of surface activities need to be assessed. First among several concerns is the possibility of loss of unique scientific opportunities because of further disruption of the pristine lunar environment. Perhaps the most obvious consequence is perturbation of the volatile assemblages in possible polar cold traps, but others may exist. The lack of atmosphere and low surface gravity mean that the lunar ballistic environment has some unusual properties; namely, fragments launched at low angles and modest velocities (1 to 2 km/sec) have phenomenal (some, circumlunar) ranges, such that ordinary surface blasting operations could prove very hazardous. Furthermore, the distribution of fragments would be global. Explosives generally liberate gaseous products that would settle in polar cold traps and on surfaces of soil particles. Specific aspects of exploration, extraction, and processing need to be addressed in a systematic way.

The back-contamination problem probably is not a serious one, based on Apollo experience; however, (as in Skylab) waste materials accumulated over time will evolve in a new and isolated environment. These biological waste heaps should be monitored to assess the evolving biological community.

Lunar activities should be planned from the beginning so as not to jeopardize optimal operation of a possible far-side radio observatory.

The principal point is that operations on the lunar surface will alter the environment to some degree; the effects of the proposed levels and kinds of activity need to be assessed. This assessment can and should proceed forthwith so that these matters are anticipated in both the technical and financial aspects of mission planning.

ASTEROIDS

INTRODUCTION

The present state of knowledge concerning asteroids of any type is insufficient to permit an evaluation of their potential resource value. To be in a position 10 years from now to evaluate the desirability and feasibility of retrieving asteroidal material for industrial purposes, a multifaceted asteroidal program will be required. The workshop participants believe the emphasis of this program should be on the Earth-approaching bodies. Both preliminary assessment and possible later exploitation will benefit from the low-energy requirements of missions to these bodies, in contrast to the higher energies required for retrieval of material from asteroids of the main belt. It is possible that unique mineral assemblages may someday be identified on main-belt asteroids that would justify their being evaluated as resources. However, on the time scale of the proposed program, principal attention must be directed to the Earth-approaching bodies.

The key elements of this program are as follows.

1. An intensified ground-based effort to discover a much larger number of Earth-approaching bodies. Furthermore, as soon as possible after each new discovery, additional observations will be required to characterize the object chemically and physically. This will permit a wide range of options in the choice of candidate objects for more intensive study by precision missions.

2. A program of related studies of comets, meteorites, meteors, and interplanetary dust particles. As explained more fully later, the ability to interpret evidence concerning Earth-approaching asteroidal bodies is limited by poor understanding of their relationship to material of these kinds.

3. Precursor missions to Earth-approaching bodies to permit more complete characterization of their physical and chemical nature. Later missions in this series, at least, will require return of samples from these bodies to laboratories on the Earth.

REVIEW OF ASTEROIDS, COMETS, METEORITES, AND THEIR INTERRELATIONSHIPS

Within the solar system, two major populations of objects in the subplanetary size range are known - the comets and the asteroids. Comets are defined by the temporary atmospheres (the name means "hairy star") that they develop when heated by close passage to the Sun, while asteroids (the name means "starlike") have no detectable atmospheres. In addition, comets are usually on eccentric orbits, often of high inclination, while most asteroids have rather planet-like orbits, concentrated primarily between Mars and Jupiter. Within this main belt, thousands of astroids are observed with diameters ranging from 1000 km down to a few kilometers. In addition, some comparatively small asteroids, possibly not genetically related to the belt asteroids, have orbits of sufficiently small semimajor axis and/or large eccentricity that they can approach the Earth to within a few 10^7 kilometers or less. Some of these Earth-approaching asteroids are the most accessible objects in the solar system, after the Moon, and they therefore represent a potential resource.

The term "asteroid" is used here to describe both the large population within the main belt and the Earth-approaching objects. In general, the same techniques have been used to study both, although much less is known about the Earth approachers, which are small and move rapidly relative to the Earth so that they present difficult targets for observation. The following subsections will discuss primarily the large belt asteroids, but with extensions wherever possible to the meager data available on the Earth-approaching objects. The final subsection discusses possible relationships between comets and asteroids and the relationships of meteors and meteorites to comets and asteroids. In this brief review, only the most recent literature, primarily review papers, are cited. Historical references can be obtained from these recent reviews.

Orbits and Terminology

Approximately 2000 asteroids have well-known orbits and have been assigned numbers (in order of discovery) and names. Most are in the main belt, occupying orbits of moderate eccentricity (typically ~ 0.1) and inclination (typically $\sim 10^o$). Most have semimajor axes between 2.2 and 3.3 AU.

Special groups of asteroids with unusual orbits are identified. Those located near the L_4 and L_5 points of Jupiter's orbit, 5.2 AU from the Sun are called Trojans. Those concentrated near 4.0 AU are Hildas. Those near 1.9 AU, on the inner edge of the belt, are Hungarias. Finally, two groups of Earth-approaching asteroids are defined: Apollo objects, with perihelia inside the Earth's orbit, and Amor objects, with perihelia between 1.0 and about 1.38 AU. The largest known Amor objects are 433 Eros and 1036 Ganymede, with mean diameters of about 30 km, while the largest known Apollo objects, 1620 Geographos and 1685 Toro, are only about 3 km across. At present, 20 Apollo objects and 19 Amor objects have rather well-determined orbits, and several others have been detected, but their orbits were not determined with sufficient accuracy to ensure their later recovery. It is interesting to note that the range of inclinations (up to 68^o) is nearly twice that main-belt asteroids and there is a large variety of eccentricities and semimajor axes.

Asteroids continue to be discovered, both as the result of planned searches and by accident. In recent years, orbits frequently have not been determined unless the asteroid appears to be of special interest, such as an Apollo or Amor object. Once an orbit is determined, a provisional designation is assigned representing year, semimonth, and order of discovery. For instance, 1976 AA is the first object in the first half of January 1976; 1977 HB is the second object in the second half of April 1977. Only after the orbit is confirmed at a second apparition are a permanent number and name assigned.

Physical Observations and Classification

Precise study of the physical properties (other than orbits) of individual asteroids is a relatively new branch of observational astronomy. Since 1950, such studies have included photoelectric photometry, which yields brightness and color information. The brightness variations provide information related to rotation period, shape (i.e., the ratios of axes of the triaxial ellipsoid that best represents the asteroid), and in some circumstances orientation of the rotation pole. By 1977, precision light curves had been measured for about 50 asteroids, and three-color (ultraviolet-blue-visible (UBV)) photometry had been extended to several hundred asteroids.

Beginning about 1970, several additional techniques were applied. The most powerful, visible and near-infrared spectrophotometry, is discussed in the next subsection. The others included photopolarization observed as a function of phase angle (ref. 15) and thermal radiometry (ref. 16). These latter techniques yield albedo and diameter, and the polarization measurements are also sensitive to surface roughness and grain opacity.

The data obtained from photometry, spectrophotometry, polarimetry, and radiometry have been synthesized to yield a classification scheme and to sketch the physical properties of the belt asteroids (ref. 17). Most of the approximately 580 asteroids with diameters greater than 50 km can be grouped into the C class, characterized by low geometric albedos (>5 percent) and rather neutral UBV colors; or the S class, characterized by moderate albedos (8 to 20 percent) and by colors that fall within a relatively restricted UBV color domain. In the main belt, 76 percent of the asteroids are of type C and 16 percent are of type S, and 8 percent in a variety of rarer classes characterized by distinctive colors and albedos. There is a gradient of type with semimajor axis; most S objects are near the inner edge of the belt, while more than 95 percent of the asteroids beyond 3.0 AU are C's. The most recent review of the distribution of these classes is by Zellner and Bowell (ref. 18).

Morrison (ref. 16) provides a review of all directly determined asteroid sizes and albedos. The largest (with the diameters in kilometers) are 1 Ceres (1003), 2 Pallas (608), 4 Vesta (538), 10 Hygiea (450), 31 Euphrosyne (370), and 704 Interamnia (350). Below 50 km, physical observations are sparse, except near the inner edge of the belt, where a number of objects have been observed down to 20-km diameter. The interpretation of these surveys of main-belt asteroids in terms of origin and evolution has been addressed primarily by Chapman (refs. 19 and 20).

Mineralogy

Knowledge of the minerals and metals on asteroid surfaces and of their abundances has been obtained by the remote-sensing technique of reflection spectrophotometry. The spectra of reflected sunlight contain electronic absorption features diagnostic of the presence and composition of specific minerals. Interpretation is based on calibrations derived from laboratory and theoretical studies of the optical properties of minerals, meteorites, and other materials. The presence, wavelength, and shape of the spectral features can be diagnostic of certain minerals and metals.

The spectrophotometric technique has been applied, with varying degrees of sophistication, to about 100 of the brighter asteroids, and the results have been analyzed by McCord and Gaffey (refs. 21 and 22). Table X, based on their work,[6] summarizes the present knowledge of asteroidal surface mineralogy.

The main-belt asteroids are found to contain the minerals olivine, pyroxene, plagioclase, metallic iron, clays, and opaque constituents. The presence of nickel, carbon, and water is inferred. The mineral assemblages seen are analogous to the major meteorite types, although the relative frequency of meteorite types recovered on Earth differs significantly from that of the analogous mineral assemblages seen in the asteroids. In particular, mineral assemblages that appear to be spectrophotometrically similar to the carbonaceous meteorites are much more frequent in the belt than among the meteorites collected on the Earth. By contrast, mineral assemblages similar to the ordinary chondrites, which dominate the meteorite collections on Earth, are very rare or absent on main-belt asteroids but appear common on Earth-approaching asteroids. Among inner belt asteroids, assemblages with abundant nickel-iron metal phases appear common.

Very little is known about the bulk composition of asteroids. Masses, approximately derived from mutual perturbations, are known for only three, and only for 1 Ceres and 4 Vesta are densities established that yield any compositional information (refs. 23 and 24). Ceres has a low density ($\sim$2.5) suggestive of a volatile-rich interior. Vesta appears volatile-depleted. However, the surface mineralogy of Ceres may not be consistent with such a model.[6] Densities are unobtainable for the Earth-approaching objects without spacecraft rendezvous.

Earth-Approaching Asteroids

Only about 40 Earth-approaching objects have been identified, although recently several new objects have been discovered each year. The total number down to an absolute visual magnitude of 18, corresponding for an assumed average albedo of 20 cent to a diameter of 700 m, can, however,

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[6] Unpublished material on mineralogical characterization of asteroid surface materials from reflectance spectra, by M. J. Gaffey and T. B. McCord.

TABLE X.- OBSERVATIONAL TECHNIQUES FOR ASTEROID STUDIES

[Asteroid surface materials; characterizations]

No.	Asteroid	Spectral type[a]	Mineral assemblage[b]	Meteoritic analog[c]	CMZ type[d]	Diameter, km[e]
1	Ceres	F	Sil (O), Opz (M)	C4 (Karoonda)	C	1003
2	Pallas	F	Sil (O), Opq (M)	C4 (Karoonda)	U	608
3	Juno	RA-1	NiFe ∽ (Ol∽Px)	Ol-Px stony-iron	S	247
4	Vesta	A	Cpx	Eucrite	U	538
6	Hebe	RA-2	NiFe > Cpx	Mesosiderite	S	201
7	Iris	RA-1	NiFe, Ol, Px	Ol-Px stony-iron	S	209
8	Flora	RA-2	NiFe ≥ Cpx	Mesosiderite	S	151
9	Metis	RF	NiFe, (Sil (E))	E. chon., iron	S	151
10	Hygiea	TB	Phy, Opq (C)	C2 (CM)	C	450
11	Parthenope	RF	NiFe, (Sil (E))	E. chon., iron	S	150
14	Irene	RA-3	NiFe, Px	Px stony-iron	S	158
15	Eunomia	RA-1	NiFe ∽ (Ol >> Px)	Ol-Px stony-iron	S	272
16	Psyche	RR	NiFe, Sil (E)	E. chon. (E4), iron	M	250
17	Thetis	RA-2	NiFe, Cpx	Mesosiderite	S	109
18	Melphomene	TE	Sil (O), Opq (C)	C3	S	150
19	Fortuna	TA	Phy, Opq (C)	C2 (CM)	C	215
25	Phocaea	RA-2	NiFe, Px, Cpx	Px stony-iron	S	72
27	Euterpe	RA-2	NiFe, Px, Cpx	Px stony-iron	S	108
28	Bellona	TE	Sil (O), Opq (C)	C3	S	123
30	Urania	RF(?)	--	--	S	91
39	Laetitia	RA-1	NiFe ∽ (Ol∽Px)	Pl-Px stony-iron	S	163
40	Harmonia	RA-2	NiFe > Px	Mesosiderite	S	100
48	Doris	TA	Phy, Opq (C)	C2 (CM)	C	248
51	Nemausa	TC	Phy, Opq (C)	C2 (CM)	C	151
52	Europa	TA	Phy, Opq (C)	C2 (CM)	C	289
58	Concordia	TABC	Phy, Opq (C)	C2 (CM)	C	99
63	Ausonia	RA-3	NiFe, Px	Px stony-iron	S	91
79	Eurynome	RA-2	NiFe ∽ Cpx	Mesosiderite	S	76
80	Sappho	TD	Sil (O), Opq (C)	C3	U	83
82	Alkmene	TE	Sil (O), Opq (C)	C3	S	65
85	Io	F	Sil (O), Opq (M)	C4 (Karoonda)	C	147
88	Thisbe	TB	Sil (O), Opq (C)	C2 (CM)	C	210
130	Elektra	TABC	Phy, Opq (C)	C2 (CM)	U	173
139	Juewa	TB	Phy, Opq (C)	C2 (CM)	C	163
140	Siwa	RR	NiFe, Sil (E)	E. chon. (E4), iron	C	103
141	Lumen	TA	Phy, Opq (C)	C2 (CM)	C	133
145	Adeona	TA	Phy, Opq (C)	C2 (CM)	C	176
163	Erigone	TA	Phy, Opq (C)	C2 (CM)	U	--
176	Iduna	TA	Phy, Opq (C)	C2 (CM)	C	119
192	Nausikaa	RA-2	NiFe ∽ (Px >Ol)	Px-Ol stony-iron	S	94
194	Prokne	TC	Phy, Opq (C)	C2 (CM)	C	191
210	Isabella	TABC	Phy, Opq (C)	C2 (CM)	C	77
213	Lilaea	F	Sil (O), Opq (M)	C4 (Karoonda)	C	90
221	Eos	TD	Sil (O), Opq (C)	C3	U	--
230	Athamantis	RF	NiFe, (Sil (E))	E. chon., iron	S	121
324	Bamberga	TABC	Phy, Opq (C)	C2 (CM)	C	246
335	Roberta	F	Sil (O), Opq (M)	C4 (Karoonda)	U	--
349	Dembowska	A	Ol, (NiFe)	Ol. achondrite	O	144
354	Eleonora	RA-1	NiFe ∽ Ol	Pallasite	S	153
462	Eriphyla	RF(?)	--	--	S	37
481	Emita	TABC	Phy, Opq (C)	C2 (CM)	C	102
505	Cava	TA	Phy, Opq (C)	C2 (CM)	C	91
511	Davida	TB	Phy, Opq (C)	C2 (CM)	C	323
532	Herculina	TE	Sil (O), Opq (C)	C3	S	130
554	Peraga	TA	Phy, Opq (C)	C2 (CM)	C	103
654	Zelinda	TC	Phy, Opq (C)	C2 (CM)	C	116
674	Rachele	RF(?)	--	--	S	102
704	Interamnia	F	Sil (O), Opq (M)	C4 (Karoonda)	U	350
887	Alinda	TD	Sil (O), Opq (C)	C3	S	5

[a]Asteroidal spectra that are ambiguous between 'TDE' and 'RF' are not characterized mineralogically but may be either. From work by Gaffey and McCord.

[b]Abbreviations indicate: NiFe (nickel-iron metal); Ol (olivine); Px (pyroxene, generally low calcium orthopyroxene); Cpx (clinopyroxene, calcic pyroxene; Sil (O) (mafic silicate, most probably olivine); Sil (E) (spectrally neutral silicate, most probably iron free pyroxene, enstatite); Phy (phyllosilicate, layer lattice silicate, meteoritic clay mineral, generally hydrated, unleached with abundant subequal Fe^{++} and Fe^{+++} cations); Opq (C) (opaque phase, most probably carbon or carbon compounds); Opq (M) (opáque phase, most probably magnetite or related opaque oxide). Mathematical symbols indicate relative abundance of mineral phases; where abundance is undetermined, the order is of decreasing apparent abundance.

[c]Meteoritic analogs are examples of meteorite types with similar mineralogy but without established genetic links; for example, objects designated as similar to mesosiderites could be mechanical metal-basaltic achondritic mixtures.

[d]Asteroidal spectral type as defined by Chapman, Morrison, and Zellner (ref. 17) and listed by Zellner and Bowell (ref. 18).

[e]From Zellner and Bowell (ref. 18), based on the scale of Morrison (ref. 16).

be estimated statistically (refs. 25 to 27). Based on the discovery rates in systematic searches, on the accidental rediscovery rate, and on impact statistics for large craters on the Earth and Moon, there are estimated to be 500 to 1000 Apollo objects and a comparable number of Amor objects to absolute magnitude 18. Extrapolation to fainter objects suggests[7] that the number of Earth-approaching asteroids with diameters larger than 100 m should exceed 10^5. These objects are unstable against perturbations by and collisions with the inner planets on a time scale of $\sim 10^7$ years and must be replenished from an external reservoir. The Apollo/Amor asteroids may be derived from the main asteroid belt or they may be the remains of extinct comets. It appears likely that both sources are represented, but their relative importance is uncertain (ref. 25).

The only Earth-approaching asteroid for which detailed physical observations have been obtained is the Amor object 433 Eros, which was extensively observed at its favorable apparition in 1975. Eros is a highly elongated, spinning fragment, 36 km in length, with an olivine/pyroxene/metal surface composition similar to that of the H-type ordinary chondrites. Sixteen papers on Eros appear in the April 1976 issue of Icarus. Table XI, adopted from Gaffey, Helin, and O'Leary,[7] summarizes the state of knowledge on the 11 Earth-approaching asteroids for which some physical observations have been made. For results on the better observed objects, reference is made to 1566 Icarus (ref. 28), 1620 Geographos (ref. 29), 1685 Toro (ref. 30), and 1976 AA (ref. 31). On the basis of the limited data available, all but two of the objects in table XI fall into either the S class or the O class, which is generally similar in color and albedo to the ordinary chondrites. Only one C-class object is known, 1580 Betulia (quoted in ref. 18). Thus, it appears that assemblages that may be volatile-rich are not as abundant among the Earth-approaching asteroids as among the main-belt objects.

Relationship of Comets to Asteroids, Meteors, Meteorites, and Interplanetary Particles (Dust)

Comets and meteors.- Typical comets are readily distinguishable from asteroids by their diffuse appearance, the frequent presence of ion and dust tails, and by their highly eccentric orbits, commonly with aphelia as much as a light-year from the Sun. It is very probable that they are genetically distinct from typical main-belt asteroids, having originated chiefly in the region of Uranus and Neptune, or even beyond. In some cases, multiple planetary perturbations, primarily by Jupiter, have reduced the aphelia of comets to the vicinity of Jupiter. In a few cases, cometary aphelia even lie within the orbit of Jupiter. The extreme example of this is the periodic comet Encke, with aphelion at 4.2 AU and perihelion within the orbit of Mercury. From an orbital point of view, it is thus more similar to an Earth-approaching Apollo/Amor object than to a typical comet.

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[7] Gaffey, M. J.; Helin, E. F.; and O'Leary, B.: An Assessment of Near-Earth Asteroid Resources. Report being prepared from NASA Ames Space Settlements Summer Study, 1977.

TABLE XI.- CHARACTERIZATION OF APOLLO/AMOR OBJECTS

Number	Name	Aphelion, AU	Perihelion, AU	Surface type[a]	Albedo[b]	Diameter[b], km
433	Eros	1.458	1.13	Olivine, pyroxene, metal ($\sim$H chondrite)	0.17	23
887	Alinda	2.516	1.15	Olivine, carbon ($\sim$C3 carbonaceous chondrite)	.17	4
1036	Ganymede	2.658	1.22	"S" - probably silicate or metal-rich assemblage	--	($\sim$35)
1566	Icarus	1.078	.19	Pyroxene (olivine, metal?)	.17	1
1580	Betulia	2.196	1.12	"C" - opaque-rich assemblage, possibly carbonaceous	.05	6
1620	Geographos	1.244	.83	"S" - probably silicate or metal-rich assemblage	.18	3
1627	Ivar	1.864	1.12	"S" - probably silicate or metal-rich assemblage	--	($\sim$7)
1685	Toro	1.368	.77	Pyroxene, olivine	.12	3
1864	Daedalus	1.461	.56	"O" - probably silicate or metal-rich assemblage	--	($\sim$2)
1960 UA	--	2.26	1.05	"U" ?	--	--
1976 AA	--	.97	.79	"S" - probably silicate or metal-rich assemblage	.17	1

[a]Where adequate spectral data are available, mineralogical characterizations and meteorite equivalents are given (from work by Gaffey and McCord). Where only UBV colors (i.e., C, S, O, U) are available, the Chapman-Morrison-Zellner classification of the object as summarized by Zellner and Bowell (ref. 18) is given. Underlined classification symbols indicate those based on a single classification criterion. Probable mineral assemblages are indicated.

[b]Albedos and diameters as summarized by Morrison. The diameters in parentheses were derived assuming an average albedo for the "O-S" class of the object and should be considered as indicative only.

Much of the material of a comet consists of a mixture of ices (water and carbon dioxide) and particulate matter contained in a nucleus $\sim$1 to 10 km in diameter (ref. 32). This is released into space by solar heating when the comet is near perihelion and produces the characteristic coma and tail. Much of the particulate matter remains in heliocentric orbit and is responsible for the meteor showers observed on Earth. Most of these meteoric particles are very small, but they also include pieces of nonvolatile cometary matter 1 kg or more in mass (ref. 33). It is generally thought that most of the extraterrestrial matter falling on the Earth, including "dust" collected by high-flying aircraft (ref. 34), is of cometary origin (ref. 35). Most of this cometary material is too weak to survive its hypervelocity entry (11 to 65 km/sec) and passage through the atmosphere of the Earth to permit recovery as an intact body.

Comets possess neither the dynamical nor physical stability necessary for long-term survival in the inner solar system. Typical comets with aphelia beyond Jupiter are perturbed into hyperbolic solar system escape orbits while they are still "active"; i.e., before they have exhausted their supply of volatile substances. Less frequently, they are perturbed into orbits, such as the present orbit of Comet Encke, which are sufficiently stable to permit loss of all their volatile material (on a time scale of 10^3 to 10^4 years) before being ejected from the solar system. In such cases, it is possible that the residual nonvolatile matter of the core remains as an intact body in a heliocentric orbit until it collides with a planet or is ejected from the solar system on a time scale of $\sim10^7$ years. An evolution of this kind has been predicted for Comet Encke, based on historical observation of changes in its orbit and on a theory of the effect of the reaction of a rotating cometary nucleus to the emitted dust and gas (refs. 36 to 38). The absence of comas and tails on two formerly active Jupiter-crossing comets (Arend-Rigaux and Neujmin 1) may have resulted from nearly complete loss of volatiles from their nuclei. Observations of large meteors ("fireballs") have been interpreted as indicating that such survival of comet nuclei is not extremely rare and that there may be $\sim$1000 extinct comets in the inner solar system at the present time (ref. 25). Both the orbits and appearance of these objects would be indistinguishable from Apollo/Amor objects of asteroid belt origin. Because such comets are of asteroidal appearance when observed, the usually clear-cut distinction between a comet and an asteroid becomes blurred. One can avoid this problem by defining an "asteroid" as a small interplanetary body that has never been seen to have the diffuse image associated with a cometary coma. When defined in this way, the Apollo/Amor objects can properly be termed "asteroids." However, the question remains as to whether they are genetically associated with comets or belt asteroids.

Meteorites.- The term "meteorite" can also be defined operationally as an interplanetary fragment that survives passage through the atmosphere of the Earth. Again, by forgoing a genetic classification, a question is avoided, in this case the nature of the larger body ("parent body") in the solar system of which the meteorite is a fragment.

Meteorites can be divided into two principal classes: undifferentiated and differentiated. The undifferentiated meteorites, also known as chondrites, have preserved to a remarkable degree the relative proportions of the nonvolatile elements in the early solar system but differ from one another in the extent to which the volatile element abundances have been preserved (ref. 39). The differentiated meteorites, which include the irons, stony-irons, and achondrites, have undergone further chemical fractionation, usually as a consequence of crystal-liquid fractionation, and in several ways are analogous to igneous rocks from the Earth and Moon. Oxygen isotope studies (ref. 40) show that these two classes of meteorites are unlikely to be genetically related, and their principal common property may simply be that they had orbits which intersected that of the Earth, even though the complex dynamic processes that led to their being in these orbits were quite different.

Knowledge of the sources of meteorites in the present solar system is very incomplete. Chondrites could be derived from comets (refs. 41 and 42), asteroids (refs. 19, 43, and 44), or from the Earth-crossing or near-Earth-crossing Apollo and Amor objects (refs. 45 and 46). As discussed previously, it is also unclear to what extent the Apollo and Amor objects are of belt-asteroidal origin (ref. 47) or represent the nonvolatile residue of cometary nuclei (ref. 48). On the other hand, with the exception of Opik (ref. 49), it has generally been agreed that the differentiated meteorites are of asteroidal origin (ref. 50). The principal basis for this, other than preconceived views regarding the chemical history of comets, has been the long ($\sim 10^8$ to 10^9 years) exposure ages of iron meteorites, which are very difficult to reconcile with the expected dynamic lifetime ($\sim 10^6$ to 10^7 years) of cometary material in the inner solar system (refs. 41, 51, and 52). More recently, strong evidence for an asteroidal origin of a major class of differentiated meteorites, the polymict-brecciated basaltic achondrites, or howardites, has been obtained from their similarity to lunar regolith breccias (ref. 53).

In the references cited, much experimental, observational, and theoretical evidence is presented relevant to the sources of meteorites of these various classes. Although these investigations have been extensive, reconciliation of much of the evidence relating meteorites to their sources is at present impossible. As discussed later in this report, the major uncertainties in this area are a severe impediment to the use of meteoritic and other data in the evaluation of the Earth-approaching Apollo/Amor objects as possible resources. Some recommendations are made in the subsection entitled "Relevant Studies on Comets, Meteorites, and Meteors" to expedite progress toward the solution of this important problem.

SEARCH FOR NEAR-EARTH ASTEROIDS

The Present Situation

More than 40 near-Earth asteroids have been discovered in the course of the past 80 years of astronomical observation. Two dozen of these objects are Apollo asteroids (Earth-crossers), of which about half were found by deliberate search programs and half were found accidentally in the course of other astronomical work. More than half of the Apollo asteroids have been discovered on photographic plates taken at Palomar Mountain, California. The remainder of the known near-Earth asteroids are Amors (1.0 AU < perihelion < 1.38 AU), most of which have been found by accident.

The population of comparatively large Apollo asteroids can be estimated from the discovery rate in systematic photographic surveys of the sky, limits on the frequency of accidental rediscovery, and the record of impact craters or impact structures on the Moon and Earth (refs. 25 and 54). All three methods yield approximately the same result. The number of Apollo asteroids equal to or brighter than absolute visual magnitude 18 is of the order of 10^3. An object of absolute visual magnitude 18 is about 0.7 km in diameter if its visual geometric albedo is 0.2, as observed for several Apollos. Applying the first two estimation methods to the observations on Amor asteroids yields a population of about 0.6×10^3 Amors to absolute visual magnitude 18 (refs. 25 and 54). Most of the known Apollos and Amors are brighter than magnitude 18.

Only a few near-Earth objects smaller than 1 km have been discovered, but it may be safely inferred that the number of these objects is very large. This number can be estimated either by use of an extrapolated magnitude-frequency distribution for main-belt asteroids or from the spatial frequency distribution of postmare lunar craters in the size range 1 to 5 km. About 10^5 near-Earth asteroids that are 100 m in diameter and larger accompany the 10^3 objects of 700-m diameter and larger. The 100-m asteroids are normally so faint that most can only be discovered with large-aperture telescopes.

Although they occasionally come close to the Earth, all but a few near-Earth asteroids have a fairly high velocity relative to the Earth (commonly more than 10 km/sec). The orbital eccentricity of near-Earth asteroids ranges from 0.06 to 0.83; 90 percent of the eccentricities are above 0.35. Orbital inclination ranges from 1.0° to 67.9°; 60 percent of the inclinations are above 10°. For low-velocity orbits relative to the Earth, perihelion should be fairly close to 1 AU; eccentricity, in general, should be close to or less than about 0.35; and inclination generally should be less than about 10°. Only a few percent of the near-Earth asteroid orbits meet these criteria. For 3 out of 43 known objects, the outbound ΔV (from low Earth orbit) required for rendezvous on direct ballistic trajectories is 6.5 km/sec or less (described in the subsection, "Resources Evaluation Mission"). In special cases, gravity-assist trajectories may be found that greatly reduce the propulsion required for rendezvous with or return from near-Earth asteroids. The return ΔV, in one known case, can be reduced to 3.1 km/sec by a Venus-Earth gravity-assist trajectory. Probably no more than 5 or 10 percent of the near-Earth asteroids will ultimately be of interest as resources, because of the requirements for low ΔV.

At the present time, one systematic search for planet-crossing asteroids is being conducted with a 46-cm Schmidt camera at Palomar Mountain, California. This program has yielded one new Apollo asteroid per year over the last 4 years. As an indirect result of the search effort, four other Apollo asteroids have also been discovered at Palomar Mountain during the same period, and observers using large Schmidt cameras elsewhere have been stimulated to identify and follow near-Earth objects.

This discovery rate is an order of magnitude too low to provide, within two or three decades, an appropriate set of candidate asteroids for investigation of resources.

Recommended Search Program

As a goal, NASA should aim for the discovery of about 400 to 500 near-Earth asteroids in the next 20 years. From among this number, a few tens of low ΔV objects will be of interest for further exploration and potential utilization as resources. Several tens of candidates are needed because asteroids of diverse composition, physical characteristics, and size need to be examined. Furthermore, in utilization of these objects, there will remain a considerable advantage in continuing to search for asteroids with the lowest discoverable ΔV. The general process of repetitive strong perturbation during close encounters with the Earth will place some asteroids on very low ΔV orbits. Because lifetimes against collision with the Earth decrease, very roughly, in proportion to ΔV, however, asteroids with ΔV's in the range of 3 km/sec or less can be expected to constitute no more than about 1 percent of the near-Earth population, according to current models. Faint asteroids, too small to be observed in the current search program, generally would be in the range of 100 to 300 m in diameter. This may be the size range most readily exploited for resources. It has been proposed that an object of this size might be returned to Earth orbit.[8] Thus, both an increase in discovery rate to find proper orbits and an increase in sensitivity of detection are important objectives.

Near-term increase in discovery rate.- Several steps can be taken that would increase the rate of discovery of near-Earth asteroids in the immediate future. The principal limitations are available observing time on wide-field, large-aperture instruments in suitable locations; and trained personnel who are committed to the task. At present, there is usable unsubscribed observing time cn existing telescopes, which could be utilized for the search program. Beyond this, it will be necessary to construct new instruments. The second limitation can be overcome simply by providing funds for a larger effort. Well-qualified observers are awaiting an opportunity to participate. A plan to increase the discovery rate of near-Earth asteroids immediately should include the following.

1. Increase the level of effort, presently ∼2 man-years/year, to 4 man-years/year. This increased effort would fully use all available time on Schmidt telescopes of 60-cm aperture and larger. Additional time on smaller instruments would provide only a small increment in discoveries. The increased effort, using appropriate instruments, would approximately double the present discovery rate.

2. Support construction of a 60-cm Schmidt camera dedicated to the near-Earth asteroid search. Optics for a new 60-cm Schmidt already exist,

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[8] O'Leary, B.; Gaffey, M. J.; Ross, D. J.; and Salkeld, R.: The Retrieval of Asteroidal Materials. Report being prepared from NASA Ames Space Settlements Summer Study, 1977.

and it may be possible that such an instrument could be placed in operation by using an existing mount, drive, and dome. If so, a 60-cm Schmidt probably could be placed in operation in 6 to 8 months for a modest cost. Otherwise, the construction will take about 1 year and will cost about $200 000 to $300 000. When the telescope is ready, the search team would shift the focus of their effort to this instrument. The yield from such a dedicated instrument would be about 5 to 10 near-Earth asteroids per year. Within a few years, this rate of discovery would substantially expand the number of near-Earth asteroids from which candidates could be selected for initial exploration by spacecraft.

Construction of a 100- to 120-cm Schmidt camera dedicated to near-Earth asteroid search.- To increase the discovery rate significantly above 5 to 10 near-Earth asteroids per year, it will be necessary to construct a still larger wide-field instrument. Full utilization of the previously discussed 60-cm Schmidt camera during any given lunation would exhaust about 70 to 80 percent of the volume of space that could be searched by this instrument for asteroids of given absolute magnitude. The residence time of near-Earth asteroids within this volume is of the order of a month, except for very faint objects. Even accounting for incompleteness of search with a single instrument owing to unusable viewing conditions, construction and operation of a second 60-cm telescope would yield a much lower return than the first. A major increase in discovery rate can be achieved only be reducing the threshold brightness for detection of moving objects.

To achieve the goal of discovering 400 to 500 near-Earth asteroids in 20 years, a dedicated Schmidt camera with an aperture of at least 100 cm will be needed. An optimum aperture would be about 120 cm. Construction of this telescope would cost about $3 to $4 million and would require about 3 years for completion. About 20 to 30 near-Earth asteroids could be discovered per year with a 100-cm to 120-cm Schmidt camera. Part of the increase in discovery rate would be achieved by searching a larger volume of space for objects of a size that could be discovered ultimately by smaller instruments and part would be achieved by discovery of asteroids too faint to be found by smaller instruments.

Approximately 700 independent fields can be photographed each year with a dedicated 100-cm to 120-cm Schmidt telescope. The task of scanning the photographic plates covering this number of fields for trailed images is immense. Development of an automated scanning system would greatly reduce the task. Although the development of such a system would be expensive (estimated cost about $300 000), it would soon pay for itself in the saving of human labor. With the assistance of an automated scanner, the search program could be performed with about a 6 man-year/year level of effort.

Central index of photographic plates.- A central index or catalog of plates, all taken with large-aperture wide-field telescopes, would facilitate orbit determination of newly discovered near-Earth asteroids. This index should include the past logs for each wide-field telescope and should be updated monthly. Full cooperation of the observatories involved would be needed. Plate centers would be punched on cards, collated on printouts, and distributed to interested observers. Many prediscovery positions of near-Earth objects could be recovered with the aid of such an index; these positions would improve the precision of calculated orbits and, in some cases, would be critical for recovery of an asteroid on a later apparition. About 1 man-year/year effort would be required to maintain the index and to measure supplemental positions. The index might also be useful in other astronomical programs.

Expected Results From Near-Earth Asteroid Search

Besides discovery and orbit determination of several hundred near-Earth asteroids, the systematic search program recommended here would yield the following scientific results.

1. Discovery and orbit determination of several hundred moderate to shallow Mars-crossing asteroids. The information on the Mars-crossing objects combined with the data on near-Earth asteroids would provide the basis for highly precise estimates of the populations and size-frequency distribution of planet-crossing objects and highly precise estimates of impact-cratering rates on the terrestrial planets.

2. Discovery and orbit determination of several hundred asteroids on the inner edge of the main asteroid belt, including Hungarias, Phocaeas, members of the Flora family, and other asteroids of special interest. Good statistics on the populations of asteroids in these regions will provide essential data for solving the genetic relationships between planet-crossing asteroids and main-belt asteroids.

3. Discovery of several dozen comets. Of particular interest are very faint periodic comets that would be detected in this search program. These may include a number of objects that are in a transitional state between that of a weakly active comet and a completely inactive planet-crossing asteroid.

4. Search of the Earth-Sun libration regions. Theoretical studies indicate that the orbits of objects in the L_4 and L_5 regions of the Earth-Sun system are dynamically stable for at least 10^4 years (ref. 55). Hence, it is plausible that "Trojan" asteroids of the Earth may exist. If so, these asteroids would have extremely low ΔV relative to the Earth and would be of great interest for potential resources.

In addition to small bodies in the solar system, the near-Earth asteroid search will occasionally yield other discoveries of astronomical interest, such as novae, supernovae, and possibly some types of variable stars. If a 100- to 120-cm Schmidt camera were constructed, a fraction of the observing time on this instrument could be made available for other astronomical research without significantly reducing the discovery rate of near-Earth objects.

CLASSIFICATION AND DETERMINATION OF SURFACE PROPERTIES

Introduction

It is necessary to characterize asteroids by their physical and chemical properties before it is possible either to estimate their potential usefulness as resources or to plan detailed utilization studies and missions. A small effort, using ground-based telescopes and several remote-sensing techniques, has been underway for several years, and the results constitute most of the available knowledge on the physical and chemical properties of asteroids (as previously discussed). Of prime interest are the size and shape of the asteroid in question, its composition and mineralogy, and the mechanical properties of the surface.

It is important to know these properties for a wide variety of asteroids to place any particular object in context and to confirm or infer other properties not easily measured. A knowledge of both main-belt and Earth-approaching asteroids is important, for example, to assess the value of studying meteorites as samples of some asteroids.

The existing ground-based observational program must be expanded and strengthened to provide the detailed characterization of a sufficient number of asteroids required for initial evaluation of the resource potential of asteroids and for future spacecraft mission planning. No other method is known of acquiring this information short of flying a much more expensive and time-consuming series of spacecraft missions to a large number of asteroids. The ground-based program should study the known asteroids in an organized and deliberate way. It should be designed to respond rapidly to the discovery of new Earth-approaching objects.

In general, large-aperture telescopes (>2 m) are required because of the faintness of most asteroids, especially Earth-approachers. The space telescope will have a large aperture (2.5 m) and the current instrument payload would allow some important measurements to be made. However, this facility will not be available until at least 1982 and then it probably will be available mostly for observing distant, faint sources. The planned Earth-orbiting infrared astronomical satellite (IRAS), although of relatively small aperture, will measure many asteroids in its planned sky-survey mission. Proper processing of these data would significantly contribute to the asteroid characterization program.

Techniques

The known observational techniques that are useful for asteroid studies are listed in table XII, along with the information they yield. This list is not intended to be exhaustive, and new techniques may be found. References listed earlier in the review of the asteroid information available describe these techniques.

Few large telescopes are available for extensive optical solar system studies. Only two major NASA-supported telescopes now exist, one at MacDonald Observatory, Texas, and the other at Mauna Kea Observatory, Hawaii. A third telescope, optimized for infrared observations, will be completed on Mauna Kea, Hawaii, within about 2 years. Several other smaller telescopes are used, when available, for bright objects. Scheduling these telescopes is possible for asteroid observations that can be planned at least 6 months in advance; thus main-belt and returned Earth-approaching asteroids can be studied. Newly discovered Earth-approaching asteroids require a response within a few days of discovery. Only the MacDonald telescope presently is scheduled in such a way as to allow such rapid response. Similar problems exist for radio telescope scheduling.

Existing groups are performing asteroid studies in all categories listed in table XII except in some types of visible and near-infrared spectroscopy.

TABLE XII.- OBSERVATIONAL TECHNIQUES FOR ASTEROID STUDIES

Technique	Direct information	Additional information	
		If given -	Can obtain -
Visible photometry	Brightness Spin rate Shape Position of spin axis		
Infrared photometry	Diameter	Visual brightness	Albedo
Visible polarization vs. phase angle	Albedo	Visual brightness	Diameter
Broad-band photometry	Classification according to general compositional type	Albedo and/or polarization vs. phase angle minimum	More certain classification
Visible and near-infrared spectroscopy	Mineralogy	Albedo	More certainty in some cases
Radar backscatter and frequency spectrum	Cross section and spin rate (for heterogeneous objects)	Diameter, spin rate, shape	Dielectric constant and roughness

Observational Approach

To characterize the asteroids, all the techniques listed in table XII must be applied whenever possible. Observations of numbered asteroids (i.e., those the orbits of which are well known) can be planned 6 months or more in advance of their close approaches to Earth. Thus, observations can be conducted under conventional astronomical procedures. Numerous unusual logistical, technical, and administrative problems are encountered in observing newly discovered Apollo/Amor objects, because of the quick response required. The discovery and subsequent followon observations of 1976 AA illustrate some of the difficulties (ref. 56).

The initial problem is that the time of discovery cannot be anticipated. Potential observers must be alerted immediately and the ephemerides sent to them as soon as it is possible. In addition, some newly discovered objects are bright enough for physical observations for only a few days. It is necessary to organize a communications network so that valuable opportunities for observations will not be lost.

After observers have been alerted and suitable telescopes have been rescheduled, a number of technical and logistical problems can still arise. These problems include, but are not limited to, finding charts, calculations, updated ephemerides, and real-time coordinating of observations and/or techniques with other observers. The problems can be overcome by advance planning, installation of standard communications equipment, and a central communications and information operation. A newly discovered object could be under observation 24 to 48 hours after discovery. This should allow one or two night observations on even the fastest moving object so far discovered before it becomes too faint.

Summary and Recommended Program

Ground-based observations with related laboratory and theoretical studies have already provided enough information to indicate asteroids to be of potential interest for resources. Most available information and the greatest observational activity concern main-belt asteroids, but Earth-crossers are of greater interest for easier utilization. This report recommends that the presently small ground-based asteroid-observing program be expanded to enable the characterization of newly discovered Earth-crossing asteroids as well as main-belt objects. This expansion should include studies of main-belt objects, which are of great value both in their own right and for the light they shed on the nature of the near-Earth asteroids.

Specific actions recommended to expand the observational program are as follows.

1. Develop new instrumentation especially for faint object studies at many wavelengths

2. Arrange for large-aperture optical and radar telescope observing time to be made available, especially for rapid response to the discovery of Earth-crossing objects

3. Expand laboratory and theoretical studies of the properties of meteorites and other materials to enable complete interpretation of observational data

4. Increase the observational program support capabilities, especially in the areas of telescope observing and data handling

5. Assure that observing time be available on Earth-orbiting telescopes when these instruments are required for asteroid observations

6. Assure that the data acquired on asteroids by the IRAS orbiting telescope be made available

7. Organize a communications network to alert observers of new discoveries and to coordinate observation at several observatories

RELEVANT STUDIES ON COMETS, METEORITES, AND METEORS

Comets and Their Relationship to Apollo Objects

Many comets have perihelia within the orbit of the Earth and therefore can also be considered as Earth-approaching objects. Spectroscopic studies of the gas emitted from comets when near the Sun show them to be sources of the volatile compounds of hydrogen, carbon, nitrogen, and oxygen, and therefore to have a bulk chemistry distinctly richer in volatile compounds than the Moon and the terrestrial planets. Although, in principle, comets could be considered as near-Earth resources of material such as water and hydrocarbons, their usual high ΔV and the small number (<100) of these bodies in predictable short-period orbits make this seem unlikely at present.

However, evidence exists that, at least in some cases, active short-period comets evolve into bodies in more accessible orbits with aphelia inside the orbit of Jupiter and perihelia near Earth's orbit. These cometary remnants may be much more numerous (i.e., by a factor of 10^3) than their much more easily detectable active forerunners. If this evolution occurs, these remnants are potential sources of compounds such as chemically bound water, polymerized hydrocarbons, and water-soluble salts, which may be unavailable on the Moon or from material originating in the asteroid belt. After comets have exhausted their supply of easily volatilized compounds, their telescopic appearance will resemble that of asteroids, and it may well be that 90 percent or more of the Earth-approaching Apollo and Amor objects are in fact cometary remnants (refs. 25 and 48).

Evidence that comets undergo an evolution of this kind is furnished by four observations.

1. The present asteroidal appearance of two objects formerly exhibiting cometary characteristics, Arend-Rigauz and Neujmin I (ref. 57).

2. The historically observed decline in the nongravitational deceleration of Comet Encke, the aphelion of which is $\sim$1 AU inside the orbit of Jupiter. Rapid decline in its activity following perihelion passage suggests that the surface of its nucleus now consists primarily of nonvolatile material. The nucleus may be resurfaced each orbital period by a small quantity of ice derived from volatiles released from its interior as the thermal pulse diffuses inward following approach to the Sun (refs. 37 and 38).

3. The existence of stream meteors (including those containing large bodies, up to $\sim 10^8$ g), indistinguishable in physical strength from those associated with observable comets, with aphelia well inside the orbit of Jupiter (table XIII) and with no presently observable cometary source (refs. 33, 58, and 59). The dynamical coherence of the stream indicates that these bodies were recently ($< 10^4$ years ago) derived from a source in a similar orbit. Most likely this source was either a comet, as Encke, which evolved into an Apollo-like orbit, or an Apollo object remaining after the object lost its cometary appearance.

4. The dynamical problems associated with extracting more than $\sim$10 percent of the Apollo objects from the asteroid belt, suggesting that some other source for these objects exists. The only plausible candidate sources are the comets (ref. 25).

For the reasons given, it would seem reasonable that Apollo objects should commonly contain volatile compounds and are potential resources of such material. However, this leads to a paradox, inasmuch as the population of observed Apollo objects appears to contain a much smaller proportion of bodies exhibiting "carbonaceous" reflection spectra than is the case for the main-belt asteroid population (ref. 22). Thus, there appears to be a major gap in understanding the dynamics of both asteroidal and cometary material, understanding the probable chemical nature of the cometary residues, or in ability to interpret reflection spectra. Failure to resolve this paradox could lead to great difficulty in estimating potential resources of observed Apollo objects.

These problems are compounded when meteoritic data are used to infer the probable physical and chemical properties of Apollo objects. Spectrophotometric studies of main-belt asteroids indicate an apparent near absence of bodies with mineralogy similar to that of the most abundant class of meteorites, the ordinary chondrites. The derivation of ordinary chondrites from comets, perhaps through the intermediate stage of extinct cometary Apollos, is generally believed to be unattractive because it is in apparent contradiction with the observed chemical composition of comets as inferred from spectra of gases emitted by active comets and with commonly held beliefs concerning the origins of comets. Similar problems are raised by data from fireball networks. For example, Ceplecha (ref. 58) has reported spectra demonstrating a carbonaceous spectrum for a relatively weak fireball with initial mass of 500 kg (terminal mass, 70 g) in a rather circular orbit (aphelion of 1.23 AU, eccentricity of 0.200). This would be a prime candidate for interpretation as a fragment of a cometary Apollo asteroid but for the fact that no carbonaceous Apollos in such orbits are known.

TABLE XIII.- METEOR STREAMS WITH COMETARY ORBITS, BUT NO COMET

	Estimated mass, kg	Aphelion, AU	Eccentricity	Inclination, deg	Mean longitude of perihelion, deg	Mean longitude of node, deg	Date
N. χ Orionids		2.22	0.79	2	281	258	12/4 to 12/15
EN041274	100 000	1.98 ±.18	0.76 ±.03	3.5	282	252	12/4/74
EN031267	14	2.20 ±.02	0.79	3.9	283	250	12/3/67
S. χ Orionids		2.18	0.78	7	101	79	12/7 to 12/12
PN39469.850	1	2.33	0.78	5	93	79	12/10/76

It is evident that these facts do not merge so as to provide a satisfactory understanding of the relationship between Apollos, belt asteroids, active and extinct comets, meteorites, and meteors. As a consequence, different workers, using differing but equally plausible assumptions, can rationally come to opposing conclusions regarding the chemical and physical nature of Apollo objects and the relevance of meteoritic studies to these objects. This then leads to uncertainties in evaluating Apollos as sources of chemical resources and understanding the physical problems associated with mining these resources.

In addition to missions to Apollo objects, there are other steps that should be taken to clarify these problems.

1. Physical studies are needed, especially spectrophotometric, of the nuclei of evolved comets such as Arend-Rigauz, Neujmin I, and Encke, and comparison of these data with asteroid composition and classes, and with measurements on meteorites and interplanetary particles collected in the Earth's atmosphere (refs. 34 and 60).

2. In the planning of possible cometary rendezvous missions, consideration should be given to the choice of targets (such as Encke) relevant to the evolution of comets into Earth-approaching asteroids.

3. Theoretical studies should be made at a more advanced level on the dynamical evolution of comets, asteroids, and meteorites, and the physical theory of meteors.

4. Reduction, compilation, and more advanced interpretation are needed of fireball orbital and spectral data being obtained from photographic fireball and meteorite recovery networks throughout the world.

5. It appears that the rate of accumulation of photographically determined orbits of recovered meteorites will be too slow to permit statistically significant results to be obtained in the next two decades. Therefore, attention should be given to other possible ways of obtaining meteorite velocities that can be combined with visual radiants to obtain orbits of sufficient accuracy to be useful. Several methods of this kind have been suggested, based on ablative loss inferred from charged particle tracks, dispersion of the fall ellipse, and cosmic-ray-induced activities. It is not certain that any of these will provide the required results, but a sufficiently serious and quantitative effort should be made to permit evaluation of these possibilities.

Meteorite Studies

In the context of a resource evaluation program, studies of meteorites can extend the understanding of probable samples of the population of Earth-approaching objects and provide baseline data to estimate the physical and mechanical properties of possible asteroidal "ores" to permit technological evaluation of materials-handling and processing equipment.

Meteorites are samples of the population of objects that encounter the Earth (meteoroids) and survive atmospheric entry. Comparison of the atmospheric entry behavior of these objects can be used to calibrate the properties of the much larger selection of objects that are too weak to survive entry (ref. 33). Such weak objects constitute the majority of large meteors (fireballs) and failure to consider their properties would ignore a significant source of information concerning near-Earth resources.

The meteorites represent probable samples of the Earth-approaching asteroids and possible samples of the main-belt asteroids (refs. 22 and 25).[9] As such, they represent the only available samples of possible asteroidal resources until a sample-return mission is accomplished. Even without a definite genetic relationship established between a meteorite and a specific parent body in the near-Earth population, the meteorites provide an indication of the range of raw materials available in this population. These materials can be studied to determine their value as sources of useful raw materials as a function of meteorite type. Additionally, they can be considered as a basis for establishing baseline mining, materials processing, and extractive techniques for the near-Earth resources.

Although it is probable that the meteorites represent samples of the near-Earth asteroids, it must also be remembered that it is a very biased sample. It is a special subset of all bodies that enter the Earth's atmosphere. Only those bodies with reasonable physical strength that encounter the Earth at relatively low velocities can survive the atmospheric entry process. Additionally, during any period of time, certain source bodies will be preferentially located to deliver material to the Earth and will therefore tend to be overrepresented in the meteorite population.

Because of their great scientific interest, much scientific work of very high quality is currently being performed on meteorites (ref. 61 includes a general treatment). All this work is highly relevant to the question of the nature of near-Earth resources. In addition, there are aspects of meteoritic studies, which have not been so thoroughly investigated, that have a special relevance to resource evaluation. These involve quantitative studies of their mechanical strength and other physical properties required to plan large-scale sampling. Although a fair amount of "lore" concerning the cutting and crushing of meteoritic material exists, little of this knowledge is available in published form. Furthermore, almost no attention has been given to large-scale chemical and physical processing that would be involved in extraction of valuable materials from meteorites.

<u>It is recommended that current meteorite studies be extended to include research directed to problems of resource evaluation.</u> This area is one in which one must proceed with considerable sensitivity to the

[9]Also Wetherill, G. W.; and Williams, J. G.: Origin of differentiated meteorites. Unpublished paper.

relative importance of funding other meteoritic work of greater scientific importance and to the need for conservation of valuable meteoritic material.

RESOURCE EVALUATION MISSIONS

Objectives

The purpose of a spacecraft mission in a resources survey program is to provide information necessary to evaluate the suitability of the target objects as sources of raw materials for space processing. An appropriate body would provide the needed materials in a form that could be mined and processed into the desired products. It is necessary to determine the availability of needed raw materials and their physical properties to design the appropriate mining equipment. It is also necessary to determine their chemical and mineralogical properties to establish the processing plant.

Based on these needs, the objectives of spacecraft missions will include determination of the following properties of the target body. Surface chemical composition, mineralogical composition, abundance, and distribution can be determined from remote or in situ measurements. High-spatial-resolution measurements are needed to evaluate the homogeneity of the body. Mass, size, and surface morphology can be used to determine bulk density, which provides a measure of bulk composition. Determination of the shape of the gravitational potential surface provides a means of establishing internal mass distribution and homogeneity. Surface mechanical strength and interior strength can be measured in situ from returned samples and inferred from density and seismic data. Conductivity measurements relate to the composition and structure of the object.

Only precursor missions to near-Earth objects are defined here. If these objects prove to be usable, subsequent mining missions would be defined. It is assumed that only Apollo and Amor objects are of immediate interest. More distant objects may also become of importance as resources, but that possibility is presumed less likely at this time. Because the overall program goal is a feasibility evaluation of retrieval of asteroid material, the trajectory and energy implications of returning large masses ($\sim 9 \times 10^8$ kg) to Earth orbit must be considered in the selection of precursor mission targets. These factors and assumptions are key to the rationale presented in the following subsections for the selection of precursor missions and an investigation strategy.

Mission Characteristic Guidelines

A fundamental step in the development of precursor missions is the identification of accessible targets. From the standpoint of retrieving resources from near-Earth asteroids, accessibility is expressed by three key mission parameters: characteristic impulse (ΔV), flight time, and frequency of opportunity. Of these three, ΔV is the most critical denominator of retrieval feasibility.

In the recently completed NASA Ames Summer Study on Space Settlements, O'Leary and others concluded that round-trip ΔV's of less than 14 km/sec and preferably in the range of 10 km/sec are desired for useful resource retrieval using the mass driver concept. It was further concluded that the outbound fraction of the ΔV should be minimized to enhance recovery effectiveness, with values of <6 km/sec desired. Another report[10] from the NASA Ames Summer Study listed 10 known asteroids that are thought to satisfy (or nearly satisfy) this outbound ΔV goal of 6 km/sec. These objects (table XIV) were taken from the 43 known asteroids with perihelia less than 1.3 AU.

The orbital elements that most directly influence transfer ΔV are semimajor axis, eccentricity, and inclination (as shown in table XIV), or, alternatively, perihelion, aphelion, and inclination. To illustrate the sensitivity of these latter parameters to ΔV, a list of objects with decreasing ΔV requirements is presented in table XV, where ΔV now includes escape from low Earth orbit (values stated represent orbit-to-orbit ΔV only). It is interesting to note, in the context of the table XV ΔV's, that a Lunar Polar Orbiter requires 4.08 km/sec with an additional 2.19 km/sec to land on the surface (ref. 3). From the standpoint of minimizing ΔV, orbital elements of yet undiscovered objects that would be most relevant to resource retrieval are shown at the bottom of table XV as one guide in the selection of promising targets from an active search and discovery program.

Although less important, launch opportunities and flight time must also be considered in the selection of both targets and mission concepts. The semimajor axis of a desirable target (table XV) ranges from 0.95 to 1.45 AU. Values near 1 AU, although potentially requiring very low ΔV, will have very widely spaced optimum opportunities, hence impeding accessibility. The object 1976 AA is a good case in point. Its semimajor axis of 0.97 AU leads to an opportunity spacing (synodic period) of more than 19 years. On the other hand, 1943 with a semimajor axis of 1.4 AU has a much shorter spacing of 2.4 years, although characteristics of its opportunities are quite variable because of its orbital eccentricity.

The remaining parameter, flight time, is one that more directly affects a 10- to 15-year assessment program and associated mission concepts than it does a retrieval program. Asteroid retrieval using mass drivers is almost certainly a 3- to 5-year operation.[8] Precursor missions, at first glance, should be performed in much shorter times. It turns out, however, that mission times could be longer than 1 year (one way) or 3 years (round trip) if ΔV's and, hence, mission requirements

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[8]O'Leary, B.: Gaffey, M. J.; Ross, D. J.; and Salkeld, R.: The Retrieval of Asteroidal Materials. Report being prepared from NASA Ames Space Settlements Summary Study, 1977.

[10]Bender, D. F.; Dunbar, R. S., and Ross, D. J.: Round-trip Missions to Low Delta-V Asteroids and Implications for Material Retrieval.

TABLE XIV.- TEN KNOWN LOW-DELTA-V ASTEROIDS[a]

Object	Semimajor axis, AU	Eccentricity	Inclination, deg	ΔV boundary[b]	
				Within	Close, but outside
1976 UA	0.84	0.451	5.9	X	
1977 HB	1.08	.346	9.4	X	
Toro	1.37	.436	9.4	X	
1973 EC	1.43	.256	8.7	X	
Eros	1.46	.223	10.8	X	
Adonis	1.87	.764	1.4		X
Apollo	1.47	.560	6.4		X
Geographos	1.24	.335	13.3		X
Amor	1.92	.436	11.9		X
Ivar	1.86	.397	8.4		X

[a]After Bender et al. (1977).

[b]ΔV <6 km/sec boundary: aphelion <1.8 AU, eccentrinty <0.45, inclination <12° where ΔV is the sum of impulses from Earth escape to rendezvous.

TABLE XV.- ORBIT ELEMENT/DELTA-V RELATIONSHIP

Object	Period, days	Perihelion, AU	Aphelion, AU	Inclination deg	ΔV,[a] km/sec	Data source
1976 UA	283	0.46	1.22	5.9	9.3	Bender, JPL[b]
1976 AA	347	.79	1.14	19.1	9.0	Niehoff, SAI[c]
1977 HB	409	.70	1.45	9.4	7.2	Niehoff, SAI
Eros	643	1.13	1.78	10.8	6.5	Niehoff, SAI
Ivar	931	1.12	2.60	8.4	6.3	Uphoff, JPL
1943	625	1.06	1.80	8.7	5.5	Niehoff, SAI
Search objects	—	1.0 ± 0.1	1.4 ± 0.4	<10	<6	

[a]ΔV is total outbound transfer ΔV from low Earth orbit to object rendezvous; in these terms, a minimum-energy Mars mission requires 6.4 km/sec.

[b]Jet Propulsion Laboratory.

[c]Science Application Inc.

are constrained. The implication is the time to complete an acceptable assessment program of several mission levels for a number of targets could take appreciably longer than 10 years. The advantage of combining sequential mission objectives into single mission endeavors to shorten the overall assessment program is something that has not yet been seriously considered but should be addressed as new objects are discovered and their mission requirements become identified.

Mission Modes

The objectives of the resource evaluation missions, as presented earlier, imply remote-sensing, in situ, and sample-return experiments. A broad range of mission modes could support these experiments. The purpose of this discussion is to present a rationale for a preliminary narrowing of the range of possibilities. Five alternatives are presented in table XVI with recommended choices. The rationale for these selections is presented in the following paragraphs.

Flyby or rendezvous.- Rendezvous is chosen primarily because it allows much more extensive coverage of the object, which is probably rotating. A flyby encounter of a 1-km-diameter object at a comparatively low velocity of 1 km/sec could require at most 30 minutes within 1000 km of the object. If rotational periods of >6 hours are expected, significantly less than complete coverage is achieved in this time. Statistical counting experiments (e.g., gamma-ray spectrometry) are particularly hindered by such short exposure times. The additional ΔV penalty for rendezvous (expected to be 0.5 km/sec for desirable targets) is considered well worth the significant gains in observing time achieved.

TABLE XVI.- PRECURSOR MISSION ALTERNATIVES AND RECOMMENDATIONS

Alternatives	Recommended choices
Flyby or rendezvous	Rendezvous
Ballistic or low thrust	Ballistic[a]
Single or multiple targets	Single[a]
Direct or gravity assist	Direct[a]
Manned or unmanned	Unmanned

[a]Alternative retained as backup option.

Ballistic or low-thrust trajectories.- Ballistic trajectories are thought to be adequate for the anticipated low ΔV targets. Ballistic flight with impulisve rocket propulsion is also more straightforward operationally, and, for low-energy missions, costs less. Programmatically, the ballistic flight mode permits the option of an early precursor mission because it would not require a major propulsion development program. However, the need for low-thrust propulsion should not be completely dismissed. Further study of an assessment program's requirements may provide a valid reason for low-thrust propulsion, which should be retained as an option.

Single- or multiple-target missions.- Single missions are selected for several reasons. As rendezvous is much preferred to flyby for investigative reasons, the ΔV requirements of multitarget missions raise a propulsion issue, which probably leads to a low-thrust requirement. More important than the propulsion consequences of multitarget missions, however, is the question of timing. With few targets yet to choose from, it could take an extremely long time before enough feasible targets are found to construct an attractive multitarget mission. In the meantime, acceptable single-mission opportunities would undoubtedly come and go. This would indeed by a poor trade, in return for the possibly enhanced cost-effectiveness of a multitarget mission. Yet the selection of single targets is a conditional one. A small possibility exists for an early multiple-target precursor mission and trajectory analysts should consider multitarget missions in their opportunity searches as new objects are discovered.

Direct or gravity-assist transfers.- Direct transfers are recommended for precursor missions on the basis of propulsion requirements. The criterion of low ΔV for resource retrieval almost certainly precludes the need for energy-assisted maneuvers on precursor missions. The drawback of gravity assist for near-Earth targets is that such maneuvers almost certainly increase flight time significantly. For a timely program of precursor assessment missions, gravity assist should not be used unless necessary. However, specific instances may occur, particularly for sample-return missions, when it becomes more favorable than delaying launch to a lower energy, direct opportunity.

Manned or unmanned.- The choice of the unmanned option for the precursor missions is clear. Both accomplished and proposed missions (e.g., LPO) support the use of automated spacecraft for initial characterization, in situ study, and sample returns from near-Earth resources. A manned requirement at this early date would significantly increase cost and mission complexity (e.g., round trips instead of precursor rendezvous) to a point of begging further justification, which could only be provided by earlier unmanned missions. Almost certainly a time will come, however, when complete geological assays of prime targets will be required before a decision to implement resource retrieval can be made. It is at that point that manned missions may be essential.

The reader is cautioned that these choices of flight modes are preliminary in nature, intended as initial guidelines. It is fully possible that further study of the alternatives and/or discovery of new objects could reverse one or more of the choices indicated in table XVI.

Mission Concepts and Strategy

The objectives for a comprehensive precursor mission assessment argue for three investigative techniques: remote sensing, in situ study, and sample return. It has already been suggested that first encounters be rendezvous, not flybys. It is reasonable to expect, for reasons of cost and limited knowledge, that such missions will carry remote-sensing payloads, not unlike LPO, designed to obtain global geochemical and geophysical data. It should be possible to orbit objects as small as 1 km in diameter as a means of mapping their surfaces. A 1-km object with a mean density of 3 g/cm^3 can be orbited with a 12-hour period at a mean altitude of 1.2 km, which is well within its sphere of influence of about 8 km at 1 AU. Shorter period orbits will exhibit non-Keplerian motion if the object is irregularly shaped or inhomogeneous, which could disturb systematic mapping objectives. Coupling between orbital period and rotation rate, when they are nearly equal, presents problems, so that stationkeeping beyond the sphere of influence could be a more effective way of gaining coverage. These operational issues need further study as they almost certainly have design implications for the expected remote-sensing experiments.

The role and phasing of in situ lander experiments are less certain in the early investigation of near-Earth asteroidal resources. Because these are low ΔV targets, the energy requirements of sample return are very low compared to other sample-return missions if direct reentry recovery is assumed upon Earth return. Hence, if the capability exists to land on the asteroid and collect samples for in situ analysis, returning those samples to Earth may only be a modest propulsion step away. It is, therefore, likely that lander and sample return will combine into one mission concept. The question of location and number of sites to sample is more difficult.

Landing on a 1-km object requires very little energy expenditure, because the surface escape velocity is less than 1 m/sec. Staying on the surface will require some kind of anchoring, however, because the surface gravity of such an object is very small (a 100-kg mass would weigh less than a 10-g mass on the surface of a 1-km asteroid). The details of such operations will depend upon the individual object's surface mechanical properties, with multisite operations further depending on its shape, rotation period, and surface properties. Additional study, before target selections and after initial rendezvous missions, will obviously be necessary. It may be that simple surface measurements, such as can be conducted by a penetrator, may be desired for engineering data on initial precursor rendezvous missions to support the design in subsequent lander/sample-return hardware. A penetrator could also provide in situ geochemical measurements for the remote-sensing payload.

The selection and implementation strategy of precursor missions can be summarized as follows. Direct, ballistic flight modes are preferred. Single, rather than multiple, mission targets are more reasonable in view of the limited number of expected objects of interest. Initially, unmanned rendezvous missions with remote-sensing payloads should be conducted to each compositionally attractive (from ground-based observations) low ΔV target discovered. The question of including a small surface payload (e.g., penetrators) is left to further study. Subsequent unmanned lander/sample-return missions should be conducted to the most promising of these targets. The level of complexity in surface study and sample collection is also a subject for further study. Although not recommended for initial precursor missions, it may become possible later in the program to further combine the rendezvous, lander, and sample-return objectives into one mission for objects with good ground-based characterization data.

The application of unmanned missions to the assessment of near-Earth asteroids should be regarded as supportive of achieving the first milestone in evaluating the feasibility and relevance of asteroid resources retrieval. Additional steps before commitment to retrieval will almost certainly be required to justify the anticipated investment for such an endeavor. Manned field studies of the prime targets will almost certainly be considered as part of such an extended evaluation effort. The requirements and objectives of such missions are beyond the scope of consideration addressed here, but they obviously play an important role in the overall determination of asteroid material retrieval feasibility.

Asteroid Return Sample

In the event that a feasible asteroid rendezvous is identified and that sampling of the asteroid is a logical next step, several activities must be planned.

1. A sampling plan must be developed, based on all available remote-sensing and orbital data and on plausible geochemical models. This should include a number of sampling sites, surficial versus buried samples, fines versus rock fragments, etc.

2. Sampling mechanisms and tools (picks, claws, magnets, hooks, etc.) should be designed to consider the great range of physical properties that might be encountered, the problem of contamination from tools and spacecraft, ease in identifying precise sampling locations, and positive "no-loss" delivery to containers that can be securely returned to spacecraft.

3. Adequate containers should be designed for all possible sample conditions within size and weight constraints including containers for rocks, metal, fines, and volatiles.

4. Photographic documentation of the environment and specific points sampled should be obtained.

5. A mode of storage during return to the Earth that provides for protection against contamination and for preservation of fragile materials should be defined.

6. A plan for preliminary examination and evaluation should be prepared.

7. A corollary technical group concerned with evaluating resource potential from the science results should work with the science team.

Advanced Studies Recommendations

This report recommends that the level of advanced studies devoted to small-body missions be expanded to include the following new tasks relevant to near-Earth resources.

1. Development of representative objectives and associated experiments relevant to both scientific and resource exploration of near-Earth asteroids.

2. Analysis of asteroid encounter operations associated with remote-sensing and surface investigations and consequent mission implications.

3. Detailed assessment of preferred flight modes for precursor missions to asteroid resource candidates.

4. Evaluation and quantification of gravity-assisted maneuvers in reducing energy requirements for returning asteroidal samples and resources.

5. Establishment of a capability for rapidly assessing the flight opportunities and associated propulsion requirements of newly discovered near-Earth objects.

6. Initiation of a feasibility study of the mass driver concept, which also would define critical technology requirements for development; an economic analysis should be included as part of this study.

The timing of these study tasks should be such as to not unduly alter the current study thrusts in small body missions for scientific exploration; i.e., these recommendations should be added to the overall small bodies study plan as possible, not replacing already planned studies.

Overall Program Strategy

An Earth-approaching asteroid resource program over the next 10 years should involve the following four major elements: (1) the search program, (2) ground-based physical and chemical characterization, (3) supporting studies, and (4) precursor rendezvous missions for detailed chemical and physical characterization. Ten to 20 years will be required before completion of inventory of several hundred asteroids; tens of these objects should be suitable as resource targets from the point of view of their composition and the energy required to reach them. The development of hardware for meeting the primary objectives of the precursor missions requires a lead time of 3 to 5 years. Such a development can proceed without knowledge of the finally selected targets and launch dates; tentative targets and launch dates during the mid-1980's can be identified and revised as new discoveries are made. This target selection philosophy should not be considered an issue, because the mission hardware recommended for a fiscal year 1980 start is intended to be applied across a spectrum of targets (more than one, and perhaps as many as six or eight), which must be visited as part of the survey program. An expanded search program will have increased the number of known Earth-approaching asteroids by a factor of 2 to 5 by 1983 when launches could begin.

This report recommends that a program of rendezvous missions to low ΔV asteroids be established for a fiscal year 1980 new start. Instrumentation would be designed to characterize the physical and chemical properties of candidate objects for launches between 1983 and 1986. The primary objectives are the determination of the chemical and mechanical properties of these targets; the secondary objectives are exploration and broad science objectives. Targets will be changed as new discoveries reveal new candidates. Candidate targets now exist (e.g., Eros, 1943, 1977 HB), to which specific missions during the mid-1980's could initially be designed.

The recommendation is made for a mission program fiscal year 1980 new start with the conviction that the information to be gained from these missions is an essential step before technology readiness can be proven for a program of retrieval of asteroidal materials. Such readiness by the mid-1980's has been set as a goal by a NASA Office of Aeronautics and Space Technology program planning group. A further delay of 1 or more years in starting these assay missions may create similar delays - or increase the risk - in implementing the retrieval program. These missions appear to be the pacing item for steps that follow and there is no significant risk in starting hardware development for precursor missions in the near future. For these reasons, the NASA should consider the urgency in understanding the resource implications of these precursor missions, separate from the scientific dividends they would yield, in its decisions on new starts for fiscal year 1980.

The support for such a program, if it is to succeed, must not be confined to the Office of Space Science and the community of planetary scientists. It is an essential part of the recommendation that this program must involve all major elements of NASA, including those responsible for technical and industrial aspects of the space program.

REFERENCES

1. Glaser, Peter E.: Solar Power From Satellites. Physics Today, Feb. 1977, pp. 30-38.

2. O'Neill, Gerard K.: Space Colonies and Energy Supply to the Earth. Science, vol. 190, no. 4218, Dec. 5, 1975, pp. 943-947.

3. Davis, Hubert P.: Long Range Aspects of a Large Scale Space Program. Lunar Utilization, David R. Criswell, ed., Lunar Science Institute, Mar. 1976, pp. 10-25.

4. Criswell, D. R.: Demandite, Lunar Materials, and Space Industrialization. Paper presented at the 3rd Princeton Conference on Space Manufacturing, Princeton, N. J., 1977.

5. Goeller, H. E.; and Weinberg, Alvin M.: The Age of Substitutability. Science, vol. 191, no. 4228, Feb. 20, 1976, pp. 683-689.

6. Gaffey, Michael J.; and McCord, Thomas B.: Mining Outer Space. Technology Review, June 1977, pp. 50-59.

7. McKinstry, Hugh E.: Mining Geology. Prentice-Hall, Inc., 1948.

8. Pfleider, Eugene P., ed.: Surface Mining. American Inst. of Mining, Metallurgical, and Petroleum Engineers, 1968.

9. Taggart, Arthur F.: Elements of Ore Dressing. John Wiley and Sons, Inc., 1951.

10. Epstein, Samuel; and Taylor, Hugh P., Jr.: The Concentration and Isotopic Composition of Hydrogen, Carbon and Silicon in Apollo 11 Lunar Rocks and Minerals. Proc. Apollo 11 Lunar Sci. Conf., Vol. 2, Pergamon Press, Inc., 1970, pp. 1085-1096.

11. Moore, C. B.; Gibson, E. K.; et al.: Total Carbon and Nitrogen Abundances in Apollo 11 Lunar Samples and Selected Achondrites and Basalts. Proc. Apollo 11 Lunar Sci. Conf., Vol. 2, Pergamon Press, Inc., 1970, pp. 1375-1382.

12. Funkhouser, J. G.; Schaeffer, O. A.; Bogard, D. D.; and Zahringer, J.: Gas Analysis of the Lunar Surface. Proc. Apollo 11 Lunar Sci. Conf., Vol. 2., Pergamon Press, Inc., 1970, pp. 1111-1116.

13. Watson, Kenneth; Murray, Bruce; and Brown, Harrison: On the Possible Presence of Ice on the Moon. J. Geophys. Res., vol. 66, no. 5, May 1961, pp. 1598-1600.

14. Jaffe, L. D.; Choate, R.; et al.: Lunar Exploration Objectives and the Role of Long-Range Lunar Traverses. NASA CR-152717, 1970.

15. Zellner, B.; and Grady, J.: Minor Planets and Related Objects. XX. Polarimetric Evidence for the Albedos and Compositions of 94 Asteroids. Astron. J., vol. 81, Apr. 1976, pp. 262-280.

16. Morrison, D.: Asteroid Sizes and Albedos. Icarus, vol. 31, June 1977, pp. 185-220.

17. Chapman, C. R.; Morrison, D.; and Zellner, B.: Surface Properties of Asteroids - A Synthesis of Polarimetry, Radiometry, and Spectrophotometry. Icarus, vol. 25, May 1975, pp. 104-130.

18. Zellner, B.; and Bowell, E.: Asteroid Compositional Types and Their Distributions. The Interrelated Origins of Comets, Asteroids, and Meteorites, A. H. Delsemme, ed., U. Toledo Press (to be published).

19. Chapman, C. R.: Asteroids as Meteorite Parent Bodies - The Astronomical Perspective. Geochim. Cosmochim. Acta, vol. 40, July 1976, pp. 701-719.

20. Chapman, C. R.: The Evolution of Asteroids as Meteorite Parent Bodies. The Interrelated Origins of Comets, Asteroids, and Meteorites, A. H. Delsemme, ed., U. Toledo Press (to be published).

21. McCord, Thomas B.; and Gaffey, Michael J.: Asteroids: Surface Composition From Reflection Spectroscopy. Science, vol. 186, no. 4161, Oct. 25, 1974, pp. 352-355.

22. Gaffey, M. J.; and McCord, T. B.: Asteroid Surface Materials: Mineralogical Characterizations and Cosmological Implications. Paper presented at 8th Lunar Science Conference (Houston, Tex.), Mar. 1977.

23. Matson, D. L.; Fanale, F. P.; Johnson, T. V.; and Veeder, G. J.: Asteroids and Comparative Planetology. Proc. Lunar Sci. Conf. 7th., Vol. 3., Pergamon Press, Inc., 1976, pp. 3603-3627.

24. Morrison, D.: The Densities and Bulk Compositions of Ceres and Vesta. Geophys. Res. Lett., vol. 3, Dec. 1976, pp. 701-704.

25. Wetherill, G. W.: Where Do the Meteorites Come From? A Re-evaluation of the Earth-Crossing Apollo Objects as Sources of Stone Meteorites. Geochim. Cosmochim. Acta, vol. 40, Nov. 1976, pp. 1297-1317.

26. Shoemaker, E. M.; and Helin, E. F.: Populations of Planet-Crossing Asteroids and the Relation of Apollo Objects to Main-Belt Asteroids and Comets. The Interrelated Origins of Comets, Asteroids, and Meteorites, A. H. Delsemme, ed., U. Toledo Press (to be published).

27. Shoemaker, E. M.; Helin, E. F.; and Gillett, S. L.: Populations of the Planet-Crossing Asteroids. Geological Romana (to be published).

28. Gehrels, T.; Roemer, E.; Taylor, R. C.; and Zellner, B. H.: Minor Planets and Related Objects. IV. Asteroid (1556) Icarus. Astron. J., vol. 75, no. 2, Mar. 1970, pp. 186-195.

29. Dunlap, J. L.: Minor Planets and Related Objects. XV. Asteroid (1620) Geographos. Astron. J., vol. 79, Feb. 1974, pp. 324-332.

30. Chapman, Clark R.; McCord, Thomas B.; and Pieters, Carle: Minor Planets and Related Objects. X. Spectrophotometric Study of the Composition of (1685) Toro. Astron. J., vol. 78, no. 6, Aug. 1973, pp. 502-505.

31. Gradie, J. C.: Physical Observations of Object 1977 AA. Bull. American Astron. Soc., vol. 8, no. 3, 1976, pp. 458-459.

32. Delsemme, A. H.: The Volatile Fraction of the Cometary Nucleus. Icarus, vol. 24, Jan. 1975, pp. 95-110.

33. Ceplecha, Z.; and McCrosky, R. E.: Fireball End Heights - A Diagnostic for the Structure of Meteoric Material. J. Geophys. Res, vol. 81, no. 35, Dec. 10, 1976, pp. 6257-6275.

34. Brownlee, D. E.; Ferry, G. V.; and Tomandl, D.: Stratospheric Aluminum Oxide. Science, vol. 191, no. 4233, Mar. 26, 1976, pp. 1270-1271.

35. Whipple, F. L.: A Speculation About Comets and the Earth. Mem. Soc. Roy. Sci. Liege, vol. 9, pp. 101-111 (discussion pp. 113-114).

36. Whipple, Fred L.: A Comet Model. I. The Acceleration of Comet Encke. Astrophys. J., vol. 111, no. 2, 1950, pp. 375-394.

37. Sekanina, Z.: Total Gas Concentration on Atmospheres of the Short-Period Comets and Impulsive Forces Upon Their Nuclei. Astron. J., vol. 74, no. 7, Sept. 1969, pp. 944-950.

38. Marsden, B. G.; and Sekanina, Z.: Comets and Nongravitational Forces. IV. Astron. J., vol. 76, no. 10, Dec. 1976, pp. 1135-1151.

39. Anders, Edward: How Well Do We Know "Cosmic" Abundances? Geochem. Cosmochim. Acta, vol. 35, 1971, pp. 516-522.

40. Clayton, Robert N.; Onuma, Naoki; and Mayeda, Toshiko, K.: A Classification of Meteorites Based On Oxygen Isotopes. Earth Planet. Sci. Lett., vol. 30, 1976, pp. 10-18.

41. Wetherill, G. W.: Cometary Versus Asteroidal Origin of Chondritic Meteorites. Physical Studies of Minor Planets, T. Gehrels, ed., NASA SP-267, 1971, pp. 447-460.

42. Wetherill, G. W.: Solar System Sources of Meteorites and Large Meteoroids. Ann. Rev. Earth Planet. Sci., vol. 2, 1974, pp. 303-331.

43. Anders, Edward: Do Stony Meteorites Come From Comets? Icarus, vol. 24, Mar. 1975, pp. 363-371.

44. Zimmerman, Peter D.; and Wetherill, G. W.: Asteroidal Source of Meteorites. Science, vol. 182, no. 4107, Oct. 5, 1973, pp. 51-53.

45. Anders, Edward: Origin, Age, and Composition of Meteorites. Space Science Rev., vol. 3, 1964, pp. 583-714.

46. Simonenko, A. N.: The Meteorite Orbit: Amor Asteroids Are a Principal Source of Meteorites. The Interrelated Origins of Comets, Asteroids, and Meteorites. A. H. Delsemme, ed., U. Toledo Press (to be published).

47. Levin, B. J.; Simonenko, A. N.; and Anders, Edward: Farmington Meteorite: A Fragment of an Apollo Asteroid? Icarus, vol. 28, no. 3, July 1976, pp. 307-324.

48. Opik, E. J.: Survival of Comet Nuclei and Asteroids. Advan. Astron. Astrophys., vol. 2, 1963, pp. 219-262.

49. Opik, E. J.: The Stray Bodies in the Solar System. Part II. The Cometary Origin of Meteorites. Advan. Astron. Astrophys., vol. 4, 1966, pp. 302-336.

50. Wetherill, G. W.: Fragmentation of Asteroids and Delivery of Fragments to Earth. The Interrelated Origins of Comets, Asteroids, and Meteorites. A. H. Delsemme, ed., U. Toledo Press (to be published).

51. Anders, Edward; and Arnold, James R.: Age of Craters on Mars. Science, vol. 149, no. 3691, Sept. 24, 1965, pp. 1494-1496.

52. Wetherill, G. W.: Origin and Age of Chondritic Meteorites. (In Russian.) Recent Contributions to Geochemistry and Analytical Chemistry. A. I. Tugarinov, ed., Nauka (Moscow), 1972, pp. 22-34. English translation, John Wiley and Sons, 1975, pp. 21-37.

53. Rajan, R. Sundar: On the Irradiation History and Origin of Gas-Rich Meteorites. Geochim. Cosmochim. Acta, vol. 38, 1974, pp. 777-788.

54. Shoemaker, E. M.: Astronomically Observable Crater-Forming Projectiles. Paper presented at the Symposium on Planetary Cratering Mechanics, 1977.

55. Weissman, Paul R.; and Wetherill, G. W.: Periodic Trojan-Type Orbits in the Earth-Sun System. Astron. J., vol. 79, Mar. 1974, pp. 404-412.

56. Helin, E. F.; and Shoemaker, E. M.: Discovery of Asteroid 1976 AA. Icarus, vol. 31, Aug. 1977, pp. 415-419.

57. Roemer, Elizabeth: The Dimensions of Cometary Nuclei. Mem. Soc. Roy. Sci. Liege, vol. 12, no. 1, 1966, pp. 23-28.

58. Ceplecha, Z.: Meteorite Populations and Orbits. The Interrelated Origins of Comets, Asteroids, and Meteorites. A. H. Delsemme, ed., U. Toledo Press (to be published).

59. McCroskey, R. E.; Shao, C. Y.; and Posen, A.: Prairie Network Fireball Data. I. Summary and Orbits. Center for Astrophysics preprint 665, 1977.

60. Rajan, R. S.; Brownlee, D. E.; et al.: Detection of ^4He in Stratospheric Particles Gives Evidence of Extraterrestrial Origin. Nature, vol. 267, May 12, 1977, pp. 133-134.

61. Wasson, John T.: Meteorites. Vol. 10 of Rocks and Minerals, P. J. Wyllie, W. von Engelhardt, and T. Hahn, eds., Springer-Verlag (New York), 1974.

LUNAR BIBLIOGRAPHY

General Lunar Science

Brett, R.; Lunar Science - Geophysics, Mineralogy and Evolution of Moon. Essays in Physics, vol. 5, Academic Press (London and New York), 1973, pp. 1-35.

French, Bevan M.: What's New on the Moon? Sky and Telescope, vol. 53, no. 3, Mar. 1977, pp. 164-169, and no. 4, Apr. 1977, pp. 257-261.

Gast, P. W.: The Chemical Composition and Structure of the Moon. The Moon, vol. 5, Sept. 1972, pp. 121-148.

Hinners, N. W.: The New Moon: A View. Rev. Geophys. Space Phys., vol. 9, no. 3, Aug. 1971, pp. 447-522.

Taylor, S. R.: Lunar Science; A Post-Apollo View. Pergamon Press, Inc., 1975.

Lunar Mare

Head, James W., III: Lunar Volcanism in Space and Time. Rev. Geophys. Space Phys., vol. 14, no. 2, May 1976, pp. 265-300.

Lunar Nonmare Areas

Walker, D.; Grove, T. L.; et al.: Origin of Lunar and Feldspathic Rocks. Earth Planet. Sci. Lett., vol. 20, 1973, pp. 325-336.

Wood, John A.: Lunar Petrogenesis in a Well-Stirred Magma Ocean. Proc. Lunar Sci. Conf. 6th, Pergamon Press Inc., 1975, pp. 881-883.

Lunar Chronology

Wasserburg, G. J.; Papanastassiou, D. A.; Tera, F.; and Huenke, J. C.: Outline of a Lunar Chronology. Phil. Trans. R. Soc. Lond. Series A, vol. 285, no. 1327, March 31, 1977, pp. 7-22.

Lunar Cratering

Horz, F.: Impact Cratering and Regolith Dynamics. Phys. Chem. Earth, vol. 10, 1977, pp. 3-15.

Heiken, G.: Petrology of Lunar Soils. Rev. Geophys. Space Phys., vol. 13, Aug. 1975, pp. 567-587.

Lunar Mineralogy and Petrology

Warner, J.: Mineralogy, Petrology, and Geochemistry of the Lunar Samples. Rev. Geophys. Space Phys., vol. 13, July 1975, pp. 163-168.

Lunar Remote Sensing

Adler, I.; Trombka, J. I.; et al.: Results of the Apollo 15 and 16 X-Ray Experiment. Proc. Lunar Sci. Conf. 4th., Vol. 3., Pergamon Press, Inc., 1973, pp. 2783-2791.

Bielefeld, M. J.; Reedy, R. C.; et al.: Surface Chemistry of Selected Lunar Regions. Proc. Lunar Sci. Conf. 7th., Vol. 3., Pergamon Press, Inc., 1976, pp. 2661-2676.

Pieters, C.; and McCord, T. B.: Characterization of Lunar Mare Basalt Types: I. A Remote Sensing Study Using Reflection Spectroscopy of Surface Soils. Proc. Lunar Sci. Conf. 7th., Vol. 3., Pergamon Press, Inc., 1976, pp. 2677-2690.

Lunar Volatiles

Butler, P., Jr.; and Meyer, C., Jr.: Sulfur Prevails in Coatings on Glass Droplets: Apollo 15 Green and Brown Glasses and Apollo 17 Orange and Black (Devitrified) Glasses. Proc. Lunar Sci. Conf. 7th., Vol. 2., Pergamon Press, Inc., 1976, pp. 1561-1581.

Chou, C. L.; Boynton, W. V.; Sundberg, L. L.; and Wasson, J. T.: Volatiles on the Surface of Apollo 15 Green Glass and Trace-Element Distributions Among Apollo 15 Soils. Proc. Lunar Sci. Conf. 6th., Vol. 2., Pergamon Press, Inc., 1975, pp. 1701-1727.

Watson, Kenneth; Murray, Bruce C.; and Brown, Harrison: The Behavior of Volatiles on the Lunar Surface. J. Geophys. Res., vol. 66, no. 9, Sept. 1961, pp. 3033-3045.

Lunar Crust

Bills, Bruce G.; and Ferrari, Alfred J.: A Lunar Density Model Consistent With Topographic, Gravitational, Librational, and Seismic Data. J. Geophys. Res., vol. 82, no. 8, March 10, 1977, pp. 1306-1314.

APPENDIX A
MEETING SCHEDULE

NASA Summer Study
Near-Earth Resources
August 6-13, 1977
La Jolla, California

Aug. 6, morning

9:00 Welcome and Introduction: Purpose of study, agenda, preliminary committee structure, etc. -- J. Arnold

Resources for what?

9:30 Humanization of Space - Status and Prospects -- G. K. O'Neill
10:30 Use of Asteroidal Resources on Earth -- T. McCord
11:15 Remarks -- Bruce Murray

Lunch

Aug. 6, afternoon

1:00 Space Solar Power Stations -- B. O'Leary
1:45 Resource Needs of Man in Space -- D. Criswell
2:45 Processing of Nonterrestrial Materials -- R. Williams
3:45 Remarks on Zero g -- O. Garriott
4:15 Lunar Colonies -- J. Burke

Aug. 7, morning

Lunar resources

9:00 Introduction
9:15 Lunar Geology -- L. Silver
10:15 Global Lunar Resource Evaluation -- J. Arnold
11:00 The Lunar Mass Driver -- G. K. O'Neill

Lunch

Aug. 7, afternoon

1:00 Prospecting From Orbit -- T. McCord
1:30 Properties of Lunar Soils -- M. Duke, E. Schonfeld
2:30 Enrichment Methods -- R. Williams
3:00 Are There Lunar Ores? -- Panel (L. Silver, C. Meyer, P. Lowman, J. Hunt)
4:00 Lunar Science and Lunar Resources - What are the Questions?

Aug. 8, morning

Asteroidal resources

9:00 Earth-Crossing Asteroids - Known Objects and Discovery Programs -- E. Shoemaker
10:00 Earth-Crossing Asteroids - Composition: Methods and Results -- M. Gaffey
11:00 Belt Asteroids -- D. Morrison

Lunch

Aug. 8, afternoon

1:00 Asteroid Populations -- G. Wetherill
2:00 Earth-Crossing Asteroid Science Missions - Trajectory Considerations -- J. Niehoff
3:00 Bringing Asteroids Back -- B. O'Leary, J. Niehoff
4:00 Asteroid Resources - What do we need to know first? -- Panel

Aug. 9, morning

9:00 The NASA Outlook -- D. Herman, J. Burke
11:00 Discussion

Lunch

Aug. 9, afternoon

1:00 Organization of committees
2:30 Individual committee meetings

Aug. 10, morning

9:00 Plenary session

Committee work

Aug. 11, morning

9:00 Plenary session
10:00 OAST Activities in Space Manufacturing -- J. Bredt

Committee work

Aug. 12, morning

Plenary session
9:00 - 10:30 Preliminary reports and draft recommendations
Discussion and drafting

Aug. 12, afternoon

Plenary session
4:00   Adoption of recommendations and summary report

Aug. 13, morning

Plenary session with NASA management
9:00   Introduction
9:30 - 12:00 Reports

Adjourn meeting

Aug. 13, afternoon

1:00   Press conference
2:30   Working committee -- Drafting

Aug. 14

Working committee
Writing and cleanup tasks

APPENDIX B
GLOSSARY

Absolute visual magnitude -- The apparent visual magnitude of an astronomical object of that object were a standard reference distance from the Earth. For solar system objects, the reference position is 1 AU from the Earth and 1 AU from the Sun.

Albedo -- A measurement of an object's ability to reflect light. It is the ratio between the reflected light intensity and the incident light intensity.

ALSEP -- Apollo lunar surface experiments package, a geophysical instrument package placed on the lunar surface by the Apollo astronauts.

Amor asteroids -- Asteroids the perihelia of which are greater than 1.0 AU, but less than 1.38 AU, the orbit of Mars. Their aphelia are greater than 1.38 AU; Mars-crossing asteroids.

Anorthite -- Calcium plagioclase ($Ca\ Al_2Si_2O_8$).

Anorthosite -- A rock composed almost wholly of plagioclase.

Aphelion -- That point of the orbit of a Sun-orbiting object that is most distant from the Sun.

Apollo asteroids -- Asteroids the perihelia of which are less than 1 AU and the aphelia of which are greater than 1 AU; Earth-crossing asteroids.

Asteroid -- A small, solid solar system object that is stellar in appearance in the telescope. Most asteroids are found in the asteroid belt between the orbits of Mars and Jupiter, but many asteroids (Apollo and Amor objects) are not found in this region.

Astronomical unit (AU) -- A unit of distance, the mean distance from the Earth to the Sun, equal to approximately 1.5×10^8 km.

Basalt -- A dark-colored extrusive rock composed primarily of plagioclase, pyroxene, and sometimes olivine.

Breccia -- A fragmental rock the components of which are angular, and therefore, as distinguished from conglomerates, not waterworn. Breccias can be of sedimentary or volcanic origin on the Earth. On the Moon breccias can be formed by the impact and abrasion of meteorites of the lunar surface.

Beneficiation -- The process or processes of concentration of valuable mineral or minerals from a crude ore, normally using physical properties or surface properties of the minerals.

Cayley formation -- The name given to a lunar highland map unit, characterized by relatively flat, rolling terrain. At the Apollo 16 landing site, the unit appears to be a thick deposit of debris from a major lunar impact crater.

Chondrite -- A class of meteorites characterized by chemical composition similar to the nonvolatile composition of the Sun and by the occurence in them of small silicate globules, called chondrules.

Comet -- An astronomical object within the solar system that presents an extended, fuzzy image in the telescope near its perihelion. It can be distinguished from galaxies and nebulae by its movement against the background of stars. Comets are of variable size and very low mass. They are distinguished from asteroids by their telescopic appearance, which is caused by volatiles.

Concentrate -- The upgraded valuable mineral product of beneficiation.

Concentrator -- The plant in which beneficiation is performed.

Craton -- A relatively stable part of a continent, such as the Canadian shield, which is generaly aseismic and generally older than surrounding parts of the continent.

Cristobalite -- SiO_2, a polymorph of quartz.

Cumulate (adj.) -- A cumulate rock is one that consists of a mass of crystals that have settled or floated out of an igneous melt, as a result of density differences between crystals and melt.

Delta V (ΔV) -- A unit that expresses the energy per unit mass required to move an object from one point in space to another point in the solar system. Hence, ΔV refers to a potential difference between two points. Examples of such points are low Earth orbit and the surface of the Earth.

Demandite -- A fictitious "material" composed of all the materials needed to operate an industrial society.

Development -- Activities performed on an ore body after discovery to prepare it for production.

Dunite -- A rock composed almost wholly of olivine.

Earth-approaching asteroids -- Apollo and Amor objects.

Earth-crossing asteroids -- Apollo objects.

Exhalation -- An emanation of gas or vapors, ordinarily formed beneath the surface of the Earth (or Moon) escaping from a volcanic conduit or fissure or from molten lava or from a fumarole or hot spring.

Exploration -- Activities centered on discovery of new ore bodies.

Feldspar -- A calcium, alkali, aluminum silicate. The three principal types are potassium feldspar (K $AlSi_3O_8$), albite (Na $AlSi_3O_8$), and anorthite (Ca $Al_2Si_2O_8$). The latter two form a solid solution series, plagioclase.

Fireball -- A meteor that is very brilliant and often explodes, leaving a trail that sometimes remains visible for several minutes.

Fiskenaesset -- A region in Greenland in which very ancient rocks occur, apparently the result of the crystallization of an immense body of melt intruded at depth.

Floras -- Asteroids of the Flora family, a group in the inner part of the asteroid belt, of which Flora (number 8) is the largest. Their orbital elements are closely similar.

Fumarole -- A hole or vent from which fumes or vapors issue; a spring or geyser that emits steam or gaseous vapor; found usually in volcanic areas.

Grade -- Proportion of product (e.g., metal) contained in crude ore, usually expressed in weight percent.

Greenland craton -- A broad region of ancient rock in Greenland that has remained stable over a long period of geological time.

Hungarias -- Asteroids of the Hungaria group, at the extreme inner edge of the asteroid belt, of which Hungaria (number 434) is the best-known member.

Igneous rock -- A rock formed from a silicate melt. Volcanic rocks are near-surface igneous rocks. Plutonic rocks are igneous rocks formed at depth.

Ilmenite -- An iron titanium oxide ($FeTiO_3$).

Inclination -- The angle formed by the plane of the orbit of an object and the plane of the ecliptic. The ecliptic plane is the plane formed by the Earth's orbit.

Mafic (adj.) -- A mafic rock is one dominated by mafic minerals (ferromagnesium silicates). It still contains a significant amount of nonmafic minerals.

Mars-crossing asteroid -- An asteroid the orbit of which crosses that of Mars. Some, but not all, are Amor objects.

Mass driver -- An electromagnetic device that can accelerate a mass to very high velocities. Any bulk material can be accelerated. The device can be used to accelerate materials, or material can be used as a reaction mass to drive a larger mass in the opposite direction. The mass driver then functions on a reaction principle, like a rocket.

Meteor -- A bright streak of light caused when a meteoroid enters the Earth's atmosphere; a shooting star.

Meteorite -- A solid metallic, stony, or carbonaceous meteoroid that is found on the Earth after falling through the atmosphere.

Meteoroid -- A very small cosmic body. It may cause a meteor or meteorite when it enters the Earth's atmosphere.

Migmatite -- A rock with both igneous and metamorphic characteristics, with alternating bands of different compositions. It may have formed at just below the melting point of the rock. Some partial melting and differentiation may have occurred.

Mill -- The grinding and sizing plant or facility.

Mineralization -- The process of impregnating a rock with additional (secondary) minerals. These minerals often contain metals and other elements, which are usually supplied by a permeating vapor or superheated aqueous phase.

Mineral resource -- All potential mineral raw material (ore) known or predicted, which is now available or may become available through new discovery or through improvements in technology for extraction or recovery.

Near-Earth asteroids -- Apollo and Amor objects.

Norite -- A mafic rock in which orthorhombic pyroxene dominates over monoclinic pyroxene.

NSSDC -- National Space Sciences Data Center.

Olivine -- An iron magnesium silicate, $(Fe, Mg)_2SiO_4$.

Ore -- Rock or mineral raw material from which a useful product may be extracted for economic advantage.

Perihelion -- That point of the orbit of a Sun-orbiting object that is nearest to the Sun.

Periodic comets -- Comets with an elliptical orbit, which return to perihelion at regular intervals. Also called short-period comets. Other comets on nearly parabolic orbits return only at intervals long compared to the history of observation.

Phocaeas -- Asteroids of the Phocaea family, a group in the inner part of the asteroid belt, of which Phocaea (number 25) is the largest. Their orbital elements are closely similar.

Pilot plant -- Preliminary, small-scale production facility performing all the functions of the ultimate full-scale plant, to test design and operation before final commitment for construction of full-scale plant (ore processing).

Plagioclase -- Sodium-calcium feldspar (see feldspar).

Precursor missions -- A mission or missions leading up to a more ambitious mission or project.

Production -- Operation of a full-scale plant (ore processing).

Pyroxene -- A variable composition mafic silicate generally of composition $(Ca, Mg, Fe)SiO_3$.

Refinery -- The plant for purification of final product (metal), normally using chemical processes.

Regolith -- The rubbly layer covering an atmosphereless planetary body. It is producted by repeated meteoroid impact.

Reserves -- Masses or rock (ore) the extent, grade, and physical character of which are sufficiently well known that they can be confidently scheduled for economic production using existing technology at specific levels of prices or other economic parameters.

Schmidt camera -- A telescope with a spherical mirror and a correcting plate to eliminate aberrations. The telescope can have very low focal ratios, and wide angular field, permitting high-resolution photography of large parts of the sky at one time. Because of the low focal ratio, images are bright. Hence, a Schmidt telescope is ideal for locating faint objects.

Spinel -- An oxide mineral group, usually containing iron, chromium, and titanium.

SR&T -- Supporting research and technology.

Synodic period -- For a planet, comet, or asteroid, the interval AS SEEN FROM THE EARTH'S CENTER between successive oppositions or conjunctions with the Sun.

Syzygy -- (Conjunction) Two objects are in conjunction when their celestial longitudes are the same. Celestial longitude is referred to the center of the Earth and the ecliptic plane. For some objects, the equality is in right ascension, which is referred to the center of the Earth and the equator of the Earth.

Tailings -- In mining, the discarded residue after extraction of the concentrate.

Troctolite -- A mafic rock containing plagioclase, olivine, and little or no pyroxene.

Trojan points -- Two of the Lagrangian points. If the two large bodies are at two vertices of an equilateral triangle, the Trojan point is at the third vertex.

Trojans -- Asteroids located at the Trojan points of Jupiter.

Tridymite -- SiO_2, a polymorph of quartz.

Volcanic -- Pertaining to the phenomena of volcanic eruption, including the emission of lava, pyroclastic material (explosion debris), or volcanic gases at the Earth's surface. To be contrasted with plutonic activity, which is magmatic activity beneath the surface of the Earth.

Waste -- Rock or mineral mass that must be removed and discarded to mine ore.

XRF -- X-ray fluorescence, a chemical analysis technique.

APPENDIX C
THE VALUE OF THE MOON AS A PLACE

One important subject excluded from the discussions of this workshop (because it calls for a different set of skills) was the use of the Moon for human activities other than those directly based on lunar resources. It seems worthwhile to set down here, for completeness, some of the better known possibilities.

1. Radio astronomy. The far side of the Moon is shielded from manmade radio emissions, which blanket most of the accessible spectrum. It has been discussed many times as a location for a major radio astronomical observatory. Location near the limb (or pole) could provide direct communication to the Earth.

The same station might also be valuable for very-long-baseline interferometry in conjuction with terrestrial observatories, extending the available baseline more than 20 times. This might make possible dramatic improvement in the resolution of sources.

2. Optical astronomy. Although currently planned space telescopes are to be in free space, some astronomers find the stability of the lunar platform an attractive alternative. A location near the South Pole has been suggested as providing 24-hour coverage (at a permanently shadowed point) in full sky darkness of the more interesting half of the sky. A permanently sunlit point nearby could provide a continous monitor for solar astronomy.

3. X-ray and gamma-ray astronomy. The Earth-Moon distance provides a delay of more than 1 second for the transit of pulsed electromagnetic radiation. The direction of X-ray and gamma-ray bursts can be determined with the help of timing information of this sort.

4. Plasma and magnetospheric studies. The Moon is normally outside the earth's magnetosphere; hence it is a station for observing the solar environment at 1 AU. At the same time, it crosses the boundary region and moves into the Earth's magneto-tail for a period of about 4 days each month.

5. Measurements of distance and time. The laser corner reflectors on the moon have improved knowledge of the Earth-Moon distance and of the relation of astronomical to atomic time. The distances between points on Earth can be measured with great accuracy in the same way.

When human activity on the Moon is resumed, projects in such areas can provide additional justification.

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16. Abstract

This preliminary report addresses possible large-scale use of extraterrestrial resources, either to construct structures in space or to return to Earth as supplements for terrestrial resources. To that end, various specific recommendations are made by the participants in the summer study on near-Earth resources, held at La Jolla, California, August 6 to 13, 1977. The Moon and Earth-approaching asteroids are considered. Summaries are included of what is known about their compositions and what needs to be learned, along with recommendations for missions designed to provide the needed data. Tentative schedules for these projects are also offered.

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