"Defense Applications of Near-Earth Resources"

Workshop held at the University of California, San Diego
Scripps Institution of Oceanography
Hosted by the California Space Institute
Sponsored by the Institute for Defense Analyses
15-17 August 1983

S. Nozette (Editor)
Workshop organizer

Cal Space Ref. No. CSI83-3

August 1983

revised
31 October 1983

Accession Number: 5368

Publication Date: Sep 01, 1983

Title: "Defense Applications of Near-Earth Resources"

Personal Author: Nozette, S. (Editor)

Corporate Author Or Publisher: California Space Institute, La Jolla, CA 92093 Report Number: Cal Space Ref.No. CSI83-3

Report Prepared for: IDA, P.O.Box 12588, Arlington, VA 22209

Comments on Document: Workshop held at the University of California, San Diego, CA

Descriptors, Keywords: Defense Application Near Earth Resource Workshop California

Pages: 00045

Cataloged Date: May 16, 1995

Document Type: HC

Number of Copies In Library: 000001

Record ID: 29997

"Defense Applications of Near-Earth Resources"

Workshop held at the University of California, San Diego
Scripps Institution of Oceanography
Hosted by the California Space Institute
Sponsored by the Institute for Defense Analyses
15-17 August 1983

S. Nozette (Editor)
Workshop organizer

Cal Space Ref. No. CSI83-3

August 1983

revised
31 October 1983

UNIVERSITY OF CALIFORNIA, SAN DIEGO

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO | SANTA BARBARA • SANTA CRUZ

CALIFORNIA SPACE INSTITUTE | LA JOLLA, CALIFORNIA 92093

August 18, 1983

Dr. James Fletcher
Institute for Defense Analyses
P.O. Box 12588
Arlington, VA 22209-8588

Dear Dr. Fletcher:

In response to your request we enclose a draft report entitled "Defense Applications of Near Earth Resources", containing deliberations conducted at a workshop held at the California Space Institute, La Jolla, Ca., Aug. 15-17 1983. This letter serves as a summary of the task groups' findings.

Our report rests on the following facts and assumptions: First, extensive space research has shown that massive and diverse resources exist in near Earth space, both on the Moon and near Earth asteroids. Second, the demand for material in the necessary Earth orbits must be large in order to justify examining the feasibility of developing these near Earth resources. We define large as a significant fraction of present or future US lift capacity. Space resources may also serve as a backup source of materials. Third, the systems developed to utilize these resources must have a favorable range and rate of mass return, i.e., the mass of launched systems and delivered mass must exceed mass delivered by Earth launched systems, by a large factor (5-10), and in a reasonable time, to be justified in terms of development uncertainty and expense. Fourth, where possible systems should be designed to enable growth of capabilities, both in mass delivered and new options made available. In response, the task force agreed on the following conclusions and recommendations.

First, if the nation is serious about deploying extensive space based defensive technology systems in the context of a national imperative, than it is reasonable to examine developing near Earth resources to protect these systems. The material needs described are indeed large (10^4-10^5 tons). Second, the scientific and technological state of the art is sufficiently advanced to warrant a research and development program designed to obtain the answers necessary to determine the technical and economic feasibility of using near Earth resources to protect space assets. The detailed program we forsee contains three parallel, synergistic, paths: Material obtained from Earth via upgraded launch capabilities, material obtained from the Moon, and material obtained from near Earth asteroids. Elements of these endeavors are currently under way at NASA, but in an unfocused and low priority vein. These include space depot and orbital transfer vehicle development, advanced propulsion and power system development, aerobraking, small scale materials processing studies, and lunar and asteroidal exploration. Third, while current information suggests that the development of near Earth resources can offer significant economic advantages over Earth launched systems, the group is presently unable to project total cost of a near Earth resource development program. However, the recommended research and development program will provide substantial information and allow reliable cost estimates. We estimate initial costs of ground based materials processing studies at $1-10 million, and enabling technology development, including precursor missions $1-2 B. It is expected that much current NASA research and development may be related to the program (space station, OTV). While total cost projections are unavailable, we can confidently suggest that the the total cost of near Earth resource development will be comparable to or less than previous national space programs (Space Shuttle and Apollo).

Serious consideration must be given to the organizational and administrative aspects of the program. The scope of any potential program to develop near Earth resources will cross institutional roles and missions of DOD, NASA and other government agencies, and involves substantial participation of the private sector and the universities. We therefore recommend the creation of a new organization designed specifically to implement this program, with a single manager responsible for the program content, resources, budget, manpower, and placed at a sufficiently high level to assure access to key administration and congressional decision makers.

Finally, the long range national and international strategic and economic impact of near Earth resource development must not be lost in evaluating relative merits of the alternatives in implementing the defensive technology program. The implications extend far beyond providing material to shield space assets. We see the research program recommended as having value in any case. The time it will require can be used to advantage in carefully deliberating on the policy issues before action.

Sincerely,

James R. Arnold
Director
California Space Institute

Stewart Nozette
Taskgroup Leader
California Space Institute

Enclosures
SDN/sh

TABLE OF CONTENTS

I. Introduction and Recommendations

Following is the statement of work between the California Space Institute of the University of California and the Department of Defense.

WORKSHOP ON MILITARY APPLICATIONS OF NEAR-EARTH RESOURCES

The California Space Institute will conduct a three-day workshop-conference at the Scripps Institution of Oceanography campus (University of California at San Diego) to explore the possibilities of using materials of the moon and near Earth asteroids for defense purposes. The workshop will encompass 30 participants and the deliberations will form the body of a report to the Fletcher Committee. The deliberations and report will be unclassified. The workshop will be held 15-17 August; with 18 and 19 August for assembly of the contributions. The report will be due in Dr. Fletcher's office 12 September 1983.

The workshop and other activities were completed on schedule. This document covers the proceedings and consensus.

Participants at the workshop included planetary scientists active in lunar and asteroidal research as well as members of the aerospace community involved in Department of Defense programs to develop advanced systems for the defense of the United States from space. The participants are listed in the Appendix. The largest subpanel of the workshop concentrated on examining the defense applications of various types of lunar and asteroidal materials.

The panel recognized that the suggested applications and sources of resources available will lead the defense establishment into new realms. This is necessary and consistent with the new policy directives of the President. Table I (p.11) presents a matrix which summarizes the potential applications of materials from the moon and near Earth asteroids. Detailed comments concerning the various matrix entries are located in Section II.

Useful resources of the moon became known through the Apollo program. Our program of planetary research over the past 20 years leads us to know that major materials resources also exist close to the vicinity of Earth orbit in the form of tens of thousands of small asteroids. We review our knowledge of the moon and asteroids in Sections III and IV and recommend how to quickly acquire the technology and knowledge necessary to utilize these resources.

Accessing, exploring and developing the presently unknown resources of the moon and asteroids will expand the presence of the United States from the seas, surfaces and air of Earth past the limits of cis-lunar space. We outline in Section IV several ways that expansion of our resources and operational realm to the moon and near Earth asteroids may create fundamentally new opportunities. We can obtain greater secure access space from the Earth in addition to strengthening the ability to meet existing needs. We can obtain growing sources of energy and means of power distribution. Activities off Earth can provide us with a considerably broader perspective of our technological capabilities for influencing the peoples of Earth. Our programs of lunar and planetary research can be quickly expanded to discover, assay and utilize these presently undeveloped but very real resources.

Recommendations are given in the technical sections for projects to be started immediately. We provide a summary of these recommendations to close this section.

- Material Identification and Location

One consequence of the Apollo program is our knowledge of many of the physical and chemical properties of the material that exists at the Apollo landing sites. To date, however, there has been no comprehensive resource assay of the entire Moon. The group recommends that a lunar polar orbiter mission be implemented as a high priority endeavor. With respect to the near Earth asteroids, we know little as yet about the chemical and physical properties of known targets; and in fact the most promising targets very likely have not, as yet, been detected. It is recommended that the current search program be accelerated coupled with expanded IR spectroscopy for initial chemical and physical characterization of newly discovered bodies. It is recommended that NASA commit to the initiation of a near Earth asteroid rendezvous program as a high priority endeavor.

- Material Extraction and Delivery

The elements required to effect local transport in Earth-Moon space must also be assessed, since it can be assumed that the processing and assembling of the shielding material will be conducted in Earth orbit. Transporting asteroidal or lunar material to facilities in Earth orbit will probably require a space-based orbital transfer vehicle equipped with an aerobraking device. The aerobrake is crucial for effecting efficient plane change maneuvers and accessing assets in high altitude orbits. It is recommended that NASA conduct an intensive technology program leading towards the early availability of a space-based orbital transfer vehicle using aerobraking. The feasibility of extracting and using lunar material can be assessed by conducting an intensive study of the development of a lunar base. For the purposes of this study the focus of the lunar base would be the mining and delivery of lunar material to a processing center. This study would involve an assessment as to all of the elements, including new transportation and power elements, that would be needed to develop and support a lunar base. The study would, of course, also include the delineation of the extraction and processing techniques that will convert raw lunar material to usable ductile metallic shielding and propellant at the operation site. It is recommended that this study be conducted immediately under the auspices of NASA and the Department of Defense (DoD).

The extraction and delivery of material from near-Earth asteroids necessitates the development of new transportation elements. Transport options for materials delivered from asteroids needs careful analysis and examination. Technology development must proceed in several promising areas.

In parallel with this technology effort, an analytical program should conducted to define optimum transport systems and trajectories to effect the maximum delivery of asteroid material to low Earth orbit.

We must understand all stages of processing from raw lunar or asteroidal material to finished protective shielding and other useful products better than we do now. A small, high-priority program of ground based studies needs to be carried out, leading to engineering development and orbital tests.

- Flight Experiments

The shuttle, and subsequently a space station, can be effectively used to overcome two major technical obstacles involved in the processing of extra-terrestrial materials and the assembly of the metal shields. This activity involves defining the separate roles of men and robotics. It is recommended that NASA and DoD immediately initiate a program to increase man's efficiency in space, including the most effective use of automation and robotics.

- Immediate Action

A working group should be formed immediately which is cognizant of United States defense needs, with emphasis on space tasks, which can explore the possibilities of growing access to resources of the moon and near Earth asteroids to meet appropriate portions of those requirements. The working group should be able to consider classified needs and have access to classified resources. Membership should include representatives from Department of Defense, Department of Energy and the national laboratories supported by DOE, the National Aeronautics and Space Administration, members of the lunar and asteroidal research community who are knowledgeable of basic research and resources potentials of the moon and asteroids, and members of the private sector who possess appropriate skills. If these resources and capabilities can be developed there will be major political, strategic, legal and economic implications. Therefore, representatives of these aspects of national life should participate as appropriate.

Summary

Implementation of this suggested program will yield needed data on the technical and economic feasibility of using lunar and asteroidal material for military processing to protect critical space assets. Elements of these endeavors are currently underway at NASA, but in an unfocused and low priority vein. It is recommended that this program be structured in a focused manner with the involvement of the Department of Defense, the Department of Energy, and NASA. The Earth based portion of this program can be completed in the 4 to 5 year time frame, and provide crucial insight into one aspect of the ballistic missile defense endeavor. A budget of 20 million dollars is recommended for the first 4 to 5 years.

The following sections provide more discussion of the five panels of the workshop. More detailed recommendations are contained therein. The working group concluded that resources off Earth will contribute directly to a space based defense system for the free world.

II. Potential Defense Applications of Near-Earth Resources

Introduction

The shift to a Defensive Technologies Program will involve the use of ground and space-based platforms in considerably larger numbers than have been projected in previous planning. Traditionally, space-based assets have remained light-weight and fragile in order to minimize launch costs. Should launch costs remain high, defensive systems of the future would be severely hindered by the economics of getting mass into orbit. On the other hand, if a relatively inexpensive (500-1000 dollars per kilogram) supply of construction materials became available high above the surface of Earth, defensive systems would likely be designed very differently, with greater capabilities and greater survivability.

Advocates of extensive space-based defensive systems have devised a wide range of conceptual designs for advanced space and ground surveillance systems; for families of advanced transportation vehicles (both manned and unmanned); for ballistic missile and satellite interceptors relying on a variety of different kill mechanisms; for advanced command, control, and communications modes and networks; and for logistical support, maintenance, operations, and reconstitution of space assets. Many of these concepts have been under consideration by the Fletcher Panels in recent months.

During the last decade, a substantial body of knowledge, informed speculation, and preliminary conceptual designs have emerged relating to civilian applications of near-Earth resources, both in space and for return to the Earth. On the largest scale, these concepts have involved the construction of large Solar Power Satellites (SPS)--massing about 100,000 metric tons each--and space settlements (colonies)--massing 30,000 to 1,000,000 metric tons each--for thousands of construction workers. (Glaser 1977; O'Neill 1975 and NASA 1979). NASA funded a set of stuides in the late 1970s exploring construction of solar power satellites from lunar materials (Bock 1979; Miller, 1979; Criswell 1978, 1979).

The August 1983 Cal Space workshop represents the first attempt to apply this body of expertise to defensive military applications in a systematic fashion.

While detailed chemical and mineralogical characterizations are available for a very restricted sampling of lunar regoliths and rocks, and for a substantial body of meteorite specimens, (whose correlations to near-Earth asteroids are presently unclear), we have no detailed engineering specifications for defensive space systems to be deployed more than five years in the future. In attempting to match near-Earth resources to potential defense applications, we were thus forced to consider the equipment and material supplies required in generic terms which would be relevant to any of the advanced defense concepts. Given such generic descriptions of the equipment and materials required by the defense systems, it would be inappropriate to attempt matching specific minerals or, in most cases, chemical elements to generic military requirements. We have lumped the types of resources available into a number of classes which can be characterized by the physical and chemical processes used to obtain them in useful forms.

A. Defense Applications

It has often been useful to analyze military systems for possible application to three primary mission areas: (1) force delivery--whether involving offensive or defensive weapons; (2) C^3I--command, control, communications, and intelligence; and (3) support services. In Earth-based military systems a complete civilian economic infrastructure is in place to provide manpower, raw materials, supplies, equipment; and services to the military. For the foreseeable future, such an economic infrastructure in space itself will be fragmentary at best, and military support services in space will be burdened by the need to provide extensive support to themselves as well. The distinctions between the three primary mission areas will thus be blurred, at least in the early stages of space-based defensive systems.

With this background in mind, we identified 12 high level categories of systems components which could be created in varying degrees from available near-Earth resources. These categories may not be exhaustive and in some cases may overlap. The order given does not reflect any systematic priority.

1. Shielding. Given an economic supply of suitable materials available on-orbit, defensive armor (shielding) could provide significant enhancement of the survivability of military spacecraft. Such armor could be useful against at least four types of threats: kinetic energy impactors, particle beam weapons, thermal radiating weapons, and nuclear warhead effects.

To provide armor against these threats, sufficient mass per unit area is required. Also, some materials are more effective than others. Among the common metals available in near-Earth bodies, aluminum would be very effective, and iron would have a figure-of-merit perhaps 80% as good as aluminum. A total shield thickness of 100 gm/cm^2 will provide a useful level of protection, corresponding to a cumulative thickness of 12.7 cm of iron or 36 cm of aluminum. Small amounts of other materials which could be brought from the surface of the Earth may be incorporated for optimal shield performance.

In defense against kinetic energy weapons, dividing up the armor into multiple layers can improve preformance of the armor. The outer plates are perforated by projectiles impacting at high velocity, but a portion of the projectile is broken into small fragments at each successive plate. The best material for the outer plates would be dense and hard, so iron is somewhat preferable to aluminum. Once the projectile has been reduced to fragments, the momentum in these fragments--most of the momentum of the original projectile--must be absorbed. An effective way to perform this absorption is by extensive plastic deformation of the inner plates, much as a trampoline. The plate material must be very ductile to accept a large amount of strain work without fracture, especially since the deformations occur at a very high rate of strain. Only a small set of known iron and aluminum alloys--including the pure elements--are sufficiently ductile for this application.

Plate thicknesses useful for armor against threat projectiles impacting at presently foreseen velocities are 9mm for iron and 25mm for aluminum. The lateral extent of the shields depend on characteristic cross-sectional areas of the spacecraft to be shielded; 20 square meters is a useful bench mark. Such a shield would have a mass of 400 metric tons. One hundred shields would thus require some 40,000 metric tons of fabricated materials, deployed in

Earth orbits at altitudes ranging from 1000 km to three times geosynchronous altitude.

Shielding designed to protect against particle beam weapons or against radiation effects of nuclear warheads would likely be designed differently. Typically, elements with high atomic numbers would be most desirable for charged particles, and for gamma and x-radiation. Shields would most likely surround the most sensitive components or subsystems, rather than an entire spacecraft. For protection against induced currents (electromagnetic pulse radiation, or EMP) delicate electronics will have to be shielded within conducting shells. Even during peactime protection will be a major consideration. For manned stations, shielding will be necessary during large solar flares, as well as against hostile radiation threats. Total shield masses in each of these applications may range from a few tons to a few tens of tons per satellite thus equipped.

Large masses of water, graphite, or other materials with low atomic numbers could provide shielding against large neutron fluxes, and may play an important role if large nuclear power reactors are used to provide power aboard defensive system spacecraft, especially if these reactors are to be serviced or visited by humans. Water stored for life support and fuel cycle on a space station might be arranged to serve this function as well. This type of shielding would also provide some measure of protection against large nuetron fluxes from nuclear warheads. Shielding for reactors may have masses ranging from tens to hundreds of metric tons per spacecraft.

2. Propellants, Reaction Mass, and Other Consumables. While the Space Shuttle can deliver sizable payloads to low Earth orbit (LEO), our presently projected capabilities for delivery of large payloads (significantly larger than two metric tons, say) to high orbits are severely limited. In large part, this difficulty arises from the necessity of providing, in LEO, for boost to higher orbits, quantities of propellants roughly one-to-three-times the mass of the payload. Several studies (Davis 1983; Bock 1979) have shown major improvements in the effectiveness of transportation systems once lunar oxygen delivered to LEO becomes available. The mass flow rates required for economical operation of a system to extract oxygen from lunar soil and to deliver it to LEO in cryogenic form (LOX) appear to be considerably smaller than those required for extraction and delivery of construction materials.

More advanced rocket engines using LOX and a variety of metals available in lunar soil have also been considered, as have engines using LOX and silanes (silicon analogues of hydrocarbon chains). These possibilities obviously involve greater technical risk than currently used LOX/liquid hydrogen engines, but may offer potential benefits.

3. Structures. Considerable attention has been given in previous studies of large-scale civilian applications of near-Earth resources (see, e.g., Bock 1979; Miller 1979) to the use of such materials for basic structural components (beams, plates, wires, tanks, etc.). Many of these results will be directly applicable to space-based defensive systems as well, although in the early stages, fabrication of structural components is more likely to be a by-product of armor fabrication.

4. Projectiles. A number of concepts for space-based defensive systems rely on kinetic energy kill mechanisms using large numbers of small, simple projectiles ("bullets" and flechettes). It may be feasible to manufacture these as a by-product of the facilities used for fabrication of armor.

5. Targets and Decoys. To maintain operational readiness of any military system--especially systems as sophisticated as those under consideration for strategic defense--periodic readiness and training exercises must be carried out under simulated battle conditions with a high level of verisimilitude. Thus significant quantities of expendable targets must be provided. It may prove advantageous to fabricate such targets in space as a by-product of other production facilities using near-Earth resources. As the enemy's capabilities to counter or to mount direct assaults against our space-based defensive systems increases in the future, decoys are likely to play some role in sustaining the survivability of these systems. Such decoys, too, may turn out to be readily manufacturable from nonterrestrial materials.

6. Stabilizing Inertia. Given access to near-Earth resources at reasonable cost, large masses could be assembled in Earth orbit to provide one or more stable platforms on which to mount space-based defensive systems. Such platforms could be assembled years before the operational hardware were ready for installation, and could be made of large chunks of an asteroid or from "bricks" of metal or physically compacted but chemically unaltered asteroidal or lunar materials. Large masses of this type would passively assist any of the defensive systems presently contemplated by simplifying optical alignment; by providing inertia to resist platform motion due to pointing and tracking; and by providing a large, visible presence early in the development cycle. Note that for this application a sizable chunk of any reasonably accessible asteroid will suffice, since inertia can be provided regardless of chemical and mineralogical characteristics of the material.

For spacecraft operating at lower altitudes, addition of dumb mass could also be used to improve the ballistic coefficient of the spacecraft, reducing the effects of atmospheric drag and increasing the intervals between visits to resupply station-keeping propellants.

7. Heat Sinks (Thermal Inertia). A number of defensive systems under consideration require very high peak rates of power expenditure for fairly short periods under battle conditions. If near-Earth resources are available at reasonable cost, then the option of accomodating high flux rates of waste heat by the use of large heat sinks should be included in engineering tradeoffs. The heat conductivity and heat capacity of metals and of some of the volatiles (including water) which are available in asteroids or on the Moon may be adequate for this purpose.

8. Energy Storage. For systems requiring high peak rates of power consumption, one design option is to combine energy storage systems with a primary energy source which produces power continuously at a modest rate. For defensive systems, total energy requirements of some of the candidate systems are very large, implying huge masses for energy storage devices. Given a supply of nonterrestrial materials, such huge masses may no longer prohibit considering large energy storage systems in the engineering trade-offs. Fused silica flywheels and capacitor banks are capable of dumping large quantities of stored energy very rapidly. Water extracted from asteroidal materials can

be split into hydrogen and oxygen by electrolysis to provide storable fuel for fuel cells, although these could not provide such rapid power surges.

9. Energy Production and Distribution. The most ambitious and technically demanding proposal for the use of near- Earth resources for energy production and distribution thus far examined is to build Solar Power Satellites in geosynchronous orbit from raw materials mined on the Moon. Some of the concepts developed in previous studies of this proposal may be applicable to space-based strategic defensive systems, but considerable adaptation would be required.

An apparently less demanding proposal which deserves study is the concept of placing large solar energy collectors directly on the lunar surface, using primarily lunar resources in construction of the system. Power could then be beamed to both civilian and defensive systems throughout cis-lunar space. This concept is discussed in more detail in Section IV.B.

10. Strategic Materials. Strategic materials are those which are considered critical to the standard functioning of the industrial base of the United States. The U.S. Army War College has tabulated a list of industrial materials which are not found in usable quantities in the continental U.S. due to the vagaries of the geochemical evolution of the Earth's crust, or are not economically extractable under present economic and technologically conditions from ores located in the continental U.S. A serendipitous by-product of economic access to near-Earth resources either for civilian applications or in direct support of space-based defensive systems may be practical access to a new supply of some of the items on the War College's list which have the highest values of "Vulnerability Index."

If we consider Canada to be a secure source of certain strategic materials, then the platinum group of metals, chromium, and manganese are the most critical materials. These elements appear to be available in extraterrestrial objects. All common classes of meteorites contain the platinum group metals in concentrations higher than those of commercially mined ores on Earth. If the meteorites are representative of near-Earth asteroids, then a rich source of these strategic metals may become readily accessible as a by-product of armoring defensive systems. Similarly, both chromium and manganese have been found in beneficiated samples of lunar soils.

11. Lunar Base/Platform. Some more ambitious scenarios have been sketched out for use of the Moon itself or one or more large chunks of asteroid in high Earth orbits (including the libration points L4 and L5) as bases or platforms for defensive systems. Some of the concepts which have surfaced thus far include very high resolution surveillance and tracking sensors; secure storage of spare spacecraft for rapid reconstitution; and large solar energy farms capable of delivering power where-ever needed in cis-lunar space. (This last concept is discussed in somewhat more detail in Section IV.B .) This entire area has received very little consideration to date, and has not been studied systematically.

12. Zero-G/High Vacuum/Space Manufacturing. Extensive study has been devoted to space manufacturing, but primarily from a civilian perspective or from the perspective of supplying very high performance materials or parts to the military services on the ground. In the long run, if space-based

defensive systems expand to a high level of strategic significance, more and more of the hardware used in space can be expected to be manufactured in space with all the sophistication expected in the civilian analyses and projections to date. However, it seems reasonable clear that this side of the utilization of near-Earth resources for defensive technologies will be a result, not a driver, of the exploitation of those resources.

B. Categories of Resources

From the above discussion, it is clear that the resources available in near-Earth space can be discussed in rather generic terms at this level of analysis, without distinctions between meteorite classes or between lunar highland and maria regoliths. We found it useful to examine the potential applications of nonterrestrial resources to defensive systems in space in terms of ten categories of resources:

1. Celestial Bodies. This includes the Moon itself and large chunks of asteroid moved into Earth orbit but otherwise unprocessed.

2. Sunlight. This resource is easily overlooked, but has been used since very early in the Space Age by most satellites and probes yet launched. Solar power could fulfill all foreseeable non-acute needs.

3. Unprocessed Non-Terrestrial Materials (NTM). Convenient quantities of raw materials which are useful merely by virtue of being repositioned in space.

4. "Bricks." Nonterrestrial materials which have been physically altered but have not been chemically processed. Compaction, sintering, melting and casting, or simple cutting can produce suitably sized and shaped pieces with convenient mechanical properties.

5. Metals. These may require chemical processing, but in some cases (such as small iron grains found in the lunar soil) these can be separated by electrostatic or electromagnetic techniques.

6. Ceramics and Glasses. These materials are based on the chemically most abundant constituents of lunar soils, and are expected to be quite abundant in most classes of asteroid materials as well. Processing and fabrication can make extensive use of solar furnace technologies.

7. Oxygen. Elementally the most abundant element in lunar soils and rocks, oxygen is a major product of most chemical extraction processes to be used on lunar and asteroidal materials.

8. Silicon. Also very abundant in all lunar soils and in most classes of asteroids, silicon and its numerous compounds will be put to numerous uses in the long run.

9. Volatiles. This includes water of crystallization in asteroidal minerals, hydrogen, nitrogen, carbon, and any other gases which may be found in the permanently frozen polar regions of the Moon.

10. Slag. Whatever residues remain after chemical processing of lunar or asteroidal feedstocks.

C. Results

Matches between generic resources available in near- Earth space and components or materials needed to support defensive military systems are summarized in matrix Table 1 on the following page. Note that no distinction has been made in the matrix between lunar and asteroidal materials; although it is presently believed that the platinum-group metals and the volatiles are much more abundant in certain classes of asteroids than on the Moon.

From an operational military viewpoint, one additional distinction should be highlighted between obtaining resources for military purposes from the Moon and obtaining them from the asteroids. In the event of unforeseen contingencies requiring large changes in the rate of flow of mass from nonterrestrial sources, the short travel time to and from the Moon (on the order of a week) would allow a lunar-based system to respond to major new requirements in a period of days to months rather than years.

Conclusions. It appears that armour (shielding) and stabilizing inertia will require, in the aggregate, the largest quantities of mass and are thus the most likely drivers, from a military point of view, for development of the capability to acquire near-Earth resources for use in Earth orbit. The deployment and operation of space-based defensive systems on a large scale will require an enormous expansion of transportation capacity above LEO. Providing propellants for that transportation system from lunar soils may provide sufficiently high leverage to justify the acquisition of lunar resources even if the total mass required is less than that required for shielding and for stabilizing inertia. A number of further potential applications of nonterrestrial materials for defensive military purposes have been identified in this workshop, and also deserve further assessment.

Recommendations. The opportunities for the use of near-Earth resources to support space-based defensive systems deserve serious and sympathetic study. A preliminary engineering assessment of the feasibility of using nonterrestrial materials for the purposes identified in this discussion could be carried out in one to two years with a team of ten or twenty engineers and physicists with suitable backgrounds. Such a study would not examine the problems of acquiring the materials, but would consider only the utility of such materials if they could be provided. Where necessary, trade-offs could be made parametrically, assuming a range of cost for the specified nonterrestrial materials. Such a study could be undertaken immediately at a cost of 1-3 million dollars, and should be updated periodically as new concepts in defensive systems emerge.

TABLE I

POTENTIAL DEFENSE APPLICATIONS OF LUNAR AND NEA

RESOURCES / APPLICATIONS	MOON AND ASTEROIDS	SUNLIGHT	UNPROCESSED MATERIALS	BRICKS	METALS	CERAMICS	OXYGEN	SILICON	VOLATILES	SLAG
SHIELDING			X	X	(X) [1]					X
REACTION MASS, PROPELLANTS, AND OTHER CONSUMABLES					X [2]		(X) (dotted) [3]	X [2]	X	
STRUCTURES				X	X	?				
PROJECTILES				X	X	?				
TARGETS & DECOYS		←--------	--------	--------	ALL --------	--------	--------	--------	--------	--------→
STABILIZING INERTIA			(X) [1]	X						X
HEAT SINKS					X				X	
ENERGY STORAGE					X	X	X	X	X	
ENERGY PRODUCTION AND DISTRIBUTION	X [4]	X						X		
STRATEGIC MATERIALS		X [6]			X [5]					
LUNAR/BASE PLATFORM	X	X [6]								
SPACE MANUFACTURING		←--------	--------	--------	ALL --------	--------	--------	--------	--------→	

[1]These tw
needed)

[2]Reaction
propulsi

[3]Lunar ox
from NTM

[4]Solar ar
source f

[5]Independ
standard

[6]General
large sc

KEY:

X – Pc

(X) – Mc

(X) (dotted) – Ve

? – Pc
of

NOTES

[1]These two applications are most likely (in terms of total tonnages needed) to drive NTMs for defense applications .

[2]Reaction mass could be dust; propellants could be liquid oxygen; more advanced propulsion systems (e.g., aluminun/oxygen or silane/oxygen rockets).

[3]Lunar oxygen returned to LEO may provide an early high-leverage return from NTMs.

[4]Solar arrays constructed on the lunar surface may provide a viable power source for high power military systems in cis-lunar space.

[5]Independent source of these materials may be sufficiently important that standard cost/benefit considerations may not apply.

[6]General proposal available from systems Development Corp. on one type of large scale lunar power system (ref. 2).

KEY:

X - Potential match of resource to military applications deserving study

(X) - Most likely drivers.

(X) - Very likely large mass system.

? - Potential application - utility depends on engineering details of military requirements.

III. Current State of Knowledge Regarding Near-Earth Resources

A. The Moon

Extensive sampling of lunar materials was conducted at the six Apollo landing sites. Examination of these samples and the associated geophysical data has provided both detailed knowledge of the surface materials at these sites and a basis to extrapolate orbital observations of other regions. The plagioclase-rich rocks of the lunar surface contain up to 18% by weight aluminum, up to 20% silicon, and up to 46% oxygen, and can be mined readily for all three. In fact, it is very unlikely that a better source for aluminum will be found in near-Earth space. Such rock (anorthosite) is used terrestrially in Norway for commercial production of aluminum. Soil such as that sampled near North Ray Crater, Apollo 16, with 15% aluminum, would be an easy feedstock to use. The terrestrial commercial process involves extraction of aluminum oxide from the ore into hot sodium hydroxide solution, precipitation of the oxide, mixing of the oxide with cryolite (Na3AlFe6), and finally, electrolysis. This process is not obviously adaptable to lunar surface or orbiting smelter use. However Jarrett et al. (1980) have proposed a scheme for direct electrolysis of raw soils using electrowinning of aluminum-silicon-iron-titanium alloy in a bipolar fluoride-type cell with inert electrodes. The fluoride process of Waldron et al. (1979) is a way of approaching the smelting of lunar anorthosite for aluminum.

Iron is present in metallic form, mostly as iron-nickel alloy, in concentrations of a few tenths of one percent in all lunar soils. This iron is easily extracted in the laboratory with an ordinary hand magnet (Shrelldalff, 1970; Goldstein and Axon, 1972). The upgraded material also contains glassy breccia fragments (agglutinates) which have incorporated metallic iron. This would have to be separated out before the iron could be used as such. Romig and Goldstein (1976) and Criswell (1982) have discussed how the terrestrial technology of powder metallurgy could be applied to free and refined lunar iron and other metals to produce products and growing manufacturing systems.

Also, lavas from the maria are rich in chemically combined iron, up to 17%. Preliminary experiments of Lindstrom and Haskin (1979) indicate that iron can be separated from material of lunar lava composition by electrolysis of molten lava. Presumably solar energy for this can be readily obtained. The fluoride scheme of Waldron et al. (1979) also yields iron.

Titanium is present in some lunar lavas in concentrations as high as 7.8%. Dense titanium minerals from lavas or related materials may have accumulated into even richer ores. Williams and Agosto (1983-personal communication) have shown that electrostatic separation can be used to upgrade the titanium mineral ilmenite from mixtures with plagioclase, in air. This technique may be adapted for use on mare soils. (Use of soils rather than rocks for many schemes eliminates the need for crushing and grinding.) Inculet (1979) has examined the general application of electrostatic separation techniques to lunar soil fractions and concludes there are strong reasons to anticipate success of industrial scale operations in the vacuum conditions of the moon. Titanium has been separated as an alloy with the cathode by electrolysis (Lindstrom and Haskin, 1979) and by the scheme of Waldron et al. (1979).

Silicon is abundant in all lunar rocks and soils and comprises about 21% by weight of most soils. It can be separated by the fluoride scheme of Waldron et al. (1979) and has been separated as an alloy by electrolysis of molten lunar simulant (Lindstrom and Haskin, 1979).

Oxygen, not available in significant amounts as the free element on the moon, is the major constituent of most lunar materials. It can be released from silicate by several schemes, including direct electrolysis (Kesterke, 1971; Jarrett et al. 1980; Lindstrom and Haskin, 1979), direct heating (Agosto and King, 1983), and by the method of Waldron et al. (1979). Water, which can be electrolyzed to oxygen, can be obtaind by reduction of iron (II) in ilmenite to iron metal using hydrogen (Williams 1983). The hydrogen can be recycled so the net process yields oxygen gas plus iron.

It has been noted by several workers that the first step in the production of the above materials in many cases involves heating of lunar soil. This drives off hydrogen (50 parts per million), nitrogen (100 parts per million), carbon (100 parts per million) (in combination with oxygen or hydrogen), and argon (1 parts per million), useful byproducts or even primary products if their value warranted heating of large amounts of soil to produce them. Also, lunar silicates can be converted to glass and ceramic products (MacKenzie and Claridge, 1979).

The lunar samples we have come from 9 small sites within a very restricted region of the Moon's nearside. Orbiting X-ray and gamma ray experiments sensed only 10% of the farside surface. These experiments yielded concentrations or relative concentrations for silicon, magnesium, and aluminum averaged over regions of 400 or more square kilometers (X-ray) or for thorium, iron, magnesium, potassium, and titanium averaged over regions of 2500 or more square kilometers (gamma ray). Such spatial resolution is too broad for detecting specific ore bodies. Thus, lunar samples provide the only measurements for most chemical elements, and the only data of high spatial resolution for nearly all of them.

Mapping of the rest of the Moon's surface at low spatial resolution with improved X-ray and gamma ray detectors, combined with multispectral scanning and the ability to obtain high resolution spectral images of selected areas, are proposed for the Lunar Geoscience Orbiter. These experiments will be very important to providing a comprehensive overview of the Moon's resources. These experiments could also detect water near the surface in permanently-shadowed floors of polar craters. These techniques would not yield the meter to kilometer survey we are used to on Earth, nor would they be sensitive to a large number of elements or minerals. However, they will enable us to select sites for mining of iron, magnesium, aluminum, titanium, and water if it is present.

A very conservative scenario would be to assume that there are no ores for minor and trace elements, and none for iron, aluminum, titanium, magnesium, silicon, and oxygen that are better than the rocks we have already studied from Apollo returns. Even in this case these elements alone make considerations of the use of lunar materials promising. In addition, significant quantities of carbon, hydrogen (or water), nitrogen, and noble gases could be collected from the lunar soils in which they have been implanted in low concentrations by the solar wind. Rationale and methods for extending our knowledge of lunar materials to obtaining more of these elements have been the subject of two workshops (Arnold and Duke, 1978; Williams and Hubbard, 1981).

Recommendations

Much is already known about the Moon's resources, but much more remains to be discovered. The two main unresolved questions regarding lunar resources at this time are: (1) do there exist concentrations of minerals of economic interest (potential ores) anywhere on the surface? and (2) is ice (along perhaps with other volatiles) present in useful amounts in the polar cold traps? In one form or another, a remote sensing satellite in polar orbit has been proposed many times as the next mission to the Moon, on purely scientific grounds.

Interest in resources may have some effect on the selection of experiments, or on the mission profile, of a Lunar Geoscience Orbiter. We do not expect such effects to be major, because of strong overlap in data requirements with the purely scientific objectives. Both require complete coverage and a polar or near-polar inclination. Extensive data collection in the polar regions is then a consequence of celestial mechanics.

While extensive lunar imaging experiments, of cartographic quality, were carried out in the Lunar Orbiter and Apollo mission series, we call attention to two limitations of potential importance. First, coverage of the polar regions, especially under varied lighting conditions, is sparse. This may limit our ability to target volatile-rich cold sites, if they exist. Second, before any site is approved for a first mining activity, detailed images will be required for site validation. So far we only have imaging at that level for the selected Apollo sites, and for a number of other candidate landing sites of that era.

One measure of necessity of a mapping mission is the extent to which it is possible to plan confidently for missions beyond it, for resource purposes. We will discuss two scenarios, out of several possible, for which the position might be clear.

First, suppose an outcome confirming known resources mentioned so far, but showing no new or unique ones, no interesting concentrations of polar volatiles, and no surprises. This would be unprecedented in planetary exploration, but it is possible. Even if it were so, however, our present knowledge of lunar materials would permit us to establish a mining-extractive operation with confidence at a front-side, low-latitude site. One might well pick an Apollo site providing access to more than one of the major geochemical provinces, in particular Apollo 15 or 17.

On the other hand, we may suppose that attractive quantities of hydrogen-rich volatiles might be discovered at high latitudes. This, along with the presently unknown (but guessable) geochemical constitution of the soils in these regions, might result in the choice of a polar region for the first exploitation site. In such a case, there are both opportunities and challenges.

Based on the military requirements, the principal materials of interest (iron, aluminum, oxygen) are already known to be present. The Lunar Geoscience

Mapper will allow optimization of knowledge regarding the acquisition of these materials, and a secondary recognition of other materials and uses. The details of the Lunar Geoscience Mapper mission must be evaluated in light of the other needs and goals for the program. We would recommend its development as a high priority.

B. The Near Earth Asteroids

There are millions of small, solid bodies orbiting in the solar system, ranging in size from numerous microscopic fragments all the way up to moon-like spheres hundreds of kilometers across. Most of these bodies follow orbits that keep them between the paths of Mars and Jupiter. While these asteroids may someday become valuable resources, this report deals specifically with those families of objects which are more accessible in the near term: the Earth-approaching asteroids.

- An asteroid is said to be Earth-approaching if its distance at perihelion, q, is within 1.3 AU of the sun, thereby admitting the possibility of passing within a few tenths of an AU of Earth. These bodies are divided into three families according to q and semimajor axis, a:

Family	Orbital Characteristics
Aten	$q \leq 1.02$, $a \leq 1.38$
Apollo	$q \leq 1.02$, $a > 1.38$
Amor	$1.02 \leq q$, $a \geq 1.38$

Figure 3 shows the orbits of representatives (the namesakes) of each of these families in relation to Earth and Mars. Members of Aten family follow paths which cross Earth's orbit, but lie entirely inside the orbit of Mars. Apollo objects may cross both planets, while Amors cross only Mars. They are known as the Aten/Apollo/Amor (A/A/A) objects.

Approximately 75 Near Earth Approaching Asteroids (NEA) with determined orbits are presently known. About 20 of these are poorly to moderately physically characterized. (Albedo, some narrow band visible spectrophotometry, some wide band infrared (IR), polarimetry and radar.) These data allow estimates of size, major mineral components, and approximate thermal inertia at surface; it has been verified that some are meteorite-like in mineral assemblage. It appears that some have surface coverings of fine particulate material to 1 cm depth. Others are unfragmented rock. In either case, most surfaces appear to consist of unaltered rocky crystals at the surface. Some near Earth approachers appear to have available free metals.

Approximately 20% of NEA orbits are accessible with $\Delta < 6$ km/s Low Earth Orbit (LEO) (one way). In the best case (so far) $\Delta V = 4.5$ km/s. This is a recently discovered asteroid 1982DB. A return to Earth from such a body, using aero-reentry or capture, is calculated to be typically less than 1 km/s and in some cases less than 100 m/s!.

Estimates of NEA populations based on current rate of discovery, are

Diameter greater than 1 km $N_a = 4{,}000 \pm 2{,}000$

Diameter greater than 100 m $N_b \sim 300{,}000$

For "favorable" orbits $N_a \sim 800 \pm 400$

$$N_b \sim 60,000 \pm 30,000$$

The compositions of asteroids are known only from their reflection spectra, but compositional information on meteorites does appear to be roughly applicable to those near Earth asteroids (NEAs) studied so far. A brief overview of spectral classes and meteorite analogues is therefore in order.

The C (carbonaceous) asteroids can be expected to contain, like their meteoritic spectral analogues, up to 10% water, 6% carbon, several percent sulfur, and useful amounts of nitrogen. The S-type or "strong" asteroids, more common near the inner edge of the main asteroid belt, may contain 10-30% free metal (iron-nickel alloys with high concentrations of precious metals). Metallic (M) asteroids may be nearly pure metal. The following figure summarizes the compositional information relevant to the resource evaluation of meteorites.

These types may be arrayed along a chart showing distinct differences in oxidation/reduction. It is now commonly accepted the C-type objects tend to predominate the farther out one goes in the solar system. These objects are extremely dark, with albedoes less than 0.1 and are therefore harder to detect.

Several classes of data are needed so that mining processes may be designed, optimized, and applied to real asteroids. First, we need to pursue actively the search for near-Earth asteroids. (This search is already underway on a moderate scale with the Spacewatch program at the University of Arizona. The dedicated Spacewatch camera should be in operation later this year.) Second, in many cases we need to know more about the mineralogical hosts of certain valuable trace elements in meteorites. Third, we need to incorporate into space process design the large body of data available on the thermodynamics of unusual meteoritic minerals, especially those that contain valuable elements. Fourth, we need spectral compositional data on every likely candidate NEA. (Dr. Lucy Ann McFadden at the University of Hawaii has done excellent preliminary work in this direction.) Fifth, in order to verify our deductions from spectral reflectivity data and to identify the asteroid spectral classes that have no analogue among known meteorite classes, we will need "ground truth" on the compositions of several of the most prominent spectral classes of asteroids. This can be achieved only by a multiple asteroid rendezvous mission. Sixth, we need advanced propulsion systems appropriate to orbital transfer of spacecraft and materials between near-Earth space and asteroids.

Recommendations

Discovery and characterization from Earth-based observations of a sufficiently large numbe of near-Earth asteroids will be required in order to characterize resources so that objects with favorable orbits and desired composition and physical characteristics are readily accessible (no serious limitation of launch window). This will be a sample of approximately 10 mineralogical classes, 2 physical classes, 10 objects per class. (By "physical" classes we mean that very rigid, individual rocks may be less easy to exploit than those with dusty or rubble surfaces.) Assuming only 20% have favorable orbits, we estimate that 1000 objects must be discovered to fulfill these requirements.

Verification and detailed characterization of target bodies by close range observations is also required. These include mineralogy, elemental composition, physical properties (such as cohesiveness, strength, grain size and fragments), heterogeneity, variation at surface, possible subsurface heterogeneity and subsurface ice. (There are reasons to believe some Apollo asteroids may be extinct comet nuclei, buried under dusty refractory layers.) We estimated the number of objects required to be 3 to 10 (an absolute requirement is 1 if satisfactory resources were verified on first try).

Additionally, samples must be returned for laboratory tests of beneficiation. We also estimate that 3 to 10 objects are needed (absolute requirement is 1 if satisfactory resources were verified on first try).

The recommended Near Earth Asteroids program is as follows:

To complete and support a 10 year Discovery Program Project of "Space Watch Camera" at the University of Arizona. The total cost of this program is approximately $1 million equipment and ($400 K/year).

To support a correlated astronomical observation program to characterize newly discovered objects. Narrow-band spectroscopy is in the range 0.3 - 4 microns and resolution of 0.01 with precision of 1% is required. The requirements are 4 man/years and a 2 meter telescope with $400 K/year. Additional work in infrared radiometry requiring 2 man/year, a 2 meter telescope and $150 K/year is recommended along with radar and polarimetry requiring 2 man/year for a favorable target, and $200 K/year.

Close investigation by spacecraft is a necessary next step. Rendezvous observations: x-ray, γ-ray, reflection spectrometry, imaging (high resolution), combined with in-situ measurements of acoustic tomography, and soil mechanics, are a needed step. The spacecraft must "land" on the body and perform imaging with a variable focus, mirror-equipped camera capable of performing spectrometry for determination of mineralogical composition. In order to fully access the resource potential of the body the return of samples to Earth from multiple, intelligently chosen sites is deemed necessary.

Finally, further conceptual work must continue concerning possible more advanced missions, including sample returns and, eventually, return to Earth orbit of usable, transformable resources.

IV. Development of Near-Earth Resources: Enabling Technologies

Introduction

Providing very large tonnages of selected materials economically to a wide range of orbits about Earth may likely require obtaining most of the materials from the moon and the asteroids. Basic considerations of energy, power, the scale of systems to supply hundreds to many thousands of tons of matter or more appears to support this view. Several approaches have been suggested for supplying materials from the moon and asteroids. We point out that the development of systems to supply large tonnages of matter, and even limited products, will almost certainly revolutionize United States capability to travel into and prosper in cis-lunar space and beyond. Most of our perceived ground rules for accessing and using space will be fundamentally changed.

The following points were brought up by workshop participants:

- The Earth is gravitationally downhill from the moon and the asteroids. It is highly likely that relatively small machines on these bodies can eject toward Earth-space steady or packaged flows of mass which are much larger than can be supplied by similar sized systems from Earth.

- The systems to supply a given flow of materials from the moon or asteroids can be relatively small and low power. It is possible then that the time to develop and emplace the systems can be reasonable. In addition, the time to expand the throw capacity of the systems can also be short whether the systems are constructed entirely from components brought from Earth or portions of the construction use native materials.

- Aerobraking in the extreme upper atmosphere of Earth may offer a way to bring packaged, non-terrestrial materials into low Earth orbits (LEO) of any inclination with equal ease from the moon or asteroids. Low mass heat shields could be provided from Earth (Davis 1983). Materials are also available on the moon to make such heat shields (Criswell 1983b). Several processes have already been suggested and can be developed with present knowledge. As our knowledge of particular near Earth asteroids (NEA) increases in-situ heat shield production should become possible.

- Lunar and asteroidal materials can be formed in-situ into reaction mass and chemical propellants to use in a wide variety of different propulsion systems. Some of these propulsion systems could have little or no dependence on supplies from Earth for their long term operation. For example, simple pressure-fed rockets using molten aluminum and LOX might have specific impulses on the order of 250 seconds (Bock 1979).

- Access to relatively large quantities of lunar and asteroidal materials with minimal inputs of terrestrial materials and expense would allow their use in clearing of debris from Earth orbits, the repositioning or destruction of ballistic objects, and creation of massive shields for unmanned and manned facilities in Earth orbits or beyond.

- Access to lunar and asteroidal materials will offer several methods to circumvent the exponential scaling effects of the rocket equation as it applies to spacecraft operating exclusively from Earth. Various possibilities include, but are not limited to, provision of reaction mass, propellants and components at key points in a mission; direct transfer of momentum from in-falling materials to debris, orbital facilities or spacecraft; and conservation of the momentum and energy of in-falling and outgoing masses via tethers and other systems (Waldron 1981; NASA 1983).

- It should be possible to develop small systems which can assist the logistics of their own rapid deployment, growth and increasing economic competitiveness;

- Introducing even very small scale materials industries onto the moon or near Earth asteroids will permit the creation of rapidly growing facilities capable of creating power and materials supply flows far greater than could be supplied from Earth and generally independent of major terrestrial inputs. After two to three growth cycles it should be possible to establish large mass driver or chemical propellant production facilities capable of supplying 10,000 tons of materials on demand throughout cis-lunar space or beyond. Far larger facilities are conceivable and have been analyzed under studies supported by NASA (NASA 1979).

- Synergisms between Earth and space capabilities such as providing materials off Earth to LEO can leverage the effectiveness of all operational transportation systems from Earth to orbit and to deep space. Secure bases could be established on the moon to beam large quantities of nuclear or solar derived power to major facilities near Earth. Beamed power could energize spacecraft which could operate efficiently in cis-lunar space and beyond.

Rocket transportation from Earth to space is embodied primarily in chemical rockets which begin their journeys on Earth and then continue to dissipate their original stores during their journeys. Many approaches are now being examined to decrease the costs of missions while increasing payloads, functional stay times and the variety of capabilities for in-space operations. Major investments can produce advances of future Earth centered transportation systems. It is certainly conceivable that turn of the century space systems will take to low orbit about Earth, several thousand tons per year of payload at freight costs significantly less than today.

Salkeld (1979) has argued that at some scales the development of very low cost Earth to orbit transportation could compete with the need for non-terrestrial resources. At a launch cost of $50-100 per Kg Earth materials could be more attractive for many uses. One very crucial goal must be to identify where the crossover occurs between terrestrial and extra-terrestrial materials, given end use, development and operational costs in each case. It will also be important to consider synergistic effects by which the use of lunar or asteroidal materials may decrease the cost of Earth to space travel. The use of lunar resources will certainly be attractive in supporting lunar surface operations, and will probably remain competitive in higher Earth orbits.

We first outline the presently perceived advantages and possibilities for using lunar resources to aid space transportation. Next we examine the exploration and acqisition of asteroidal resources. We recommend both studies and engineering projects.

A. Transportation

In the section we consider extensions of present transportation technologies and discuss new approaches that might result from access to non-terrestrial materials. Figure 1 is the classic illustration of the gravitational wells of the Earth and Moon as measured by the minimum energies (or velocity squared) necessary to eject a ton of material from the surfaces of the two bodies. The vertical scale is measured in units of 1,000 kilowatt-hours (Uo). A theoretical minimum of 800 kw-hours per ton is required to eject materials from the moon.

To escape from Earth requires over 11.2 km per second, and from the moon 2.4 km per second. Earth escape is not 4 or 5 times harder (11.2 divided by 2.4) but more like 50 to a few hundred times harder. Also, progress farther out is uphill from Earth and not downhill as from the moon (Figure 1). For these and other reasons it presently costs between 3 and 10 E6 $ (1 E6 is one million) to ship one ton of materials from Earth-to-orbit even though the minimum energy cost would be approximately 800 $ per ton for 0.05 $ per kw-hour energy. Given generally similar level of technology lunar facilities should utilize much smaller overal machine systems and power levels to provide a given large flow of materials to Earth orbit than rockets operating from Earth. It seems likely the unit costs of mature lunar operations can be driven to significantly lower levels than could Earth supply systems. There are synergistic effects. Cheaper rocket transport from Earth will decrease costs for installing facilities on the moon. Lunar materials can leverage the effectiveness of transportation from Earth by reducing the need to uplift many materials in bulk. Availability of lunar materials and products in low Earth orbit (LEO) permits leveraging the use of the present Space Transportation System (STS) and future versions to carry high priority cargo (people, complex systems, special materials,...) from Earth. A healthy competition will be fostered.

One general principle of design would be to devise productive facilities for the moon which use the minimum mass of equipment and consumables from Earth per unit of product mass made on the moon or later in Earth orbit. Mass multiplication (MM) is used to denote this concept of leverage. Clearly MM must be greater than one. We anticipate MM > 10 is desirable to provide clear economic advantage compared to providing a similar good from Earth. We expect that MM > several hundred is possible for many uses of non-terrestrial material. We will describe how this matter and its additional energy can be used directly near Earth to aid various factors of space transportation.

REACTION MASS AND PROPELLANTS

Oxygen may constitute about 70% of the payload to orbit of future STS supported operations. Oxygen can clearly be obtained from any locale on the moon for the support of chemical propulsion systems. Most lunar materials are 40% or more by weight oxygen. Chemical, electrochemical and thermal processes have been proposed to extract this oxygen and make it available on the moon or in space. Experimental work exists indicating that MM > 2 can be expected for the extraction of oxygen from lunar soils (Davis 1983). Lunar oxygen may be burned with propellants from Earth such as hydrogen or preferrably with lunar derived fuels.

Other common lunar elements can be considered for use as fuels. The lunar metals (aluminum, iron, magnesium) may be useful in the forms of powders, slurries, liquids, or solids for metal-oxygen rockets of moderate specific impulse (200-250 seconds). Rocket cycles which use aluminum or magnesium as fuels and run heated oxygen to power pumps and other system elements have been investigated and warrant further work. Lunar derived metals and oxidizers may be formed into solid rockets of several varieties. Proposed new approaches such as the detonation wave rocket might be especially useful because of the elimination of propellant containers (Beichel, private communication). Silanes are the silicon equivalent of hydrocarbons and may be useful as hydrogen stretchers (Criswell 1980; NASA 1982). Various theoretical calculations indicate a silane-LOX rocket might have 300 to 350 seconds isp. Silanes and other primarily non-terrestrially derived compounds might also be useful as fluids to support various industrial operations.

Rather than return liquids to low Earth orbit it might be more reasonable to return solid fractions of lunar materials such as SiO2 to LEO and process it there into propellants for use near Earth. Trajectory #1 in figure 2 depicts the path of a payload coming from the moon or an asteroid, intersecting the upper atmosphere of the Earth where aerobraking (shaded area) occurs and then being placed in a closed orbit about the Earth by means of a rocket burn (dot).

Operational engines such as ion drives and demonstrated or proposed engines which use non-chemical sources such as sunlight or nuclear power can expell matter which does not release its won chemical energy. The moon can be a source of such reaction mass for devices starting close to the Earth or far away. Mass drivers of various types, induction devices, electrostatic accelerators, plasma engines and others could be serviced with lunar derived materials. Very high MM values (> 100s to 1000s) could be expected for the supply systems.

ELECTROMAGNETIC ACCELERATORS

Several groups have investigated possibilities for establishing long electromagnetic accelerators or mass drivers on the moon. Electric power provided by nuclear reactors or solar power sytems would be utilized by these machines to propel compact payloads (10 grams to a few hundred kilograms) off the moon and into escape trajectories (#2 in figure 2). Mass drivers offer a fundamental advantage. Because electric energy can in principle be produced on the moon in unlimited quantities the mass driver can have very high mass multiplication. MM of 1000s may be reasonable. MM could be primarily limited by catastropic failures or replacement of parts from Earth. Mass drivers are potentially very efficient in converting electric energy into payload energy. In addition, the payload packets might be very simple. They could consist of fused lunar soils. Thus, the mass driver approach might require a minimum of installed power and facilities on the moon. Several mass driver designs have been proposed and an extensive literature is developing in response to past NASA funding and active funding by the U.S. Army and Department of Energy. Extensive technology exists in electrical engineering, computer science, and celestial mechanics which could expedite the development of lunar mass drivers.

A major problem with mass drivers is the need for extremely accurate launching of many payload packets so that they may be collected in space for use at the collection point or elsewhere. A second problem is that small mass drivers which are suitable for initial lunar installations have been designed to launch only small rugged payloads of tens of grams. Efficient, sophisticated means of tracking and collecting an extended stream of projectiles will be needed. Both passive (gravitational focusing) and active methods have been proposed. Development of growing industrial capability on the moon will likely allow the expedient construction of very large mass drivers.

POSSIBILITIES FOR NEW USES OF LUNAR MATERIALS

The following concepts are presented to illustrate future possibilities that have not been analyzed in detail. Low lunar gravity and lack of an atmosphere offers fundamentally different opportunities compared to Earth in dealing with bulk materials. For example, rotating machines or mass drivers could propel selected lunar materials accurately along trajectories tens of kilometers above the moon (see trajectory #3 in figure 2). A lunar transfer vehicle (#4) equipped with lunar derived shields could intercept such a stream of dust and lose most of its orbital velocity prior to landing as is proposed for aerobraking near Earth. In this manner a major increment of velocity change could be accomplished by non-rocket means.

It is possible in principle to use, rather than fight, the gravitational force Earth exerts. A payload of lunar materials can approach Earth as shown by trajectory #5 in figure 2. Streams of materials can be released in the forward and aft directions forming a long string of infalling matter (solids or encapsulated fluids). This matter can be directed so as to intersect debris in orbit about Earth and force the debris to reenter the atmosphere. Infalling materials could modify orbits of objects or degrade orbiting facilities. Considerable control over access from Earth to space could be maintained in this manner.

Waldron (1981) describes how to use lunar materials to assist in Earth-to-orbit operations. A rocket traveling from Earth-to-orbit expends about 5% of its energy reaching orbital altitude and 95% achieving orbital velocity. For example, one hundred tons of cargo could be lofted above the atmosphere by a relatively small solid rocket so as to intersect streams of infalling lunar materials. The payload would deploy a 100 meter parachute so as to intersect a significant fraction of the streams from several incoming lunar packets. A force of less than 2 lbs per square foot on the parachute would be sufficient to accelerate the payload to orbital velocity in less than 10 minutes. This is a new way to use small flows of energy, materials from the moon and the gravity of Earth to help us overcome the gravity of Earth.

A less dramatic approach is possible for scaling down the size of terrestrial launch systems by means of lunar materials. Lunar materials provided in LEO via aerobraking could be reformed into heat shields and structural components. An expendable-like rocket with a high payload fraction could be used for Earth-to-orbit operations. Such rockets can deliver 3 to 10 times more payload per flight to orbit than a fully reusable system of similar takeoff weight. On orbit the expendable-like rocket could be equipped with temporary heat shields, braces and other components to allow reentry and return to Earth. The lunar derived components are removed and the expendable-like rocket reused (Criswell, private communication). The economics of low cost entry to orbit from Earth may be linked with use of non-terrestrial materials. Many other possibilities should be considered for supporting operations in space by the use of lunar and asteroidal materials. These include but or not limited to the supply of raw materials to stations in orbit about Earth, to transfer facilities in resonant orbits between the Earth and the moon (#7 in figure 2), to stations in orbit about the moon or to facilities on the lunar surface.

Tethers have been receiving increasing attention for application by NASA to operations in Earth orbit (NASA 1983). Tether systems oriented by gravity gradient forces or rotating tether systems could be used over a series of steps to intercept incoming lunar materials and pass the materials to lower altitudes. In this way the tether systems could conserve most of the energy and momentum of the incoming lunar materials by increases of altitude or spin rate of the mass of the tether system. This energy and momentum could be released later to raise other payloads to higher altitudes, change the inclinations of satellites or provide energy to orbital systems.

The foregoing concepts illustrate that the materials and energies of the Moon-Earth system can be used in principle to circumvent many of the presently perceived limitations for Earth-only space transportation systems. There are additional real possibilities for small systems which can provide large net flows of materials to be used in-space and also enable new forms of space transportation.

ASTEROIDAL MISSIONS

Most of the advantages of using the moon to aid transportation also apply to the asteroids. The basic advantage of asteroids is that the energy to leave and return slowly toward Earth can be as low as a few watt-hours per ton. Higher energy inputs can result in the quicker return to the Earth-Moon system from larger regions of space. Primary disadvantages are: the lack of detailed knowledge of target asteroids to allow immediate use of resources and in-situ growth; long mission cycles; and less continuity of supply lines.

The following notes list the basic conclusions resulting from discussions concerning transport to and from the asteroids.

⊕ Advantages of near earth asteroids (NEA) as sources from a mission (Trajectory) standpoint.
- Perhaps as many as 20% of NEA can be reached for less energy required than going to the Moon.
- Future discoveries may provide a reasonable number of minimum energy targets.

⊕ Mission characteristics.
- Favorable launch opportunities exist to a variety of targets every year.
- These opportunities repeat on approximately 2 year intervals (Amors & Apollos)
- The launch window for a favorable Aten type can be 2-3 years long.
- Round trip flight times are, on average, approximately 3-5 years. The round trip flight time to Aten-types can be as short as 1 yesar.
- Ballistic ΔV requirement for departing the most favorable asteroids on

Earth-return trajectory is ~100-500 m/sec. (Post launch ΔV)
The ΔV requirement for departing the most favorable asteroids on our Earth-return trajectory is ~100-500 m/sec.

- Precursor Mission
  - 3-10 precursor sample return may be required to return 1-10 kg samples to totally characterize asteroid material before committing to the Resource mining program.
  - Missions of this type are possible now, using today's technology with confortable margins.

- Initial Feasibility Calculations

  It is not clear at present which propulsion scheme is most appropriate for returning material from the asteroids. An excellent initial measure of the viability of a given propulsion scheme is the ratio of payload mass returned to LEO or some other orbit to initial mass delivered to that orbit. This mass payback ratio (MPR or MM defined earlier) has been calculated in detail for some propulsion schemes and roughly for others. A general feeling at this workshop was that MPR's of 2 or so are too low and that MPR's on the order of 10 or greater are required for practical systems. A very rough calculation for return of metal dust from the most favorable, currently known asteroid using optimistic assumptions, electric propulsion outbound and conventional propulsion inbound, with aerobraking indicates an MPR in the range of 5. This number is very sensitive to factors such as total return ΔV required, aerobrake mass required, and electric propulsion stage optimization. There was some controversy over all these numbers and more research and analysis is required. The MPR may be significantly improved by use of other proposed propulsion technologies such as solar sails, mass drivers, and tethers.

Recommendations

Experiments should be started immediately on the key types of propulsion, power, and processing operations appropriate for growing lunar and in-space operations to supply large mass flows to Earth orbits. We strongly recommend an analysis of all reasonable advanced propulsion schemes, at least to the level of determining a steady state MPR range, be done very early, if not first, in future work.

B. Power Systems

Power systems to energize the acquisition, processing and ejection from the moon of 10,000 tons of materials a year would be on the order of several megawatts. Much smaller power systems would be appropriate to systems which are using lunar resources on a smaller scale to aid in deployment of the initial machines or to satisfy smaller materials needs over longer periods of time. Both the small and large systems could be supplied from Earth. Solar panel systems such as the Power Extension Package proposed by NASA for the STS or various unmanned satellites have been designed to provide the order of 30 to 100 kw in orbit about Earth. For operation on the Moon they would be useful primarily during the lunar day at their maximum rated power output. Several units could supply the start-up power needs of a lunar supply facility. Operations during the long lunar night would be power limited due to the need for power storage.

A cooperative program between DARPA, NASA and DOE is underway to create space-borne nuclear reactors which can supply tens to several hundred kilowatts of power. Space-photovoltaic, thermal and nuclear power concepts should be considered for energizing materials supply systems, lunar bases and asteroidal missions.

Availability of well studied materials on the moon offer several opportunities to establish power systems which are composed primarily of lunar materials. A few examples are presented.

Lunar soils are good thermal insulators due to the granular nature of the soils and the lack of air and water to circulate heat. Low mass solar mirrors could be used to heat or even melt lunar dust. The heated materials could be placed in ditches in the lunar surface and covered with a high temperature blanket and lunar soil. Thus, large heat sources could be produced to provide rather constant temperature heat energy both day and night to thermo-electric generators.

It is likely that electrostatic or magnetic beneficiation can be used to select and separate from the various lunar soils large quantities of dark and light colored lunar soils. These soils could be placed inside very large plastic or fiber bags (made of lunar materials) lying directly on the surface. Over the course of several lunar days they would come to different temperatures. Reflectors and shades could be used to augment or reduce solar input to the two areas of soil. Small quantities of low pressure gasses could serve to transfer heat throughout each bag and also between bags via a turbine or other type of heat engine. Steady flows of thermal and electric energy could be obtained.

The natural environment and known materials of the lunar surface appear to provide opportunities to emplace very large solar power conversion systems directly on the lunar surface. The conversion systems could be photovoltaic, thermophotovoltaic, electrostatic, thermal or several other classes of devices which can be made primarily out of lunar materials. Even low conversion efficiency devices may be very attractive. It may be possible to make both power storage and power redistribution systems from local materials to service operations on the moon and in space.

Proprietary concepts and preliminary systems analyses exist for the construction of lunar power systems. This proprietary work forms the basis for a proposal by the System Development Corporation (1983) to evaluate the lunar power concept. Relatively small sets of machinery may be able to emplace systems to supply solar power during the lunar day using primarily lunar derived components. The order of tens of days of energy output would be required to pay back the energy investment in construction of each segment of the lunar surface systems.

Preliminary studies of this approach also reveal that a large fraction of the materials to make the machines of production can also be made of lunar derived components. Thus, as power production builds up on the moon small in-situ manufacturing plants can provide more facilities to increase the emplacement rate. Gigawatt power levels may be achieved after a few years of build up. If such high power capacity systems can be manufactured on the moon primarily out of lunar materials then the possibilities of using microwave, laser or other systems for beaming the power to other uses in space or even on Earth can be seriously considered. Other users could include transfer spacecraft operating out of LEO, processing facilities in orbit or military installations on Earth which need secure secondary supplies of power.

The extensive physical and operational data base generated during and after the Apollo program is adequate to the detailed examination of the engineering and economic feasibility of the various lunar power concepts in a reasonable period of time. Pre-phase A work could be completed in less than a year. If the results are as some workers expect then serious studies on the implications of lunar power systems for support of much wider national goals could be started immediately.

Recommendations

Approximately 500 k$ should be allocated for careful examination of the lunar power concepts, use of lunar materials for the construction of power systems and the use of lunar materials for fabrication of major fractions of the systems of production on the moon and in support of logistic operations.

Available photoconversion and nuclear technologies should be examined as to their roles in supporting growing and steady state levels of materials supply systems. Their operational and economic limitations should be examined both in terms of materials supply systems and other possible support roles in transporation, processing and operations.

Implications for the new national defense initiative of the availability of power from the moon which could be supplied to users on the moon, in space and even on Earth should be examined. Studies should not only focus on direct defense factors such as providing power for defense installations, advanced means of space transportation or isolated military installations on Earth but should also include considerations of second sources of supply of major energy flows, international economic implications and of national prestige.

C. Materials Processing

Processing here is defined as mining, beneficiation, local transport including materials handling, refinement or chemical separation and fabrication of simple shapes (for solid materials).

C-1. Mining

Lunar mining will probably consist of recovery of fine-grained regolith material. Particle size reduction will either be unnecessary or relatively simple to accomplish. No major research and development effort need be expended at this stage to improve confidence in ability to mine lunar regolith.

Asteroidal mining will probably involve size reduction of massive bodies of unpredictable strength. The acquisition, movement and size reduction of such matter under very low gravity will require an appreciable level of research and development effort. A limited level of research on technical problems such as grappling or retention of mining tools, surface penetration and fracture technology and materials handling under gravity levels typical of asteroids should be undertaken at this time to develop a reasonable confidence in ability to perform such operations. An increased level of development may be appropriate when target asteroids are better characterized as to surface and subsurface textures and strengths.

C-2. Beneficiation

Beneficiation is defined here as primarily physical processes for partial or complete separation of compositionally distinct particle or other fractions of mined material (e.g., free-metallic from non-metallic fractions or separation of different minerals). For lunar materials some techniques can probably be evaluated with simulated materials but reasonably reliable predictions of separation efficiency can only be gained following some testing on actual lunar soils. The major, minor and trace element distributions can be of vital importance to some processing methods which have been proposed.

Asteroidal material may be studied using simulants or actual meteoritic samples. Laboratory apparatus or facilities for the most part could study both classes of materials. These studies should be predominantly experimental.

C-3. Local Transport and Materials Handling

Lunar mining transport and materials handling under reduced by not negligible gravity levels (1/6 Earth G) has been studied in some detail. The absence of atmosphere may permit ballistic or other transport methods from mine pit to processor or storage facility. Some analytical or preliminary design studies in support of such technology is recommended.

For asteroidal transport the principal difference is level of local gravitational forces. Fragmentation processes could result in particles acquiring velocities sufficient to gravitationally escape from an asteroid if unconfined. Retention of such matter and control of motion or flow of large and small particle streams of asteroidal matter requires additional analytical studies.

C-4. Refinement or Chemical Separation

If iron-based alloy materials are the sole or overriding requirement determining the cost efficiency of materials delivery to Earth orbit, it is possible to operate with little or no refining operations either on the Moon or asteroid or in Earth orbit. Such scenarios will require local energy sources of very low levels (approximately 1 KJoule/Kg). If propellant oxygen or other refined elements are desired processing energy levels in excess of 1 MJoule/Kg are needed.

Many possible refining processes have been proposed and some experimental work has been undertaken. Additional bench scale and engineering studies are needed to properly evaluate and compare the various processes for sizing, throughput, durability or reliability, output purity, etc.

C-4a. Metallic Refinement

(Fe-Ni Free Metal) The free metallic grains from either the Moon or asteroids can be separated by chemical means into iron, nickel, cobalt, and trace element and inclusion fractions. At least two methods have been proposed: carbonyl purification and aqueous electrorefining. Further studies on both systems including preliminary engineering, analytical and experimental efforts are recommended as well as any new proposed methods which appear promising. A wide range of approaches should be considered. For example, zone refining may be useful in some applications.

(Other Metals, Al, Mg, Ti) Separation of these materials will generally require chemical or other separations from the raw or non-metallic fractions of lunar or asteroidal sources. Most will require use of reagents not locally available which must be recycled and regenerated. Reduction processes for obtaining free elements from purified compounds (oxides, halides, etc.) of Al, Mg, or Ti can include electrolytic or reduction by an active metal (Na, Ca, Si, etc.). Such processes can possibly furnish very high throughputs for metals production and should be studied and developed further.

C-4b. Non-metallic Refinement and Separation

This category includes recovery of minor fractions of adsorbed or converted volatiles by combinations of heat and vacuum treatment which can be important in systems using water-based processes.

The objectives of such processes are either to recover oxygen and reduction products such as iron or other elements of varying degrees of purity or to separate relatively pure oxides or other compounds of the major constituent elements for use as non-metallics or later reduction to pure elements.

The non-metallic processes can be separated into three classes:

1) Reagentless processes,
2) Processes using reagents present in local sources in higher than trace amounts, and
3) Reagent processes requiring elements which must be brought

from Earth.

The degree of complexity of such systems and their capabilities of providing diverse purified compounds of elements increase from classes 1 through 3.

Some examples of processes worthy of additional study in the above classes include:

Class 1: Degassing studies of beneficiated fractions of actual lunar soil samples.
  a. Degassing of lunar soil samples.
  b. Whole soil (simulant) electrolysis using various anode systems.
  c. Gradient or zone-cooling.
  d. Ultrahigh temperature thermal pyrolysis.

Class 2: Separation systems using
  a. sodium or potassium
  b. silicon
  c. sulfur or sulfides
  d. phosphorus or phosphides.

Class 3:
  a. HF acid leach system.
  b. Hydrogen-ilmenite system.
  c. SO2-H2O--H2SO4 System.

All of the studies except those in class 1a can be performed using soil simulants and most would apply to both lunar and asteroidal materials.

E. Fabrication

Fabrication of metal or ceramic shapes and parts can be performed using powder metallurgical or chemical techniques, casting and forming operations, etc.

Fabrication of iron parts using iron containing low-levels of silicate and other inclusions should be studied. Alloy chemistry and metallurgical studies on Fe-Ni-Co alloys is also recommended so that metal alloys with optimal strength, ductility, etc. can be obtained.

Heat requirements for metal fabrication can be provided using solar furnaces. Materials requirements in high-temperature soaker furnace applications need further investigation.

The use of thermite-type reactions to form near-net shape iron parts should also be investigated. The advantage of this processing technique is that high-temperature furnaces are not required to carry out the melting and casting process. Other alloy compositions such as Fe-Ni, Al-Ni and Al-Fe may also be formed and cast by this technique.

V. Conclusions

A. Program Implementation and Cost Estimates/Research and Development Plan

For planning purposes, it is useful to divide the required RDDT and E into three phases: (1) research, (2) engineering development, and (3) implementation. The required resources increase with each phase, but the decision to proceed will be based on sound technical information developed in the previous phases. One "strawman" implementation is presented below:

a.) Research - The research phase is designed to address the fundamental understanding of candidate processes and systems implementation, and to develop the necessary technical base for a decision to proceed with engineering development. This work if initiated in FY '84 is projected to continue through FY '89 at a total cost of approximately $20 million.

The following specific research and development strategy for the next 5 years is recommended.

Part 1. Conversion of raw materials into useful products. This requires basic industrial research for utilizing lunar and asteroidal materials. These include gathering, beneficiation, extraction, thermal and chemical processing, and basic product manufacturing. An expenditure over 5 years of $10 million is recommended. Details are contained within the report in Sections III and IV.

Part 2. Asteroid location, identification, and characterization. A ground based remote sensing program of asteroid location and identification including Spacewatch Camera is recommended. Specific details are contained within the text. An expenditure of $4 million over 5 years is recommended.

Part 3. Systems exploration. Detailed systems analysis of options for implementation, including cost analysis where feasible is necessary. These include identification of major systems and tradeoffs in transport, power production, materials processing, manufacturing, handling and distribution. It is recommended that $6 million over 5 years be devoted to systems analyses.

b.) Engineering Development and Precursor Missions - The development phase will include development of process steps, equipment components, process controls, reliability data, system interactions, etc., as well as construction and operation of transport systems and pilot plants as required. In addition, necessary precursor missions are included at this stage. The time and cost will depend on the results of the research, on the nature of the processes and products, and where processing is to be done. For relatively simple processes such as production of oxygen and iron using the finite gravity of the Moon, a development phase of $100-200 million/year for ten years (total = $1-2 billion) is a reasonable preliminary estimate.

c.) Implementation - Implementation will include: (1) design, procurement and fabrication of processing equipment, power plant, control and communications equipment and transport vehicles for equipment and products; (2)

transportation of the equipment to the operating site; (3) assembly installation and start-up; (4) operations, including maintenance and repair. The time and cost obviously depend on process, product, location, and on the results of the development phase, as well as the degree of bootstrapping developed in the program.

B. Organizational Implementation

Serious consideration must be given to the organizational implementation of the proposed program. Since the idea is new and interdisciplinary, no existing structure is optimally designed to tackle it. Additionally, there may be limited personnel with sufficient breadth of background to plan and develop a program.

It is therefore recommended that a special committee or task force be appointed to examine the problem, Such a committee should have members from relevant government agencies, private industry and universities. Committee members should possess experience in the planning, development and execution of complex, interdisciplinary, long range programs with significant technological strategic, political and economic components.

Acknowledgements

This report represents the ideas and the work of the various members of the workshop. In particular we would like to acknowledge David Brin, David Criswell, Peter Vajk and Beth Di Julio for technical and editorial assistance and report preparation.

REFERENCES

Agosto W.N. and King E.A., In situ solar furnace production of oxygen, metals and ceramics from lunar materials, LUNAR AND PLANETARY SCIENCE XIV (abstracts - Special Session-A return to the moon), p.1-2, Lunar and Planetary Sciences Inst., Houston, TX, 1983.

Arnold, J.R. and Duke M.D. (editors), SUMMER WORKSHOP ON NEAR-EARTH RESOURCES: A WORKSHOP SPONSORED BY THE UN. OF CALIFORNIA AT SAN DIEGO & THE LYNDON B. JOHNSON SPACE CENTER (6-13 August 1977), NASA Conference Publication 2013, 1978.

Bock, E.H. (study manager) LUNAR RESOURCES UTILIZATION FOR SPACE CONSTRUCTION; FINAL REPORT, vol. 3, NASA CONTRACT NAS9-15560, 1979.

Brin G.D., Astrophysical Journal237, p.265, 1980.

Criswell D.R., EXTRATERRESTRIAL MATERIALS PROCESSING AND CONSTRUCTION: FINAL REPORT, pp. 350, NASA Contract NSR-09-051-001 mod 24, Lunar and Planetary Inst. (Houston, TX), 1978.

Criswell D.R., EXTRATERRESTRIAL MATERIALS PROCESSING AND CONSTRUCTION: FINAL REPORT, pp. 450, NASA Constract NSR-09-051-001 mod 24, Lunar and Planetary Inst. (Houston, TX, 1980.

Criswell D.R., The roles of powder metallurgy in the development of space manufacturing, Progress in Powder Metallurgy, Vol. 38, p.115-146, 1983(a).

Criswell D.R., A transportation and supply system between low Earth orbit and the moon which utilizes lunar derived propellants, pp. 5, Lunar and Planetary Sciences XIV, Houston TX, 1983(b).

Davis H., Lunar oxygen impact upon STS effectiveness, Eagle Engineering, Houston, TX, NASA Contract from the Johnson Space Center., 1983. (report available Eagle Engineering).

Galloway E., AGREEMENT GOVERNING THE ACTIVITIES OF STATES ON THE MOON AND OTHER CELESTRIAL BODIES (U.S. Senate, Committee on Commerce, Science and Transportation), Washington, 2 parts, U.S. Government Printing Office, 1980.

Glaser P.E., Solar power from satellites, Physics Today, pp.30-69 (Feb. 1977); see also Letters to the Editor, pp. 9-15 and 66-69 (July 1977).

Goldstein J.I. and Axon H.J., Proc. Lunar Science Conf. 3, p. 1037, Pergamon Press, 1972.

Inculet I.I., Electrostatic separation of lunar soil, SPACE MANUFACTURING III, p.109-112, American Institute of Aeronautics and Astronautics, N.Y., 1979.

Jarrett N., Das S.K. and Haupin W.E., Extraction of oxygen and metals from lunar ores, Space Solar Power Review, Vol.1, #4, pp.281- 287, 1980.

Kesterke D., U.S. Dept. of Interior, Bureau of Mines, Report of Investigation

RI 7587, 1971.

Lewis J. and Meinel C., Asteroidal materials and space bunkers, DEFENSE 2000, July 1983.

Lindstrom D.J. and Haskin L.A., Electrochemical preparation of useful materials from ordinary silicate rocks, SPACE MANUFACTURING III, p. 129- 134, American Inst. Aeronautics and Astronautics, N.Y., 1979.

Mackenzie J.D. and Claridge R.C., Glass and ceramics from lunar materials, SPACE MANUFACTURING III, p.135-140, American Inst. Aeronautics and Astronautics, N.Y., 1979.

Miller R. (principal investigator), EXTRATERRESTRIAL PROCESSING AND MANUFACTURING OF LARGE SPACE SYSTEMS, 3 volumes, NASA Contract Report 161293, 1979.

NASA, NASA SP-428, Space Resources and Space Settlements, pp.288, Government Printing Office, Washington, D.C., 1979.

NASA, NASA CP-2255, Advanced automation for space missions, pp. 393, U.S. Government Printing Office, Washington, D.C., 1982.

NASA, Applications of tethers in space (draft report), Workshop 15-17 June 1983 at Williamsburg, VR., sponsored by NASA Headquarters and Marshall Space Flight Center, two volumes, 1983.

O'Neill G.K., Space colonies and the energy supply to the earth, Science, 190, 4218, p.943-947.

Puzzo P.A. (editor) BIBLIOGRAPHY OF TOPICS IN SPACE INDUSTRIALIZATION AND HABITATION, pp. 33, (available Cal Space, A-021, UCSD, La Jolla, CA, 92093), SIO Ref. 82-25, 1982.

Romig B.R. and Goldstein, Powder metallurgical components from lunar materials, LUNAR UTILIZATION, p.120-123, Lunar and Planetary Institute, Houston, TX, 1976.

Salkeld R., Terrestrial, lunar and asteroidal materials costs - impact of advanced Earth to orbit transportation, SPACE MANUFACTURING 3, American Inst. Aeronautics and Astronautics, p. 569-574, 1979.

SHRELLDALFF, Proceedings of the Apollo-11 Lunar Science Conf., vol. 2., p. 5003-5030, 1970.

System Development Corp., Proposal to Evaluate Construction on the Moon of Large Solar Power Stations to Support Growing Lunar, Cis-Lunar and Terrestrial Industries, SDC Proposal 83-5232, Submitted to NASA, direct inquiries to D.R. Criswell (619-452-2047-concept) or R. Salkeld (805-987-9311-project management).

Waldron R.D., Useful properties and novel methods for transportation of lunar soil in or to Earth orbit, SPACE MANUFACTURING 4, p. 331-342, American Inst. Aeron. and Astronautics, N.Y., 1981.

Waldron R.D., Erstfeld T. and D.R. Criswell, Role of chemical engineering in space manufacturing, Chemical Engineering, pp.80-94, 12 February 1979.

Williams R.J., Enhanced production of water from ilmenite: an experimental test of a concept for producing lunar oxygen, Lunar and Planetary Science XIV, p.34-35, Lunar and Planetary Inst., Houston TX, 16 March 1983.

Williams R.J. and Hubbard N., REPORT OF WORKSHOP ON METHODOLOGY FOR EVALUATING POTENTIAL LUNAR RESOURCE SITES, pp. 59, Johnson Space Center, Houston, TX, NASA Technical Memo TM-58235, February 1981.

FIGURE 1

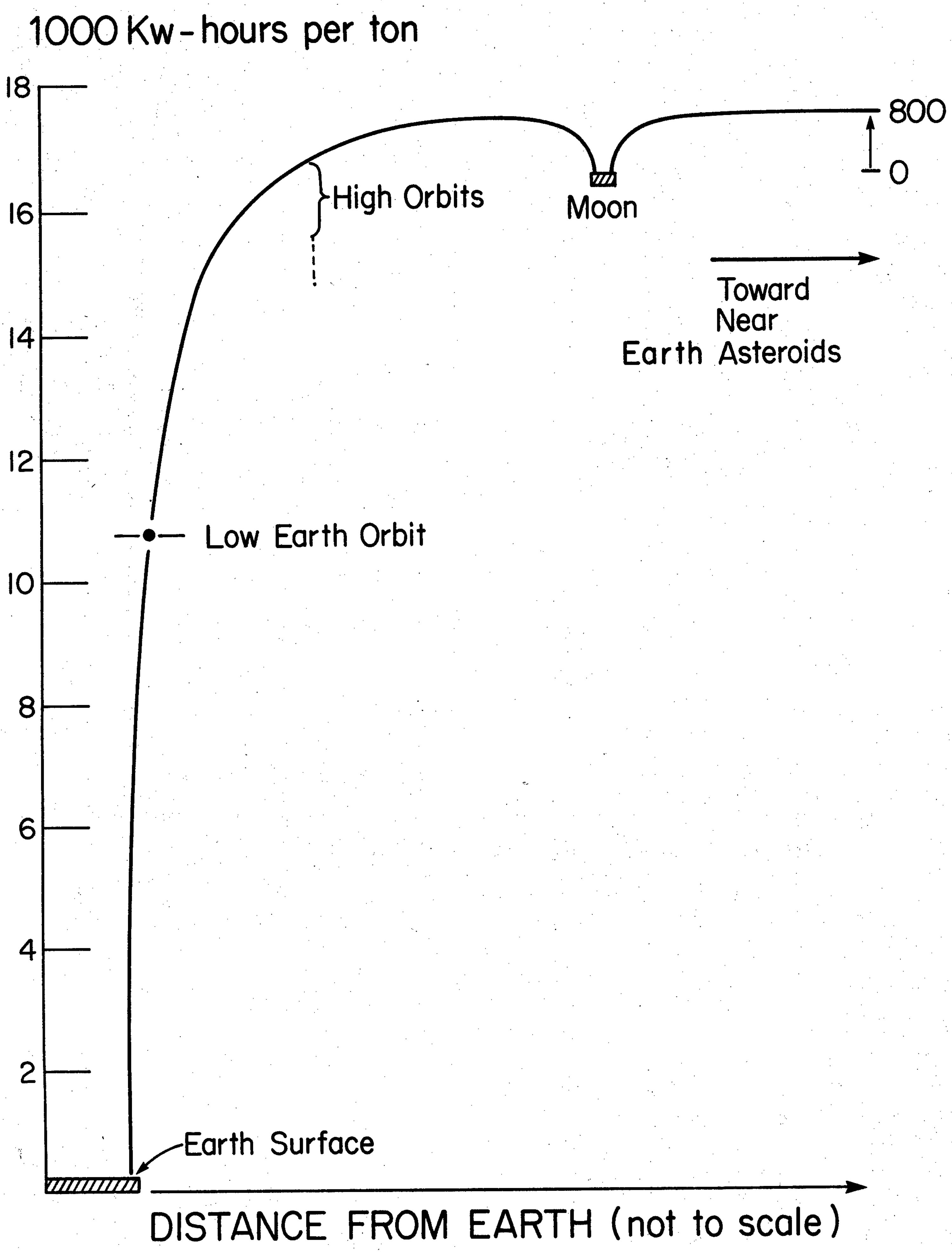

1000 Kw-hours per ton
18
16
14
12
10
8
6
4
2
800
0
High Orbits
Moon
Toward
Near
Earth Asteroids
Low Earth Orbit
Earth Surface
DISTANCE FROM EARTH (not to scale)

FIGURE 2

A FEW OF THE MANY POSSIBLY USEFUL PATHS OF LUNAR MATERIALS AND SPACE FACILITIES IN CIS-LUNAR SPACE.

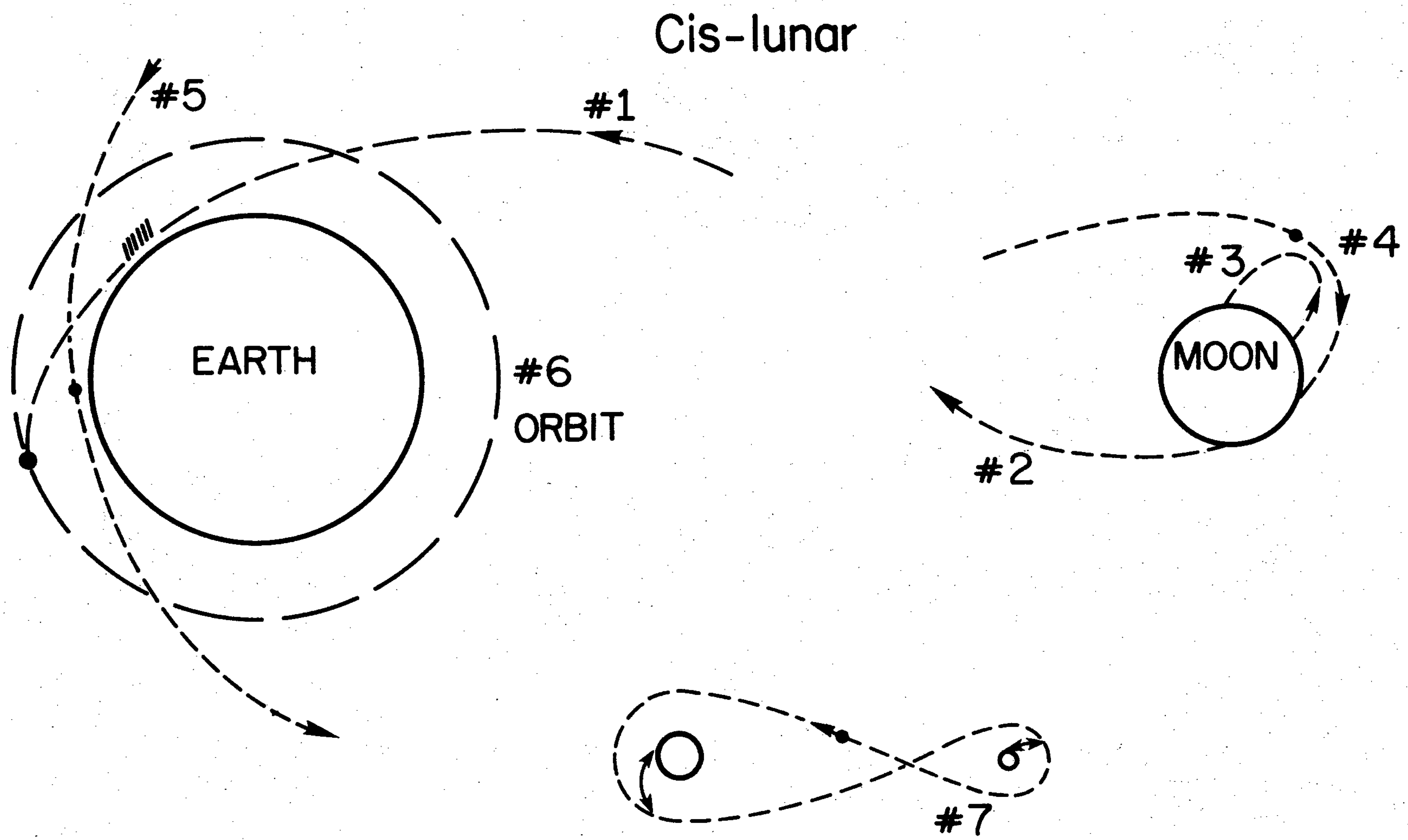
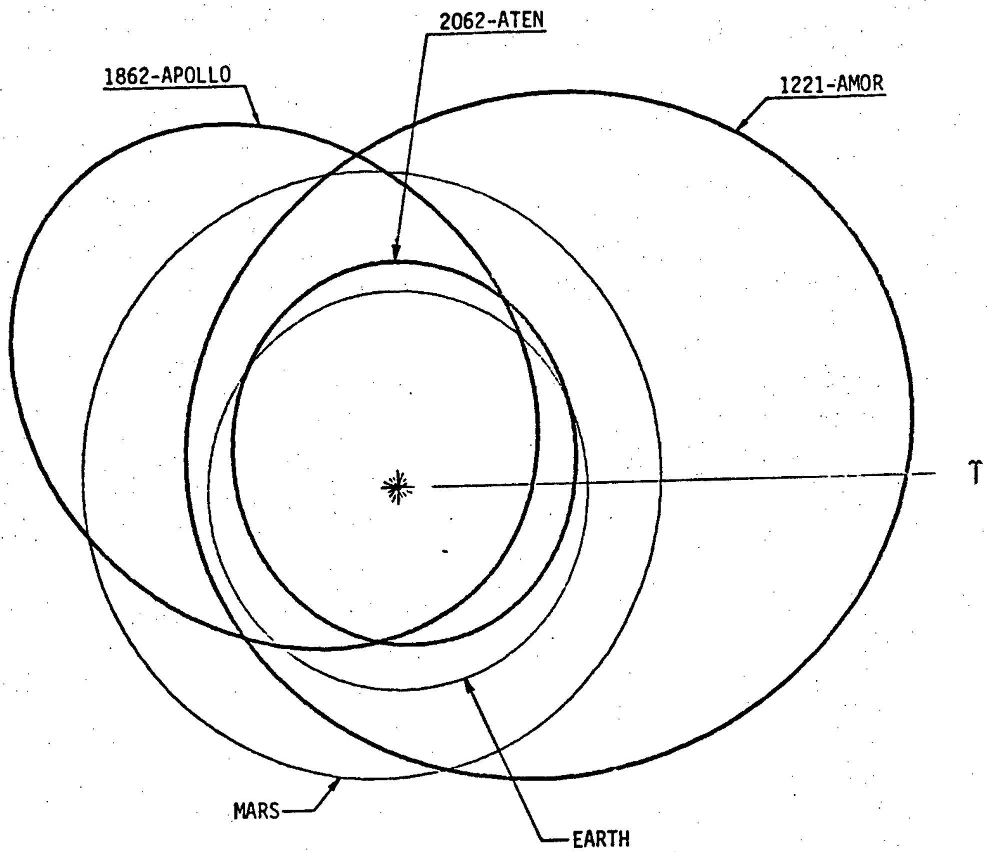
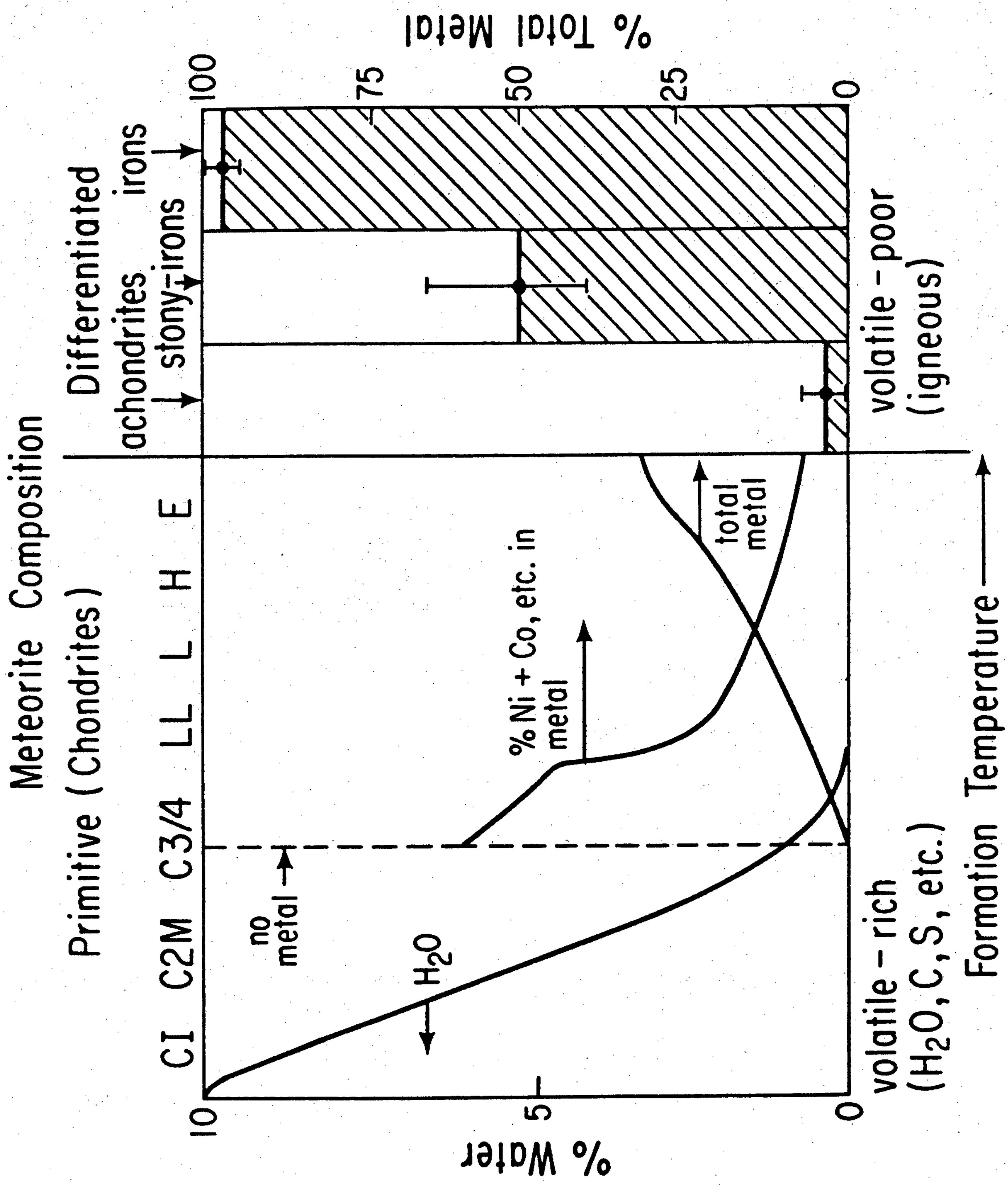


FIGURE 3



Typical Orbits for Aten/Apollo/Amor Objects

FIGURE 4



Meteorite Composition
Primitive (Chondrites)
Differentiated
CI C2M C3/4 LL L H E
achondrites
stony-irons
irons
no metal
H_2O
% Ni + Co, etc. in metal
total metal
% Total Metal
100
75
50
25
0
% Water
10
5
0
volatile - rich (H_2O, C, S, etc.)
volatile - poor (igneous)
Formation Temperature

APPENDIX

List of Workshop Participants

August 15-17, 1983

James Arnold
Cal Space

Robert Behrens
Los Alamos Nat'l. Lab.

Rudi Beichel
Aerojet General

Geoffrey Briggs
NASA Headquarters

David Brin
Cal Space

Joe Carroll
Cal Space

Terry Chern
Cal Space

Aaron Cohen
NASA/Johnson Space Ctr.

Leslie Cohen
McDonnell Douglas

Gene Conecii
University of Texas

David Criswell
Cal Space

Andy Cutler
Cal Space

Mike Duke
NASA/Johnson Space Ctr.

Eric Gelfand
Los Alamos Nat'l. Lab.

William Haynes
Aerospace Corp.

Daniel Herman
NASA Headquarters

Don Humes
NASA/Langley Research Ctr.

Maxwell Hunter
Lockheed

James King
Jet Propulsion Lab.

Wallace Kirkpatrick
DESE Research & Engineering

John Lewis
University of Arizona

Tom McCord
University of Hawaii

Stewart Nozette
Cal Space

Alden Oyer
Los Alamos Nat'l. Lab.

Henry Ponsford
Pacifica Technology

Robert Salkeld
System Development Corp.

Eugene Shoemaker
Cal Tech/USGS

John Soldner
Science Applications, Inc.

Jim Somers
Headquarters DNA (DTST)

Bill Stump
Eagle Engineering

Ken Taylor
NASA/Marshall Space Flight Ctr.

Peter Vajk
Science Applications, Inc.

Robert Waldron
Rockwell International

E. Ronald Weiner
Inst. for Defense Analyses

Peter Worden
Inst. for Defense Analyses

Chen-Wan Yen
Jet Propulsion Lab.