NASA Conference Publication 3017

Report of the In Situ Resources Utilization Workshop

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Proceedings of a workshop cosponsored by
National Aeronautics and Space Administration,
Department of Energy, Large Scale Programs Institute,
United Technologies Corporation, Kraft Foods, and
Disney Imagineering, and hosted by
United Technologies Corporation
Lake Buena Vista, Florida
January 28-30, 1987

National Aeronautics
and Space Administration

Scientific and Technical
Information Division

1988

PREFACE

This report contains the results of a workshop that investigated potential joint development of the key technologies and mechanisms required to enable the permanent habitation of space. Fifty representatives from the public and private sectors met at the United Technologies Center, Lake Buena Vista, Florida, January 28 to 30, 1987, to begin a joint public/private assessment of new technology requirements of future space options, to share knowledge on those required technologies that may exist in the private sector, and to investigate potential joint technology development opportunities. This report also provides input to a NASA technology development plan and documents possibilities for collaborative technology development among the public, private, and academic sectors.

This workshop represents the first "nucleation" phase of a continuing process. The participant list represents only a small fraction of all organizations that will contribute to future development of space technologies and activities. We attempted to assemble a representative cross section of business, academic, and government organizations to investigate the feasibility of potential technological collaborations and the organizational structures that would enable most effective collaboration. If it appears that the timing is correct for this sort of activity, we can then consider the "implementation" and "production" phases, where-in the entire national - and perhaps international - corporate, academic, and public communities will have an opportunity to participate.

The workshop consisted of a series of plenary meetings to acquaint participants with current space policy issues and the state of long-range planning within NASA. Then, five working groups convened to exchange ideas on ways in which the Nation can realize the potential of space development.

This report contains the conclusions of the working groups, as well as preliminary recommendations to be used in near-term development priority decisions. Finally, steps are outlined for potential new activities and relationships among the public, private, and academic sectors.

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WORKSHOP ACKNOWLEDGMENTS

Sponsors
NASA Lyndon B. Johnson Space Center (JSC)
NASA Headquarters Office of Aeronautics and Space Technology
NASA Jet Propulsion Laboratory (JPL)
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SUMMARY

The In Situ Resources Utilization Workshop was held at Lake Buena Vista, Florida, from January 28 to 30, 1987. Sponsoring organizations included the NASA Lyndon B.Johnson Space Center (JSC), the NASA Jet Propulsion Laboratory (JPL), the Los Alamos National Laboratory, the Large Scale Programs Institute, United Technologies Corporation, Kraft Foods, and Disney Imagineering. Attendance was by invitation only and was held to about 50. The NASA installations that were represented included JSC, JPL, Lewis Research Center, George C. Marshall Space Flight Center, and NASA Headquarters. The rest of the attendees came from other Federal and State agencies, universities, and nonaerospace industry.

The concept for the workshop arose from lunar base studies at JSC. Attempts to characterize mass flows, power requirements, crew sizing, launch rates, Space Station impact, lunar surface infrastructure, schedules, and costs for lunar base scenarios depended critically on technology estimates from nonaerospace industry such as mining, surface transportation, thermochemical processing, construction, utilities, and even agriculture. Since the studies were being performed in house on very restricted budgets, much of the required technical information had to be gathered informally through commercial contacts. The workshop was an attempt to exchange information with industrial representatives about the needs and the potential for advances in the relevant technologies. One element of the interaction was discussion of the possibility for more direct involvement by industry in the planning and execution of space initiatives targeted (tentatively) for the turn of the century.

After formulation of the workshop was well under way and after the invitation list had been developed, the Office of Aeronautics and Space Technology (OAST) requested that the participants examine the issues associated with the new Civilian Space Technology Initiative being advocated in that organization. In response to the request, the steering committee for the workshop organized the meeting around working groups on various technology issues. Topics included mining, prospecting, transportation, construction, assembly, power generation, life support, automation and robotics, manufacturing, and materials processing.

The first half day of the meeting was devoted to background briefings on the state of NASA advanced planning. The rest of the time was spent in working group meetings or periodic progress reporting to the entire group. Some working groups had an initial problem with focus because the planning scenarios were not highly defined and because most of the attendees were unfamiliar with the space program or with conditions on the Moon and on Mars. However, by the end of 2 days, all groups had agreed on a conceptual structure and had produced a series of recommendations on approaches to future technology definition in the "Pathfinder" and "Pioneer" categories (OAST terminology). A subgroup, consisting of industrial executives, spent part of the time examining the potential for private development of marketable space technology. They concurred on a set of future actions to explore the concept of "technology spinoff inversion," whereby a long-range program is

designed to produce intermediate commercial products while preparing for 21st century leadership.

Although activity was intense, the brief duration of the meeting precluded production of a finished report. All groups have prepared written presentations, and they have been edited and combined into this document. This report is being made available to all interested NASA, public, private, and academic sector managers. A major product of the workshop will be discovery by commercial industry of opportunities for participation in the space program of the coming decades.

OVERVIEW

INTRODUCTION

The NASA Administrator recently articulated a long-range vision for the U.S. space program which included the challenge to "Expand human presence beyond the Earth into the solar system." This goal derives from the report of the President's National Commission on Space (NCOS), which argues for "exploring, prospecting, and settling the solar system ...." The NCOS report envisions the solar system as humanity's extended home and outlines a stepwise expansion of the "inhabited sphere" from low Earth orbit (LEO) to the Moon and ultimately to Mars.

As humankind moves to the planets, the resources needed to sustain the expansion cannot always be brought from the Earth. Eventually, the in situ materials on planetary surfaces must be utilized to support habitation, transportation, industry, and exploration.

This principle can be illustrated by considering the most elementary extrapolations to the first lunar outpost. If the initial Earth-to-Moon transportation system is based on current technology and operational philosophy, then the delivery costs make any object imported to the Moon worth three times its weight in gold. Thus, a very real economic incentive exists to use lunar materials on the lunar surface.

Attempts to carry this example a step further lead to uncertainties in the cost-benefit analysis. To produce a commodity in any quantity from lunar feedstock by a chemical or physical process requires capital investment in a plant, which must be imported from Earth. The demand for some commodities may be high enough to amortize the surface production facility, but any conclusions are strongly dependent on the assumptions behind the analysis.

On the other hand, demand for lunar products may not be limited to lunar surface operations. The energy required to launch a lunar payload into space is more than an order of magnitude less than that required to launch a terrestrial payload into LEO. Not only is the lunar gravitational field weaker than the Earth's, but no atmospheric drag exists on the Moon. Spacecraft launched from the Moon do not need to be aerodynamic and can be simpler in construction. As a result, the domain within which lunar products could be economically competitive might extend to applications in Earth orbit and other locations in space.

The foregoing observations provide a context within which to discuss lunar manufacturing as a possible future space activity.

A frequently raised issue is whether private sector investment in lunar production can make sense. Skeptics argue that the only customer in space is the Government and that the demand will never be great enough to justify private investment. Advocates point out that an expanding human presence will create its own demand; in the early stages of a lunar base, production capacity yields benefits in the form of programmatic cost savings and enhancement of operational capability. If the private sector can be involved somehow in the buildup phase, many believe that the development of space will grow rapidly and that the necessary markets will be created in the process.

Lunar base conceptual studies performed at the NASA Lyndon B. Johnson Space Center (JSC) have been based on the assumption that resource utilization will be an important objective. The production of liquid oxygen as a propellant has been included in modeling work. As the system models have grown in detail, JSC engineers have found that the search for relevant technologies has led more and more to the nonaerospace industrial sector. A resource oriented lunar base encompasses activities such as mining, thermochemical processing, construction, megawatt power generation and distribution, surface transportation, habitation and life support, and extensive use of robotics or automation.

The exploitation of local planetary resources has been considered in other contexts. The NASA Jet Propulsion Laboratory (JPL) has worked on in situ propellant production (ISPP) as a component of martian exploration. The Los Alamos National Laboratory (LANL) has explored innovative technologies in excavation, sintering, power generation, and propulsion in support of NASA planning for piloted missions to the Moon, to Mars, and to the moons of Mars.

WORKSHOP ORGANIZATION

The sponsoring organizations, JSC, JPL, LANL, Large Scale Programs Institute (LSPI), United Technologies Corporation, Kraft Foods, and Disney Imagineering invited approximately 50 people to Lake Buena Vista, Florida, to participate in the In Situ Resource Utilization (ISRU) Workshop. Approximately half the attendees were familiar with some aspect of advanced planning in the space program. They came from NASA centers, Federal laboratories, government agencies, and universities. The rest of the invitees came from the industrial sector, and brought to the meeting a background in the technologies considered to be relevant to planetary surface operations. Many of the private sector participants had little knowledge of the issues of space development.

All invitees received packages of background material before the meeting and received an orientation on the state of advanced planning on the first morning. The presentations covered piloted lunar and martian missions, the NCOS report, strategic planning in NASA Headquarters, and the new Civilian Space Technology Initiative (CSTI) within the NASA Office of Aeronautics and Space Technology (OAST). The new OAST programs were characterized as the CSTI (now in the fiscal year 1988 (FY88) budget), the Pathfinder augmentation (to be added to FY88), and the Pioneer follow-on (to be added in later years).

Each participant was assigned to one of four working groups, with each group covering a set of technology issues considered to be relevant to future planetary surface bases. The groups were titled (1) Construction, assembly, automation, and robotics; (2) Prospecting, Mining, and Surface Transportation; (3) Biosystems and Life Support; and (4) Materials Processing. Each group met more or less independently, reporting progress and problems in plenary sessions held during the deliberative process. On the morning of the third day, each group reported its findings on the key technology issues which should be addressed by NASA.

A few members of each of the technology groups broke away briefly during the meeting to form a fifth, Innovative Ventures, group. This latter assemblage considered the obstacles to private investment in space endeavors, particularly long-range scenarios, and discussed possible mechanisms to encourage private sector initiatives.

RESULTS OF THE WORKSHOP

The objectives of the ISRU Workshop were fourfold:

1. To introduce space planners to representatives of the nonaerospace industrial sector for the purpose of future interaction or collaboration or both and to inform them of space policy that might be of interest

2. To obtain the options of industrial technologists on the key issues facing the space program in the development of analogous technologies for space applications

3. To formulate technology development recommendations for assisting space planners in setting priorities in development options

4. To explore possible routes for increasing private investment in space development and to implement promising strategies

Overall, the meeting accomplished the first objective. The NASA planners now have a network of interested and informed experts for consultation and advice. Possibilities for more formal working relationships also were explored during the meeting.

The second, third, and fourth objectives were achieved through the final reports of the working groups.

WORKING GROUP SUMMARY

Working Group I.- Construction, Assembly, Automation, and Robotics

Members of the Construction, Assembly, Automation, and Robotics Working Group structured their deliberations around the five phases of lunar base development assumed in lunar base systems study now being conducted at JSC.

During the initial phase of exploration and site selection, unmanned missions using orbiters, surface rovers, and penetrators (launched from orbit) would return a global set of information on the environment and resources of the Moon. Key technologies at this stage would include automated surface operations such as vehicle mobility, sample collection, and remote scientific analysis.

The second phase is defined as an outpost supporting temporary habitation. Relevant capabilities include moving and lifting payloads (20 metric tons maximum), site preparation, drilling, trenching, excavating, moving of lunar soil or "regolith," cleaning, and uncomplicated assembly of large components. New technologies needed to support this operation are lunar surface construction machinery, regenerative life support (mechanical recycling of air and water), dust control, nuclear power generation, energy distribution (utilities), and pilot plant processing.

In phase III, the site can support 5 to 10 people on a continuous basis. Surface transportation increases in range. Space transportation increases in payload capacity (40 versus 20 metric tons). Power generation grows from 1 to 10 megawatts. Controlled ecological life support system (CELSS) experimentation begins. Enclosures increase in size with concomitant growth in regolith moving capacity. Commercial propellant production commences. Assembly processes are more complex and roadways are constructed.

Phase IV begins when the base can exploit enough local resources to significantly reduce terrestrial imports. The population might range as high as 100, with a power generation capacity as great as 100 megawatts. Propellant might be sold to nonlunar markets in space. Agriculture, lunar volatile materials recovery, metallurgy, and construction from local materials are performed in pilot stages. Volatiles are those elements that are easily vaporized and lost into the vacuum of space. These include elements useful for life support and other activities such as oxygen (O_2), hydrogen (H_2), nitrogen (N_2), carbon (c), and helium (He). A mobile "volatile harvester" to extract and capture these elements from the regolith is a significant technology application, along with a construction industry using concrete mixing, bricklaying, glazing, sealing, and foundation building techniques.

A truly self-sufficient base is the goal for phase V, the final phase. Long-term operation and growth could be maintained without terrestrial supply. To attain this hypothetical state, the lunar community would need a metal castings plant for structural steel, fabrication plants, self-sufficient farms, and indigenous propulsion and power generation capability.

The group noted that very little long-term, continuous single activity is required during lunar base evolution. Rather, many diversified tasks arise, by which specialization of equipment is precluded. Many presumed activities are actually contingent on the environment, an implication that improvised, unplanned activities will emerge. Human intervention on the surface is constrained by the radiation environment.

As a result, four design principles are suggested. Multipurpose designs are preferable to single-purpose machines. Self-repair and self-configuration are major design goals. Machine autonomy must be high, or when that is not feasible, teleoperation or remote supervision must be emphasized.

Lunar construction will be enabled once methods are invented to bind the regolith, either to support the roofs of excavated volumes or to form actual structural elements such as beams or bricks. Concrete has been suggested as a lunar construction material because the appropriate oxides are bound up in lunar minerals and because water would be a byproduct of propellant production. The actual utility of concrete will depend on whether cementitious materials can be produced without large energy costs.

Working Group II.- Prospecting, Mining, and Surface Transportation

Prospecting on the Moon can begin with unmanned orbital remote-sensing spacecraft and continue with robotic or teleoperated surface rovers. The NASA has studied extensively the technology needed for geochemical, mineralogical, and geophysical characterization of the lunar surface from orbit, and the working group adopted the general lunar observer concept. The group suggested automated rovers as part of the reconnaissance capability associated with the base.

The two components of mining, extraction of material and concentration of target minerals, can be power-intensive activities. The continuous operation of a mine makes reliability and low maintenance major technology goals. Excavation may well require massive machinery specifically designed for operation in the lunar environment, but excavation using explosives should be studied as an alternative. Processing plants have particularly high power demands and must be centrally located rather than mobile. Feedstock concentrators should be located at the mining site.

For covering short distances between concentrating and processing facilities, wheeled multicab transportation systems with active suspensions are acceptable. More exotic systems become attractive when transport distances are larger. On the Moon, magnetically levitated vehicles appear particularly promising. On Mars, airplanes with small payload capacity are feasible, and ballistic hoppers can be designed to extract fuel and oxidizer from the environment for propulsion.

Since the radiation environment on the surfaces of the Moon and Mars is carcinogenic for long-term exposures, continuous surface tasks (such as strip mining) will be done by machines with a high degree of automation, robotics, and teleoperation. Automation technology developed for the Space Station will carry over to a lunar base initially, but, as lunar operations mature, autonomy of machine operations will increase. Lunar base operations will require a high-capacity communications network to sustain contact among the base elements, mining and industrial tasks, possible remote reconnaissance elements, and supporting organizations on the Earth. The degree of local machine autonomy and remote monitoring and control has no parallel; extensive research and development in these fields will be required.
Materials to be mined should be selected on the basis of usefulness and ease

of extraction. The working group discussed specifically the mining of ilmenite for production of liquid oxygen (LOX) propellant, extraction of oxides for use in preparation of cement, and extraction from the soil of volatiles such as helium-3 (^{3}He), a stable isotope of helium and a potential fusion energy fuel. The first two processes are extremely energy intensive with projected requirements of several megawatts. An ilmenite reduction reactor runs at a temperature of about 1000°, but the extraction of calcium oxide from feldspars may well demand very high temperatures achievable only in a solar furnace. Most production processes can be serviced by a nuclear reactor. Rejection of waste heat will be a significant engineering issue on the lunar surface.

Since volatiles are dispersed at a low concentration throughout the regolith, an extraction facility might best be mobile. Capture and retention of very light gases such as hydrogen and helium will be a design challenge.

Working Group III.- Biosystems and Life Support

The Biosystems and Life Support Working Group realized that support for the activities of human beings on a planetary surface will evolve into a complex set of functions. The subjects discussed ranged from hardware to psychological settings to legal systems.

The CELSS is the major technological issue. A CELSS is an ecological entity and not just a controlled environment. Therefore, implementation is more than a straightforward engineering development program. Currently, identifiable questions on basic concepts far outnumber agreements on approaches. Hydroponics as opposed to agriculture, energy sources, initial module sizes, biological components (plants and animals), degree of automation, control philosophy (detailed monitoring vs. reservoirs), sources for chemical elements critical to biological processes, toxicity of ubiquitous lunar dust, and implications of one-sixth Earth gravity are some of the topics for study.

A few requirements can be quantified. The CELSS will be energy intensive, but its demands may be satisfied by low grade heat as well as by electricity. An industrialization emphasis at a lunar base may supply the perfect energy byproducts for life support, and the overall system design must include consideration of this important synergism. An unmanned precursor resource survey, such as can be performed by a lunar observer spacecraft, is vital for defining the global inventory of volatiles on the Moon. Availability of biogenic elements is a pivotal parameter for long-term strategic planning.

Certain elements of a research program have clear, immediate implications for terrestrial problems. A fundamental understanding of ecology, particularly the degree of closure as a function of scale, can be applied to problems of communities in various environments on Earth. A lunar system will have a large degree of automation, expressed as advanced control technology, expert systems, and even robotics. Advances in these fields should find marketable applications on Earth relatively soon.

Anticipation of a CELSS must be part of planning the buildup of even the first lunar outpost. Since elements needed to support life (i.e., carbon, nitrogen, hydrogen, potassium (K), etc.) may well be difficult to extract from the lunar regolith, the normally expendable hardware used in initial landings (e.g., descent stages, containers) should be designed with a view to being recycled on the Moon. Human waste is a valuable commodity, but probably will require sterilization before incorporation into a biosystem.

A life support system (LSS) in its broadest definition, must not only supply the elements essential for survival but also an environment for a productive existence. Communications, stress reduction, entertainment, a sense of well-being, freedom to innovate, a sense of self-determination, and adequate facilities and support are all part of a long-term presence. Many of these characteristics will require not only new approaches to program management but advances in technology as well.

Working Group IV. - Materials Processing

The Materials Processing Working Group did not try to define all the technologies needed for developing lunar industry, because the information available to them was insufficient for that task. Rather, they started from the point of view that the requisite technologies reside for the most part in the commercial sector. Consequently, conceptual definition of lunar processing can be an expensive effort if NASA must buy expertise in all conceivable processing technologies. In the long run, space development will be more robust if private enterprise is intimately involved. Is there some way to get the commercial sector involved soon in the conceptual design? Are there joint strategies involving NASA and industry which will enable us to exploit potential payoffs in lunar surface products?

Any evaluation of the commercial potential of lunar products must start with some determination of commodities which might have satisfactory markets, a characterization of the terrestrial processes used to produce those commodities, and finally an understanding of the constraints placed on those processes by the lunar surface environment. It is to be expected that the most common terrestrial processes will not be directly transferable to lunar production because of differences in economics, feedstocks, and services, as well as in environments.

Potential markets are activities on the lunar surface and in space, including low Earth orbit. Commodities marketable on the Earth ought to be rare, because of the high transportation and production costs. Exceptions include scientific samples, souvenirs, and the extremely scarce isotope ^{3}He, which conceivably could be a desirable fuel for future fusion reactors. Space applications which might utilize lunar products are life support; propellants; structures; binders to make structures, containers, and utensils; and catalysts, absorbents, and desorbents for industry and life support. Some of the elements needed for these products and processes are difficult to access on the Moon (as far as we know). Most products cannot yet be specified, but markets for all these items can be anticipated.

The working group recommended specific steps to promote the involvement of nonaerospace companies, which have traditionally produced goods and services and have not been associated with NASA technology development. A new relationship, initiated with modest joint endeavors, could have significant long-range benefits for both NASA and industry. The NASA could tap into expertise in technologies such as process engineering, fabrication, metallurgy, thermochemical processing, casting, and metals forming. Industry could gain new perspectives on technology development and have an opportunity to structure future space markets.

The group presented four proposed process schemes which might serve to catalyze a NASA/industry interaction. These candidate development projects were extraction of oxygen from lunar ilmenite, extraction of volatiles from the lunar regolith, retrieval of water and other volatiles from the martian moons, and production of propellants from the martian atmosphere.

Working Group V.- Innovative Ventures

The diversity of function in lunar base scenarios suggests major participation by nonaerospace industries. The postulated growth in the phases of development is a characteristic of privately financed projects, whereas public sector programs tend to remain constrained in scope. The Innovative Ventures Group addressed the question of whether or not the private sector could be brought into the planning process now as an active participant.

In the space program today, certain barriers exist which discourage private investment. For one thing, the context of space activities is unfamiliar to most industries. The NASA designs and operates its own projects, involving the private sector only as a contracted service function. In addition, markets for space technologies are limited, the only customer being the Government. Although future programs such as lunar base seem to require technologies which are more familiar to nonaerospace industry, corporate planning horizons do not normally extend to two or three decades over which a lunar project might be realized. Even if long-term plans were adopted, there would be an unacceptable gap between current investment and future profit.

If a company believes that its products or services might be adaptable to operations on a planetary surface, its options for exploring that possibility are limited. It can wait for NASA to declare a lunar or martian program and bid on requests for proposals involving technology development. In other words, it remains a client of NASA and stays dependent on public sector goals for project definition.

More freedom of choice in structuring technology development would accrue to the private sector if NASA (i.e., the Federal Government) guaranteed markets at a given level for a stated period of time. Although privatization of space services could lead to real growth in space investment, it is unlikely that NASA will change its method of operation soon.

The private sector can seize control by readying space technology in anticipation of its applicability. However, this strategy is realistic only if the development plan includes identifiable plateaus at which the research produces new marketable products to support the long-term investment. Companies may well wish to collaborate in the concept definition stage in order to spread risk.

The working group endorsed the third approach, despite difficulties in implementing it, because it offers the best chance to create an environment attractive to investment in space. A vigorous and viable private technology initiative can prepare U.S. industry for leadership in space, improve national competitiveness through cooperative technology enhancement, educate business leaders on future opportunities, establish the relevance of space exploration to the quality of life on Earth, and encourage NASA to think about the long term. The group adopted a plan for initiating a demonstration project, involving nonaerospace industry, by which the model for a private space technology development would be validated.

CONCLUSIONS

As NASA begins to consider planning settlements on planetary surfaces, the agency should recognize that major benefits would derive from collaboration with the private sector as a true partner. However, a joint vision requires restructuring of preconceptions about space development in both the public and the private sectors. The NASA must pay special attention to its roles as a purveyor of scientific exploration and as a developer of mature technology from high-risk research and development. Entrepreneurs can see profit potential already. Once they can reliably evaluate investment risk based on knowledge and predictability, they could change the U.S. space program from a small set of glamorous projects to an arena for national economic growth with the potential for world leadership. On the other hand, NASA policies are captive to the political process; therefore, visionary realists in the private sector are strongly encourged to establish foundations for future space investments through concrete demonstrations of benefits to investors and to the Nation at large. It is essential that both sides work to promote a vigorous civilian space presence because the vitality of 21st-century America may well depend on it.

WORKING GROUP REPORTS

INTRODUCTION

The primary products from this workshop were generated by the five working groups. Once given basic overall guidelines and the organizing committee's charge, the groups were allowed to function autonomously. There is some overlap of topics, due to each group's interpretation of its own responsibilities. Reinforced concrete and ^{3}He, for example, are discussed by more than one group.

An outline for working groups, titled "Charge to the Working Groups," was given to each group to provide a framework for discussion. The groups were also provided a list of questions to assist in defining details of potential resources, required technologies, space applications, NASA and industry planning, joint venture possibilities, and terrestrial commercial applications, as shown herein. It was not expected that anyone would have the answers to all these questions. However, this list can be used to structure thought on the issues that need to be addressed to realize the Nation's goals for space development.

The task of the working groups was not to detail every aspect of their assigned area, but to provide an overall understanding of the potential each offers, to define possible barriers, and to outline possible mechanisms for accomplishing this development. The groups were asked specifically to make recommendations as to the technology development needed to enable these options. The working group results can be used to assist space planners in making technology development decisions, as well as in offering the public, private, and academic sectors guidance on the manner in which each might fit into overall plans for space development.

Charge to the Working Groups

From studies of human exploration and settlement of space beyond LEO, an important planning principle has emerged. As we move away from the Earth, we must utilize resources as we find them. The locations of raw materials are the Moon, Mars, and the asteroids. Advanced planning scenarios have focused on the surfaces of the planets because they represent the most logical destinations for an extrapolation of the present Space Transportation System (STS).

For the Moon and Mars, the first practical utilization of resources seems to be the production of propellant. This activity demands a certain base level of infrastructure such as mining, thermochemical processing, transportation, communications, power generation, and habitation. The goal of human settlement of the solar system can expand upon this basic set in various ways.

Our goals will be (1) to describe these activities in terms of the technologies required, and (2) to evaluate these technologies as to readiness for utilization in space. For achieving these goals, we suggest the following process.

1. Identify and quantify (as far as possible) the types of planetary surface activities.
2. Identify technologies required to conduct these activities.
3. Quantify the projected performance level for the technologies and estimate the timeframes they will require.
4. Evaluate the readiness of technologies to meet requirements at the time they are needed.
5. Identify improvements needed so that projected performance will meet requirements for space initiatives in the appropriate timeframe.
6. Recommend NASA and industry directions and level of funding for adequate development.

Questions to be Addressed by all Working Groups

1. Resources
    a. Materials availability - What is the availability and ease of utilization of local materials?
    b. Power Capability - What are the power requirements and generation/cogeneration possibilities?
    c. Human productivity - How many people will be required to perform all functions?
2. Technologies
    a. What are the enabling technologies (i.e., those required)?
    b. What are the enhancing technologies (i.e., those that increase capability with nominal investment)?
    c. What are reasonable development plans and schedules?
3. Applications
    a. What products can be used locally (e.g., for lunar base)?
    b. What products can be exported and at what cost?
    c. Can raw materials be exported to be used as is (e.g., for radiation shielding) or to be used elsewhere for manufacturing finished products (e.g., solar power satellites)?

4. NASA and industry planning - What actions need to be taken now by NASA and industry to ensure national preeminence in space and space technologies?

5. Joint venture possibilities

   a. Is this the appropriate time for the public and private sectors to outline joint short-term and long-term space development activities?

   b. How should this joint activity be implemented?

6. Terrestrial commercial applications - What technologies have direct near-term terrestrial applications that can be used to encourage space technology development funding?

WORKING GROUP I
CONSTRUCTION/ASSEMBLY, AUTOMATION/ROBOTICS

Introduction

Working group I sought to understand and develop the requirements associated with the construction and assembly activities of a planetary base. There will be a strong emphasis on automation and robotics (A&R). Automation and robotics can augment human resources to decrease significantly both capital and operating costs. Working group I chose, as their example, the development of a permanent lunar base. This project is a leading candidate for the first planetary base to be developed as part of establishing permanent human presence in space. In addition, nearly all of the construction and assembly functions have analogous, if not direct, applications to other planetary surfaces.

The approach of working group I was to define the general construction activities associated with the most probable scenario for a permanent lunar base. The lunar base construction/assembly and A&R activities will be correlated to lunar base development phases for the purpose of tying technology developments to lunar base strategies rather than to dates and of permitting coupled decisions. The construction and assembly requirements and the technologies required to develop the necessary hardware can be related to the following five-phase development scenario.

1. Phase I: Exploration and site selection
    a. Orbiting geochemical mappers
    b. Surface explorers/sample return
2. Phase II: Temporarily inhabited outpost - Human access to surface
3. Phase III: Permanently inhabited base - Continuous human presence
4. Phase IV: Self-supporting base - Productive humans on the Moon
5. Phase V: Self-sufficient base - Independence from Earth supply

Certain functions and capabilities transcend many phases of the base evolution, specifically, multipurpose machinery and bulk building materials (e.g., concrete). These are discussed at the end of this section.

Phased Evolution of a Lunar Base

In previous studies, NASA has proposed various scenarios based on one or all of the rationales of scientific research, commercialization, or self-sufficiency. In the process of assembly, it soon became apparent that the development of the lunar base could be subdivided into mutually interactive phases, and that technologies, systems, and elements developed in earlier phases are prerequisite to the later phases.

I. Site Selection and Precursor Exploration

Because the scientific data base is incomplete, particularly in the polar regions, the first step in phase I is global mapping of the Moon, both with relatively high-resolution imagery and with remote-sensing measurements to determine the chemical variability. This task can be accomplished with an unmanned satellite, the lunar geochemical orbiter (LGO), which is a proposed mission in the NASA planetary program and could be flown in the 1990-92 timeframe. The LGO is in the Planetary Observer mission class, a low-cost approach to planetary exploration recommended by the report of the Solar System Exploration Committee (1983).

As a second step, phase I should include research on technologies necessary to exploit lunar resources. Technology development in resource problems on Earth is typically a long-lead-time process. At the conclusion of Phase I, the initial site for a base will have been defined and planned activities will be understood in some detail. Concurrently with this preliminary phase in the lunar program, development of Space Station and orbit 21 transfer vehicle (OTV) systems and elements capable of supporting a lunar base would be performed in the NASA STS program.

A site selection and precursor exploration would require the following capabilities:

1. Topological mapping
2. Geochemical assessments
3. Subsurface data acquisition
4. Sample return
5. Resource mapping
6. Lunar gravity mapping
7. Seismic data gathering
8. Analysis of data

Systems and elements for the lunar base would include

1. Geochemical orbiter mapper
2. Communication satellite located at second Laquangian point (L-2)
3. Surface landers
4. Rovers for sample return
5. Penetrators

No activities for construction, and assembly would be required, but A&R capability for autonomous sample collection and analysis would be needed. New technologies required for phase I are automated geochemical analysis technology, terrain recognition and obstacle avoidance for rovers, and teleoperation.

II. Temporarily Inhabited Outpost

At phase II, an initial surface facility would establish limited research capability for scientific, materials processing, and lunar surface operations. Depending on the long-term objectives of the lunar base program, the detailed studies and the experimental plans start to diverge at this phase for different scenarios. A focus on lunar science and astronomy would result in local geological exploration, the establishment of a small astronomical observatory, and emplacement of automated instruments. If production were the focus, a pilot plant for lunar oxygen extraction could be set up instead and study of the fabrication of aerobrakes from lunar material could be initiated. If the program goal pointed to achieving self-sufficiency, the emphasis at this stage could be on agricultural experiments utilizing lunar soil as substrate and recycling water, oxygen, and carbon dioxide.

To accomplish phase II in any hypothesized scenario, the STS must have the capability for descent to and ascent from the Moon, for transporting manned capsules (about 10 000 kilograms) to and from the lunar surface, and for delivering payloads of about 20 000 kilograms to the lunar surface. This capability involves delivering approximately 40 000 kilograms into lunar orbit using OTV's. Storage of the return vehicle on the Moon for extended periods (14 days to 3 months) may require new high-performance, storable-propellant systems at this phase of development.

In summary, a temporarily inhabited outpost would require the following capabilities:

1. Research and development (R&D) for lunar liquid oxygen (LLOX) products
2. Total Earth dependence
3. Habitation for as many as 4 persons
4. Power of 0.1 to 1 megawatt
5. Lift capability of 20 metric tons
6. Limited scientific experiments
7. Full-closure life support systems
8. Local, short-range personnel transportation
9. Earth to lunar surface delivery

Systems and elements for the lunar base would include

1. Gravity wave experiment
2. Far-side radio astronomy
3. Far-ultraviolet observations
4. Gamma-ray observatory
5. Infrared telescope
6. Search for extraterrestrial intelligence (SETI)
7. Geosynchronous orbit (GEO) relay communication satellite
8. Crane/soil mover
9. Solar and nuclear power
10. Unpressurized rover
11. Habitation unit
12. LLOX pilot plant

Activities for construction/assembly/A&R include

1. Moving and lifting 20-metric-ton payload
2. Preparing surfaces
3. Trenching
4. Covering with regolith (shielding)
5. Cleaning and dust removal
6. Minor assembly of large components

New technologies required include

1. Multipurpose construction equipment
2. Fully closed physical life support system
3. Airlock - dust control
4. Utility distribution - ground-grid power, thermal energy
5. Drilling

6. Explosive site preparation
7. Nuclear power generation
8. LLOX process

III. Permanent Occupancy

At phase III, permanent occupancy is the objective. The surface infrastructure would include greater access to power, better mobility in and away from the base, and more diversified research capability. Still, depending on the long-term objectives, the nature of the base can vary. A scientific base might emphasize long-range traverses for planetological studies or extension of observational capability with larger telescopes. A production base would incorporate highly automated systems to produce and transfer liquid oxygen for use in the near-Moon transportation system. Advanced research for self-sufficiency would lead to the first extensions of the base utilizing indigenous materials. The production and the self-sufficiency scenarios require a scaled-down version in lunar space (lunar orbit or an Earth-Moon libration point) of the Earth-orbit Space Station to provide for transfer, refueling, and maintenance of the lunar lander and the OTV's.

Permanent occupancy would require the following capabilities:

1. Additional scientific experiments
2. R&D for bioclosure LSS
3. LLOX utilized in near-Moon transportation system
4. Power of 1 to 10 megawatts
5. R&D for ceramic process
6. Long-range personnel transportation
7. Earth to lunar surface delivery capability of 40 metric tons
8. Permanent habitation for 5 to 10 people

Systems and elements for the lunar base would include

1. CELSS experimental laboratory
2. Life science research module
3. Low lunar orbit space station
4. LLOX production plant
5. Laboratories

6. Shops
7. Pilot ceramic plants
    a. Fiberglass
    b. Building blocks
8. R&D for primitive construction techniques
9. Pilot powder metallurgy plant

Activities for construction/assembly/A&R include

1. Major assembly tasks of large units delivered from Earth
2. Building roadways

New technologies required include

1. Commercial LLOX production techniques
2. Metallurgy processes
3. CELSS technologies
4. Ceramics processes
5. Massive soil handling
6. Primitive enclosures - inflatable
7. Shaped-memory effect techniques

IV. Self-Supporting Base

At phase IV, the base is envisioned as having achieved a balance of trade with the Earth. It is not self-reliant to the extent that the umbilical to Earth can be severed; however, its productive value has increased and its support requirements have been reduced so that imports are balanced by exports. For a scientific base, these exports are largely intangible because they are knowledge products from significant lunar laboratories and astronomical telescopes. For a production-oriented base, lunar oxygen supports not only the near-Moon transportation system, but supports all transportation out of the LEO spaceport as well.

A self supporting base would provide the following capabilities:

1. LLOX marketed to other users
2. Habitation for 10 to 100 persons
3. Capability to expand living space with in situ resources
4. Power 10 to 100 megawatts

Systems and elements for lunar base would include

1. Operational ceramics plant
2. Pilot volatile recovery
3. Pilot metallurgy plant
4. Habitats of primitive construction
5. Pilot agriculture

Activities for construction/assembly/A&R include

1. Automated, long-term, long-range, volatile harvesting
2. Primitive construction - Bricklaying, concreting, foundations, and airtight structures

New technologies required include

1. Mobile machinery to extract volatiles
2. Primitive construction
3. Glazing/sealing
4. Concrete technology

V. Advanced Self-Sufficient Base

The advanced self-sufficient base, phase V, is even more specialized. Depending on the long-term plan, it produces more types or a greater range of scientific investigations, adds products to the growing lunar industrial base, or enters a phase of significant expansion of capabilities using lunar materials for most of the feedstock. Phase IV was the terminal phase for the scientific and production scenarios. Future growth in phase IV may occur by enlarging the number of experiments or products produced on the Moon, but a self-sustaining capability is not included. The production base might even develop toward a highly automated state in which permanent occupancy would be unnecessary. For the production and science scenarios, the base should begin paying its own operational costs. However, in the self-sufficiency scenario, research and development of pilot plants aimed at a broad range of indigenous lunar technologies would be pursued. The final phase of the self-sufficiency scenario is truly an autarkic settlement, a lunar colony, in which the link to Earth is optional.

An advanced self-sufficient base would provide the following capabilities:

1. Long-term operation with interruption of Earth supply
2. Farms
3. Capability for growth without Earth supply
4. Power of >100 megawatts
5. Complex construction-metals-fiberglass-welding
6. Lunar-derived power, habitation, and propulsion
7. Advanced technology materials processes
8. Habitation, for >100 persons

Systems and elements for the lunar base would include

1. Metal castings plant - structural steel
2. Farms
3. Operational lunar-based propulsion and power

Activities for construction/assembly/A&R would include fabrication and complex construction.

New technologies required include metal cutting and welding.

Lunar Base Elements, Activities and New Technologies

The nature of the requirements for construction and assembly of the primary lunar base systems evolves with the growing base. Initial emphasis is on soil movement to prepare the site for simple docking-type assembly of prefabricated elements delivered from Earth. Much of this activity should be automated or teleoperated since lunar base crew size will be limited and maximum leverage of human resources will be needed.

As the base grows, the construction and assembly requirements become more diverse. The greater use of local materials, will complicate both construction and assembly. Construction projects will become much larger. Greater diversity will also be seen in habitats, with perhaps subsurface and inflatable habitats augmenting the buried common modules.

Lunar development will be largely underground, to protect against the natural radiation environment. Techniques for excavating, covering structures with lunar soil, and tunneling will be required. Larger crew sizes will allow hands-on use of multipurpose construction equipment for the diverse activities which we can not fully predict now. These activities may be automated after the process is well known and routine.

Initially, most construction and assembly will be performed in the lunar vacuum. With growth of larger volumes, some construction within pressurized spaces will be possible. Eventually, facilities will be developed to manufacture certain machines or parts of machines.

Multipurpose Construction Machinery

The increasingly diverse nature of the lunar base will require construction equipment that can perform a large number of functions. In addition, this equipment may be operated in a number of modes - initially with a hands-on operator, then teleoperated, and eventually completely automated once the process is well known.

At least four factors affect design considerations for all construction machinery in the early stages of a lunar base: 1. Very little long-term continuous single activity is required, contrary to activity in normal terrestrial applications. 2. Many diversified tasks are necessary; therefore, specialization of equipment is precluded. 3. Activities are contingent on the details of the environment. New tasks will be defined as requirements emerge, accomplished by new applications of existing equipment. 4. All activities performed outside the habitat (i.e., in vacuum) must be done with minimum human intervention.

As a result, four design requirements emerge: (1) exchange of single-purpose machine designs for others capable of diversification, (2) Setting of self-repair and self-reconfiguration as important design goals, (3) achievement of a high degree of autonomy, and (4) maximization of teleoperated/telesupervised functions.

Building Materials

There is a great need for basic, innovative thinking with respect to building materials. The lunar base will never approach economic viability until a substantial portion of the materials needed for base growth are produced locally. Construction materials from the Moon include sintered or melted soil or rock, concretes, and metals. Other options include utilizing process slag from metals production for materials feedstock and volatiles extraction or even filling lunar-fiberglass bags with regolith. Techniques for producing basic materials, such as sintered blocks or cementitious materials for concretes, are needed, as are new techniques for assembling, joining, and forming these materials in the lunar environment.

Concrete was identified as a candidate for the construction of structures, shapes, and shielding on the Moon. Concrete has high compressive strength and impact resistance, is an effective radiation shielding and a good thermal insulator, and can be cast in various shapes and sizes (precast and moved, or cast in place with inflatable forms). However, concrete has relatively low tensile strength, and must therefore be reinforced to withstand significant stress.

Perhaps the most important fact is that 99 percent of all the materials necessary for the production of cement and concrete are readily available on the Moon. All Apollo samples contain the major constituents of cement: silicon (Si), aluminum (Al), and calcium oxides (although some were relatively deficient in calcium oxide). Suitable aggregates are available to be combined with cement to form concrete.

The main compound missing is water. It would be very valuable to find water below the surface or in shadowed polar craters. If water is not found on the Moon, then hydrogen will probably have to be imported, possibly as methane or ammonia. Ilmenite (iron titanium oxide) can be reduced with hydrogen to produce iron (FE)(for reinforcement) and oxygen (for breathing, water, or export).

Water is expected to be found in usable quantities on the martian moon Phobos and could be imported to the Moon when economically viable transportation systems become available. Another option is to replace the water with polymeric materials for concrete production. Initial findings show increased strengths while using a larger portion of readily available lunar compounds.

WORKING GROUP II
PROSPECTING, MINING, AND SURFACE TRANSPORTATION

Introduction

The Prospecting, Mining, and Surface Transportation (PMST) Working Group focused on locating, extracting, and transporting useful resources. In a manner similar to that used by the Materials Processing Working Group, they also made an assessment of the useful resources that exist in the inner solar system. Whereas the Materials Processing Group focused on the value of nonterrestrial resources as marketable commodities and the infrastructure required to develop and market them, the PMST group evaluated the resources from the stand-point of availability and ease of extraction and utilization. Specifically, they investigated this activity in development phases:

1. Prospecting, to assess the resources available, the locations, and the quantities

2. Materials selection, to choose the resources of greatest value with minimum extraction and processing effort

3. Mining, to define parameters and potential optimum development paths

4. Transportation, to understand the options and considerations of moving resources and support elements (including people) to necessary locations

The PMST group also identified automation/artificial intelligence (AI)/robotics as key elements for PMST activities.

Automation/AI/Robotics

Significant advances are required in automation/AI/robotics for mining, transportation, and prospecting. It is predicted that early missions can be accomplished using applications based on Space Station controls technologies and automation as used in unmanned planetary exploration missions. Tasks will become more complex as activities evolve. Increasing human resources (i.e., larger crew sizes) will allow humans to perform the most complex and least understood tasks initially; eventually, more and more of functions will be performed by machines as the tasks are better understood and machine intelligence technology is improved.

Automation must be distinguished from robotics. Automation implies use of standard control systems and is available now for the PMST equipment proposed. Robotics implies use of nonstandard control systems and will require new R&D for the PMST equipment. Space Station automation and robotics R&D should satisfy most of the requirements, at least making telerobotic control systems possible at the outset of lunar operations.

Control systems must be designed to evolve from a telerobotic to an autonomous state in advanced stages of lunar operations. Several stages of semiautonomy are required, characterized by increasing difficulty of hardware and software design and by reduction in the number of people required for onsite operations. Maintenance technicians will be required throughout all phases of human presence.

Semiconductor-computer industrial experience with telerobotics should be applicable in the early stages. University research will be essential for latter stages, particularly in the areas of expert systems development, simulation and modeling, multisensor input analysis, judgmental decision-making, image reduction and interpretation, real-time response, and efficient bioheuristic algorithms.

A lunar knowledge base must be designed, loaded with all data presently available, and kept current during all Space Station and lunar operations. This knowledge base should be structured for easy access by individuals and by expert systems and should be language-independent. It should also feature standard key-coding of all equipment parts and tools. Finally, it should be archived on Earth.

A high-capacity communications network must be designed to become operational during the initial stage of lunar development. It must be capable of sustaining all nodes of the infrastructure in parallel, including the lunar base, Earth stations, and the PMST equipment. It also must be capable of handling full-color video data, of compensating for transmission time delays, and of using standard protocols.

Computing systems capable of managing communications and telerobotics are available, but further development is required for telescience applications. These include man-machine interfacing, bandwidth management, network topology, and nodal design.

Computing systems capable of managing autonomous robotic equipment are not yet available and will require extensive research and development to achieve confident supervised use. This stage may be reached in Space Station R&D.

Prospecting

Robotic prospectors will precede extensive human exploration of the Moon. A dedicated, state-of-the-art lunar orbiter will be capable of covering a much larger area than would ground vehicles for general evaluation of potential areas of useful resources. Ground rovers will be highly instrumented and will make the final assays of resource availability. Telescience (onboard collection and analysis with findings transmitted to humans at a central location) will be a key aspect of rover system design.

General objectives of surface prospecting will be primary differentiation of mineralogy and petrology, location of water, and return of samples to base for detailed analysis. The prospecting vehicles will be expected at a minimum to be capable of traversing 40 to 50 kilometers round trip to obtain diverse samples or to survey and investigate a single site (1 to 10 km/day traverse capability). The prospecting vehicles might be expected to operate autonomously for several years.

The scientific instrumentation package for the prospecting vehicle (rover) has yet to be defined. Instruments or capabilities that could be developed for rover deployment include

1. Sample collection, manipulation and preparation hardware (including drill)
2. Stereoscopic visual imager
3. Ultraviolet photometer
4. Atmospheric pressure/temperature sensors
5. Mass spectrometer (chemistry)
6. Gamma-ray spectrometer
7. Alpha-backscatter spectrometer
8. X-ray fluorescence spectrometer
9. X-ray diffractometer
10. Optical microscope
11. Scanning electron microscope
12. Magnetometer
13. Active seismometer (explosive charges)
14. Passive seismometer
15. Scanning calorimeter
16. Soil water detector
17. Biology experiment

The specific instrument complement will depend on the application to the Moon or to Mars and on the intent (e.g., science, resource assay).

Given the restricted payload capacity of the rover, a decision will have to be made regarding the number of samples to be returned and the size of each sample. Other considerations include complexity of the sample collection tools and the systems automation required. Initially, a variety of sampling tools, each used for a limited set of environmental conditions, probably will be employed. This approach would minimize the complexity of any particular tool and thereby simplify the determination of possible failure modes. Thus, a strong arm would be used to obtain and position large rocks and a high-resolution arm would be used to take the sample. The quantity of tools, however, would complicate storage and consume mass and volume that might otherwise be occupied by payload.

Once environmental conditions are better understood, advanced versions of the rover will likely use a flexible arm, a dexterous hand, and a limited number of tools. This change will increase the complexity of both the hardware and the software and thus will require control architecture which incorporates tactile feedback at fingertips for dexterous manipulation and parallel processing of multiple sensor inputs. Neural networks may be used to control the automated sample acquisition systems.

Materials Availability, Selection, and Power Requirements

Figure 1 contains a list of useful resources and the sources from which they can be obtained. These materials have been identified for mining on the basis of the ease of extraction from the environment, the manner in which the resources can be used, the power required for processing, and the amount of bulk material that must be processed to obtain the ore (degree of beneficiation). Based on the propellant required for transportation to Earth orbit, the Moon, martian moons (Phobos and Deimos=, P/D), other "wet" asteroids, and Earth-crossing metal-rich asteroids have been identified as exporters, whereas Mars and the gas giants are nonexporters. Figure 2 shows the markets (and nonapplicability, N/A) for these resources.

The Moon is composed of 42 percent oxygen, 21 percent silicon, 13 percent iron, 8 percent calcium, 7 percent aluminum, 6 percent magnesium (mg) and 3 percent other materials. These lunar resources can be processed into useful materials including shielding regolith, ceramics, anhydrous structural glass, other structural materials, oxygen, iron, titanium (Ti), silicon, carbon, nitrogen, hydrogen, and helium. Unfortunately, the volatiles (C, H_2, H_2, and He) are in fairly low concentrations.

It might be possible, however, to obtain many different materials from the same ore. For example, the iron-titanium oxide ilmenite, is relatively plentiful. To manufacture 1000 tonnes of LOX propellant, 100 000 tonnes of raw regolith must be processed. This same ilmenite can then be used to produce around 3400 tonnes of iron, 5200 tonnes of titanium oxide, 7 to 13 tonnes of silicon, 1 to 15 tonnes of carbon, 1 to 10 tonnes of nitrogen, 0.6 to 7 tonnes of hydrogen, 0.3 to 3 tonnes of helium, and 140 to 1400 grams of helium-3. The plant power requirements are forecasted to be 2 to 6 megawatts.

The martian moons, Phobos and Deimos, resemble a class of carbonaceous asteroids that may be similar to carbonaceous chondrite meteorites, which contain 2 to 20 percent water. These moons could be used to produce large quantities of bulk regolith, water, oxygen, hydrogen, and carbon compounds. If they are 10 percent water, 1000 tonnes per year can be mined using about 0.2 megawatt of power. The water can be electrolyzed to produce about

Material / Source	Regolith	LOX	H_2	^3He	Fe	Ti	Carbon compounds	H_2O
Moon	X	X		X	X	X		
Mars	X	X	X		X			X
Phobos/ Deimos		X	X				X	X
Asteroid		X*	X*		X	X	X*	X*
Gas giants				X				

*Chondritic asteroids

Figure 1.- Nonterrestrial material sources within the solar system.

		Location produced					
		Moon	Earth	Mars	P/D	Asteroids	Gas giants
Location utilized	Moon	▨	All mfg. H_2	N/A	C H_2O	Cond. (as P/D) Ni, Fe, precious metals	H_2, H_2O ^3He
	Earth (LEO, GEO)	LOX Reg. ^3He	▨	N/A	C	Cond. (as P/D) Ni, Fe, precious metals	^3He
	Mars	^3He	All mfg.	▨	C	Cond. (as P/D) Ni, Fe, precious metals	^3He
	P/D	N/A	All mfg.	N/A	▨	N/A	N/A
	Asteroids	N/A	All mfg.	N/A	N/A	▨	N/A
	Gas giants	N/A	All mfg.	N/A	N/A	N/A	▨

Figure 2.- Markets for nonterrestrial resources.

900 tonnes of oxygen and 100 tonnes of hydrogen using 0.8 megawatt of power. These products can be used as chemical propellants to significantly lower the cost of Mars-Earth transportation.

Certain research issues in materials availability and power requirements should be examined. What is the impact of the lack of "ground truth" samples for Mars, Phobos, and Deimos? What is the most appropriate method to extract lunar volatiles (i.e., crushing vs. heating, solar vs. nuclear power, and collection methods)? What is involved with the extraction of metals, e.g., iron and nickel (Ni) (asteroids)? A complete systems analysis is needed, from collection to production, with practical validation. The competing processes should be ranked. For example, what are the advantages of extracting hydrogen as opposed to carbothermal production of oxygen from ilmenite? Finally, regolith beneficiation processes should be more precisely defined.

Selected Applications - ^{3}He and Concrete

Two examples are used to illustrate the uses of nonterrestrial resources. These are ^{3}He and reinforced concrete.

Helium-3

Large-scale space development will be accelerated if nonterrestrial resources that would have a market on Earth can be found. This is not an easy task. The transportation costs of getting a commodity to the surface of the Moon is three times its mass in gold with similar costs to ship from the Moon to the surface of the Earth. Therefore, the only resources that can be economically exported to the Earth are those that are extremely rare or nonexistent on the Earth. The first material discovered that meets this specification is ^{3}He. There may be others on the Moon. The ^{3}He isotope serves as a useful example to understand something of this potential.

Lunar ^{3}He is proposed as a potential fuel for fusion reactors in space and on Earth. The ^{3}He has certain advantages over the other two potential fusion fuels, deuterium and tritium. Unfortunately, almost no ^{3}He is available from the Earth. Apollo samples reveal small quantities of ^{3}He, implanted in the lunar regolith by the solar wind. Although the ^{3}He exists in very low concentrations (e.g., 100 square miles would be required to obtain 20 tonnes of ^{3}He), the Moon is predicted to contain approximately 1 000 000 tonnes. This is enough ^{3}He to provide 40 000 years of electrical energy to the United States at current consumption rates.

One kilogram of ^{3}He can produce 10 megawatt-years of electrical energy. Therefore, 20 tonnes of ^{3}He, an equivalent Space Shuttle Orbiter payload, can supply U.S. energy needs for a year, at a value of $50 billion.

Energy is produced in the D/^{3}He reaction by fusing 3 parts ^{3}He with 2 parts of readily available deuterium. There are many technological reasons to pursue D/^{3}He fusion for terrestrial as well as space applications. Greatly reduced neutron production results in reduced radioactivity, 2 to 3 orders of magnitude less than that of deuterium/tritium (DT) fusion and 6 orders of magnitude less than that of fission. Thus, no geologic waste disposal is required.

Radiation damage is also reduced. Reactor walls are expected to last 30 years at full power production. Because no tritium breeding is required, operations are simpler and material choices are more flexible. It is inherently safe, with no chance of meltdown and with greatly reduced tritium inventories. The cost of electricity is lower, at least a factor of two less than that produced by DT, because of higher net plant efficiency, higher availability, and lower complexity required to isolate the reaction.

At a possible projected value of $2.5 million per kilogram, ^{3}He is the only material discovered so far on the Moon that is economically worth bringing back to the Earth. The energy payback ratio to mine, evolve, separate, and transport the ^{3}He from the Moon to the Earth is about 250. Less than 2 percent of the Moon's ^{3}He could provide 50 percent of the projected world energy requirement in the 21st century.

Concrete

Concrete is a candidate for the construction of structures, shapes, and shielding on the Moon. Concrete has high compressive strength and impact resistance, is a good radiation shield, is a good thermal insulator, and can be cast in various shapes and sizes. However, because of relatively low tensile strength, it must be reinforced when stressed. Ninety-nine percent of all materials necessary for the production of cement and concrete are available on the Moon.

The largest single obstacle to traditional cement production on the Moon is the need for water. Because the Moon has very low concentrations of water, hydrogen would probably have to be imported, possibly as methane or ammonia. Another option that bears research is the possibility of non-water-based cement, using, for example, polymers instead of water.

Concrete materials processing has been considered. It may be possible to separate cementitious materials by differential heating and evaporation. Calcium, aluminum, silicon, magnesium, and iron have condensation temperatures at least 200 degrees K higher compared to noncementitious materials. Temperatures as high as 3000 K needed for some processes may present containment problems.

Lunar rocks can be crushed to coarse aggregate sizes. Lunar soils can be sieved to provide fine aggregates. Casting and curing chambers will be needed to control temperature and humidity and to recapture excess water. Concrete may be cast in place using inflatable forms or precast and moved to the construction site.

Most of the foregoing discussion also applies to Mars. There are some differences. Because water is available on Mars, importation of hydrogen is not necessary. It is believed that cementitious materials are available on Mars, but this availability must be confirmed. Similarly, martian aggregates are probably adequate, but this adequacy remains to be verified. Because of the greater gravity on Mars compared to the Moon (2/5g vs. 1/6g), concrete sections may have to be thicker, and thus more materials and longer construction time may be required.

Certain research issues arise. The cementitious materials that can be derived from the Moon must be determined. The performance characteristics of preferred cements using lunarlike aggregates should also be determined. The process, feasibility, cost and power requirements for separation of cementitious materials from noncementitious materials should be studied. A conceptual design is needed for aggregate processing and transporting, and for concrete mixing, forming, placing, and curing, including cost estimates and power requirements. The research issue for Mars is the determination of the suitability and adequacy of soil and rock resources for cementitious materials and aggregates for concrete.

Mining

Mining activities will evolve from small, exploratory sites to large, open-pit mines. The easiest material to mine will be loose regolith deposits. Mining of regolith containing large boulders or hard rock layers will require some sort of fragmentation technique to prepare the material for processing. This preparation could possibly be done with solar energy (during the 14-day daylight cycle) using parabolic collectors for thermal fragmentation or by standard drill-blast methods.

In one mining scenario, the excavation, transport, and dumping into the crusher is performed by an excavation vehicle powered by solar energy (collector) and Stirling-type engine. The crusher is a movable in-pit type which also runs on solar energy. The crushed regolith is moved to the electrostatic separator. As the pit area grows, a dozer vehicle will be required to transport the mined regolith to the separator.

The electric processing plant is stationary and should be placed near the mine. The plant is used for the hydrogen reduction of ilmenite and consists of

1. Electrostatic separator
2. Reactor for removing oxygen from ilmenite using hydrogen (the reactant to produce water vapor)
3. Electrolytic separator for extracting oxygen from water vapor and recycling the hydrogen
4. Oxygen refrigeration (to liquid) for storage and local use or export

Power requirements for the excavation, transport, and dumping of the ore vehicle can be met by a 20-foot-diameter solar energy collector with

Stirling engine. The estimated power needed is 500 kilowatts. The power requirements for the crusher vary with the deposit and the capacity. The estimated requirement is 300 to 600 kilowatts. Electric power will be most convenient for the crusher and also may be used for the excavation/dozer vehicle for short distances from the crusher using ground cable with takeup reel.

All machinery in this scenario uses solar-electric power. Other options include cabled electric power from a central nuclear source or a small nuclear power generator onboard. The excavator and the dozer could also be replaced by a drag supported by cables and three pylons on the periphery of the mine. The cable lengths are adjusted to determine the path of the drag.

Research issues that must be given further attention include a definition of the lunar environmental effects on

1. Surface friction
2. Regolith/rock characteristics
3. Fine-particle characteristics
4. Surface adhesion
5. Mining equipment design selection
6. Mining equipment performance
7. Material handling and storage

Innovative mining and processing methods and systems for use in the lunar environment are also needed. These issues also apply to the Mars environment.

Transportation

A number of options are available for surface and atmospheric (Mars) transportation. Four examples will be shown here to illustrate the general classes of transportation. They are wheeled vehicles, magnetically levitated vehicles, ballistic hoppers, and the Mars airplane. Except for small variations, the surface vehicles can be used on the Moon or on Mars.

Wheeled Vehicles

Wheeled vehicles can include standard round wheels, loop wheels, or treads. Maintenance/reliability can be a problem because of many moving parts with bearings and friction, dust occlusion, outgassing of lubricants, and problems with dissimilar metals and bearings. Vehicle materials are generally aluminum and fiberglass. System command and control will be teleoperated initially, with later versions fully automated. The guidance, navigation, and control (GN&C) system design will build on rover GN&C technology developed for the Mars rover sample return (MRSR) mission. Design options include multicab vehicles (three or more cabs). Active coupling between cabs would provide pitch/roll/yaw control and self-righting capability following a tipover.

Magnetically Levitated Vehicles

Traditional magnetically levitated, or maglev, vehicles require only 60 percent of the power of wheeled vehicles. With the advent of high-temperature superconductors, this power requirement may be lowered significantly more.

The vehicle rides on a central aluminum or iron support rail. Dust on control or electromagnetic surfaces could be a critical problem. The vehicle is made primarily of aluminum and fiberglass. Magnets would have to be ferrous with some rare Earth elements (trace). Windings for the motors could be aluminum but should be copper. Insulation material would be critical. The system command and control would be fully automated with advanced computer and video controls. Communication systems usually use frequency-modulation-band, wire, or antenna.

The primary problem with maglev is that it is not flexible to new routing as are wheeled vehicles. However, for frequently traveled routes, maglev has some decided advantages. Capital costs of maglev and wheeled vehicles are about the same. Maglev requires only 15 percent of the maintenance of wheeled systems. Operating costs for maglev should be lower. In addition to requiring only 60 percent of the power of wheeled vehicles, maglev vehicles also require only 60 percent of the manpower support. For comparable capability, maglev is 50 percent of the gross weight of a wheeled vehicle.

Ballistic Hopper

The ballistic hopper was developed primarily for Mars. It uses rocket propulsion to cover large distances in short time periods. The martian environment is well suited to this concept. The moderate gravity allows for lower propellant requirements than on Earth. The atmosphere can also be used to produce propellants using ISPP. The atmosphere is dense enough to be used as a re-entry brake, but produces only moderate drag in launch mode. The design vehicle weighs 2100 kilograms, with a payload of 750 kilograms, propulsion system of 1000 kilograms, and structure of 350 kilograms.

A Mars hopper is considered a viable concept. It can be developed based on near-term technology. Such a system will allow long distance martian exploration, with simultaneous extensive and intensive science capabilities. Mass required on Mars surface is equal to the baseline for the MRSR mission. The ISPP technology will be required. Restartable, highly reliable engines will also be required. The autonomous computational requirements are fairly simple. There are also a minimum of indeterminate interactions with the martian surface.

Mars Airplane

The final class of transportation examined is the Mars airplane, which has been under study at the JPL and elsewhere for many years. The Mars airplane would be a small (500 to 1500 kilogram) unmanned vehicle to traverse large distances and perhaps collect remote samples from areas such as the polar caps. Of the many options studied, the hydrazine-powered, reciprocating engine using a kinematic Stirling cycle appears to be the best option.

WORKING GROUP III
BIOSYSTEMS AND LIFE SUPPORT

Introduction

The working group on Biosystems and Life Support for the ISRU Workshop attempted to focus on many issues facing long- and short-term lunar base life support systems and its infrastructure. The range was from legal, ethical, and psychological issues to complex hardware and biology. It was apparent that there was not one simple answer to such a complex problem. The following sections will deal with the salient issues that were raised and the potential solutions.

In addition, a program of achieving the goal of a self-sustaining lunar base was developed. This program, although sketchy and incomplete, could assist in the future planning for a lunar base.

LSS Requirements

The following items are required for a successful lunar base:

1. Atmosphere
2. Food
3. Water
4. Light (natural and artificial)
5. Energy
6. Waste management
7. Communications
8. Health maintenance
9. Training and operations
10. Maintenance and resupply
11. Contamination control
12. Fire and damage control

Atmosphere

The atmosphere of a lunar base must contain all of the essential gas components in the correct proportions (O_2, CO_2, etc.). The maintenance and regeneration of this atmosphere could be performed with physicochemical (PC) systems, biological systems, or hybrid systems. Each of these systems has an advantage during different stages of a lunar base development.

PC Systems.- Physicochemical systems of proven reliability and relatively compact size and weight should be utilized in the early stages of lunar base development. Systems similar to those planned for the Space Station would be sufficient for short-duration missions to the Moon. Although usable for short-duration, exploration missions, PC systems require excessive energy, are expendable, and will eventually require resupply. A longer mission would require a biologically-oriented system.

Hybrid Systems.- Hybrid systems such as the existing CELSS technology should be considered for longer duration lunar missions. These systems are not totally biological, but essential biological components help close the air and water cycles a little tighter than to PC systems.

Biological Systems.- Only a fully complex and diverse biological system is capable of providing closed-cycle support of a long-duration lunar base with ecological stability and resiliency. The agricultural systems contained in such experiments as Biosphere II can serve as prototypes for these biologically based systems. The basis of these types of systems is the extensive utilization of microbial action to cycle water, atmosphere, and nutrients in a manner similar to natural recycling processes.

Food

Food is an essential component of any viable life support system. Quantity, quality, and variety are the basics for long-term psychological and physical support. Merely meeting the bare nutritive needs of the personnel will not suffice for long periods. There are three ways of providing food for the lunar missions. The method chosen would be closely coupled to the mission type and duration. Short-term missions would not need a food production system and could easily utilize the existing food processing technology developed for other space missions. Missions of longer duration would need food production systems based upon CELSS technology. The CELSS food production is based upon a limited variety of food crops and supplemental calories and vitamins. Permanent lunar bases would need extensive biologically based agricultural systems with a wide variety of cultivars. The system would need to be closed and totally regenerative. Research in this area is also required. Work is already well under way at The Environmental Research Laboratory, University of Arizona.

To ensure proper function of a microbial-based food production system, good soil systems must be developed. The work at The Land Pavilion, EPCOT Center, on lunar soil simulants will greatly help in this development. Compared to hydroponic systems, soil-based agricultural systems are far more resilient and can be made as productive. Soils research is imperative for a permanent LSS.

Water

The recycling of water is essential to any lunar base mission. For short-duration missions, the PC recycling systems would be adequate. For longer term missions, CELSS-type systems would provide this water recycling along with some mechanical systems. For permanent lunar bases, a full bioregenerative system would be required. Closing the water cycle is extremely important for permanent lunar base LSS's.

Light

Because of the 14-day/night cycle and the need for radiation shielding, transparent lunar structures are not very practical. Some natural lighting could be brought in to the shielding habitat by way of lightguides and pipes. Light would have to be provided by artificial means during the lunar night. This lighting could be of the conventional electric type or could even be radioisotope-based lighting.

Energy

A lunar base of any duration would be, by nature, energy intensive. Short-term missions would require energy to drive the PC systems, but energy is also required in the operation of CELSS-type systems and of fully biological systems. Energy could be provided by solar systems with large storage capability, or, more practically, nuclear power could provide the entire lunar base energy requirement. Bioregenerative systems should be considered as net energy consumers and open to energy exchange.

Waste Management

The management of biological waste is an essential function of an LSS. Again, the type of management system chosen would depend on the mission duration.

Human waste materials must be sterilized to prevent spread of human pathogens. Sterilization by radioisotopes would be very effective. Permanent lunar bases would utilize a complete biological waste decomposition system.

Communications

All lunar base missions would need extensive communications support both for logistics and for entertainment. Design of the LSS should incorporate audio, video, and data communications with sufficient reliability and redundancy so as to remain operational during resupply interruptions or power outages.

Health Maintenance

The health maintenance of a lunar base LSS falls into two basic categories - plants and people. The health maintenance of the people also has two aspects: physiological and psychological. Careful consideration must be given to these systems.

Plants.- The plants will require an extensive and sophisticated program of integrated pest management, which includes control of insects and pathogens, and effective cultural techniques that promote optimum plant productivity. The plant/soil/ microbial system is an essential and critical element of a self-sustaining bioregenerative LSS and therefore must be given careful attention. Proper sizing, management, maintenance, and operations of plant systems are required. Immediate research in this area is necessary to ensure readiness when the technology is needed.

People. - The people will require medical support, proper nutrition and environmental support. The medical infrastructure should be further developed. It is clear that the larger the lunar base population, the better can be the medical care, since full-time medical support personnel would become a reality. In addition, experience has shown that the quality of life is very important in order to have a viable, long-term habitation. The psychological and esthetic needs of the lunar base inhabitants should be considered carefully. The mental stress of living in a confined mechanical system has been shown to have deleterious effects on the inhabitants over a long period. Humans have a basic need for interactions with other forms of life, both plants and animals. These plants and animals not only could satisfy the psychological needs, but could also provide the essential components of the LSS.

Training And Operations

Proper training and operational support is required for lunar base LSS's. The complex PC systems will require maintenance and operating knowledge. Bioregenerative systems will require training and operations in different disciplines (horticulture, agriculture, pathology, entomology, etc.).

An LSS based on CELSS technology or a fully bioregenerative system would require considerable operations time to ensure proper function. Food production would consume a substantial amount of time. There is a need to automate the food production and recycling system as much as possible. The use of robots could greatly assist in managing the workload.

Maintenance And Resupply

The capability to maintain and resupply a lunar base LSS is extremely important. Resupply schedules should coincide with crew rotation schedules. The lunar base LSS must have sufficient redundancy to ensure continuity if resupply schedules are interrupted. The PC systems have limited capability to withstand long-term interruptions and thus are more prone to failure. On the other hand, closed biological systems have built-in mechanisms which can help mitigate resupply interruptions. In fact, properly designed closed biosystems would not require resupply for extremely long periods.

Contamination Control

The capability to decontaminate the air and water of a lunar base habitat is very important. There are PC systems which, for short periods extract contaminants from the air and water. These contaminants are generally stored and then disposed of externally. For permanent lunar base LSS, contaminants need to be decomposed and returned to the LSS as usable material. Microbiological systems are capable of recycling most of these contaminants (organics, nitrogen and sulfur compounds, etc.) efficiently.

Fire & Damage Control

One of the greatest hazards facing a lunar base would be fire. Because of the presence of organic materials in an LSS (based upon CELSS technology), fire detection and control is important. Penetrations of the containment envelope (which would result in loss of atmosphere) would be the next greatest hazard.

LSS Implementation Strategy

A strategy of lunar base LSS implementation was developed during this workshop. The following schedule would be useful in the implementation of a permanent lunar base:

1. Use existing/technology to establish lunar base
2. Integrate CELSS R&D experiments with initial lunar base
3. Bring bioregenerative systems on line
   a. Use PC systems as buffers or backups
   b. Use terrestrial and Space Station demonstrations

Use of Existing Technology

To establish an initial lunar base, existing technology should be used as much as possible for accomplishing the mission. Each mission (short duration) would be self-contained and not dependent on permanent LSS's. Expendables and waste products from these missions should be carefully designed and managed so as to be the organic feedstocks for longer, more permanent lunar base LSS's. All equipment, hardware, and expendables should be considered building blocks and feedstocks for the permanent LSS.

Integration of CELSS R&D With Initial Lunar Base

To accelerate the process of establishing a self-sufficient, self-supporting, permanently manned lunar base, CELSS technology must be developed as rapidly as possible. Some CELSS R&D experiments and pilot systems should be included on the early missions in order to prove the technology as soon as possible.

Activation of Bioregenerative Systems

As the lunar base matures (i.e., extensive short-duration missions and ISRU pilot project implemented), bioregenerative systems should be brought on line as primary LSS's with the PC systems already in place serving as backup systems and buffers to the biological systems. There will be a critical point at which the lunar infrastructure (people, resources, energy, materials, etc.) will be sufficiently large to support a fully bioregenerative LSS.

To prepare for this critical point, terrestrial systems (e.g., Biosphere II) and Space-Station-based analogs should be developed and tested. Detail design and performance models should be developed, verified, and validated against experimental systems both at one-g and micro-g conditions. Because of the long-term nature of biological systems experiments, this work should be aggressively started now so as to be ready at the appropriate time.

LSS Implementation Stages

Lunar Base Stages

Three stages of lunar base life support system development were envisioned at the ISRU workshop. These stages would lead to a final goal. However, each stage of development would be independent, given existing technology at the time of implementation, and will exist as the Space Station technology matures.

Stage I (Growth).- The first stage of lunar base implementation, would use existing technology, and the product would be the building blocks for stage II. Because the technology for stage I is immature, extensive research and development is required.

Stage II (Mature).- The second stage would be a follow-on lunar base system referred to as a "Growth Lunar Base." Stage I would grow into stage II. If proper planning and design were exercised, the building blocks and feedstocks for a CELSS/soil system would be available as waste products from stage I development. There would be a number of modular stage I subsystems feeding into Stage II. Extensive and long-term research will be required to produce mature technology for this stage.

Stage III.- Stage III the "goal"- would culminate in a fully bioregenerative system with all the necessary infrastructure in place (people, materials, etc.). Stage III would result in recycling all air, water, and nutrients, utilizing makeup elements only as the leakage rate demanded.

WORKING GROUP IV
MATERIALS PROCESSING - A COMMODITIES APPROACH

Introduction

The evaluation group for materials processing was convinced that commercial processes or sound technical approaches exist to produce the commodities commonly associated with lunar base studies. However, we felt that the processes (particularly their associated efficiencies, economics, maintainability, and process parameters) are, at best, poorly understood in the fractional-g/vacuum environment of the Moon. Thus, our group considered methods of focusing NASA's understanding of candidate materials processes and recommended incorporation of nonaerospace companies experienced in process technology into the planning and evaluation process associated with a lunar base.

Materials Processing Agenda

The goal of our materials processing agenda is to identify the process opportunities with high commercial potential and the uncertainties associated with transferring these processes to the lunar environment. Identification of the technology opportunities/needs depends on three primary inputs: (1) commodities, (2) terrestrial processes, and (3) constraints in space.

We define commodities as products that either are necessary for existence on the Moon or are useful in LEO. The constraints of space are the environmental conditions to which the process or technology must be adapted on the Moon. These constraints include reduced gravity (microgravity in space or 1/6g on the Moon), vacuum, thermal conditions, and lack of important components (e.g., water) which are routine elements of terrestrial process technology. Terrestrial processes are industrial approaches that are routinely used on Earth and could be adapted to produce the necessary commodities on the Moon.

In Situ Materials Processing

The rationale for establishing a materials processing facility on the Moon makes sense from a materials processing point of view as well as for several other reasons discussed elsewhere in this report. The main lines of this argument are

1. Even though other planets may appear to be more geologically interesting compared to the Moon, the Moon is a convenient base of supply for at least two materials of importance to immediate and long-term space programs.

2. The capability of a lunar facility to supply LEO vehicles with LOX propellant makes the Moon base a key not only to planetary missions but to any mission that begins from LEO.

3. The Moon allows for the development of prototype automated facilities since the response time for repairs and servicing is acceptable.

The working group identifies the supply of oxygen as the strongest rationale for lunar processing of immediate importance and the supply of ^{3}He as the longer term development thrust. With these two materials as the reason for lunar processing, a number of other materials processing opportunities become feasible. Each of these is discussed in more detail.

In proposing this materials processing objective, the working group stresses that NASA is the major customer for these commodities from space. There does not appear to be any commercial demand from industry at this time to justify this base. Having said this, the working group recognizes that commercial industry will be the major source of the technologies with which to build the facility.

The next issue is a means of attracting these firms, which appear to be nonaerospace companies, to participate in the development of the in situ lunar facility. The suggestion is to develop the requirements in finer detail and use them to fund development programs at such a level that representatives of industry perceive participation in the program and in funding as being necessary to protect their competitive position in commercial markets.

Commodities Considered

The commodities considered in our material process assessment for a lunar base have been defined broadly as those needed for life support in space, propellants, those applicable to structures, and other materials. Candidate commodities for life support in space include water/hydrogen, carbon, nitrogen, and a broad category of catalysts, absorbents, and desorbents.

The essential function of water, hydrogen, carbon, and nitrogen in life cycle to meet the primary needs of humans and to produce the necessary food supplies is well known. A less obvious need of the LSS's are the materials associated with catalysis, absorption, and desorption. These are key components in the LSS's to produce important commodities and to purify and condition elements of closed environmental systems.

Propellants are an important commercial commodity on a lunar base or at LEO. Oxygen has been identified as the most important current propellant which can be derived from processing lunar material. Other propellants, such as hydrogen, aluminum, silane, carbon monoxide, and methane, may also be useful and can be produced on a lunar base.

The commodities that can be produced by lunar-based processes and that are applicable to structures include iron, titanium, and aluminum. In addition to properties that make these materials useful as structural members, structural sheets, or electrical conductors, their high specific heats, melting points, and thermal conductivities make them attractive commodities in which to store low-quality heat produced as waste by high-temperature processes. For example, during periods of sunlight, excess process heat could be stored below ground in an iron or aluminum mass to be retrieved later as lower quality thermal energy.

The fourth category of commodities is a group which includes refractories (ceramics or glasses), binders, ^{3}He, catalysts, and absorbents/desorbents necessary for industrial processes, for the control of emissions, or for recovery of byproducts of commercial processes.

Adaptation of Existing Processes

Existing terrestrial processes which might provide the commodities necessary on the Moon or in LEO may not be transferred directly to the Moon. For example, existing processes have been developed and practiced in the one-g environment of Earth. This environment provides convection, gravity settling, and other phenomena which have been considered in developing commercial processes. The reduced gravity, the vacuum, the absence of liquids (e.g., water), manpower limitations for operation and maintenance, and power constraints require that common commercial processes must be reevaluated in terms of the space environment.

An additional consideration when adapting a process to the Moon is the potential value of even minor byproducts or contaminants. A mechanism for the complete capture and possible future retrieval of byproducts (carbon dioxide, water, nitrogen, and helium-3) including volatile process emissions or waste heat, must be incorporated into the existing processes. This adaptation of current process technology will not only aid in preserving potentially valuable material for future use, but will also minimize restock requirements by maximizing recycling of processed byproducts.

Recommended Process Development Program

Our recommended process development program involves the private sector - nonaerospace companies which are traditionally associated with the technologies to produce and provide the necessary commodities. These nonaerospace companies traditionally have not been involved with NASA in developing technology. Rather, these companies have provided goods and services. Incorporating these companies in establishing a technology development program is crucial to the process. A program can be divided into four primary activities.

The first element of a program is to select candidate commodities (e.g., oxygen) and to identify lunar feedstock materials. The selection of primary commodities and of the starting materials will provide a focus for NASA and the private sector to begin work on defining common problems to which each can offer his complementary expertise in achieving technology transfer to the Moon. The second step is to select candidate processing techniques for producing the commodities from the starting materials, and to evaluate the existing processes and attempt to modify them so that they are applicable to the environmental conditions (reduced gravity, vacuum, etc.) on the Moon. Traditionally, these technologies are not associated with aerospace industries. The evaluation and attempted adaptation of existing processes will then provide a basis for identifying the technical or engineering problems resulting from environmental constraints. This activity should provide the design basis for lunar commercial processes. Finally, this information (technical and engineering) will be necessary to identify opportunities for industry to adapt or develop the necessary process equipment. The program should provide NASA with a better foundation to evaluate the investment/ payoff ratio associated with producing commodities on a lunar base.

Benefits for NASA

A cooperative relationship between NASA and nonaerospace companies skilled in commercial processes in producing important commodities can provide NASA with a number of immediate benefits. The industry/NASA relationship will develop a new constituency in the private sector for NASA's exploration missions. It will also provide NASA with an opportunity to understand the motivations, the expectations, and economics of nonaerospace industry. This relationship can be started with a modest investment from industry. Industry's contribution may take the form of matching services. Finally, the relationship will demonstrate to the nonaerospace industry that NASA is sincere in broadening its industrial contacts.

An additional benefit accruing from a NASA/industry relationship is that the agency has the opportunity to acquire skill in process engineering, fabrication technology, metallurgy, chemical reaction engineering, casting, and metals forming. All of these activities will be important skills to lunar base activities. However, they are based on skills and technical knowledge developed over the years in a terrestrial environment.

Benefits for Industry

A relationship between the chemical process industry and NASA can provide both near-term and long-term benefits to industry. An initial investment (e.g., matching services) for process development in the 1/6g environment could be significantly enhanced by the acquisition of NASA expertise and resources. Important examples would include the areas of fluid flow, combustion, heat and mass transport, and advanced sensor technology. The NASA/industry relationship offers industry a near-term payoff. Considering the application of processes in the reduced-gravity environment could provide industry with basic information which might enhance their existing terrestrial processes. In short, participation in the program with NASA would provide a company with additional knowledge for their modest investment.

The fact that the adaptation of industrial processes to the Moon would probably require a high degree of remote or teleoperated operations and process control will add additional support to the industry for advanced manufacturing technology developments. Finally, the participating companies will enhance their technology (intellectual property) base in the form of patents on processes or process equipment, which then can be used either as the foundation for future space marketing or as a mechanism to promote advances in their terrestrial processing.

WORKING GROUP V
INNOVATIVE VENTURES

Introduction

The long-term goal of human settlement in space leads to strategies stressing operational and material self-sufficiency on planetary surfaces. Consequently, the early activities at a lunar base may well be concentrated on the building of skills and the development of tools as much as on exploration and basic research. This emphasis on learning to live and work in space places less importance on the construction of esoteric, special purpose experimental apparatus and calls for the adaptation of terrestrial machinery and processes to exploit local material resources and to construct and maintain habitable, enclosed volumes on the lunar surface.

An example of the implications of long-term goal setting can be found in a paper by Duke et al., in Lunar Bases and Space Activities of the 21st Century, where development phases for a lunar base are described.* A typical model derived from this point of view incorporates a small plant for producing LOX propellant from lunar minerals. A glance at an artist's conception of even the most basic installation for processing lunar material reveals application of technologies outside the traditional aerospace fields. If the lunar installation is to grow in capability and complexity, then we can expect to master skills in construction, mining, power generation and distribution (i.e., utilities), surface transportation, habitation support, chemical and industrial engineering, communication, human services, and local management functions.

Assuming that these projections are realistic, we conclude that the space program of the next century will be more complex than it is now. Either NASA must grow in both scope and size to encompass these new functions or the private sector must play a larger and more independent role in a future space economy.

We, the Innovative Venture Group, believe that a vital and growing space sector is possible only with private investment and entrepreneurial initiative. However, belief in large scale commercial space ventures will remain a matter of faith or principle until gateways for genuine private sector involvement in space can be identified. Therefore, we attempted to identify strategies, which can be implemented now, to initiate investment in technologies that seem to be pivotal in advanced planning scenarios.

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* Duke, Michael B.; Mendell, Wendell W.; and Roberts, Barney B.: Strategies for a Lunar Base, <u>Lunar Bases and Space Activities of the 21st Century</u>, The Lunar and Planetary Institute, 1985, pp. 57-68.

Barriers to Investment

First, we tried to identify barriers to investment in space technology as seen by the private sector. For example, the current space program does not offer familiar contexts within which a company might find a way to offer its products or services. Most companies do not see an obvious connection of their skills and experience to the peculiar needs of the space environment.

Furthermore, NASA designs and operates projects itself, only contracting specific tasks to the private sector. The space program is operated on a project by project basis whereby contractors are limited to participation in rigidly defined roles. The LEO Space Station illustrates the types of constraints placed on industry. Although bidders on the Space Station are encouraged to offer alternative concepts, none of the proposals will differ in any significant way from the NASA baseline. Only in rare instances will a company such as Space Industries, Inc., develop an LEO capability aimed at a general market rather than simply responding to a specialized NASA solicitation.

The Space Industries orbital platform is also unusual because most industry sees a market in space limited to government customers. More space investment would occur if companies perceived the potential for a broader customer base.

The concepts for planetary surface installations answer some of these objections in principle. That is, a lunar surface production facility employs many commercial technologies in settings analogous to those on Earth. A bustling space economy would include markets outside purely governmental projects. However, such a scenario lies at least 20 years in the future, when the necessary space transportation systems are in place. Corporate planning horizons do not extend that far, and the timelag between investment and payback is incompatible with standard financing arrangements. Thus, we find a number of barriers to private investment in long-range space technology development.

Options for Private Enterprise

Despite a lack of incentives for adapting commercial technologies to space utilization, some in the corporate world believe that a strong industry involvement in space is a prerequisite for a vital civilian space program and that financial benefits will accrue to companies that establish sound bases in appropriate space technologies. What options are open to these visionaries of private enterprise?

The safest strategy recommends that a company do nothing until NASA announces funding of R&D in technologies associated with the company or until a human or martian mission is declared. At that time, the company responds to requests for proposals and participates in NASA programs in the standard way. This client option leaves policy initiatives with the public sector and perpetuates rigidly defined relationships that now exist between

NASA and its client industries. Markets remain small public sector projects, and participation in space development is constrained.

Some commercialization advocates have argued that private investment in space can be greatly accelerated if the Government will provide guaranteed markets for goods and/or services. The contracts would act as temporary subsidies to shelter industry from the high risk of development costs for an uncertain market environment. This approach gives the private sector the freedom to create nongovernment markets and to design products with commercial potential.

Although the guaranteed market has real potential from the industry point of view, such a policy would be a distinct departure from current space program philosophy. The working group felt that broadly subsidized space ventures would require a redefinition of space policy and a restructuring of the NASA management culture. Since opposition from NASA would eviscerate any effort at major change in space policy, the guaranteed market option was judged to be an advocacy position with low probability of success.

A third alternative involves creating a gateway to space investment within a mostly private sector context. If viable space development scenarios could be generated and supported from within industry, they would be much more likely to contain reasonable profit potential than would scenarios devised by NASA. The eventual success of the planning would depend on the support by industry and the meshing of objectives with the national interest in space. Currently, NASA has no clear plans for the post-Space-Station era, and there is no reason to doubt that a carefully reasoned and explored commercial view would be considered fully and even welcomed.

Such a commercial initiative would have to be structured to minimize financial risk, to demonstrate near-term return on investment, and to attract participation by corporations with technical and financial resources. The working group then discussed an approach which would satisfy these demanding criteria.

Approach to Private Initiative

The central theme of a private initiative must be the creation of both a vision and a real technology development plan that does not explicitly depend on immediate NASA sponsorship. The vision will define the technology goals, the ultimate fulfillment of which may lie 20 years in the future. The development plan will define a series of steps such that intermediate successes on the way to the final goals will yield technologies marketable on Earth. If the financing and execution of the plan can be independent of NASA funding in the beginning, then the continuity of the effort will not be disrupted by vacillating and ill-defined space policy. In fact, a self-consistent and well-considered plan from the private sector could have a salutary and stabilizing effect on the public sector decision process and provide an external incentive for NASA to develop Pioneer and Pilgram technologies.

The success of a private initiative will depend on the highly visible participation of companies with substantive technical resources. The participants should come from the nonaerospace sector to demonstrate that belief in the future of space is broadly based and that the initiative is not simply a self-serving exercise by the NASA client industries.

The initiative would best be structured as a collaborative demonstration project having (1) a long-term objective of developing technology for living and working in space and (2) a short-term goal of attacking contemporary problems of living on Earth. The space program has long been touted as spinning off technology advances that improve our daily lives. There is no reason why the spinoff process cannot be inverted to yield mundane applications en route to the solutions for space applications, particularly in support of human extraterrestrial communities for which ecological, physiological, and sociological complexities must be dealt with in a microcosm.

From considerations such as these, a general plan began to emerge from the working group. We wish to create a demonstration project (or projects), involving multiple (a minimum of five) major companies, that will address specific problems on Earth using developmental technologies with a space application context. Initial objectives must be modest, yet must yield genuine substantive accomplishments and demonstrable return on investment. The initial effort should be designed as a pilot project of which success can lead naturally to expansion or diversification. The project is a demonstration because it will stand as a statement to the Nation on the future potential of space to industry as well as to the space agency.

Themes

An independent private initiative for space technology development can be the first step toward regaining leadership in space by using the strength of the Nation's economic infrastructure. It can add to our economic competitiveness through cooperative technology enhancement. While educating industrial leaders on future opportunities in space, it also can encourage bolder, long-range planning in NASA. Finally, a well-designed project can demonstrate forcefully the relevance of space exploration to improvement of life on Earth.

Actions

The working group realizes that creating and sustaining a meaningful activity will not be easy, but a few members accepted actions to pursue four tasks. First, look for candidate technologies associated with the major components of the space program: a lunar/martian base, the Space Station, terrestrial applications, and the Strategic Defense Initiative. Second, explore possible industrial interest through individual contacts or through space interest commercial groups such as the Business Higher Education Forum. Based on finding enough interest, a small workshop devoted to brainstorming might be in order. Third investigate a possible industrial connection with the NASA Advisory Council. Finally, develop examples such as Alaskan/Canadian arctic life support.

The working group adjourned with the hope that new gateways for private investment in space could be created to accelerate the development of a new frontier and to enrich our domestic industrial base with innovative technology applications.

WORKING GROUP TECHNOLOGY REPORTS

The five working group reports are summarized into six recommendations for the technology development that must precede future space activities. The NASA Technology Initiatives (shown in app. A) served as a baseline against which each group compared its findings. At the end of this section, the five groups' individual technology reports are presented.

SUMMARY OF TECHNOLOGY RECOMMENDATIONS

The general theme of all working groups is that future large-scale space development should evolve with economic viability in mind. In this regard, the working groups did not find a significant difference in the technology development proposed by the Technology Initiatives (primarily the Pathfinder initiative) and their recommendations. There may be some difference, however, in the means of implementing this development.

1. Space transportation - NASA and its client industries must adapt new systems and processes to lower the cost and complexity of space transportation. Innovative entrepreneurs may be able to occupy distinct niches within this community by identifying specific innovations that do not require major changes to the NASA management culture. The most urgent requirement for continued space development in this area is for reliable systems with minimum operational costs, particularly the Earth-to-orbit phase.

2. Manned planetary activities - A large portion of the U.S. industrial base should eventually assume a major responsibility for manned planetary activities and perhaps some aspects of in-space facilities. This responsibility will involve extrapolation of their terrestrial expertise into the space environment.

3. Non-NASA public sector involvement - Other agencies within the Government can assume a larger role in certain regimes of space development. For example, the U.S. Army Corps of Engineers could provide coordination for large facilities construction.

4. New relationships and mechanisms - As responsibilities for space development become increasingly diverse, new relationships will be needed. Potentially, the Government can promote this process by legislation.

5. Evolutionary technologies with intermediate products - Technology development paths should be formulated with two prevailing themes: (1) The technologies that are to be pursued must be evolutionary in nature, with new technologies building upon existing ones; and (2) New technologies need to be developed in ways that will produce identifiable intermediate spinoffs that are marketable.

6. ISRU/life support/automation - Certain key technologies are crucial to providing long-term economic viability of the permanent habitation of

space. They also are amenable to evolutionary development and can be applied to many terrestrial problems. The following technologies should be pursued most vigorously: (1) ISRU (2) bioregenerative LSS's, and (3) autonomous systems.

DISCUSSION

Minimum-Cost Space Transportation

Two-thirds of operating costs to maintain any extraterrestrial facility would be for space transportation. Of that, a significant portion is used merely to fly 250 miles from the Earth's surface. The economic viability of space development can be improved substantially with advances in this area. The general feeling was that space transportation is primarily the purview of NASA and the aerospace industries, although there may be some avenues for innovative private sector involvement with new types of launch vehicles and operational methods.

New Relationships

The fifth working group foresees the private sector taking the initiative, instead of waiting for the Government to act. Institutional inertia within the Government and aerospace sectors tends to suppress novel approaches and innovation. This initiative might take the form of demonstration projects, independent of long-term Government funding, with intermediate marketable products. This approach is being pursued by a few participants from the private sector. They will be examining candidate technologies associated with major components of the space program, exploring possible industrial interest, and investigating a possible industrial connection with the NASA Advisory Council.

The NASA matching investment is in the form of Technology Initiatives, which are not a guarantee of continued long-term funding but could be sufficient to initialize a joint public/private technology development activity. If this activity proved successful and beneficial to both sectors, continued support would be much more likely.

Evolutionary Development

Technologies and hardware that have already been developed should be used to enable continued growth and expansion. For example, the Space Station common module can be used for initial lunar base habitation and thereby can minimize development costs. This is an underlying philosophy of the NASA Technology Initiatives and current NASA scenarios for the Space Station, the lunar base, and the manned Mars mission. Unfortunately, the choice between adapting existing technology and investing in new technology is not always clear cut. Existing technologies, in the short term, may be cheaper and more reliable. New technologies, however, may prove cost effective in the long run with increased capability and by spinoff applications.

In Situ Resources Utilization

Lunar and planetary resources can be mined and fabricated into products for the evolving space-based communities, and perhaps for eventual export to Earth. At issue is the matching of resources (i.e., commodities) markets, based on acquisition costs. A reasonably clear case has been developed for resource exploitation once the initial investment has been made and the infrastructure has been built. A more difficult problem is building the mechanisms to enable this development.

Regenerative LSS'S

The LSS's must be capable of recycling consumables to minimize resupply requirements from outside sources. This requirement was outlined in detail by working group III and also mentioned in the other working groups as a significant capability. With current transportation costs to the Moon, for example, at three times the price of gold, a substantial benefit can be realized by recycling as much as possible and augmenting operational requirements with locally available resources.

Systems Autonomy

At planetary outposts, many systems must be capable of functioning independently without significant human intervention. This requirement was identified by all groups as a critical technology development area. The capability to maximize human resources using machines can substantially lower establishment and operating costs. The degree to which this capability will be possible is a function of the amount of technology investment made. Ultimately, it would be optimum to use machines to do the well-known, routine, and repetitive tasks associated with space activities. Routine tasks are also the most difficult for human beings to consistently accomplish satisfactorily. Humans are best at demanding, unforeseen tasks requiring new approaches that cannot be defined in advance. A proper balance of humans and machines must be found and maintained.

TECHNOLOGY REPORTS BY WORKING GROUP

Construction/Assembly, Automation/Robotics

Figure 3 shows the projected capabilities and technologies required for the five phases of lunar base development. Phase I (site selection) and Phase II (temporarily inhabited base) are most closely associated with the Pathfinder technologies, whereas Phase III (permanently inhabited base) and Phase IV (self-supporting base) are more associated with Pioneer technology development. The self-sufficient base of phase V will use technologies expected to evolve from previous activities, to be augmented by the currently undefined Pilgrim program.

Pathfinder technologies required for construction and assembly will be focused heavily on autonomous systems. Previous lunar missions have mapped only a small part of the lunar surface with fairly low resolution. Final site selection will require analysis of very detailed, high-resolution imagery from many locations obtained using unmanned lunar orbiters, particularly a polar orbiter that will be capable of mapping all points of the lunar surface. Autonomous systems will be used to perform much of the site preparation and initial prototype testing. Human crews will only be available on the surface for limited periods of time initially, and will be needed primarily to handle unpredictable or unforeseen tasks.

Pioneer technologies will also increase capabilities for soil movement, habitat construction (including inflatable and underground structures), and the assembly of large facilities (e.g., astronomical). There will be greater use of local materials for construction. Initially, bulk materials can be used for construction. Eventually, more sophisticated methods will be developed to create large, habitable volumes with minimum labor and power. The technologies to build multifunction construction and manufacturing equipment will be needed.

Prospecting, Mining, and Surface Transportation

Figure 4 shows the technologies defined by the Prospecting, Mining, and Surface Transportation Working Group. Once again, autonomous systems will be an important component, particularly regarding on-orbit and surface prospecting. Because of the heavy power requirements of mining and materials handling, nuclear fusion has been identified as an important technology, particularly with the potential availability of ^{3}He on the Moon. Design of equipment for all aspects of PMST will require heavy emphasis on teleoperation and autonomy. Much of the basic technology research required is expected to be performed at the LEO Space Station. An important aspect of that research will be to assist in defining the growth paths for Space Station technology evolution to best lay the groundwork for future research.

Biosystems and Life Support

Figure 5 shows the projected life support evolution and the required technologies. This evolution will proceed from the current Space-Shuttle-type consumables resupply and carbon dioxide absorption, to the Space-Station-type mechanical recycling of air and water, to a tightly controlled bioregenerative ecological system (augmented by locally produced resources). Technological development has begun with Earth-based test chambers and basic plant growth and CELSS research. This activity should be expanded, and potential collaboration with nonaerospace organizations should be pursued. Examples of these organizations include those developing very large, closed bioregenerative systems such as Biosphere II in Arizona, or even the U.S.S.R. experiments with small, closed ecological experiments in Siberia (Bios). The mechanical PC regenerative technologies planned for Space Station will be an important step in developing bioregenerative systems. A PC regenerative system is expected to be used initially at a lunar or Mars

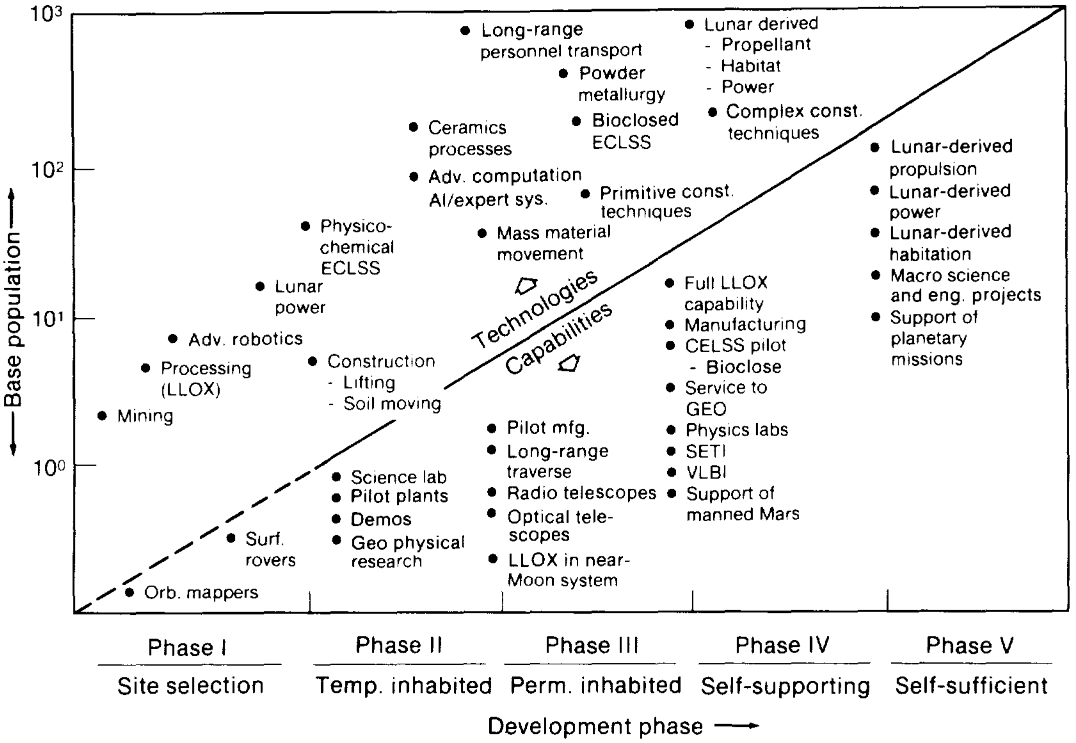

Figure 3.- Lunar development phases vs. capabilities and technology developments.

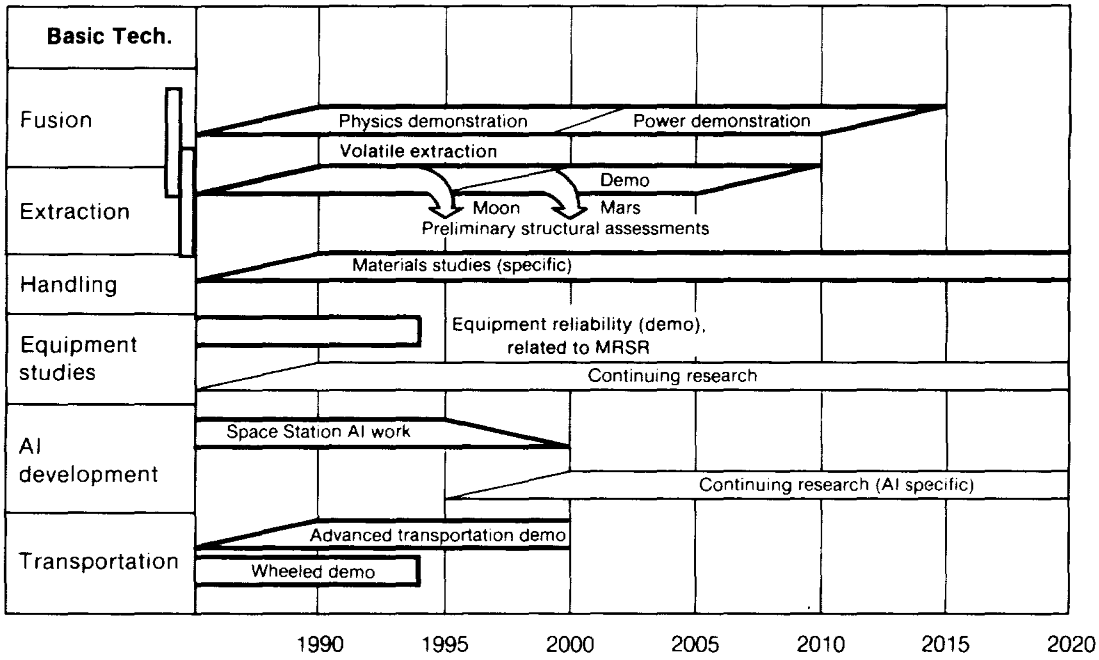

Figure 4.- Technology plan - prospecting, mining, and surface transportation.

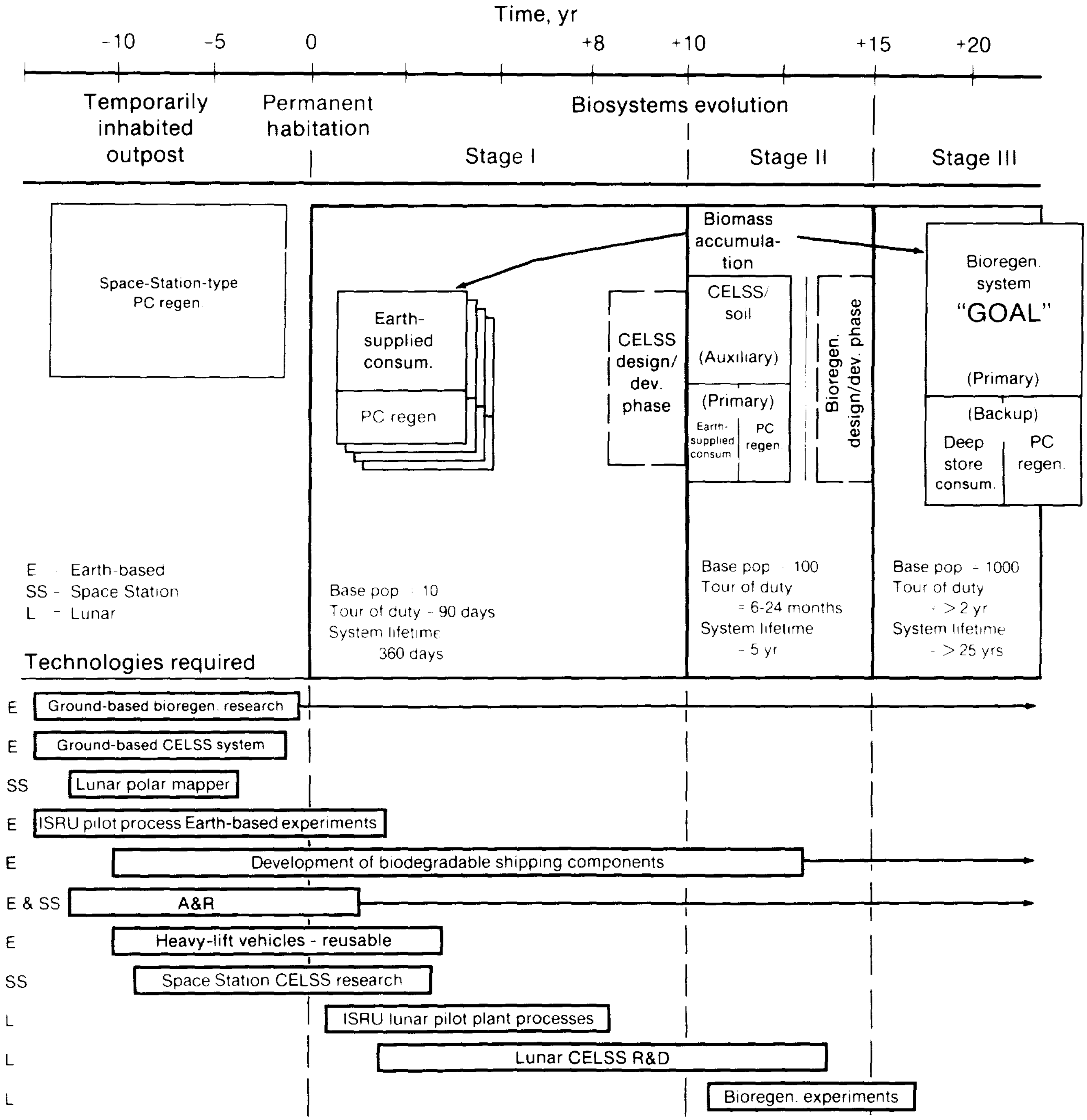

Figure 5.- Technology plan - lunar base biosystems and life support.

base, while stores of volatiles are being built to prime the bioregenerative systems. Once these systems are initiated, the PC equipment will be used as backup. Terrestrial-based experiments and analogs will lead to space and surface-based component prototype testing.

Other technologies will become increasingly important for life support. These include techniques to use locally available resources - particularly the extraction of volatiles, if feasible. Another possibility to minimize resupply from Earth would be the use of volatile rich (hydrocarbon) structural components for landers and packaging that can be reused by the base. In addition, robotics and automation will be very important, particularly automated sensor and control systems.

Materials Processing

The Materials Processing Working Group advocates a technology development program that first identifies, in great detail, the materials commodities of greatest use. The public and private sectors can then better understand their potential roles. Candidate process techniques are defined for each commodity. Many of these processes may already exist in the private sector. The adapting of these processes to the extraterrestrial environment also should be assessed. A synergy may be possible by obtaining more than one commodity from the same resource. In addition, technical and engineering problems will become more readily apparent. This activity should provide the design basis for lunar and planetary commercial materials processing and provide NASA with a clearer assessment of the benefit-to-cost parameters associated with producing commodities at a lunar base and elsewhere.

Innovative Ventures

Instead of advocating a particular technology development plan, the Innovative Ventures Working Group focused on new approaches for technology development. Under the premise that a vital and growing space sector is possible only with private investment and entrepreneurial initiative, they sought gateways for the private sector to invest in key new technologies. If this approach is to be feasible, a technology plan must be devised to build technologies that enable living and working in space while allowing near-term intermediate milestones that will yield technologies marketable on Earth. The working group's approach to this objective is to formulate a demonstration project involving a small group of major companies that will address a major problem on Earth with use of emerging technologies derived from space applications. These applications are likely to be some subset proposed for the Pathfinder or Pioneer initiatives. A close collaboration may allow an eventual merging of objectives to meet differing goals, which would result in commitment of finite public and corporate resources.

CONCLUSIONS

The ISRU Workshop brought strategic planners for space policy together with technologists and corporate executives from the nonaerospace sector of private industry. The objective of the interaction was to explore the hypothesis that the next generation of space goals will incorporate technologies derived from industries outside the aerospace transportation sector. For example, the word "settlement" appearing in the long-range vision from the NCOS implies the possibility of complex LSS's, networks of human services, extraterrestrial resource utilization, and production of commodities in space in addition to transportation infrastructure.

The working groups validated the working hypothesis as a reasonable one. Each group then produced an assessment of technologies that would be required to maintain permanent habitation on a planetary surface. Since the workshop was short and isolated from extensive reference material, the reports cannot be viewed as exhaustive in their levels of detail. The value of the reports lies as much in the point of view expressed as in the technical content.

All supported the rejuvenation of the NASA technology development program. However, there also was general agreement that the scope of the program was excessively limited. The long-range planning scenarios presented to the workshop predict a space transportation capability to deliver payloads to the lunar surface within 20 years. Two decades is roughly the time required to achieve operational status of a major industrial plant on the Earth. If utilization of extraterrestrial resources is to be a legitimate option for space development early in the 21st century, preliminary investigation of candidate materials processing schemes must be started immediately.

Resource assessment missions such as lunar and martian orbiters are recommended. The absence of data from a lunar geochemical orbiter, a cartographic mission, geophysical exploration, and surface sample studies increases the technology development risks through lack of complete and accurate information on planetary surface conditions. Such exploration missions have intrinsic scientific value and can be incorporated in NASA planning without necessarily implying large commitments to planetary surface installations.

Automation, robotics, control systems, high reliability designs, and various LSS's will be critical elements of lunar surface bases. These technologies lie in the mainstream of major manned programs such as Space Station, but their development must be performed with the long-range goals in mind. In particular, the function of life science research at the LEO Space Station must be expanded to allow realistic planning for long- duration space missions and long-term surface habitation.

Manned space programs of the past have consisted largely of short-duration missions conducted near the Earth. These characteristics have led to design solutions featuring turnkey systems constructed and tested on the Earth. As missions grow longer in duration, as payloads grow more massive, and as destinations farther from the Earth are chosen, transportation becomes a dominant mission cost element. At some point, engineering systems must incorporate local resources. Thus, some turnkey systems must yield to general-purpose tools. For example, a tunneling or excavating machine may be used to construct habitable underground volumes on the Moon instead of importing large numbers of habitation and laboratory modules, which must be interconnected and buried. However, the change in mission design philosophy from emphasis on closed engineering solutions is profound. It may never occur naturally within the NASA technology development programs, and part of the new initiatives should be devoted explicitly to exploring novel and unorthodox solutions to the general problems of habitation and materials processing.

For some, these considerations imply open-ended activities having scopes that far exceed those of familiar NASA programs. The very scale of such activities precludes them from consideration as practical alternatives. Although the affordability of large programs can be debated, there is no doubt that public sector investment in technology leadership and/or prestige will never be large in terms of the whole national economy. Yet there is no reason for NASA to view itself as the only party interested in space development and exploration. Settlements, production and manufacturing, and transportation systems are the mainstream of the Nation's economic engine. Many parts of the private sector appreciate the value of technology advances and know efficient ways to provide goods and services. If there is real investment interest in a new "space sector" of the economy, NASA should encourage that interest through partnerships in the vision and in the research. However, the private sector requires the possibility of rewards, both soon and late. Therefore, NASA must rethink its role in space and find room for nourishment of private enterprise in its long-range plans.

The workshop as a whole believes that a strong partnership can grow between public and private sectors in space. Whether it will occur depends on vision and leadership from both sides.

RECOMMENDATIONS FOR FUTURE ACTIVITIES

RECOMMENDATION: NASA MUST IMPLEMENT THE PATHFINDER TECHNOLOGY INITIATIVE BEGINNING IN 1988 IN ORDER TO SUPPORT HUMAN EXPLORATION MISSIONS TO THE MOON AND/OR MARS.

The workshop concluded that any major human exploration initiative for lunar and planetary space will require many new technologies. The capabilities proposed by the Pathfinder initiative (shown in app. A) and timetables for development have been formulated from the studies of many NASA and non-NASA space policy planning groups, including the NCOS the NASA Advisory Council, and the National Academy of Sciences. These recommendations form a fairly accurate representation of the systems that must be in place to support advanced space development, as identified by this workshop. Many of these new technologies, however, are in areas in which NASA and the aerospace community have little or no expertise. Some of these technologies have close terrestrial-based counterparts (e.g., lunar mining and manufacturing). For others, relatively little knowledge exists (e.g., small-scale bioregenerative LSS's).

RECOMMENDATION: NASA SHOULD FORM NEW RELATIONSHIPS WITH INDUSTRIAL PARTNERS, SHARING RESPONSIBILITY FOR DEVELOPMENT OF FUTURE SPACE TECHNOLOGIES.

The workshop participants recognized a potentially large set of new technologies that meet long-range space planning goals yet have near-term terrestrial applications. Many of the technologies are special, automated applications of terrestrial expertise. Others are systems and subsystems for habitation and production in alien environments. Additional studies should be continued, to compare technology that is needed for future space development with technology that can be provided by the current terrestrial industrial base. We recommend that these comparative sessions probe the NASA strategies toward development of extraterrestrial surface habitation and operations. The development of the site preparation, construction, mining, and production technologies needed by NASA could be influenced by the needs of the interested industrialists to promote their interests as well. There will still be opportunities for industry to participate as a client of the Government. The results of this workshop suggest however, that the needs of the country may be best served in certain areas by the public and private sectors working together to influence NASA strategies such that the industry partners can reap technology benefits before NASA implements the technologies into these advanced missions. This is contrary to the usual approach of NASA - determining requirements, then commissioning industry for implementation. This joint development approach would be on a level more fundamental than requirements definition. It would define strategies for technology development in areas that have near-term terrestrial application, such as surface system development, construction, mining, and production. Industry can justify sharing development costs with NASA in these areas by the potential for a reasonable return on investment.

To further pursue potential cooperative developments, a small, ad hoc team should be funded by industry and supported by NASA.

APPENDIX A
NASA TECHNOLOGY INITIATIVES

INTRODUCTION

No future space development is possible unless the enabling technologies are in place. The word technology really means technical capability, with performance within certain specifications. The NASA has defined a set of 7 technology readiness levels that chart the development of an operational capability from an understanding of the basic scientific principles (level 1) to successful testing in space of a prototype model (level 8). This development takes investment of capital and time. The technology development for many of the activities identified in this report has not been started. Many of these activities will require long lead times. It is possible that certain goals for space development cannot be met because the required technologies are not already sufficiently developed to be ready in time.

Technology development is guided by the overall goals of space development and the objectives toward achieving those goals. Generally, the goals in space for the Nation, as well as for the rest of the world, revolve around continued exploration and eventual settlement of the solar system. Most space planners envision human involvement in all aspects of this activity which, in the near term, translates into learning to live in space permanently.

To meet these goals, a significant initial capital investment is required. It is quite likely that very little human development of space will happen without demonstrated economic advantages of the associated activities. Certainly, if the private sector is to be involved in any sort of cooperative development, the eventual economic potential must be apparent.

This distinction forms a general division between enabling and enhancing technologies. Enabling technologies are those that provide the means to accomplish a mission. Unless these technologies are in place, human exploration and settlement will be impossible. In contrast, enhancing technologies are needed primarily to ascertain the economic viability of space activities. There is an inherent danger, however, in interpreting economic viability in terms of the potential benefit-to-cost ratio of an individual technology. When economic viability is a major objective, to consider a single technology in isolation is difficult because space development activities and the development philosophies that guide them are tightly synergetic. In some sense, a certain set of enhancing technologies could actually be considered enabling, since it is exceedingly unlikely that funding mechanisms will be available without them.

NASA TECHNOLOGY STATUS

The NASA has been under considerable criticism recently for allowing its technology base to erode. Indeed, a curve of agency investments in research and technology (R&T) from 1964 to the present shows nearly exponential decay. This deficiency has been recognized as a major shortfall and steps are being taken to rebuild this base.

Specifically, the agency has proposed three technology development initiatives, the Civilian Space Technology Initiative (CSTI), Pathfinder, and Pioneer. These initiatives and the proposed timelines, funding levels, and general classes of technologies are shown in figure 6. The proposed technology development is evolutionary, with each set building on the base of those that precede it. The thrust of the CSTI is to enable more effective access to, and operation in, low Earth orbit and geosynchronous orbit. The Pathfinder technologies will enable space science and precursor lunar base and Mars exploration missions. The Pioneer technologies will enable a lunar base and the human exploration of Mars. A fourth, less defined category called Pilgrim is proposed to enable actual settlements on the Moon and Mars.

Most of the technologies discussed in this workshop are associated with the Pathfinder technology initiative. The CSTI is NASA's first step in rebuilding and restoring its technical strength with focused activities that fill critical gaps in the program base. Project Pathfinder will help develop the technologies that will enable new missions for the U.S. space program. With a longer term horizon, Pathfinder will build on the Space Shuttle and the Space Station and will address common technologies that support a wide range of missions including a return to the U.C. Moon, a mission to Mars, and expanded exploration of the solar system. The program objective is to develop, within reasonable timeframes, enhanced mission capabilities and system concepts.

Pathfinder includes technology thrusts to enable precision aerorecovery techniques for costly and critical space launch system elements such as propulsion and avionics modules; an on-orbit cryogenic fluid depot capable of generating, storing, and transfering liquid hydrogen, oxygen, and other gases; tether systems that extend either inward or outward from orbiting vehicles to probe atmospheres and perform a variety of functions including power, thrust, and artificial gravity generation; autonomous, reconfigurable, intelligent, and fault-tolerant flight systems for terrestrial, lunar, martian, and deep-space mission life enhancement; extraction of materials from lunar and planetary bodies; the extension of Earth-return entry and capture; an autonomous rover for lunar and martian application; high-performance electric propulsion systems to more effectively explore the outer planets and beyond; and the communications techniques for very-high-density information transfer over deep-space distances. The program elements are briefly described as follows.

Launch and Flight Operations

1. Precision aerorecovery - Development and flight demonstration of technology concepts for aerodynamic configurations and data bases, high-temperature flexible fabrics, and packaging and reusable deployment techniques

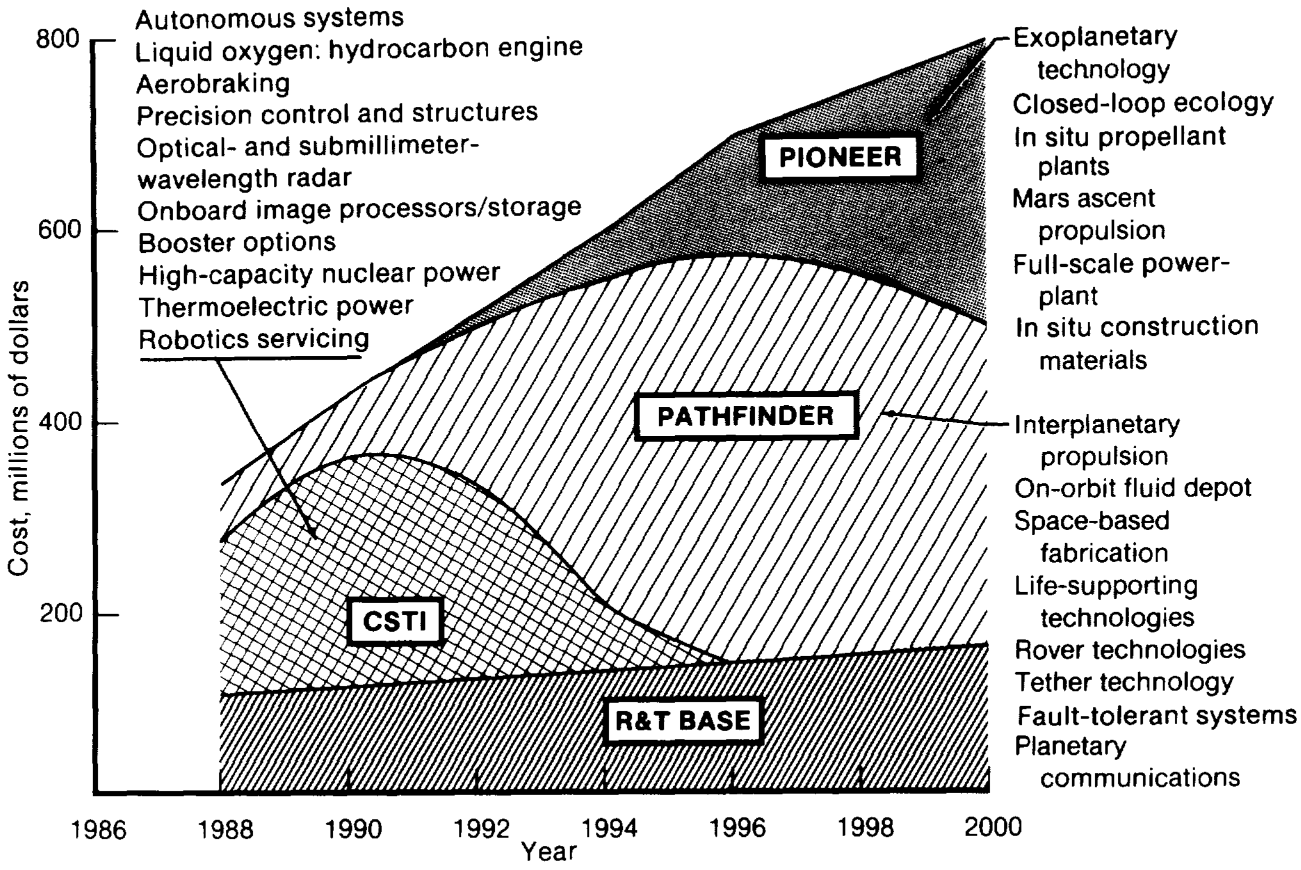

Figure 6.- NASA's proposed technology initiatives.

2. On-orbit cryogenic fluid depot - Development and flight validation of the technologies for cryogenic fluid production, storage and transfer utilizing residual propellant scavenging, and water and other inert fluids decomposition

3. Tether technology - Generating the analytical tools of dynamics and controls, and investigating and demonstrating in flight the properties of materials suitable for the design of a wide variety of tether systems

4. Fault-tolerant flight systems - Providing significant advancements in fault-tolerant information and avionics systems through newly emerging techniques such as photonics-based circuitry, artificial intelligence (AI), and integrated optical control architectures

Lunar and Mars Exploration

1. Human capability - Enhancing astronaut productivity and teamwork effectiveness in remote, confined, and alien environments on long-duration missions with improved garments, crew system designs, and mission simulation techniques

2. Human health - Reducing the adverse consequences of exposure to reduced gravity and space radiation, and providing techniques to cope with injury or illness

3. Lunar/planetary/asteroid materials processing - Enabling the extraction and processing technologies for lunar, asteroid, and martian plants that will provide in situ oxygen, propellants, and construction materials

4. Planetary return flight experiment - Using the results of the CSTI aeromaneuvering flight experiment to develop and demonstrate the technologies for high-energy Earth entry and the capability to rendezvous and dock with Space Station

5. Autonomous rover - Conducting the technology developments and demonstration programs to enable extended-range rover vehicles for automated site survey, geological exploration, mapping, and surface sampling of Mars

Expanded Solar System Exploration

1. High-performance propulsion - Conducting research and development for both magnetoplasmadynamic and very-high-efficiency ion thrusters to enable increased performance and reduced cost of outer planet and solar system escape missions

2. High-performance communications - Generating advances in laser materials, coatings, and sensors for deep-space applications of solid-state

laser transmitters, receivers, and signal encoders and demonstrating concept readiness with both ground and flight test experiments

NASA STRATEGIC PLANNING

A brief look at the technologies in figure 6, and those that follow in this section, reveals many examples of areas in which NASA has little or no experience. For many of these technologies, existing experience resides in the nonaerospace community. In fact, most of the activities associated with planetary surface operations are closely related to activities performed routinely in the private sector. Thus, NASA is turning to the nonaerospace community to help define these activities and the steps that must be taken to enable them. This step is further amplified by performance of NASA-wide strategic planning activities. Table I shows NASA's current operational technologies and capabilities as defined by Lyndon B. Johnson Space Center (JSC) strategic planning activity. The following list indicates JSC predictions of the key technologies and capabilities that will be particularly important for future space activities. Of particular interest are technologies that are traditionally nonaerospace (superscript 1) and technologies for which no expertise exists (superscript 2).

Technologies

1. Human life support
    a. Physicochemical regenerative environmental control and life support system (ECLSS)
    b. Bioregenerative ECLSS (controlled ecological life support system)[2]
    c. Physiology/psychology of long-duration space flight[2]
2. Extravehicular activity
    a. Habitat/crew accommodation/health maintenance
    b. Radiation management
    c. Artificial gravity capability[2]
3. Man/machine systems
    a. Automation and robotics
    b. Systems autonomy/expert systems/AI
    c. Systems maintainability by crew

Technologies (cont)

4. Space transportation
    - a. Materials
    - b. Propulsion
    - c. Aerobraking
    - d. Debris management
    - e. Human-tended transportation nodes
5. Information systems
    - a. Hardware
    - b. Software
    - c. Information management
6. In situ resources utilization
    - a. Mining/bulk materials handling[1]
    - b. Materials processing[1]
7. Space servicing
    - a. Fluids transfer
    - b. Vehicle assembly[2]
8. Construction (space and planetary)[1]
9. Power[1]

·pabilities

Multiprogram management

Operations and analysis (mission planning, technology evolution)

ystems engineering and integration

gh-efficiency launch systems

TABLE I.-CURRENT NASA OPERATIONAL TECHNOLOGIES/CAPABILITIES

Project management	Space vehicle development	Manned space exploration	Manned space operations
• Systems integration • Configuration control • Risk management/control • Cost/schedule control • Systems engineering and testing • Manufacturing • Safety, reliability, and quality assurance • Logistics	• Environmental definition • Concept and systems design • Structures/materials mechanisms • Propulsion • Power • Thermal control • Guidance, navigation, and control • Avionics • Recovery (if necessary) • Automation/robotics/AI • Aerothermodynamics	• Environmental control and life support • Environmental definition and protection • Extravehicular activity • Communications • Man/machine interface (human factors) • Biomedical • Information systems/data management • Crew recovery/escape	• Mission planning (including contingency) • Flight design • Training • Ground and flight control • Information systems/data management • Tracking/ranging/docking/recovery • Automation/AI • Science/technology • Servicing/maintenance

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5. Charles Harper - Bechtel
6. Malcolm Sherman - Engineering Products and Automation
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8. Peter Wood - Booz, Allen & Hamilton
9. Ken Ito - Yamaha
10. Norma Paige - Astronautics Corp.
11. Barney Roberts - NASA Lyndon B. Johnson Space Center (JSC)

Working Group II - Prospecting/Mining/and Surface Transportation

- Remote and Manned
- Strip Mining and Tunneling

1. Gail Klein (Chair) - NASA Jet Propulsion Laboratory (JPL)
2. Mike Duke - JSC
3. Mike Moore - NASA George C. Marshall Space Flight Center (MSFC)
4. Egons Podnieks - Bureau of Mines
5. Gerry Kulcinski - Fusion Technology Institute
6. Ken McIntyre - Stone and Webster
7. Dave Vaniman - LANL

8. Terry Triffet - University of Arizona
9. Jeff Taylor - University of New Mexico, LAPST
10. Geoff Coates - American MagLev

Working Group III - Life Support and Services

- Physical (Mechanical and Chemical) Systems
- Biological Systems

1. George Mignon (Chair) - Environmental Research Laboratory, University of Arizona
2. Stuart Lyon-Smith - Science Council of Canada
3. Gene Konecci - University of Texas at Austin
4. Kyle Fairchild - JSC
5. Tom Albert - Alaska North Slope Borough
6. Joe Angelo - Florida Institute of Technology
7. Don Kerr - EG&G
8. Scott Nesbitt - American MagLev
9. Hank Robitaille - EPCOT Center, The Land
10. Joe Keilbach - United Technologies Research Center
11. Andy Schuerger - EPCOT Center, The Land
12. David Messner - Eaton Corp.
13. Bill Easterwood - EPCOT Center, The Land

Working Group IV - Materials Processing

- Solid - Preprocessing, processing, and storage
- Gas/Liquid - Preprocessing, processing, and storage

1. Terry Wallace (Chair) - Department of Energy
2. Lou Rancitelli - Battelle Columbus Laboratories
3. Bob Frisbee - JPL
4. Laurel Wilkening - National Commission on Space, University of Arizona

5. Bob Stubbs - NASA/Lewis Research Center

6. Robert Guidic - NASA/MSFC

7. Hy Lyon - North Texas Commission

Working Group V - Innovative Venture Proposal

- Investigation of new organizational mechanisms to stimulate defined development options

1. Wendell Mendell (Chair) - JSC
2. George Kozmetsky - LSPI
3. Gene Konecci - University of Texas at Austin
4. Peter Glaser - ADL
5. Stuart Smith - Science Council of Canada
6. Lou Rancitelli - Battelle Columbus Laboratories
7. Mike Duke - JSC
8. Norma Paige - Astronautics Corp.
9. Geoff Coates - American MagLev
10. Peter Wood - Booz, Allen & Hamilton
11. Don Kerr - EG&G

WORKSHOP AGENDA

WEDNESDAY, JANUARY 28

8:00	Introduction and Review	
	Organization, logistics	K. Fairchild
	Workshop goals, overview	W. Mendell
	National Commission on Space	L. Wilkening
	NASA Headquarters Strategic Planning	B. Roberts
10:00	Break	
10:30	Advanced Planning Scenarios	
	Space Resource Utilization	B. Roberts
	Civilian Space Technology Initiative	S. Sadin
Noon	Lunch	
1:00	Group meetings, A category	
5:00	Group B meets independently	
6:00	Dinner	
	Individual work on assignments from group	
9:00	Meeting of working group leaders	

THURSDAY, JANUARY 29

8:30	Plenary
	Working group reports on plan of attack
	Coordination of objectives and topics
10:00	Groups A and B meet to outline report
Noon	Lunch
1:00	Groups work on draft report, turn in to typists
5:00	Plenary status review
6:00	Dinner
7:00	Individual writing, turn in to typists by midnight
9:00	Meeting of working group leaders

FRIDAY, JANUARY 30

8:00	Group A reports - Open discussion
10:00	Break
10:15	Group B reports - Open discussion
Noon	Lunch
1:00	Groups resolve remaining issues
2:30	Closing remarks and future activities
3:30+	Depart for Orlando
	Organizing committee wrapup

APPENDIX C
LETTERS

NASA JSC LETTER OF INVITATION

The Johnson Space Center joins the Jet Propulsion Laboratory and the Los Alamos National Laboratories in convening a workshop "In Situ Resource Utilization" to be held on January 28-30, 1987, at EPCOT Center in Orlando, Florida. I invite you to participate in the workshop.

This workshop is considered a significant activity in JSC's effort to establish initiatives that advance space flight technologies and identify opportunities for future manned activities in space. It will bring together representatives of the space technology community and a variety of industries that are not now major participants in space development, but which could participate in a broader program concentrating on utilizing planetary resources.

We plan to keep the number of participants small, so that discussion can be intense. We hope to develop a framework for NASA to work with other Government organizations, universities, and private industry to carry out the research and technology development necessary to make in situ resource utilization feasible and beneficial.

I hope that you will be able to attend. The logistics for the workshop are being handled by the Large Scale Programs Institute, Austin, Texas, which is sending a separate letter with additional details.

Sincerely,

Aaron Cohen
Director

LARGE SCALE PROGRAMS INSTITUTE LETTER OF INVITATION

The Large Scale Programs Institute would like to take this opportunity to invite you to participate in a workshop entitled, "In Situ Resource Utilization," to be held on January 28-30, 1987, at EPCOT Center, Orlando, Florida.

Both NASA and outside advisory groups (e.g., The National Commission on Space) have recognized that future manned space initiatives that will include lunar and planetary facilities will require use of in situ resources. This will involve technologies and expertise not currently utilized by the space program. These include construction, mining and materials processing, innovative manufacturing and production, agriculture and bioengineering, automation and robotics, and a variety of service industries. These new technologies, as well as meeting future space objectives, have significant terrestrial commercial development potential. Consequently, planners have come to realize that space development in the next few decades may best be accomplished through public/private partnerships.

This workshop will match the space development strategists with representatives from industrial areas not traditionally associated with the space program. It is hoped that this initial exchange will lead to a working relationship which will incorporate a viable, vigorous, and growing commercial component into future space planning. The workshop agenda will explore avenues whereby the private sector, working perhaps within consortia, can assume more of a leadership role in space development.

The workshop will review future scenarios and their associated uncertainties, identify near-term activities which have high leverage on long-term goals, explore mechanisms for coordinated in situ resource technology development with both space and commercial applications, and develop a plan of action to follow up on promising approaches. Since the success of this initial interaction depends critically on a candid and wide-ranging exchange of ideas, attendance will be kept small and limited to invitees only.

The enclosures provide necessary logistical information. Additional materials will follow. For further information please contact Dr. Stewart Nozette, Lisa Guerra, or Ophelia Mallari at (512) 478-4161.

George Kozmetsky
President

Hans Mark
Chairman

Large Scale Programs Institute

ORGANIZING COMMITTEE LETTER OF INVITATION

Dear ISRU Workshop Attendee,

Enclosed is an agenda and a description of the format for the upcoming In Situ Resources Utilization Workshop. You will also find an information package describing the meeting and lodging facilities at the EPCOT Center. We are looking forward to a lively and productive exchange of views on technological and policy issues arising from new planning initiatives within the U.S. space program.

For the first time since 1970, NASA is considering the explicit adoption of ambitious, long-range goals in space exploration, based on the recommendations of the National Commission on Space (NCOS). Permanent installations on the Moon and on Mars are key elements in the visionary scenario presented by the commission. General strategies for human exploration of the solar system must focus on planetary bases capable of providing support and resources for advanced missions.

However, attainment of permanent human presence in space requires the implementation of technologies and the acquisition of operational skills which extend beyond the scope of the Space Shuttle program. The Office of Aeronautics and Space Technology is formulating a research and development program, the Civilian Space Technology Initiative (CSTI), to address these new technology issues and to respond to the call by NCOS for a significant acceleration of civilian space technology development.

A major task of the workshop will be the review, critique, and supplementation (where appropriate) of these CSTI goals which support the long-term human settlement of space. Many of the appropriate technologies are extensions of commercial applications utilized in the industrial and service sectors of the U.S. economy. Therefore, the participants for the meeting were selected to include private sector expertise which might be transferable to space applications beginning in the next decade.

Since this workshop will introduce nonaerospace industry to a set of views on the potential of space development, a second objective will be an examination of roles for private investment in future space activities and in related technologies. It is generally conceded that the rate of space development will increase as private sector participation increases. However, a major question remains whether future markets in space can possibly support investment without massive public sector involvement. A working group will evaluate strategies for creating commercial opportunities in space through combinations of private and public initiatives.

The In Situ Resources Utilization Workshop is intended to initiate a dialogue between advanced planners in the space program and representatives of those industries which one day will produce goods and services in space as they now do on Earth. Although recommendations to NASA on directions for technology development will be an important product, this interaction will have added value if it can lead to the establishment of collaborative relationships which expedite space development. We look forward to the beginning of a continuing interaction on the road to space.

Wendell W. Mendell
Technical Chairman

INNOVATIVE VENTURES GROUP BACKGROUND INFORMATION

January 21, 1987

In another week, we will be meeting at the EPCOT Center in Orlando, Florida, at the In Situ Resources Utilization Workshop. The organizing committee has identified you tentatively as a participant in a working group devoted to consideration of private sector involvement in scenarios of future space development. I will be chairing the group, and I wanted to give you some background information in advance to save time at the workshop.

The participants in the workshop as a whole can be divided roughly into two categories, sponsors and invitees. Participants from sponsoring organizations or groups have all been involved at some level in a resurgence of long-range policy examination within NASA. The work has not always been centrally coordinated, and various people may have somewhat different views or emphases in their thoughts about the future.

The other half of the workshop, the "invitees," come from private industry, government, and universities. Most have some expertise in technologies which we, the sponsors, think will become much more important in the space program of the next century. For the most part, these technologies appear in our scenarios as part of planetary surface infrastructure, first as part of a permanent surface base but later in the context of a permanent settlement.

Within the U.S. space program, a lunar base or a martian base will be initiated as an NASA project. However, many of us believe that the permanence, the scale, and the scope of planetary surface bases will depend on the involvement of the private sector. On the other hand, many people in the space program find it difficult to extrapolate the current situation to a space marketplace where goods and services are available routinely. At the present time, planning simple operations is a complex process; and access to space is limited (although access elsewhere in the world is increasing). In the operational Space Station being planned, human and physical resources will be scarce and heavily subscribed by NASA projects.

Our working group will be tasked to suggest pathways by which the space program of today can evolve into the 21st century to include active participation and leadership from nongovernmental sectors of our society. Any such evolutionary path is obviously sensitive to Government policy, to real growth of markets in space, to reliability and affordability of space transportation technology, and to an immediate commitment to leadership from some quarter.

Earth orbital space will be rife with activity in 50 years. Who is there and what they are doing will be determined in the next 20 years, which is typical of the time scale for implementing any complex and large technical project. Therefore, the future in space will hinge on plans laid today and on the ability to carry out successfully a proper strategy. The NASA is currently working on strategic planning, but its priorities in defining goals lie with its perception of national leadership in space technology. If elements of the private sector want to guarantee a favorable environment for investment and participation, then they need to identify appropriate objectives from that point of view.

In the information package you have already received was a summary of private research and development consortia, compiled by the Large Scale Programs Institute. Consortia formation is a potentially powerful tool for focusing resources toward well-defined goals and will have advocates at the workshop. However, the creation of markets in space begins with NASA; and its relationship with the private sector must also be examined in terms of changes that would increase access to space. At registration for the workshop you will be provided with a copy of "Space: America's New Competitive Frontier" from the Business-Higher Education Forum, a prestigious committee from commerce and academia, which presents a private sector point of view.

I am enclosing with this letter a condensed version of a briefing by Coopers & Lybrand, Inc., on results of a commercialization study for the Space Station project. I like it because it touches on issues which we will be discussing in Florida and presents concerns from the private sector that need to be addressed.

Our time at this workshop will be very full. At the end of the two and a half days, we will be expected to have a rough draft of a report on the issue of private sector involvement in advanced space endeavors. I do not expect to have all the answers in that amount of time, but we do need to formulate the questions clearly and precisely. In addition, I hope that seeds planted in the interactions will bear fruit in our future efforts toward realizing the potential of the space frontier.

Sincerely,

Wendell Mendell

Enclosure

cc: Kyle Fairchild, General Chairman

APPENDIX D

ACRONYMS AND ABBREVIATIONS

ADL	Arthur D. Little, Inc.
Adv.	advanced
AI	artificial intelligence
A&R	automation and robotics
bioregen.	bioregenerative
CELSS	controlled ecological life support system
cond.	condensed
const.	construction
consum.	consumables
CSTI	Civilian Space Technology Initiative
demo	demonstration
dev.	development
DT	deuterium/tritium
eng.	engineering
FY	fiscal year
GEO	geosynchronous orbit
GN&C	guidance, navigation, and control
ISPP	in situ propellant production
ISRU	in situ resources utilization
JPL	NASA Jet Propulsion Laboratory
JSC	NASA Lyndon B. Johnson Space Center
LANL	Los Alamos National Laboratory
LEO	low Earth orbit
LIDAR	laser radar
LGO	lunar geochemical orbiter
LOX	liquid oxygen
LLOX	lunar liquid oxygen
LSPI	Large Scale Programs Institute
LSS	life support system
maglev	magnetically levitated
mfg.	manufacturing
min.	minimum
MRSR	Mars Rover Sample Return
MSFC	NASA George C. Marchall Space Flight Center

N/A	not applicable
NASA	National Aeronautics and Space Administration
NCOS	National Commission on Space
OAST	NASA Office of Aeronautics and Space Technology
Orb.	Orbiter
OTV	orbital transfer vehicle
PC	physicochemical
P/D	Phobos/Deimos
PMST	prospecting, mining, and surface transportation
pop.	population
prop.	property
reg.	regolith
regen.	regeneration
R&D	research and development
R&T	research and technology
SETI	search for extraterrestrial intelligence
STS	Space Transportation System
surf.	surface
SR&QA	safety, reliability, and quality assurance
sys.	system
temp.	temporary
VLBI	very long baseline interferometry
vs.	versus

NASA
National Aeronautics and Space Administration

REPORT DOCUMENTATION PAGE

1. Report No.
NASA CP-3017

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Report of the In Situ Resources Utilization Workshop

5. Report Date
November 1988

6. Performing Organization Code

7. Author(s)
Kyle Fairchild and Wendell W. Mendell, Editors

8. Performing Organization Report No.
S-581

9. Performing Organization Name and Address
Lyndon B. Johnson Space Center
Houston, Texas 77058

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Conference Publication

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report presents the results of a workshop of 50 representatives from the public and private sectors which investigated the potential joint development of the key technologies and mechanisms that will enable the permanent habitation of space. Held at the United Technologies Center, Lake Buena Vista, Florida, January 28-30, 1987, this workshop is an initial step to develop a joint public/private assessment of new technology requirements of future space options, to share knowledge on required technologies that may exist in the private sector, and to investigate potential joint technology development opportunities.

The majority of the material in the report was produced in five working groups: (1) Construction, Assembly, Automation and Robotics; (2) Prospecting, Mining, and Surface Transportation; (3) Biosystems and Life Support; (4) Materials Processing; and (5) Innovative Ventures. In addition to the results of the working groups, prelimininary technology development recommendations to assist in near-team development priority decisions are presented. Finally, steps are outlined for potential new future activities and relationships among the public, private, and academic sectors.

17. Key Words (Suggested by Author(s))

Space Commercialization
Technology Development
Technology Innovation
Public/Private Ventures
Lunar Development
Life Support
Innovative Ventures
Planetary Development
Mining
Materials Processing
Biosystems

18. Distribution Statement
Unclassified - Unlimited

Subject Category: 88

19. Security Classification (of this report)
Unclassified

20. Security Classification (of this page)
Unclassified

21. No. of pages
100

22. Price
A05

For sale by the National Technical Information Service, Springfield, VA 22161-2171

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NASA
Permit No. G-27

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