NASA SP-509
VOLUME 1

SPACE RESOURCES

Scenarios

Frontispiece

Advanced Lunar Base

In this panorama of an advanced lunar base, the main habitation modules in the background to the right are shown being covered by lunar soil for radiation protection. The modules on the far right are reactors in which lunar soil is being processed to provide oxygen. Each reactor is heated by a solar mirror. The vehicle near them is collecting liquid oxygen from the reactor complex and will transport it to the launch pad in the background, where a tanker is just lifting off. The mining pits are shown just behind the foreground figure on the left. The geologists in the foreground are looking for richer ores to mine.

Artist: Dennis Davidson

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Space Resources

Scenarios

Editors

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Preface

Space resources must be used to support life on the Moon and exploration of Mars. Just as the pioneers applied the tools they brought with them to resources they found along the way rather than trying to haul all their needs over a long supply line, so too must space travelers apply their high technology tools to local resources.

The pioneers refilled their water barrels at each river they forded; moonbase inhabitants may use chemical reactors to combine hydrogen brought from Earth with oxygen found in lunar soil to make their water. The pioneers sought temporary shelter under trees or in the lee of a cliff and built sod houses as their first homes on the new land; settlers of the Moon may seek out lava tubes for their shelter or cover space station modules with lunar regolith for radiation protection. The pioneers moved further west from their first settlements, using wagons they had built from local wood and pack animals they had raised; space explorers may use propellant made at a lunar base to take them on to Mars.

The concept for this report was developed at a NASA-sponsored summer study in 1984. The program was held on the Scripps campus of the University of California at San Diego (UCSD), under the auspices of the American Society for Engineering Education (ASEE). It was jointly managed by the California Space Institute and the Lyndon B. Johnson Space Center, under the direction of the Office of Aeronautics and Space Technology (OAST) at NASA Headquarters. The study participants (listed in the addendum) included a group of 18 university teachers and researchers (faculty fellows) who were present for the entire 10-week period and a larger group of attendees from universities, Government, and industry who came for a series of four 1-week workshops.

The organization of this report follows that of the summer study. *Space Resources* consists of a brief overview and four detailed technical volumes: (1) Scenarios; (2) Energy, Power, and Transport; (3) Materials; (4) Social Concerns. Although many of the included papers got their impetus from workshop discussions, most have been written since then, thus allowing the authors to base new applications on established information and tested technology. All these papers have been updated to include the authors' current work.

In this Scenarios volume, a number of possible future paths for space exploration and development are presented. The paths set the scene for the more detailed discussion in the remaining volumes of the issues of power and transport, nonterrestrial materials, and human considerations.

This is certainly not the first report to urge the utilization of space resources in the development of space activities. In fact, *Space Resources* may be seen as the third of a trilogy of NASA Special Publications reporting such ideas arising from similar studies. It has been preceded by *Space Settlements: A Design Study* (NASA SP-413) and *Space Resources and Space Settlements* (NASA SP-428).

And other, contemporaneous reports have responded to the same themes. The National Commission on Space, led by Thomas Paine, in *Pioneering the Space Frontier,* and the NASA task force led by astronaut Sally Ride, in *Leadership and America's Future in Space,* also emphasize expansion of the space infrastructure; more detailed exploration of the Moon, Mars, and asteroids; an early start on the development of the technology necessary for using space resources; and systematic development of the skills necessary for long-term human presence in space.

Our report does not represent any Government-authorized view or official NASA policy. NASA's official response to these challenging opportunities must be found in the reports of its Office of Exploration, which was established in 1987. That office's report, released in November 1989, of a 90-day study of possible plans for human exploration of the Moon and Mars is NASA's response to the new initiative proposed by President Bush on July 20, 1989, the 20th anniversary of the Apollo 11 landing on the Moon: "First, for the coming decade, for the 1990s, Space Station *Freedom,* our critical next step in all our space endeavors. And next, for the new century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars." This report, *Space Resources,* offers substantiation for NASA's bid to carry out that new initiative.

Contents

Introduction

James D. Burke and Barney B. Roberts

A major objective of this workshop was to develop scenarios for NASA's advanced missions. The first scenario, business as usual, we labeled the "NASA baseline plan." It shows the expected development of NASA programs under existing budget trends. We developed two, more aggressive scenarios that would require funding above the steady-state budget projection. These scenarios were built on the assumption that significant nonterrestrial resources would be available. The workshop then sought to identify additional technologies that would support the alternative scenarios.

In proposing alternative scenarios, we debated what goals were most promising or would have the most public support. It was apparent that limiting the concept of space resources to tangible materials from the Moon or asteroids could fail to support many popular space initiatives, such as a manned Mars mission, significant commercial applications in low Earth orbit (LEO) or geosynchronous Earth orbit (GEO), and tourism. Thus, although the general thrust of the alternative scenarios was toward the utilization of nonterrestrial resources, one scenario emphasized the Moon ("space resource utilization") and the other was more general ("balanced infrastructure buildup").

To avoid being short-sighted on the subject of space resources, the workshop expanded its list to include such items as vacuum, low gravity, and location/view. We also note that our more complete list might not exhaust the possibilities.

Once these points were agreed upon, the workshop divided the analysis and reporting tasks among its members. The contributed sections discuss the baseline scenario, generic alternatives, potential sociopolitical conditions, the common or nodal technologies required to support the alternative scenarios, and issues for further study.

Baseline Program

Barney B. Roberts and Jesco von Puttkamer

Assumptions

The workshop agreed to use a proposed NASA plan as the baseline program. This assumed program has been developed from several sources of information and is extrapolated over future decades using a set of reasonable assumptions based on incremental growth. The principal source of basic data was a presentation given to the workshop by Jesco von Puttkamer, representing NASA's advanced planning activities. This work shows the space program planning efforts divided into four domains (fig. 1). Future activities are planned with balanced emphasis among these four domains.

It was considered reasonable to assume that the level of activity would remain constant in order to stabilize the use of public resources. This assumption resulted in a sequence of programs with waxing and waning budget requirements. As one program decreases in construction and development costs and becomes operational, public resources are made available for the next program. This approach levels the impact on facilities and capital investments and maintains a skilled and experienced work force.

As for budget estimates, only low to moderate growth after adjustment for inflation was assumed. A key principle underlying the proposed program is that maximum benefits will be obtained from commonality and subsystem evolution. Technologies and program elements will be synergistic and integrated to allow one project to use capabilities developed by another. In addition, the NASA planners tried to make realistic and practical estimates of the technology developments required to support each phase of design and construction. Using this information and previous history on the programmatics involved in the development of space hardware, NASA constructed a phased, evolutionary set of scenarios that we consider reasonable.

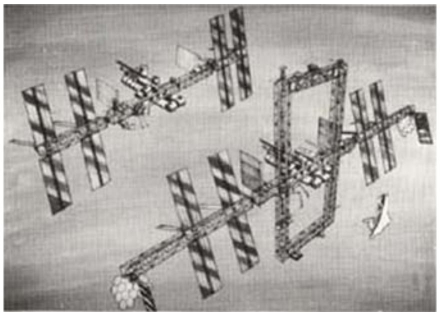
To summarize, the assumptions for the NASA baseline program are as follows:

- Balanced emphasis in four domains
- Constant level of activity
- Low to moderate real budget growth
- Maximum use of commonality
- Realistic and practical technology development

Figure 1

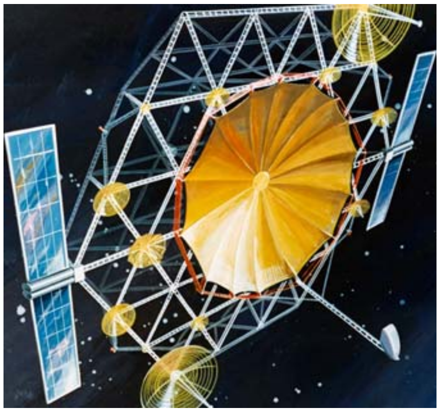
NASA's Advanced Planning

NASA is planning a balanced program, with roughly equal emphasis given to each of four domains. The first domain is low Earth orbit (LEO). Activities there are concentrated on the space station but extend on one side to Earth-pointing sensors from unmanned platforms and on the other to the launch and staging of unmanned solar system exploration missions. The second domain is geosynchronous Earth orbit (GEO) and cislunar space. Activities there include all GEO missions and operations, both unmanned and manned, and all transport of materials and crews between LEO and the vicinity of the Moon. The third domain is the Moon itself. Lunar activities are to include both orbiting and landing missions; the landings may be either unmanned or manned. The last domain is Mars. Missions to Mars will initially be unmanned but they will eventually be manned.



(1) LEO Space Station

Although the Soviets have had cosmonauts continuously occupying their Mir *spacecraft for some time, the U.S. space station will be the first permanently occupied space outpost in the American space program. The space station will be the location for a variety of Earth observations and for many scientific and engineering experiments in microgravity. It will also be a transportation node and servicing center for satellites and space vehicles.*



(2) GEO Platform

Location in geosynchronous orbit is required for most types of communication satellites. Because this orbit is filling up, a trend may develop to cluster multiple users on a single platform. The large platform shown in this drawing contains about a dozen separate antennas, each of which can be aimed at a different user. To be cost-effective, such large platforms must be able to be serviced and repaired. For service and repair, either the entire platform must be returned to the space station by orbital transfer vehicle or astronauts must travel to geosynchronous orbit for onsite maintenance.

NASA photo: S78-23610

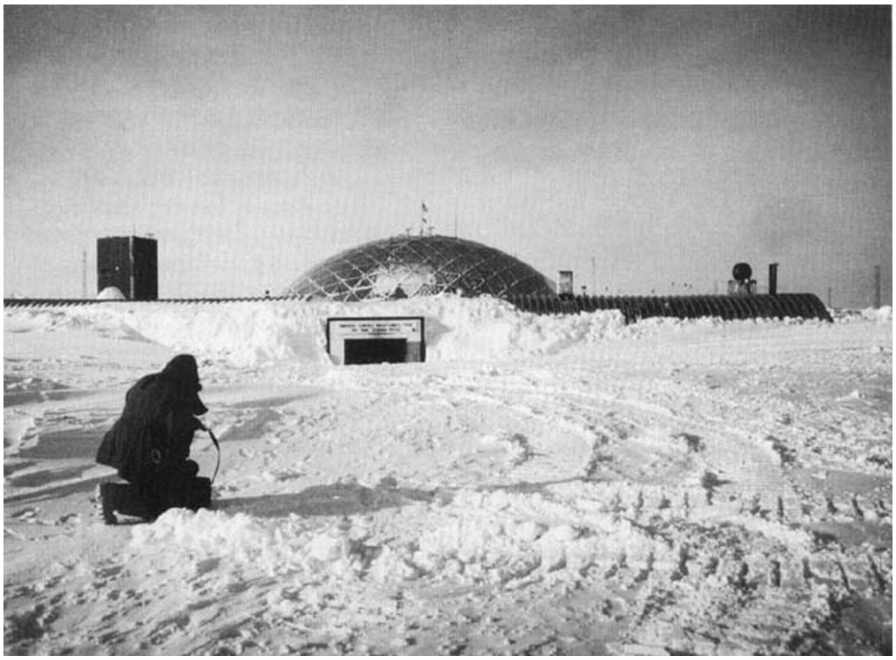
(3) Spartan Lunar Base

The early lunar base may consist of several modules similar to habitation and laboratory modules for the space station, which can be transported to the lunar surface and covered with lunar regolith for radiation protection. In some scenarios, the early lunar base would be totally dependent on transport from Earth for all supplies and consumables. In other scenarios, a small plant would be emplaced, which would allow the production of oxygen for life support.

NASA photo: S78-23251

(4) Closeup of the Surface of Mars From the Unmanned Viking Lander

While Viking provided spectacular pictures of the surface of Mars and some chemistry data for the two lander sites, an indepth understanding of martian samples and the detailed data necessary to describe the evolution of Mars (age dating, mineralogy, possible fossils) can be gained only from actual samples of rocks and soil returned to Earth for detailed analysis using sophisticated laboratory instruments.



American Station at the South Pole

The station consists of several buildings within a large-diameter (approximately 100-meter) geodesic dome. The buildings include laboratories, service areas, and habitation modules. This station is probably the closest thing we have to a base on another planet. The South Pole station is continuously occupied, but crewmembers arrive or depart only during the summer season. While the occupants can venture outside with protective clothing ("space suits") during the winter, they are mostly dependent on the shelter provided by the geodesic dome and the buildings within the dome, much as they would be at a Moon or Mars base. Most of the supplies must be brought in by air, but some use is made of local resources. Local ice is used for water, and, of course, local oxygen is used for breathing and as an oxidizer for combustion, including operation of internal combustion engines.

Photo: Michael E. Zolensky

Program Elements and Descriptions

The first domain shown in figure 1 (LEO) emphasizes the space station and includes the recommended program of the Solar System Exploration Committee (SSEC), Earth observation satellites, manufacturing in low Earth orbit, and other commercial ventures such as tourism. The second domain (GEO) emphasizes commercial activities in geosynchronous orbit—mostly communication satellites or platforms. Other GEO facilities would include an experimental platform and later a manned "shack" to support and maintain the GEO facilities.

The third domain (the Moon) consists of the establishment of a temporarily manned science and research camp, similar to an Antarctic outpost. The lunar base would be totally dependent on Earth-supplied consumables and transportation. The fourth domain (Mars) includes an unmanned sample return mission.

Folding these four domains into a baseline program in accordance with the above assumptions results in the plan depicted in figure 2.

Critiques of the NASA Baseline

The workshop participants offered some critiques of the baseline plan, which are documented in this subsection in order to use them in the next section on alternative scenarios.

1. *Critique:* Devote more emphasis to asteroids as a source of nonterrestrial resources.

   Rebuttal: Resources on the Moon may be more limited than those of asteroids; however, the high leverage items such as oxygen for transportation and mass for shielding are available there, and the Moon has many other advantages to science and human presence that asteroids may be lacking.

   Resolution: Seriously consider asteroids as a viable source of resources in conjunction with other potential sources.

2. *Critique:* The baseline program demonstrates a lack of vision which is a result of conservative budget requests (or vice versa).

   Rebuttal: NASA is aggressive in its budget submittals and is

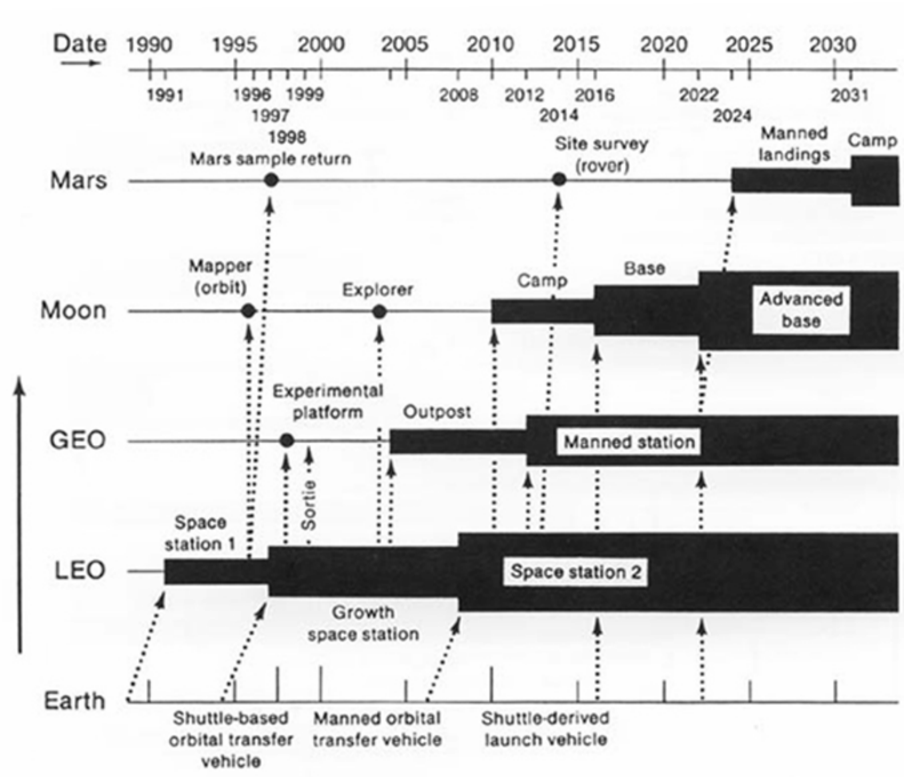


Figure 2

Baseline Scenario

If NASA continues its business as usual without a major increase in its budget and without using nonterrestrial resources as it expands into space, this is the development that might be expected in the next 25 to 50 years. The plan shows an orderly progression in manned missions from the initial space station in low Earth orbit (LEO) expected in the 1990s, through an outpost and an eventual space station in geosynchronous Earth orbit (GEO) (from 2004 to 2012), to a small lunar base in 2016, and eventually to a Mars landing in 2024. Unmanned precursor missions would include an experiment platform in GEO, lunar mapping and exploration by robot, a Mars sample return, and an automated site survey on Mars. This plan can be used as a baseline scenario against which other, more ambitious plans can be compared.

demonstrably second only to the Department of Defense (DOD) in budget growth. However, the fact remains that policy guidelines established by the Administration and Congress do not permit much more than the proposed baseline.

Resolution: A small portion of the planning exercise should not constrain itself within budget limitations but direct its attention to truly visionary space objectives in order to have an impact on our near-term technology developments and thereby contribute constructively to future budget drafts. NASA needs to make a better effort to "sell" its proposed programs to Congress and to the public.

3. *Critique:* The NASA baseline plan should be compressed in time to allow an earlier start on some selected programs.

   Rebuttal: An unlimited budget cannot resolve all problems involving the factor of time. Technology developments require significant time for resolution even when adequately funded. In addition, the technology developed for each new program feeds on or evolves from the technology developed for a precursor program.

   Resolution: Identify key technologies for early development and, where possible and practical, compress schedules.

Alternative Scenarios Utilizing Nonterrestrial Resources

Charles H. Eldred and Barney B. Roberts

This section of the report provides a collection of alternative scenarios that are enabled or substantially enhanced by the utilization of nonterrestrial resources. Here we take a generalized approach to scenario building so that our report will have value in the context of whatever goals are eventually chosen.

One significant finding of this workshop is that to discuss only tangible materials from asteroids or the lunar surface is probably too limiting an assumption to permit consideration of all viable scenarios. Thus, although we decided to discuss the following space resources, we realize that this list is nonexhaustive.

- Tangible materials
  - Lunar
  - Asteroidal
  - Martian
- Vacuum
- Energy
- Low to negligible gravity
- Physical location/view

The following paragraphs will discuss, in varying detail, each of these resources.

Space Resources

Tangible Materials

Lunar materials: The foremost lunar resource we identified was lunar oxygen for rocket propulsion (see fig. 3). The Moon can also

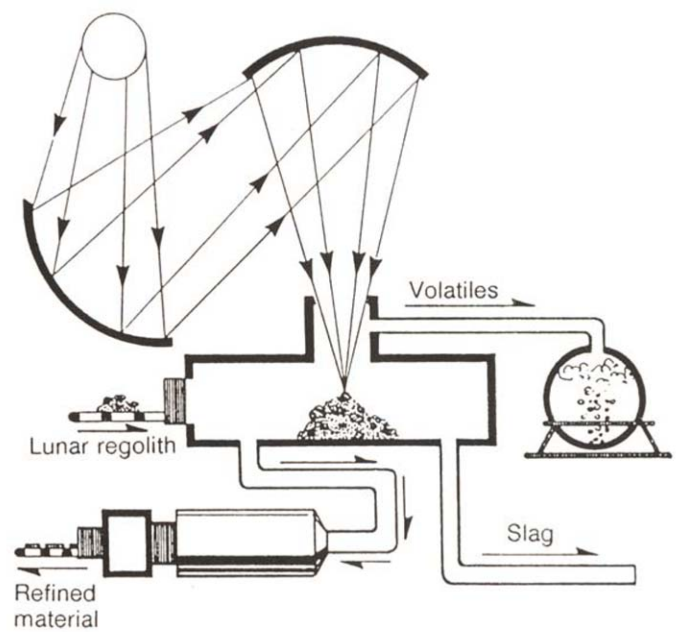


Figure 3

Lunar Materials Processing

This schematic drawing shows three main classes of products (volatiles, metals, bulk construction material) which can be made from lunar raw material. Lunar regolith is carried by a conveyor belt into a reactor, where it is heated by concentrated solar energy. Simple heating will cause it to release trapped solar wind volatiles, including hydrogen and rare gases. If it is heated in an atmosphere rich in hydrogen or another reductant, chemical reduction will take place, causing the lunar material to release oxygen from oxides and silicates. When sufficient oxygen is released, some of the reduced metals formed by the process can be refined and formed into ingots or cast into useful shapes. The remaining material can be withdrawn as slag, which can be used for construction of buildings and roads or as radiation shielding.

be a source of metals (iron, aluminum, magnesium, titanium) and nonmetals (glass, ceramics, concrete), which may find use as structural or shielding materials on and off the Moon. The Moon is relatively deficient in some of the more volatile elements—hydrogen, carbon, and nitrogen.

Asteroidal materials: Earth-approaching asteroids are rocky bodies that can provide useful materials, including some elements not found in abundance on the Moon. Some asteroids contain substantial quantities of water and carbonaceous material; others have abundant metal, including iron, nickel, cobalt, and the platinum group (see fig. 4). Some asteroids are energetically more accessible than the lunar surface; however, trip times are generally long and low-energy opportunities limited. For this reason, these asteroids don't offer convenient staging points.

Martian materials: The utilization of martian resources, particularly to produce propellants, is a probable aspect of an intensive Mars exploration program. Propellants could be extracted from Mars' atmosphere or from materials on the surface of Mars, Phobos, or Deimos (see fig. 5). These satellites have characteristics of carbonaceous asteroids and for many purposes, including access, may be considered as asteroids.

Vacuum

Vacuum, used in many scientific experiments and manufacturing processes, is expensive to create and limited in volume on Earth. Workshop participants were not convinced that going into space to utilize the vacuum would lead to

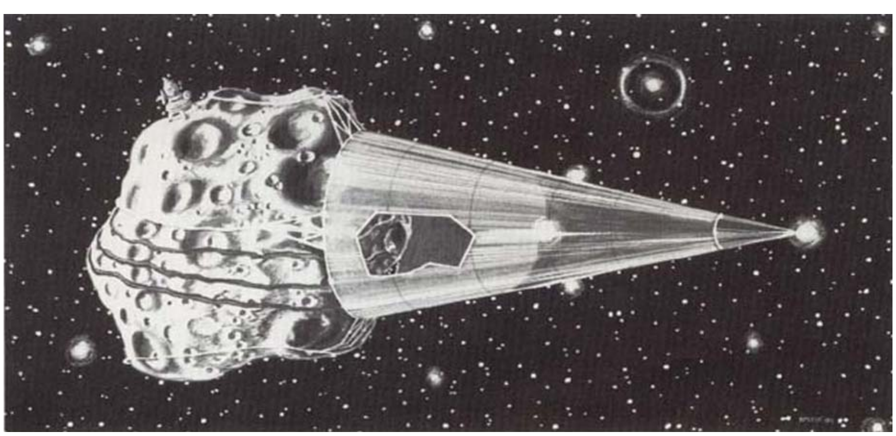


Figure 4

Mining an Asteroid

Mining asteroids will be a major technological challenge. Here is one concept in which a robot mining vehicle with paddle wheels moves around the surface of the asteroid and throws out material, which is caught in the cone-shaped catcher attached to the asteroid with cables. When it is full, attached thrusters will propel the catcher back to near-Earth space, where the asteroidal ore can be processed for water, carbonaceous materials, and metals.

economic benefits, considering the high cost of space transportation today. However, the potential of the limitless vacuum available in space kept it on the list as a viable resource. The unlimited vacuum could enable new analytical or testing procedures that depend on the surface properties of materials or the transmission of molecular beams. The vacuum of space could enable accelerators with no need, or a substantially reduced need, for containment devices. Such vacuum might permit new uses of the metals sodium and potassium, which are difficult to handle in the Earth's atmosphere. And it could allow the high-temperature vacuum processing of glasses, metals, and cement.

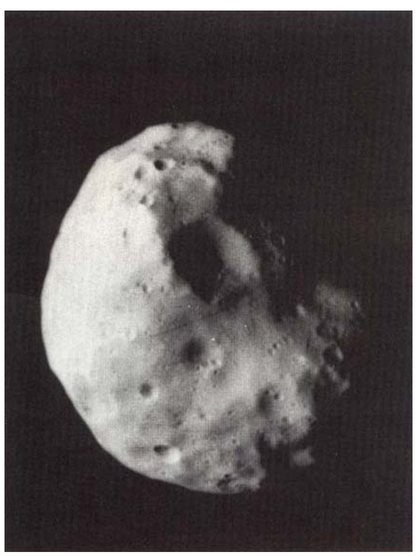


Figure 5

Phobos

Phobos, one of the two moons of Mars, is a likely target for any future martian missions. Phobos is 27 by 19 km and has a relatively low density of 19 gm/cm^3. The escape velocity from Phobos is only 11 m/sec. The optical properties of Phobos are similar to those of a type of asteroids that are thought by many to be of carbonaceous chondrite composition. Phobos has a well-developed groove structure, which may reflect major internal fracturing originating from large impacts. Phobos is inside the Roche limit for Mars and is being pulled even closer by tidal forces. Within about 50 million years, Phobos will be completely torn apart by these tidal forces and will become a ring around Mars.

Energy

Energy from space has been of practical use for many years. The primary energy source is of course the Sun. The most prominent application is solar photovoltaic power for satellites now in orbit. In the state-of-the-art process, solar cells directly convert incident solar energy into electrical energy. The advantages of collecting solar energy in space rather than on Earth arise principally from two facts: The first is that one can get more solar energy by choosing an orbit that has more "daylight" hours, and the second is that one can avoid interference from the atmosphere.

Energy from space may be utilized in space to power facilities (including those on the surfaces of planetary bodies) or can be returned to Earth for conversion to electrical energy. Alternatively, the Sun's energy may be used directly. The propulsive power of solar photons may be used to drive a solar sail. Direct use of thermal energy to provide process heat may be important in space. The Sun's light could be reflected, selectively, to the Earth to light cities, agricultural areas, or arctic night operations (see fig. 6).

Large space facilities, such as the space station or a lunar base, will

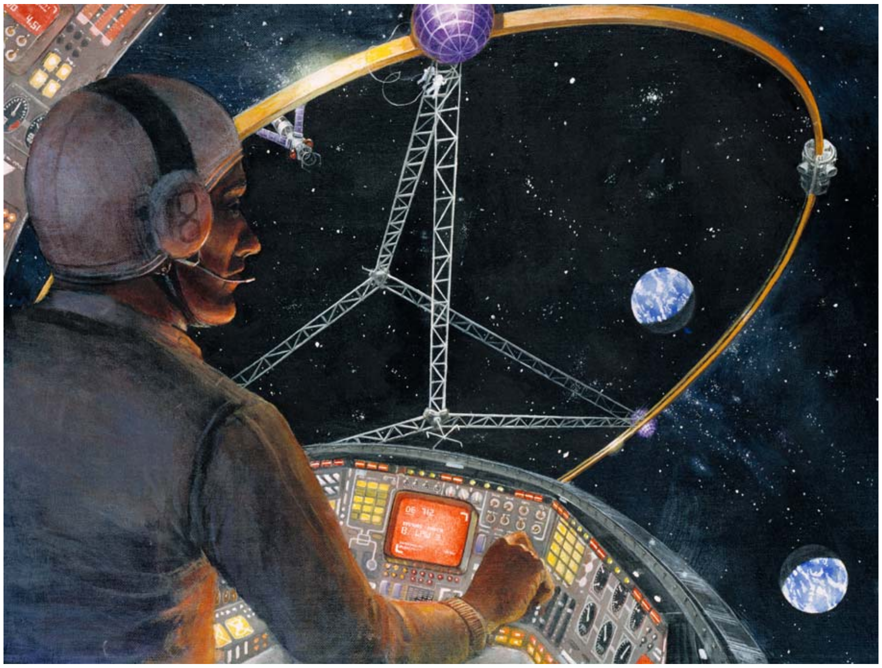


Figure 6

Reflected Sunlight Illuminates the Earth

In a simple example of how solar energy from space might be useful, large-diameter mirrors provide illumination where needed on Earth. In this concept, a mirror, 300 meters in diameter, made of thin Mylar film and supported by a ring and girder structure, is being set up in geosynchronous orbit. Such mirrors would provide nighttime illumination equivalent to full moonlight for any area about 300 km in diameter. A number of mirrors could be pointed at the same area to provide much brighter illumination. This illumination might be useful for lighting cities, agricultural areas, or arctic night operations. Other potential uses are to light up a disaster area or an area undergoing a power blackout.

NASA photo: S76-25254

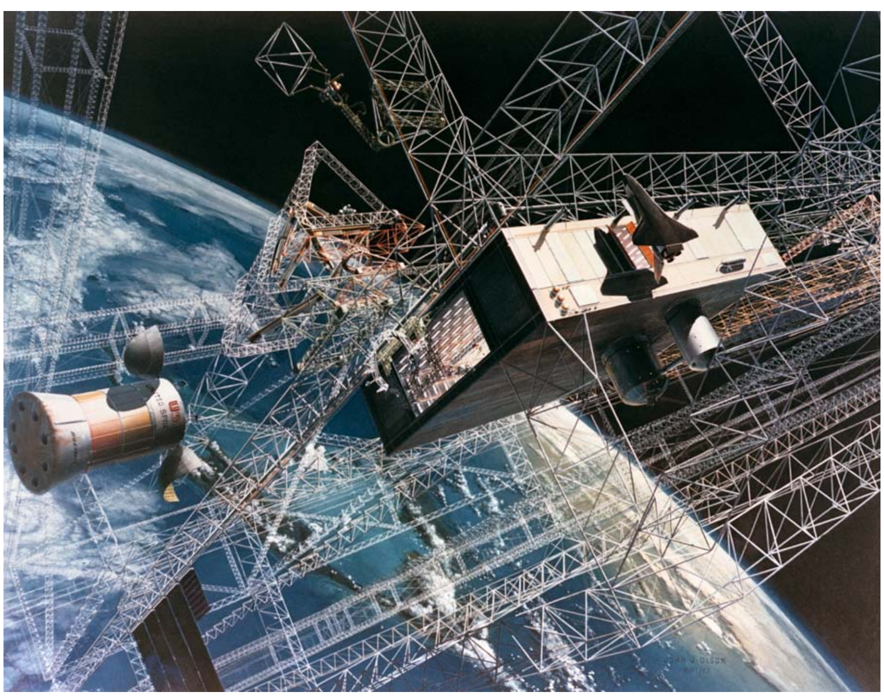


Figure 7

Construction of a Large Solar Power Station

In the future, large structures built in space may include solar power stations that will collect solar power using photovoltaic arrays. This power could be used in advanced space stations or beamed to a lunar base by microwave. In this view, a framework for such a station is being constructed. The station includes a service and equipment bay, in which subcomponents can be assembled, tested, and repaired.

Artist: John J. Olson

NASA photo: S78-23143

require significant power (see fig. 7). The power requirements for the current space station configuration are so large that the structural design and control system requirements will be driven by the solar panels if photovoltaic devices are used. A competing design concept being considered is solar dynamic (see fig. 8). This approach would use an energy-focusing mirror and a heat engine to drive a generator. Another approach would use electrodynamic tethers to exchange orbital energy for electrical energy. This very efficient process may be useful in low Earth orbit for energy storage but could not produce the high power levels needed for the primary supply system.

Several NASA and privately funded efforts have been undertaken to define ways in which space-supplied energy might be used to replace energy from nonrenewable Earth-based resources. One of these was the solar power satellite (SPS) system, which would ring the Earth in geosynchronous orbit with 5- by 20-kilometer solar-powered satellites designed to microwave the energy to the Earth. Another proposal for supplying power from space to the Earth

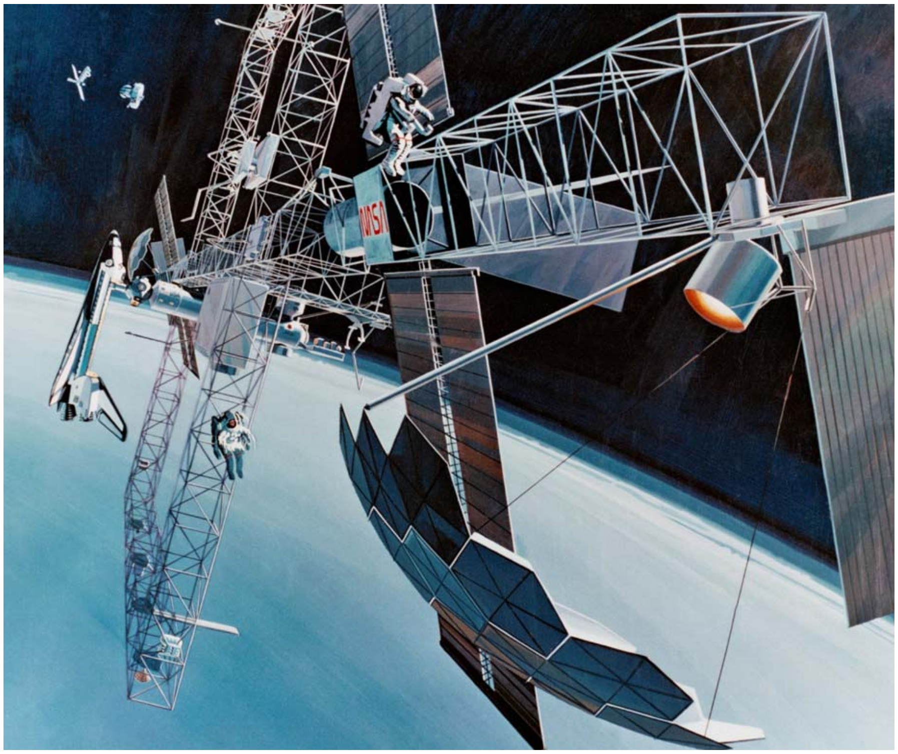


Figure 8

Solar Dynamic Power for the Space Station

In this artist's conception, a solar dynamic power generation system uses concentrated light from the Sun to heat a fluid, which turns a generator to provide electrical power for the space station. Solar dynamic power generation may have some advantages over solar photovoltaic: potentially higher efficiency per unit area of reflector and possibly lower cost for large power capacity. A solar dynamic system may also be easier to maintain.

NASA photo: S86-41477

uses large areas on the Moon for relatively low-efficiency photovoltaic devices utilizing indigenous lunar material, such as silicon. The lunar power station would also transmit energy to Earth by microwave.

The Sun's energy is a perpetual source of clean, nonpolluting power, and major technological advances in photoconversion and energy transmission could substantially alter any space scenario.

Low to Negligible Gravity

Many manufacturing processes may be enabled or improved by the utilization of the low to negligible gravity of space. An electrophoresis process for separating cells having small differential charges is being developed by private industry. In the absence of gravity, an electrical field can cause the desired cells to migrate toward a collector. The great selectivity of this process and the purity of its products may lead to drugs effective in the treatment of cancer, diabetes, and other diseases (see fig. 9). Other processes may produce new alloys, high strength glasses, and more efficient semiconductors. The more space transportation costs are reduced, the wider the range of economical microgravity processing will be. This is an area of potentially significant commercial investment.

Figure 9

Electrophoresis in Space

Manufacturing or materials processing in the microgravity of space may prove to be a major activity. Here, astronaut Jack Lousma is handling an electrophoresis column used for human cell separation on the STS-3 flight. Space manufacturing and processing of biological and pharmaceutical materials may prove cost-effective because of the potentially very high value of these substances per unit mass.

NASA photo: S82-28916

Physical Location/View

Physical location in space and the view from off the Earth have shown themselves to be a resource of great benefit to the public (see figs. 10 and 11). The particular characteristics of the geosynchronous orbit, both from the standpoint of view (weather satellites) and from the standpoint of stability (communication satellites), have been heavily exploited and have provided substantial benefits in revenue and in public safety. Significant public and private (as well as joint venture) technology developments are under way to further utilize this unique space resource for communication, navigation, search and rescue, and other purposes. The location of astronomical facilities in space has been demonstrated to be of fundamental scientific importance (see fig. 12). Another potential utilization of location/view would be for recreation in low Earth orbit. Studies have shown that a market does exist for the public to use space as a recreational area, if transportation costs can be made affordable.

Figure 10

The "Big Blue Marble"

Location in space must be considered a resource in the sense that it enables some very valuable activities. In this whole Earth view taken by the crew of Apollo 17, it is apparent that large-scale weather patterns can be photographed, that the geology and vegetation of large land masses can be observed by remote sensing, and that many points on the Earth can be reached by a single data transponder for enhanced communication. Most of the economic payback from space activities has so far been in these three areas, all of which take advantage of location in space.

NASA photo: AS17-148-22727

Figure 11

Space Shuttle and Horizon as Seen From the Shuttle Pallet Satellite (SPAS)

This is a satellite view of the Orbiter taken on the STS-7 mission. The Orbiter had previously launched two communication satellites (Telesat Anik C2 and Palapa D), and the protective cradles for these satellites can still be seen in the cargo bay. The Space Shuttle has been used heavily as a launching vehicle for communication satellites. Much of this task may now be taken over by expendable launch vehicles. The location in space of communication satellites gives them such high value that the enormous expense of building and launching them can be paid back by revenues in a reasonable length of time.

NASA photo: S83-35802

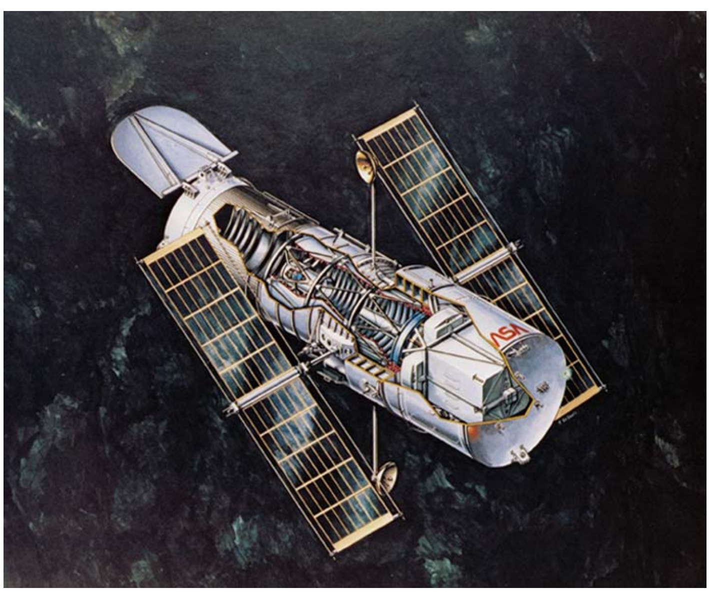


Figure 12

The Hubble Space Telescope

Another priceless advantage of a location in space is illustrated by this artist's concept of the Hubble Space Telescope. This telescope will be above the Earth's atmosphere, which greatly interferes with the optical clarity of an Earth-based telescope and which also absorbs important parts of the light spectrum. The Hubble telescope can be serviced in space and can even be returned to Earth by a Space Shuttle mission for extensive maintenance or overhaul, if needed. Eventually, telescopes on the Moon may also be feasible and desirable. Radio telescopes located on the far side of the Moon will avoid the ever-increasing electromagnetic noise from the Earth.

NASA photo: S86-30463

Other potential developments in the cultural and societal arena are certain to appear but difficult to quantify. Historical evidence suggests that humankind always modifies its culture and societal norms to adapt to major alterations of its sphere of influence. It is conceivable that artistic and sporting activities could find a role in space and may be marketable.

By way of concluding this section on space resources, we, the members of the workshop, want to stress that the list of space resources is not limited to those we have mentioned. Other usable resources might be isolation (for nuclear waste disposal or very hazardous research projects) and extreme temperature gradients (for heat engines).

Generic Scenarios for Utilization of Nonterrestrial Resources

In order to suitably characterize the future utilization of nonterrestrial resources, we should assess scenarios broad enough to bring to the surface all or most of the key technology issues. The exploitation of nonterrestrial resources encompasses a very broad range of potential products, benefits, resources, supporting systems, and technology requirements. The evolution of space activities into the 21st century also holds the potential for a much changed mix of space users, with increased levels of commercial, international, and military space activities. The objective of this section of the report is to view the broad range of mission alternatives that may use space resources and to select a few examples that illustrate a mix of mission characteristics.

Mission Characteristics and Options

Table 1 illustrates the variety of options that are possible for future missions. Most missions can be described by one or more of the options related to each item. Therefore, a specific mission can be characterized by a total set of option choices.

Mission goals: Four broad goal options are shown. The identification of relevant goals is imperative to advocacy of the overall program and its technology requirements. Each of the goals represents a valid component of the total space program. Although some goal from the leadership/ human spirit class may be the only goal of a specific mission, most space missions have been dominated by a strong set of scientific or applications goals. Such human goals can often be attained with only marginal costs when added to more concrete goals.

TABLE 1. *Options for Aspects of Mission Development*

	Item	*Options**			
1.	Goals:	Leadership Exploration Human spirit	Public applications	Commercial	Security Military
2.	Participants: Type: Countries:	 Government National	 Government/commercial International	 Commercial	
3.	Purpose:	Science/research	Enhanced mission	Valuable product	Prestige/power
4.	Space resource:	Materials	Vacuum Energy	Gravity	Location/view
5.	Resource location:	LEO GEO	LEO/cislunar (debris expendables)	Lunar Asteroidal	Planetary (Mars & moons)
6.	Product:	Materials Volatiles Low value solids High value solids	Information/data	Energy	Pleasure
7.	Processing: Location: Type:	 In situ None	 LEO Automated	 Other Manned	
8.	Transportation: Resource site } Processing site } Use site } Mode:	 Same Chemical rocket	 In situ processing/ used elsewhere Aerobrake	 Intermediate site Other	 At use site
9.	Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments	Planetary bases or outposts

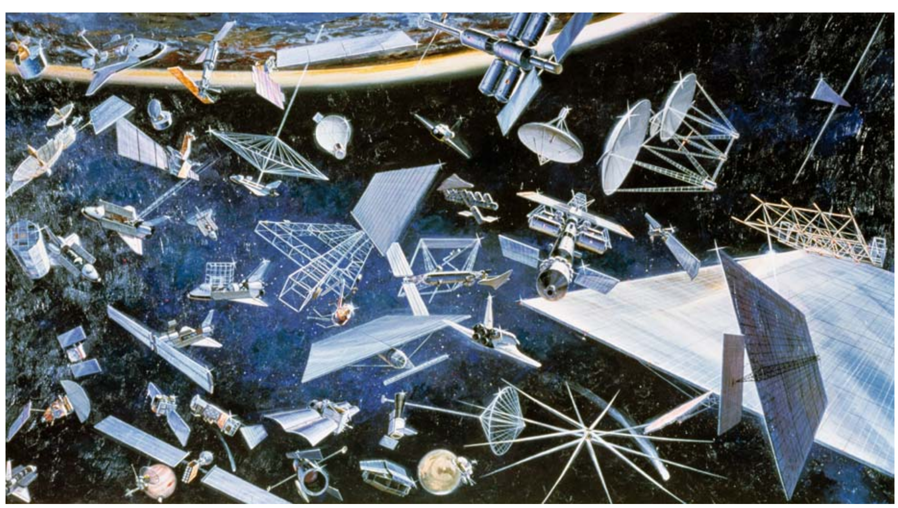
*The columns in this table do not represent related categories but are used simply to enumerate options for each item.

Participants: The mix of participants in space activities is rapidly changing from the historical dominance of the U.S.A.'s civilian space agency and the more military space effort of the U.S.S.R. In the United States, military funding of space activities now exceeds that of NASA. The U.S. program is encouraging commercial participation. And most of the advanced countries and many developing countries are pursuing space capabilities to increase their military options, to advance technology, and to gain prestige. These developments may drastically change the way in which space activities are pursued in the 21st century. It will be necessary for the nations of the world to agree on policies for the utilization of space resources because they are limited. Already at issue are the filling of geosynchronous Earth orbit and the problem of orbital debris.

Purpose: Use of space resources spans a range of purposes from pure science (planetary observations) through mission enhancement (such as in situ propellant production) to the production of products with value to a third party. National prestige and the development of new technology have been strong motivators of national space programs.

Space resource: The details of indigenous space resources have been discussed earlier in this section. We consider materials placed in space for one purpose and then recycled for another to be a special category of space resources.

Resource location: The location of the resource has tremendous implications for the transportation requirements of the mission and for the possibility of human participation. One early exploitation of space material resources may be the scavenging of Space Shuttle cryogenic propellants and external tank materials, which are potentially available in low Earth orbit. The development of resources on planetary bodies (Moon, Mars) is



Overcrowding in Space

This artist's concept shows a wide variety of existing and future satellites. In view are satellites for surveying Earth resources and mapping them, communication satellites, orbiting platforms, various types of space stations, solar power satellites, astronomical observatories, and manufacturing facilities. Geosynchronous orbit is already becoming crowded and satellite densities in other orbits must also be considered. This view also hints at the potential hazards of having large numbers of satellites in space; namely, the possibilities for collision and generation of orbital debris. The issue of orbital debris must be more carefully considered as space becomes more crowded.

Courtesy of Grumman Aerospace Corp.

NASA photo: S78-23311

considered essential to any long-term activities there.

Product: Products of value include not only materials but also energy, information (as with communication satellites), and possibly pleasure and entertainment (as represented by tourism and national parks).

Processing: The process for converting a raw resource into a valuable product, the location for this process, and whether or not humans are directly involved in the process are key considerations.

Transportation: Transportation between key locations, which include the operations base, the resource site, the processing site, and the use site, is one of the major factors in feasibility and achieving favorable economics. The transportation strategy, the transportation system, and the transportation technology level are key issues in this set of tradeoffs.

Infrastructure: The activities of each chosen mission will require that a set of facilities be established in space. These facilities will be a subset of this general set: (1) some form of transportation from Earth to orbit, (2) a service and operations station in low Earth orbit, (3) observation instruments, (4) a means of getting from LEO to higher orbits (orbital transfer vehicles), (5) bases or outposts, manned or otherwise, on various planetary bodies.

Selected Mission Examples

Four mission examples are shown to illustrate the variety of options in the various areas listed in the previous subsection. These four missions are not intended to be all encompassing; readers are encouraged to use table 1 to create and characterize other missions of interest.

Mission 1 – lunar or asteroidal propellant extraction: Table 2 and figures 13 and 14 illustrate the characterization of these missions, which were combined because of the high degree of similarity. Such a mission has many attractive features. It has a combination of goals, including elements of both exploration and commercialization, with a probable evolution from exploration to commercialization. Participants could combine government and private investment. The product could be used to enhance the basic mission in the early phases and provide a valuable output in the later phases of the program.

Development of the processing systems and transportation systems are key technology challenges. The infrastructure supports growth to exploitation of solid materials and can complement military technology requirements.

TABLE 2. *Lunar or Asteroidal Propellant Extraction*

	Item	*Options*			
1.	Goals:	Exploration	Public applications	Commercial	
2.	Participants:				
	Type:	Government	Government/commercial	Commercial	
	Countries:	National	International		
3.	Purpose:	Science/research	Enhanced mission	Valuable product	
4.	Space resource:	Materials			
5.	Resource location:			Lunar Asteroidal	Moons of Mars
6.	Product:	Materials Volatiles			
7.	Processing:				
	Location:	In situ	LEO	Other	
	Type:	None	Automated	Manned	
8.	Transportation:				
	Resource site, Processing site, Use site	Same	In situ processing/ used elsewhere	Intermediate site	At use site
	Mode:	Chemical rocket	Aerobrake	Other	
9.	Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base Asteroidal outpost Mars base Phobos outpost

Mission 2 – climate modification for agricultural productivity: Table 3 illustrates this mission, which focuses on critical world population needs for food. This program would be a cooperative international government project and would exploit the energy resources of space. Options exist for utilizing nonterrestrial materials to construct space energy facilities. Requirements for transportation to GEO would be increased under this plan. The potential for direct benefits to major portions of the world's population could motivate a large-scale effort of this type.

Mission 3 – information or entertainment: Table 4 and figure 15 illustrate this mission area, which focuses on the development of commercial opportunities in space that affect the individual person. This effect is illustrated in two ways: (1) bringing world information and communication to the individual (i.e., complexity inversion) and

Figure 13

A Propellant Tank Farm on the Lunar Surface

Here, robots are moving tanks of liquid oxygen into position for transport into space. Liquid oxygen is produced in the reactor units shown in the background. These reactors are heated by solar radiation, which is reflected into them by Sun-tracking mirrors. Other possible export products include hydrogen, bulk materials for shielding, and metals for space construction.

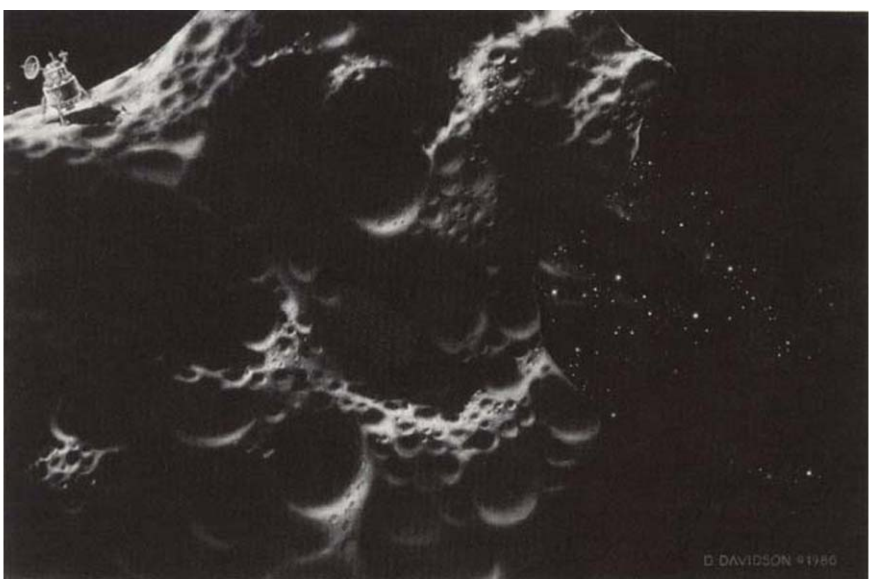


Figure 14

Asteroid Mining

Asteroids also have resource potential, notably the potential for providing water, which can be decomposed into hydrogen and oxygen for propellant use. Asteroids may have rough cratered surfaces, as illustrated in this painting. If they are water-rich, they are likely to be similar to carbonaceous chondritic meteorites, which are very black, with extremely low albedos. Such asteroids may be rather soft and friable and thus easily mined.

Artist: Dennis Davidson

TABLE 3. *Climate Modification for Agricultural Productivity*

	Item	*Options*			
1.	Goals:	Human spirit	Public applications		
2.	Participants:				
	Type:	Government			
	Countries:		International		
3.	Purpose:			Valuable product	
4.	Space resource:		Energy		
5.	Resource location:	GEO		Lunar	
6.	Product:			Energy	
7.	Processing:				
	Location:	In situ	LEO	Other	
	Type:	None	Automated	Manned	
8.	Transportation:				
	Resource site / Processing site / Use site	Same	In situ processing/ used elsewhere	Intermediate site	At use site
	Mode:	Chemical rocket	Aerobrake	Other	
9.	Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base

(2) enabling tourist-type access to space. If the much lower transportation costs necessary to enable tourism could be achieved, then the expansion of the market to the individual would enable tremendous business and economic opportunities.

Mission 4 – Strategic Defense Initiative (SDI): Table 5 illustrates a mission to support the strategic defense initiative. SDI systems could benefit from large amounts of low-grade shielding materials for systems in low Earth orbit. Although there are some areas of technology commonality with mission 1, the goals, participants, and products of interest are substantially different from those of the other missions. Also, critical tradeoffs would be decided on the basis of much different assessment criteria.

TABLE 4. *Information or Entertainment*

Item	*Options*			
1. Goals:			Commercial	
2. Participants:				
Type:			Commercial	
Countries:	National	International		
3. Purpose:			Valuable product	
4. Space resource:	Materials			Location/view
5. Resource location:	LEO GEO		Lunar	
6. Product:		Information		Pleasure
7. Processing:				
Location:				
Type:	None			
8. Transportation:				
Resource site				
Processing site	Same			
Use site				
Mode:	Chemical rocket	Aerobrake	Other	
9. Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base

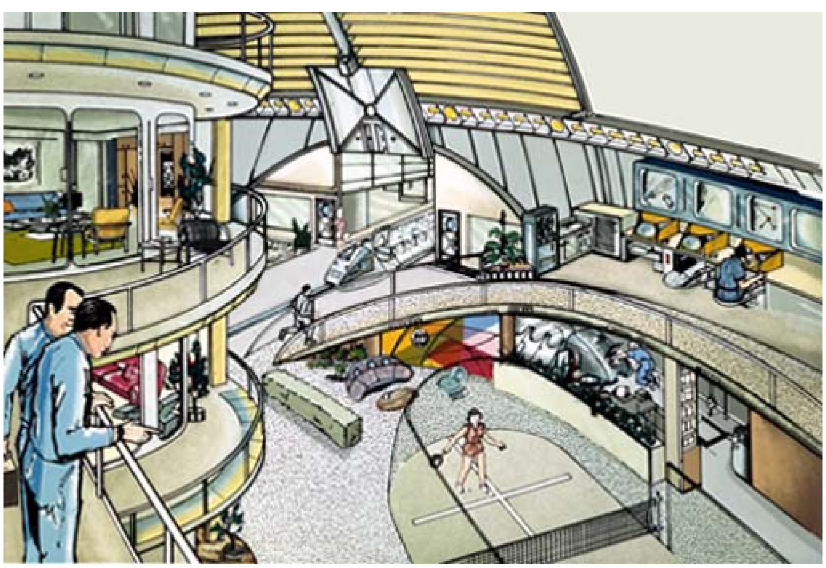


Figure 15

Tourism

Tourism may eventually be an important activity in space or even on the Moon. This drawing shows a hotel module at a lunar base. The hotel has recreation facilities, viewing ports, and TV monitors for viewing activities at remote locations. Excursions onto the lunar surface are made on the small monorail train. While tourism will not be possible very early in the development of a lunar base, it might be a logical intermediate step between a utilitarian base and a self-supporting lunar colony.

NASA photo: S71-4297V

TABLE 5. *Strategic Defense Initiative*

	Item	*Options*			
1.	Goals:				Security Military
2.	Participants:				
	Type:	Government			
	Countries:	National			
3.	Purpose:				Prestige/power
4.	Space resource:	Materials			Location/view
5.	Resource location:	LEO GEO	LEO/cislunar	Lunar Asteroidal	
6.	Product:	Materials Low value solids	Information/data	Energy	
7.	Processing:				
	Location:	In situ	LEO	Other	
	Type:	None	Automated	Manned	
8.	Transportation:				
	Resource site Processing site Use site	Same	In situ processing/ used elsewhere	Intermediate site	At use site
	Mode:	Chemical rocket	Aerobrake	Other	
9.	Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base Asteroidal outpost Phobos outpost

Summary: Space Resource Mission Alternatives

The mission options of table 1 present the basis for the assessment of a broad range of space resource scenarios. The four example missions were selected to illustrate the variety of possible options. Issues, systems, and technologies with common threads in these missions should be of particular interest to long-range planners.

To clarify the technology issues associated with this broad range of possible goals, we developed in greater detail two variants of the first goal, lunar or asteroidal propellant extraction. We chose to develop these two scenarios because they are driven by the utilization of space resources rather than merely augmented by the availability of such resources. Because of the focus of these scenarios, we expected their technological requirements to be clearer.

The first alternate scenario (fig. 16) emphasizes lunar and asteroidal resource extraction, with manned Mars missions as a long-term objective. The second alternate scenario (fig. 17) follows a broader developmental strategy that places less emphasis on lunar and asteroidal propellants and more emphasis on exploration and scientific study of the solar system.

The Moon

The Moon has a wide variety of terrains, rock types, and regolith types. While much has been learned from analysis of the American Apollo samples and of the Soviet Luna samples, most of the Moon has neither been sampled nor been mapped by orbital chemistry mappers. Consequently, the potentially useful resources are not well understood; additional exploration may bring some surprises.

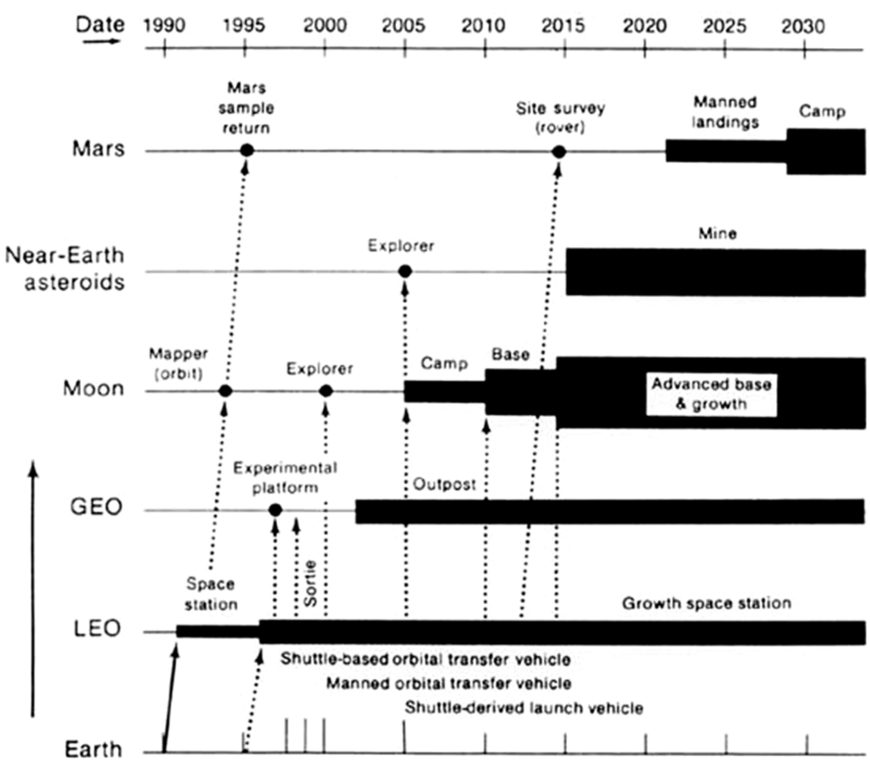


Figure 16

Scenario for Space Resource Utilization

Space resource utilization, a feature lacking in the baseline plan, is emphasized in this plan for space activities in the same 1990–2035 timeframe. As in the baseline scenario, a space station in low Earth orbit (LEO) is established in the early 1990s. This space station plays a major role in staging advanced missions to the Moon, beginning about 2005, and in exploring near-Earth asteroids, beginning about the same time. These exploration activities lead to the establishment of a lunar camp and base which produce oxygen and possibly hydrogen for rocket propellant. Automated missions to near-Earth asteroids begin mining these bodies by about 2015, producing water and metals which are returned to geosynchronous Earth orbit (GEO), LEO, lunar orbit, and the lunar surface. Oxygen, hydrogen, and metals derived from the Moon and the near-Earth asteroids are then used to fuel space operations in Earth-Moon space and to build additional space platforms and stations and lunar base facilities. These space resources are also used as fuel and materials for manned Mars missions beginning in 2021. This scenario might initially cost more than the baseline scenario because it takes large investments to put together the facilities necessary to extract and refine space resources. However, this plan has the potential to significantly lower the cost of space operations in the long run by providing from space much of the mass needed for space operations.

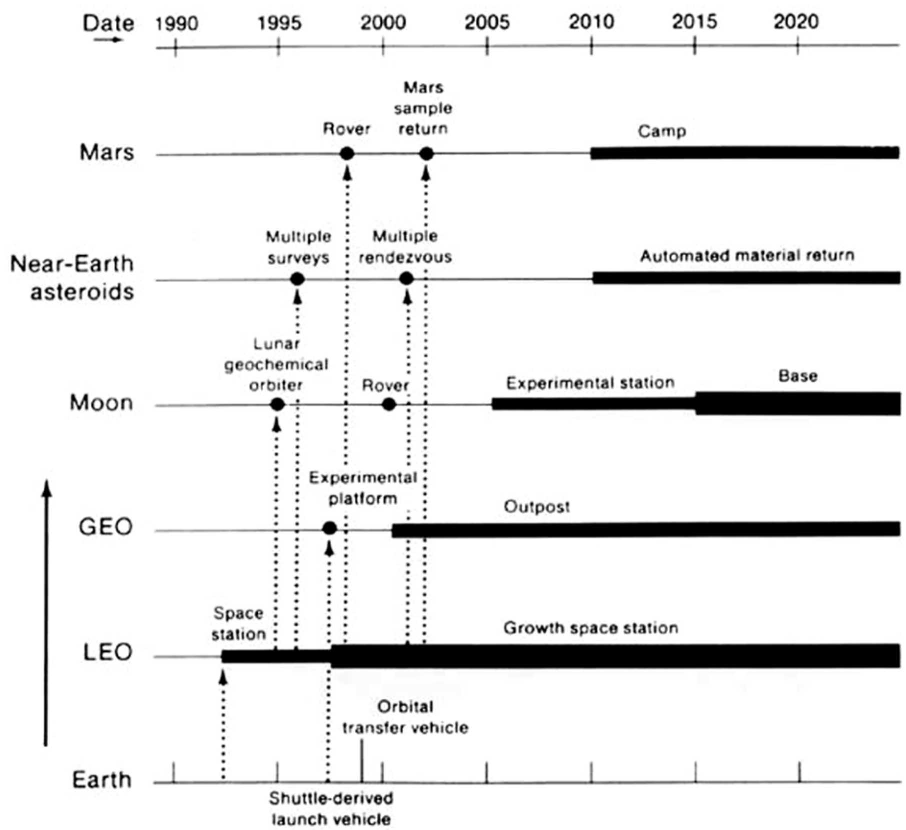
Phobos

The resource potential of asteroids and the satellites of Mars (Phobos shown here) is even less well understood than that of the Moon. It may be that many asteroids as well as the satellites of Mars have abundant useful resources, including water and hydrocarbons. Additional exploration is clearly needed before the resource potential of these objects can be evaluated.

Figure 17

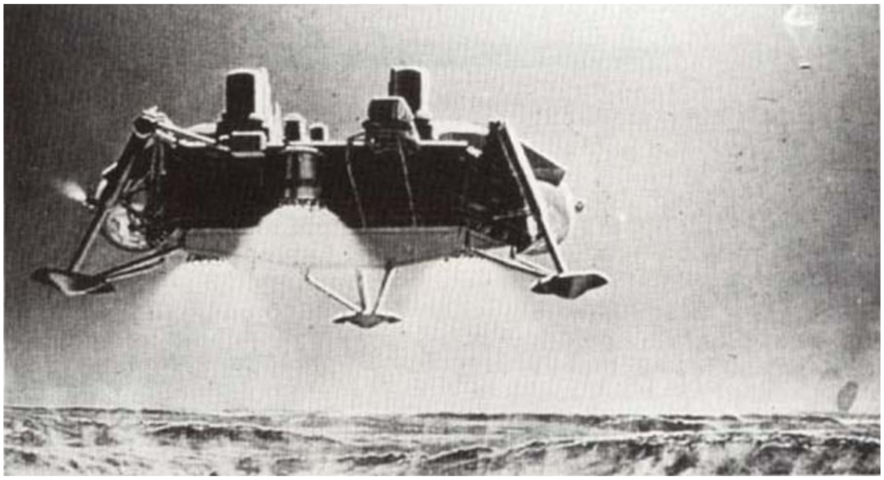
Scenario for Balanced Infrastructure Buildup

In this scenario, each location in space receives attention in a balanced approach and none is emphasized to the exclusion of others. The scenario begins with the establishment of the initial space station about 1992. This is followed by the establishment of a manned outpost in geosynchronous Earth orbit (GEO) in 2001, an experimental station on the Moon in 2006, and a manned Mars camp in 2010. In parallel with these manned activities, many automated missions are flown, including a lunar geochemical orbiter and a lunar rover, multiple surveys of near-Earth asteroids and rendezvous with them, and a martian rover and a Mars sample return. Automated mining of near-Earth asteroids beginning in 2010 is also part of this scenario.



Mars Lander

Here an unmanned lander is descending to the martian surface. A variety of unmanned scientific missions have been proposed for Mars, including the most ambitious and potentially most useful: sample collection and return. Such missions would be useful precursors to piloted Mars expeditions, but they may not be absolutely necessary before people go to Mars.



Impacts of Sociopolitical Conditions

Ben R. Finney

To what extent will scenarios of space development, and the choice of technologies to carry these out, hinge upon future social, economic, and political factors outside the range of currently discussed scientific and commercial rationales for venturing into space? Outside factors have greatly influenced the course of space development in the past—as witness the initial drive to develop large rockets and the subsequent race for the Moon. Although space technology has now reached a level where it has demonstrable scientific and commercial utility, there is no reason to assume that this utility must exclusively or even largely determine the course of space development.

We should be prepared to consider how changing conditions, outside of space development per se, may impact that development. For example, an emphasis on space weaponry, and defense against that weaponry, might lead to a significant requirement for lunar or asteroidal materials for shielding. Alternatively, superpower rivalry might once again be expressed in peaceful competition in space, where the goal of setting up the first Moon or Mars base could override the logic of orderly, evolutionary development. Or a global environmental crisis might stimulate an effort to magnify remote sensing capabilities and lead to the revival of the solar power satellite concept. Geopolitical developments might lead to major international cooperation in space—such as between the United States, Europe, and Japan or between the capitalist and socialist blocs or between First World and Third World nations or some combination of these. Finally, a major cultural upheaval—such as might be occasioned by the discovery, through NASA's Search for Extraterrestrial Intelligence (SETI) program, of intelligence in some other star system—could dramatically impact our conception of the human role in space.

It is, of course, impossible to predict the future. However, any scenario of space development, and the technology requirements engendered, in effect assumes a future vision—not only of that development but also of outside forces and events. Space development scenarios are inherently part of larger scenarios of human development.

Common Technologies

Terry Triffet

Common to the baseline and alternative scenarios presented above are a number of intersecting or nodal technologies. That is, regardless of whatever divergent paths such developments may take, they will intersect at these points and cannot move beyond them until certain problems specific to these technologies have been solved. Thus, in a sense, these nodes are the invariants of the system, and concentrating attention on them should be the most efficient way to proceed. It is a primary purpose of this study to point to these pivotal technologies and highlight their barrier difficulties.

Transportation

Surely the most fundamental nodal technology, because of its high leverage on the entire evolution of space development, is transportation. The cost of delivery into low Earth orbit, which had been moving downward as a result of Space Shuttle efficiency, is now, as a result of the *Challenger* accident, estimated to be over $3000 per pound and the extrapolated cost for delivery to the Moon over $20 000 per pound.

Technologies that have been proposed to cut delivery costs to low Earth orbit and beyond fall into three categories: (1) improvements to the performance of earthlift vehicles, (2) development of space-based orbital transfer vehicles and associated propulsion technologies, and (3) production of propellants using nonterrestrial resources.

Complex system tradeoffs are required to determine which approach will be optimal in a given scenario. For example, reducing the cost of Earth-to-orbit (ETO) transportation will reduce by a similar proportion the cost of Earth-to-Moon transportation and will thus reduce the cost of obtaining propellants from the Moon. However, if the ETO costs are reduced enough, the expense of establishing a lunar facility to produce propellant to reduce transportation costs may not be merited. Aspects other than transportation costs may need to be considered. For example, at some level of activity, modification of the Earth's environment due to high launch rates may become intolerable.

The first objective in all scenarios is to reduce the cost of ETO options. The general approach is well understood, and several options are discussed later in this report. Expected costs for various options are given in table 6. Shuttle-derived launch vehicles are a class of vehicles in which the manned elements of the Space Shuttle are replaced by cargo-carrying capacity (see fig. 18). Heavy lift vehicles apply Space Shuttle propulsion

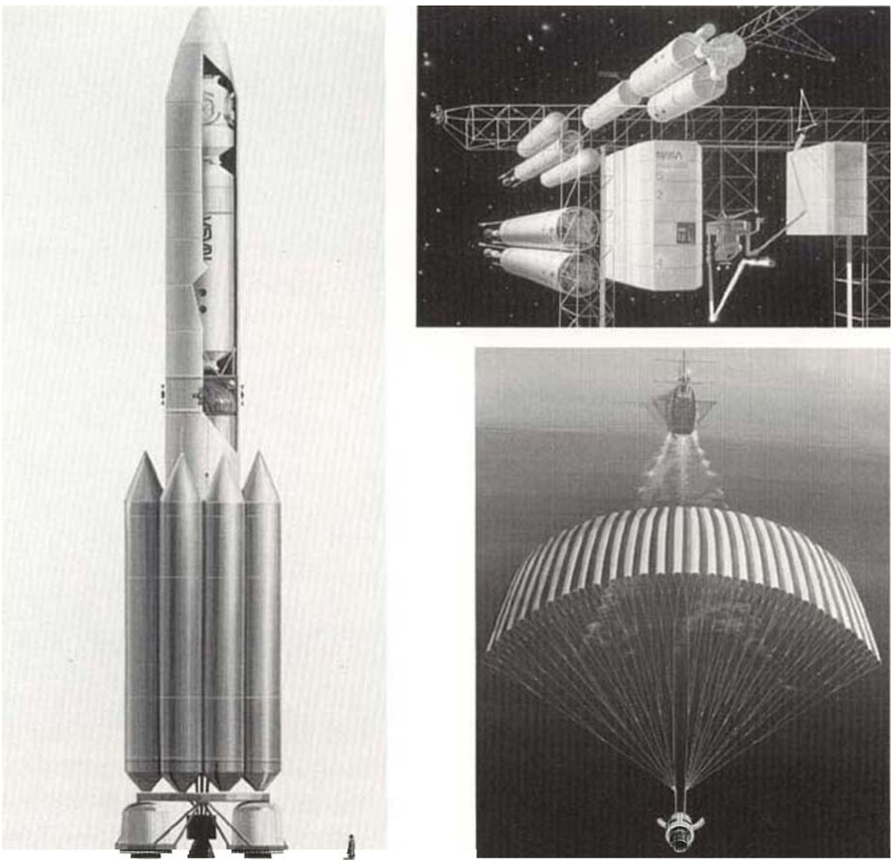


Figure 18

Consort

Since the Challenger *accident, it has become increasingly clear that unmanned launch vehicles must be developed to transport large cargoes into space at relatively low costs. In the concept shown here, the liquid-fueled* Consort *vehicle is launched into space with five Space Shuttle main engines. At the staging point in the ascent, four of these engines are jettisoned, returned to Earth by remote-controlled parachutes, recovered dry by a ship with arresting gear, and reused. The eight strap-on oxygen and hydrogen tanks are also jettisoned and allowed to fall into the ocean. The second stage delivers its cargo housed in a Titan IV fairing. This second stage, which includes one Space Shuttle main engine, internal fuel tanks, and support equipment, might then become the basis of an orbital transfer vehicle.*

Courtesy of Davis Aerospace Company

TABLE 6. *Potential Earthlift Options*

1. Space Shuttle	$3300/lb
2. Shuttle-derived launch vehicle	$500–1000/lb
3. Heavy lift vehicle	$300–500/lb
4. Hybrid electromagnetic launches and rockets	<$300/lb

Figure 19

"Fat Albert"

Another approach to the launch of heavy cargoes is a massive single-stage-to-orbit booster, such as "Fat Albert," from a 1976 design study. This booster has 48 engines, half of which burn liquid hydrogen and half of which burn rocket propellant type 1 (RP-1). After putting its cargo into low Earth orbit, the booster makes a deorbit burn, reenters the atmosphere, and then uses some of its engines to decelerate to near-zero velocity before touchdown in water, where it is recovered. Tradeoffs between boosters that are completely reusable and boosters that are totally expendable include complexity, design and manufacture costs, operation costs, and recovery and refurbishment costs. It is not always obvious which concept will ultimately be more cost-effective.

NASA photo: S76-24315

Figure 20

Lunar Orbit Space Station

Proximity to lunar-derived propellant and materials would make a space station in orbit around the Moon an important transportation node. It could serve as a turnaround station for lunar landing vehicles which could ferry up liquid oxygen and other materials from the lunar surface. An orbital transfer vehicle could then take the containers of liquid oxygen (and possibly lunar hydrogen) to geosynchronous or low Earth orbit for use in many kinds of space activities. A lunar orbit space station might also serve as a staging point for major expeditions to other parts of the solar system, including Mars.

Artist: Michael Carroll

technology to a new class of large rockets (see fig. 19). Hybrid systems, air-breathing rockets, and electromagnetic propulsion technologies have also been studied.

Development and improvement of the performance of space-based orbital transfer vehicles involves propulsion technology, aerobraking technology, and lightweight structures. Aerobraking is a technology that replaces the propulsion system for deceleration upon return to Earth with an aerodynamic deceleration device. The task is to build an aerodynamic braking system that is lighter than the propulsive braking system. Lightweight structures improve performance by exchanging vehicle weight for payload weight. The payoff is almost always greater than 1 pound of payload for each pound of structure, because structure must be carried throughout all the vehicle's velocity changes whereas the payload is usually dropped off somewhere along the way.

Propulsion technology for orbit-to-orbit transportation involves a wider variety of options because low-thrust systems are usable and the spacecraft do not have to travel through a planetary

atmosphere. The list of options in table 7 is most likely incomplete.

Using propellant produced in space for orbital transfer and lift-off from planetary surfaces is of interest because the energy required to achieve low Earth orbit from either asteroids or a lunar base is much lower than that required to fight the gravity well of Earth. (See figure 20.) For a system to be viable, the cost of developing and operating the nonterrestrial facility must be less than the cost of delivering propellant from Earth. Thus, in general, the larger or more remote from Earth the usage, the more competitive the nonterrestrial resource will be.

Before costs can be assigned to the products, extensive development of process concepts and operational techniques is required. However, table 8 lists potential sources and types of propellants, which will be the focus for technology development.

TABLE 7. *Propulsion Technology Options for Orbital Transfer Vehicles*

1.	Chemical—high performance O_2/H_2
2.	Thermal—nuclear, solar, laser
3.	Electric—ion accelerators, mass accelerators
4.	Light—solar sails
5.	Tethers—momentum storage and exchange, plasma thrusting power production

TABLE 8. *Nonterrestrial Propellant Options*

1.	Asteroids—water for liquid O_2 and liquid H_2
2.	Moon—oxygen-hydrogen (Earth supplied hydrogen), oxygen-silane (Earth hydrogen for silane), oxygen-aluminum (Earth-supplied binder)
3.	Shuttle external tanks in orbit—aluminum and lunar or Earth oxygen
4.	Electric propulsion—solar energy and nonterrestrial mass (lunar oxygen), electromagnetic accelerators and solid reaction mass, nuclear thermal energy and nonterrestrial mass, hybrid electromagnetic launchers and rockets

Energy

Equal in importance to transportation as a nodal technology is the development of energy sources in space. Space operations are impossible without appropriate power supplies; and any projects involving extended human activities in this hostile environment will necessarily be energy-intensive. Energy technology can be divided into two general classes: energy sources transported from Earth (chemical, nuclear) and those using in situ resources. Both classes will be utilized in the development scenarios considered.

Solar energy is usable as far out as Mars (and possibly Jupiter, using high concentrator systems). Beyond Jupiter, solar energy is too diffuse to be gathered in useful amounts. From there out, other sources, such as chemical and nuclear, are required.

The photovoltaic system with electrochemical storage has been the mainstay of space power to this time and will remain a serious contender for future space applications. This passive system is relatively maintenance-free and thus offers low life-cycle costs. Advanced photovoltaic systems, such as radiation-resistant indium phosphide cells and high-efficiency point-contact cells, promise greatly improved performance. Their potential is further increased when they are coupled with storage systems with high energy densities, such as advanced regenerative fuel cells and innovative bipolar batteries.

Solar concentrators with dynamic systems (Stirling-, Brayton-, or Rankine-cycle thermal engines) offer an alternative to photovoltaic arrays. This technology becomes increasingly attractive as power demand goes up. The compactness of a solar thermal dynamic system is an advantage for missions subject to aerodynamic drag; its smaller cross section may significantly reduce the demand for orbit maintenance propellants. The ability of such a system to produce high point-source temperatures (several thousand versus one or two hundred degrees) make it a candidate for an integrated thermal electric distribution system; in such a system, the waste heat from the thermal engine could be piped in and used directly for onboard processes.

On the other hand, solar dynamic technology is less advanced than photovoltaic technology, and thus a greater development effort would be needed. Experience has been accumulated in solar Rankine systems, Brayton rotating machinery, and a Stirling free-piston engine. But problems remain in heat receiver design, materials compatibility, concentrator design, and heat rejection and thermal control systems. Nevertheless, because its power characteristics more closely resemble those of conventional sources, this alternative should be vigorously pursued.

Nuclear reactor energy sources deserve special mention (see fig. 21). Though posing formidable transport problems because of their mass, they offer high power levels, high temperatures, and long unattended operating times. In cases where solar energy is not continuously available (e.g., shadowed by Earth; on most of the lunar surface), a nuclear system may even have a mass advantage because a solar system would require an energy storage subsystem during shadowed periods. The shielding required to protect people from the radioactive energy source could, in planetary installations, be provided using local materials.

The technology underlying nuclear power is well understood, a large amount of Earth-operating experience has been accumulated, and miniaturization efforts are well advanced. Because this energy resource could take the greatest advantage of existing power technology, it, too, should be pursued with high priority. It could probably be ready for safe, reliable, and versatile use before any of the others.

Technologies for transmission and delivery of power in space also require development. Use at or near the point of collection in space or on the Moon offers minimal technologic challenge. Beamed transmission (laser, microwave) is considered applicable on the Moon or from place to place in space. Rectenna development is under way. Transmission from space to Earth faces additional problems but may also be a viable concept.

A variety of other technologies bear on our ability to collect, condition, store, and utilize energy in space. Conversion of solar or nuclear energy through chemical processing to produce propellants is one of these. The use of tethers to transfer momentum is another. Storage of energy for use in peak periods and for solar energy systems with intermittent illumination (like the lunar surface) is especially important. These technologies and others may have significant roles in a mature space operations system.

With the advent of high-temperature superconductivity (now in the range of liquid nitrogen), many additional advances in space power systems are on the horizon. An example is superconducting magnetic energy storage. Its advantages include high charge-discharge efficiency, less mass (because less refrigeration is required), and increased operating flexibility. If superconductor temperatures can be brought up to 0 °C, the system, buried about 1 meter below the surface, could operate without any refrigeration through the lunar day/night cycle.

Other advances could improve future space power system applications. System control and monitoring by means of artificial intelligence could enhance autonomous power system operation. Advanced heat rejection systems such as the liquid droplet radiator could greatly reduce power system mass.

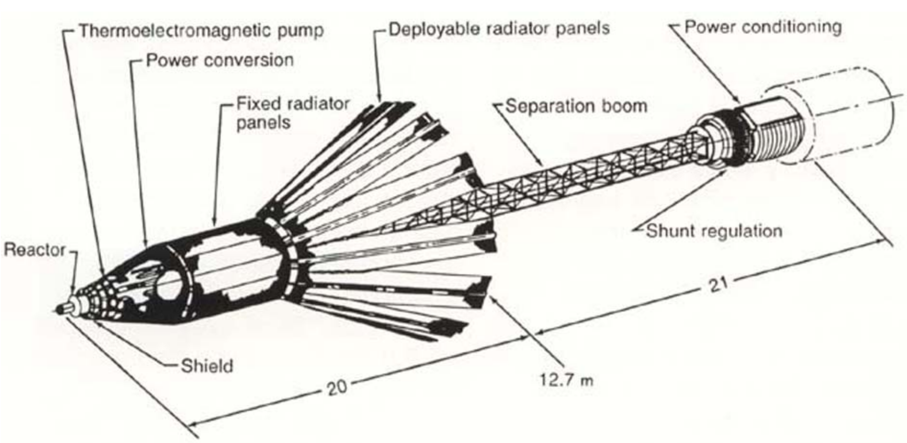


Figure 21

SP-100

The “SP-100” (not an acronym) is a nuclear power reactor for space applications. It has a nominal design power of 100 kW and uses a closed-cycle working fluid heated by the small reactor, thermocouples both to convert thermal energy to electric power and to operate the pump moving the working fluid, and both fixed and deployable radiators to reject the waste heat. Most of the cone-shaped structure in the illustration is radiator surface. Nuclear reactors are currently used in space to power some Soviet intelligence satellites. And radioisotope generators have been used in space for many years, including use on the Apollo lunar surface experiments package (ALSEP) and the Voyager spacecraft.

Computing Technology

Computing technology, or more specifically the development of software for knowledge-based information and control systems, is a critical area. In the case of manned operations, greatly improved systems are needed to reduce the number of humans required, complement their capability, and relieve them of hazardous and routine tasks. The natural first step should be to expand the capabilities of the computing system already central to every operation in space. This step would involve further reducing processing time and increasing main memory, while adding a more versatile communications interface and continuing to reduce the system's weight and physical dimensions. Ideally, in addition to its data collection and "housekeeping" management functions, this machine should offer access to an extensive body of mission-specific information, and each person present should have an open channel to it at all times. Moreover, this system should be capable of self-contained operation, in case communications with Earth are interrupted.

To accomplish all these improvements is well within the range of contemporary computing technology. Also within that range is the possibility of incorporating appropriate expert system programs which may make rapid, error-free decisions and, if required, explain their reasoning. Together with instant access to a self-contained and specialized data base, this capability is essential to the success of even the simpler kinds of missions discussed above in the scenarios section. For the more complex missions, such as asteroid or lunar resource acquisition and processing, "intelligent" robotic assistance will be needed.

Given the present state of computing technology, it is entirely practical to target development of operational expert systems that incorporate strategic models and natural laws, weighted decision-making algorithms, and complex data frames, in addition to elementary inference engines, algorithms, and data bases of single facts. Such systems (see fig. 22) would possess the potential not only of assisting humans to make accurate, informed decisions under pressure but also of expanding the breadth and depth of human thought on this new frontier.

For extensive LEO, GEO, asteroidal, low lunar orbit, or lunar base operations, the economic advantages of using automated systems are plainly evident. These systems would be capable of supporting humans by making simple instant decisions, such as course- and handling-corrections based on sensor input, and of carrying out involved tasks under remote control. No life support system or protective environment would be needed, exposure to hazardous conditions would be no problem, and boredom, no factor. We must stress that the recommended technology objectives are to develop more intelligent robots, not to eliminate humans from operations in space. Both are needed. Robot or automated systems are envisioned to be synergistic with humans (see fig. 23). Structuring the objectives in this way would greatly improve the chances of creating these sophisticated automatic systems within the time available.

Materials Processing

Materials processing technology is required to transpose to the space environment familiar terrestrial processes, such as mining, ore concentration, extraction of useful materials, and manufacturing (see fig. 24). Even though the specific processes to be developed are mission-dependent, materials processing in general must be regarded as fundamental, because it changes the nature of the space enterprise from dependence on the Earth for all materials to the degree of independence afforded by the use of indigenous materials. Some

Figure 22

Expert System

"Expert system" is a term used to refer to an integrated computer and physical system in which very comprehensive software manages the system, handles a large variety of states and conditions, and even reacts to unexpected situations. Here is a prototype for an expert system that controls the removal of CO_2 from a space station habitation module. This system continuously monitors the CO_2 levels, gives instant readouts of environmental conditions from any terminal, provides feedback to reduce the levels as needed, and offers a variety of controls, checks, balances, and alarms on the condition of the environmental habitat atmosphere. As computer technology improves, such systems become more practical and less expensive.

NASA photo: S85-41215

Figure 23

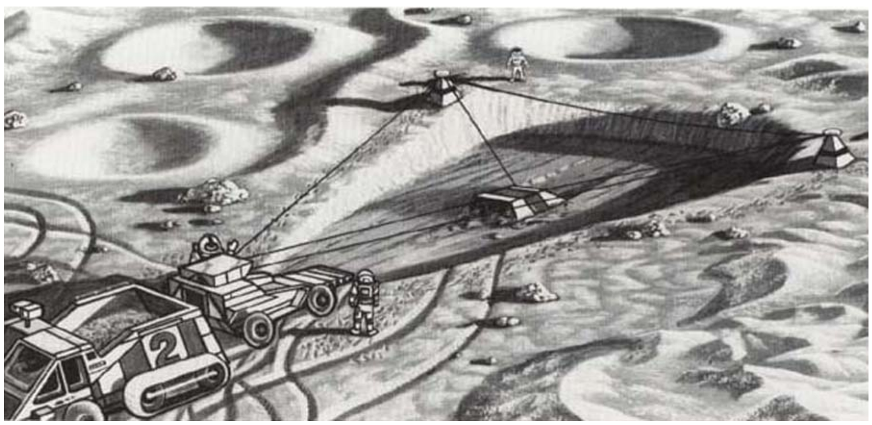
Robot Rescuing an Astronaut on the Lunar Surface

Completely automated robots are a logical extension of comprehensive expert systems. Here, a robot with a contained expert system is rescuing a worker who has become ill while making a geological survey on the lunar surface. Although such robots could also be teleoperated from a control room, a completely automated version with a self-contained expert system might be the eventual goal. As the technology improves, teleoperated and expert system robots will become more and more useful for hazardous space activities, including lunar surface operations. Ultimately, many of the routine surface operations at a lunar base may be performed by such robots, leaving for humans the activities, such as scientific exploration, requiring very nonroutine observations and decisions.

Figure 24

Three-Drum Slusher

This lunar mining system is called a "three-drum slusher." It is similar to a simple two-drum dragline, in which a bucket is pulled by cables to scrape up surface material and dump it into a waiting truck. The third drum allows the bucket to be moved from side to side to enlarge the mining pit. Surface mining of unconsolidated lunar regolith, using versions of draglines or front-end loaders, will probably be done at a lunar base initially, although deeper "bedrock" mining is also a possibility and underground mining may even be attractive if appropriate resources are located.



missions would place heavy emphasis on the processing of mineral ores in space to recover useful metals, while others would place a premium on processing techniques aimed at the recovery of oxygen and hydrogen. Technologies in mining, materials handling, chemical extraction, storage, and manufacturing are applicable to various resources. Early development of these common technologies can improve the performance of the transportation, energy, and other systems.

Communications

Communications technology has already proven its worth and is at a relatively advanced stage of development. But further technological advances are possible in coupling communications equipment to computers, in developing large communication platforms in space, and in increasing the power and defining the focus of transmissions from space.

The economic, social, and political potential for worldwide applications of communications technology, particularly in Third World countries, is very great and should not be overlooked. Incremental advances in existing technologies should be sufficient to handle the communication and computing aspects, but the sociopolitical problems involved in creating an enhanced global communications network are of a different order and beyond the scope of the present report.

New Technologies

We can take for granted that new methods and machines will be needed to adapt known techniques to operations in space. This almost amounts to a general principle: Old technologies will require new technologies in order to be applied in space (see fig. 25). What these needs may be cannot be known in advance, but allowances should be made to provide for them. Otherwise, time and cost overruns will inevitably result.

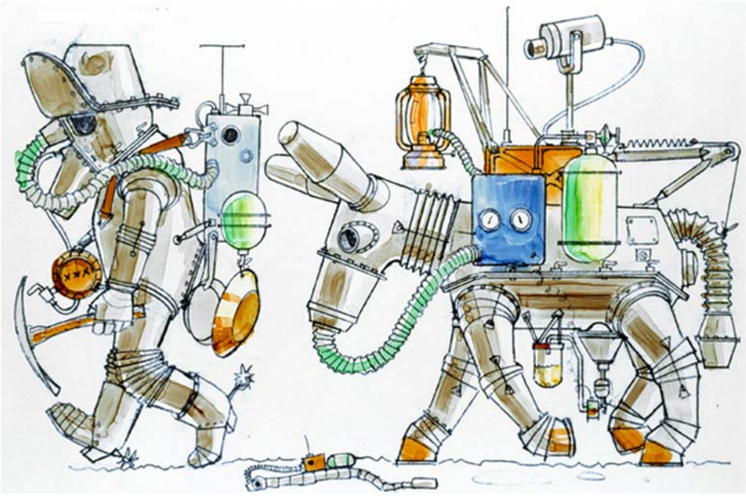
In this same vein, we should recognize that the development of entirely new technologies, such as those needed to effect weather/ climate control, atmospheric cleanup, or purging of the ionosphere, may prove to be desirable. These are massive undertakings and yet they cannot be disregarded. Like nearly continuous remote sensing of and almost instant communication with any point on Earth, these climate-control technologies are of enormous potential benefit to humankind. In the end, the successful accomplishment of any one of them could justify the entire space program.

Figure 25

Lunar Prospector?

One approach to the lunar environment is to simply modify old technologies somewhat to fit the new conditions. Here, that approach is taken to the extreme in this lunar resource prospecting system. The other extreme is to develop totally new technology, such as a completely automated expert system for lunar prospecting. The most workable approach is probably a compromise between old technology and new technology, using the best of both. What elements of this "old technology" are likely to be found at a lunar base in 2010?

NASA photo: S68-13536



Issues for Further Study

Hubert Davis

Overview

The mind-expanding nature of our future activities beyond Earth leads to a plentiful flow of new ideas and major improvements on earlier concepts. The recent discovery of numerous Earth-crossing asteroids, for example, adds greatly to the magnitude and diversity of the material resources in space of which we are aware. However, a serious question arises. Does there exist any orderly process for gaining general awareness of these new ideas or for evaluating their importance to society? Membership in a specific academic, government, or industrial group, coupled with persistence and eloquence, are today's means of hearing and being heard. These mechanisms may not, however, be the optimal means for flushing out and eventually implementing the best new ideas.

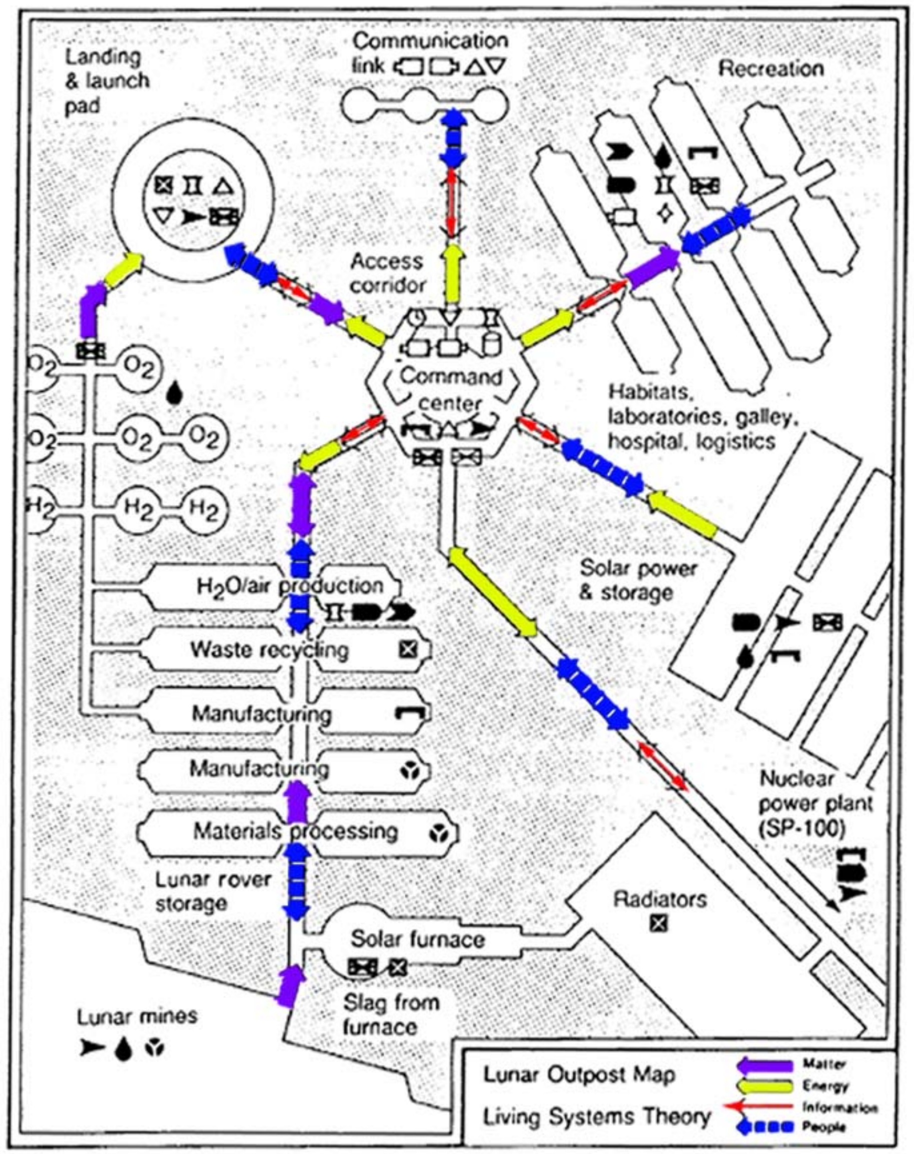
One small step toward achieving the goal of preserving for use the best of the suggested new concepts is the "systems study" approach. In this approach, a set of future needs and a straightforward means of satisfying these needs are described in quantitative terms as a "scenario." This scenario is then set forth as a benchmark case for testing the relative merit of new, alternative means of meeting one or more of these needs. This systems approach should be used to assess the merits of new concepts and to identify the most important advancements in technology needed to establish or enhance the merit of the concept. (The map of a lunar outpost illustrates the application of another kind of systematic study, known as "general living systems" theory and analysis.)

Ideally, as needs change and new concepts and data become available, the "baseline" scenario should be revised to incorporate some of the new ideas. When that occurs, the technology development of the newly incorporated approaches should actively begin to remove residual uncertainties. But the effort should, in most cases, stop short of "prototyping."

It is very important to remain as generic or flexible as practical in order to be ready to adapt the scenarios and associated technologies to changes in the social norms, political climate, and economic health of the nation.

To further complicate matters, once a new "baseline" scenario is accepted for testing of new concepts, earlier conclusions must also be reexamined since former "new" ideas that were earlier rejected may be found to be highly desirable given the new scenario.

Some formalized means should be found for establishing, testing and refining, utilizing and maintaining

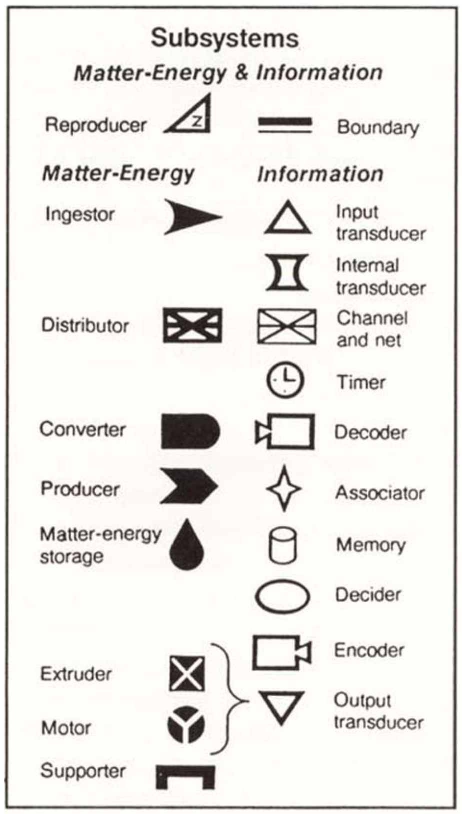


Communication link
Landing & launch pad
Recreation
Access corridor
Command center
Habitats, laboratories, galley, hospital, logistics
O_2
H_2
H_2O/air production
Waste recycling
Manufacturing
Manufacturing
Materials processing
Solar power & storage
Nuclear power plant (SP-100)
Lunar rover storage
Radiators
Solar furnace
Slag from furnace
Lunar mines
Lunar Outpost Map
Living Systems Theory
Matter
Energy
Information
People

Lunar Outpost Map

General living systems theory is a conceptual integration of biological and social approaches to the study of living systems. Living systems are open systems that input, process, and output matter and energy, as well as information which guides and controls all their parts. In human organizations, in addition to matter and energy flows, there are flows of personnel, which involve both matter and energy but also include information stored in each person's memory. There are two types of information flows in organizations: human and machine communications and money or money equivalents. Twenty subsystem processes dealing with these flows are essential for survival of systems at all levels.

The general procedure for analyzing such systems is to map them in two- or three-dimensional space. This map of a lunar outpost indicates its subsystems and the major flows within it. Such an analysis would take into account the primary needs of human systems—foraging for food and other necessary forms of matter and energy; feeding; fighting against environmental threats and stresses; fleeing from environmental dangers; and, in organizations which provide a comfortable, long-term habitat, perhaps reproducing the species. This study would analyze the effects on human social and individual behavior of such factors as weightlessness or 1/6 gravity; limited oxygen and water supplies; extreme temperatures; available light, heat, and power; varying patterns of light and dark; and so forth. A data bank or handbook could be developed of the values of multiple variables in each of the 20 subsystems of such a social system.



a baseline scenario of long-range space activities and of supporting, refereeing, and reviewing the application of this scenario in system studies of new concepts. This process was begun by NASA's Office of Aeronautics and Space Technology (OAST) in the mid-1970s, but it was abandoned in the late 1970s because of budgetary constraints and the press of nearer term needs, as perceived by NASA management. Total cost to NASA of restoring and enhancing these efforts would be only 0.01–0.02 percent of NASA's yearly budget.*

* Since this report was drafted, significant long-term planning activities have been undertaken, initiated by the work of the National Commission on Space. The commission's report, *Pioneering the Space Frontier,* is available from Bantam Press.

Lunar Resource Utilization

Resource Prospecting

Early priority should be given to an automated lunar polar spacecraft to perform a global survey of the Moon with instruments appropriate to detect the presence, location, and concentration of useful materials. This mission may have to be repeated or extended to follow up on areas of particular scientific and economic interest.

Lunar Assay

Automated surface rovers, with the capabilities of coring, assaying materials, and possibly returning samples to Earth, should be sent out to gather data. This activity should be completed several years before final commitment is made to the location of the initial lunar base. (See figure 26.)

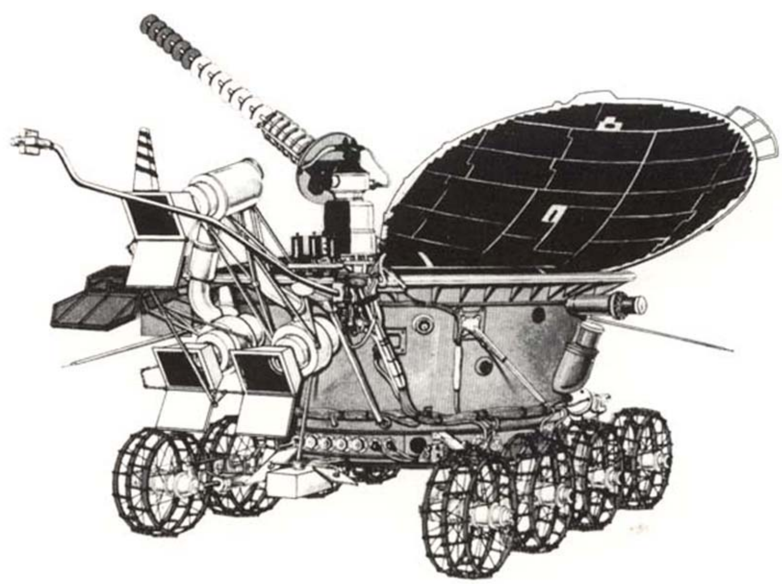


Figure 26

Lunokhod 1 and Apollo 17 Rover

a. Automated vehicles roving over another planetary body were first used in the early 1970s by the Soviets on their Lunokhod missions. These lunokhods were capable of traveling tens of kilometers at speeds up to 2 km/hr. They were run from a Soviet control center by a crew of five—commander, driver, navigator, operator, and onboard-systems engineer. The crew used television images and systems readouts to drive and operate the vehicles. The lunokhods carried several scientific instruments, including an x-ray fluorescence spectrometer for determining the chemical composition of lunar regolith. Lunokhod 1 traveled about 10 km and Lunokhod 2 traveled 37 km, each over a period of months.

Lunar Mining

Mining the Moon will present new challenges. Surface mining will probably be the norm, although subsurface mining may be necessary in some cases. The movement of large amounts of material will degrade the scientific utility of the mining site, alter its appearance, and release gases into the tenuous lunar atmosphere. Thus, the effect of lunar mining on the environment will have to be carefully evaluated before mining begins.

Process Development

Ideas for getting oxygen from lunar materials have been generated since the 1960s and '70s.* Now, preliminary design studies and process engineering should

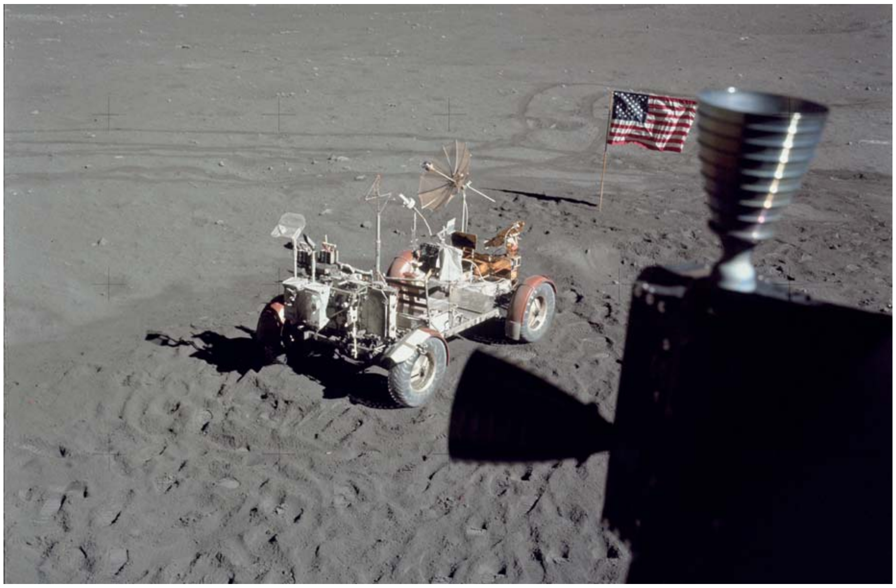
* See, for example,

Rosenberg, S. D.; G. A. Guter; and F. E. Miller. 1964. The On-Site Manufacture of Propellant Oxygen Utilizing Lunar Resources. Chem. Eng. Prog. **62**:228–234.

Rosenberg, S. D.; G. A. Guter; and F. E. Miller. 1965. Manufacture of Oxygen from Lunar Materials. Ann. N.Y. Acad. Sci. **123**:1106–1122.

McKay, David S., and Richard J. Williams. 1979. A Geologic Assessment of Potential Lunar Ores. In Space Resources and Space Settlements, NASA SP-428, pp. 243–255.

Rao, D. Bhogeswara; U. V. Choudary; T. E. Erstfeld; R. J. Williams; and Y. A. Chang. 1979. Extraction Processes for the Production of Aluminum, Titanium, Iron, Magnesium, and Oxygen from Nonterrestrial Sources. In Space Resources and Space Settlements, NASA SP-428, pp. 257–274.



b. The Rover was used on Apollo missions 15, 16, and 17. Here, the Apollo 17 Rover is seen near the Lunar Module. While not intended for automated operations, the basic rover systems (motors, power, communication, TV, steering and control) could easily be adapted to unmanned exploration traverses. Experience gained in the design and operation of the Apollo Rover, combined with the Soviet Lunokhod experience, will provide a basis for future lunar and martian rover designs.

NASA photo: AS17-140-21354

be performed to derive a comprehensive plan involving laboratory experimentation, bench testing, and pilot plant development for the purpose of testing, developing, and refining the beneficiation and feedstock conversion steps necessary to produce useful products from lunar regolith material. (See figure 27.). This plan should permit examination and quantification of the optimal conversion pressure, temperature, and concentration, conversion efficiency, energy requirements, heat rejection, catalysts, carrier fluid consumption, and the scale effects so as to allow confident design of an operational chemical plant.

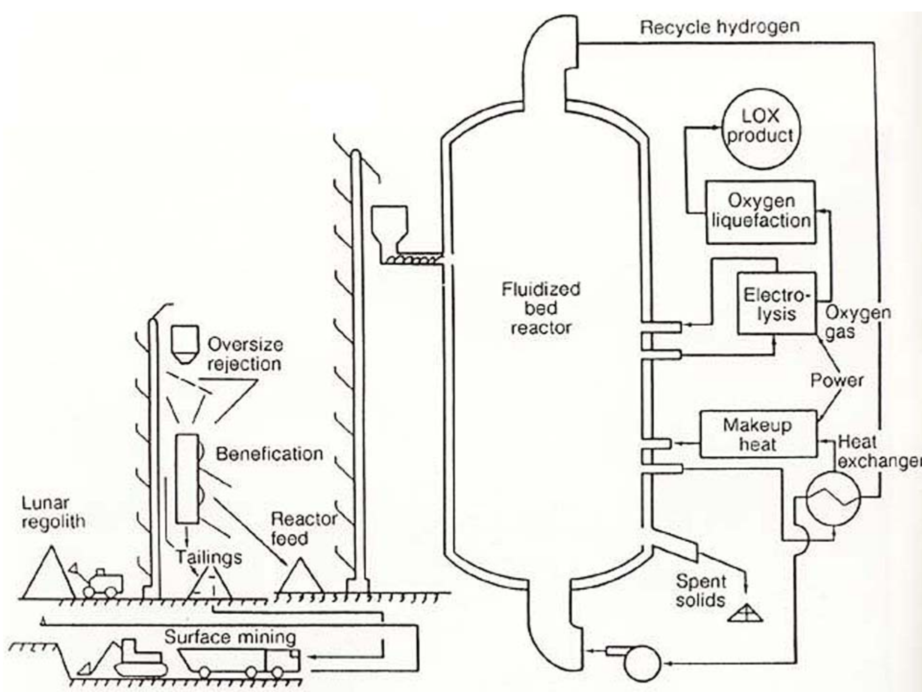
Ancillary Equipment Development

Equipment for automated mobility; solid material conveyance; feedstock material insertion and extraction (into and from the converter); water vapor condensation; electrolysis; gaseous oxygen and hydrogen refinement, movement, and storage; oxygen liquefaction; liquid oxygen storage and transport; and other purposes must be conceptualized, designed, tested, and developed for the minimum

Figure 27

Oxygen From Lunar Ilmenite

In this concept for a lunar oxygen plant, ilmenite ($FeTiO_3$) is concentrated from lunar regolith and then fed into a three-stage fluidized bed. In the upper stage, the ilmenite concentrate is preheated by hot hydrogen passing through the powdered ilmenite. The hot ilmenite then goes into the second stage, which is the main reactor bed. Here, even hotter hydrogen reacts with the ilmenite, extracting one oxygen atom from each ilmenite molecule, forming H_2O, metallic iron (Fe), and TiO_2. The H_2O and excess hydrogen are extracted and circulated through an electrolyzer, which breaks down the H_2O. The released oxygen is then cooled, compressed, and stored as liquefied oxygen. The spent feedstock enters the third stage, where heat is extracted by hydrogen gas before the spent material is dumped from the reactor.



of human intervention. (See figure 28.).

A virtue of these activities is that each of these elements is individually a rather straightforward application of advanced automatic or teleoperative technology. And with the appropriate mix of this technology and the human element, the optimal manufacturing capacity can be placed on the Moon.

Development of Space Transportation Equipment

Large, automated orbital transfer vehicles and lunar landing vehicles must be better defined before we can quantify performance, life, and cost factors. Numerous technology developments will be needed before we can confidently begin full-scale development. The key technologies of these vehicles appear to be the following.

High performance oxygen/ hydrogen rocket engine: A new-generation rocket engine will be needed early. It should generate higher specific impulse than current engines (480–490 sec, as compared to 446 sec for the RL-10), produce a thrust of approximately 7500 lbf, provide moderate throttling capability, and be designed for long life with maintenance in space.

Figure 28

Ancillary Equipment at a Lunar Base

This lunar base sketch illustrates some of the ancillary systems that are necessary for a productive lunar base. The sketch includes a mining system, a processing plant, a construction-block-making unit, a solar power generator, a buried habitat and agricultural unit with solar lighting reflector, automated materials handling equipment, cryogenic storage tanks, surface transportation vehicles, communication antennas, and a rocket system for transportation to lunar orbit. All of these systems require technology development.

Owing to these requirements, an advanced space engine will have to be designed for a very high chamber pressure (1500–2000 psia) and a high expansion ratio (2000:1). (See figure 29.)

Cryogenic propellant handling and preservation: The ability to store, transfer, measure, and condition cryogenic fluids (including liquid oxygen, hydrogen, and argon) with zero loss requires extensive development and testing. (See figure 30.)

Aerobraking technology: Although theoretically very attractive for returning payloads to LEO, many uncertainties, including aerobraking equipment mass, must be resolved before aerobraking is practiced. (See figure 31.). Advanced concepts in guidance, navigation, and control will need investigation, particularly for uses that involve higher velocity return to Earth orbit. Early Shuttle-launched test missions should be considered.

Advanced composite structures: Overall spacecraft systems design using advanced composite structures requires data on micrometeoroid impact effects, cryogenic fluid compatibility, equipment attachment, inspection and repair, and other aspects.

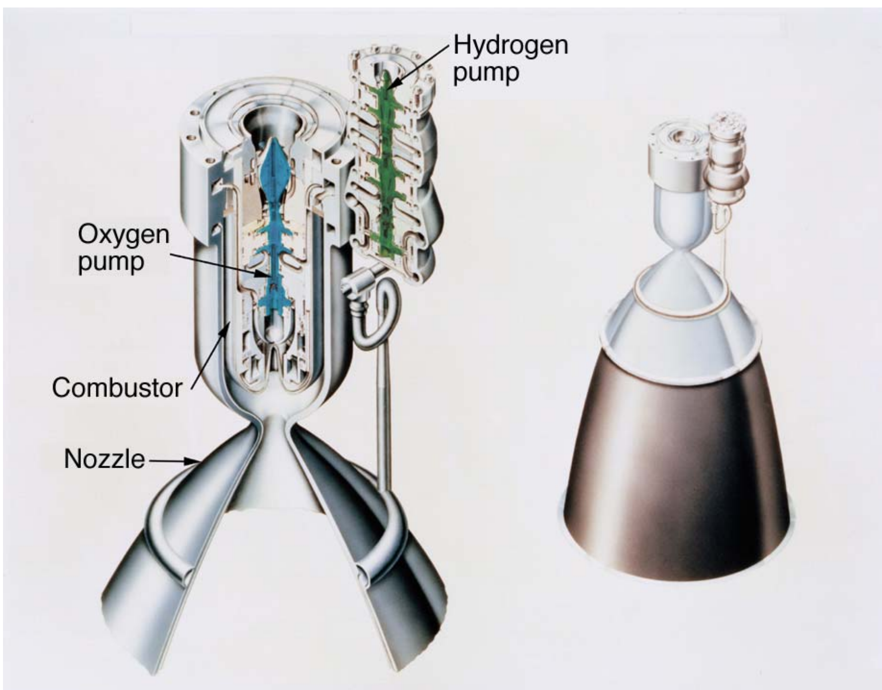


Figure 29

Advanced Engine

New, high performance engines for orbital transfer vehicles must be developed. Here is an oxygen-hydrogen engine concept developed by Aerojet TechSystems Company specifically for use in a reusable orbital transfer vehicle designed to shuttle between low Earth orbit and either geosynchronous Earth orbit or lunar orbit.

NASA photos: S85-37605 and S85-37365

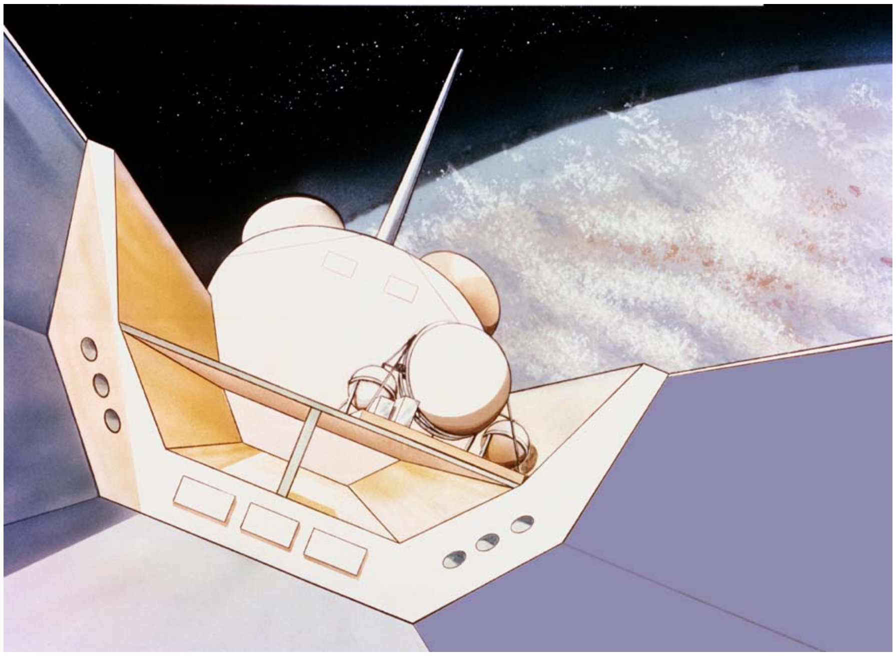


Figure 30

Cryogenics

Technology must be developed and tested for complex space operations. Here is a sketch of a proposed cryogenic fluid management experiment, which will test on the Shuttle orbiter some of the necessary equipment to transport, transfer, measure, and store cryogenic fluids in space. This technology is needed to make reusable orbital transfer vehicles and lunar landers practical. Cryogenic handling technology is also critical to future space operations that make use of lunar-provided rocket propellant.

NASA photo: S85-37601

Figure 31

Aerobraking Technology

Aerobraking technology must be developed before efficient transfer can be made from lunar or geosynchronous orbit to low Earth orbit. Aerobraking is also necessary for any Mars return mission, whether manned or unmanned. Without aerobraking, considerable rocket propellant must be used to slow down a spacecraft coming toward the Earth. Here is an aerobrake on an orbital transfer vehicle returning from lunar orbit. The aerobrake uses friction with the Earth's uppermost atmosphere to slow down the vehicle and divert it to a low Earth orbit. This procedure requires a combination of very heat resistant brake surfaces, precisely known aerodynamic properties, and very careful trajectory and attitude control.

Artist: Pat Rawlings

NASA photo: S85-34649

Operations technology: The infant art and science of maintaining, servicing, storing, and checking out complex space vehicles (both manned and automated) whose entire service life is spent in the space environment requires nurturing. (See figure 32.). Many facets of this problem require both hardware and software development. A design goal of operations technology must be efficiency. Current operation procedures for the Space Shuttle are so costly that, if applied directly to reusable orbital transfer vehicles, they could invalidate the cost-savings potential of these vehicles over expendable vehicles.

Debris control, collection, and recycling: Our future operations in space must not litter. Active measures are needed to prevent littering. A plan of action is needed to remove discarded objects from valuable space "real estate." (See figure 33.). And the technology for recycling waste materials in space needs to be developed. The Shuttle external tank represents a resource in space which can be employed—perhaps early in the space station

Figure 32

Space Servicing

As the hardware for complex space operations is developed, the technology for maintaining complex hardware in space must also be developed. Here is a General Dynamics concept for a space hangar and maintenance facility associated with the space station. This facility can be used to refuel, service, and repair the orbital transfer vehicle shown in the foreground.

NASA photo: S88-28959

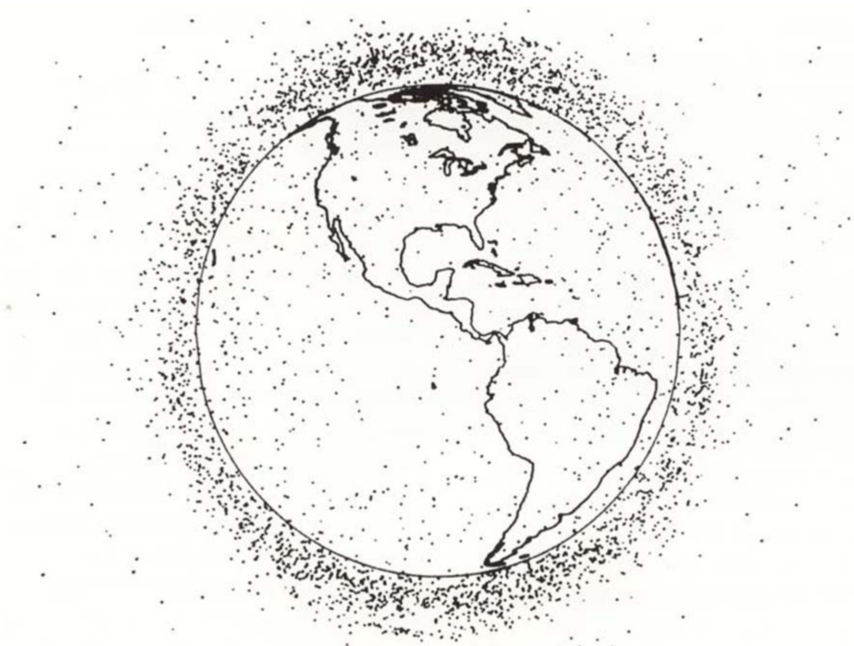


Figure 33

Orbital Debris

Orbital debris is a growing problem, which will require more and more attention as space operations increase in volume. Above is a map showing all the objects larger than 10 cm (baseball size) that were found in low Earth orbit by the U.S. Space Command on May 30, 1987. (The size of the objects is, of course, not to scale on this map; if it were, they could not be seen.) Most of these objects are spent rocket stages, dead satellites, and fragments from the breakup of old spacecraft. The map emphasizes the need to minimize new sources of orbital debris and even to clean up existing debris using "debris sweepers." A satellite designed to capture large pieces of orbital debris is shown below the map.

Artist: Ray Bruneau

NASA photo: S78-23821

program. Thirty tons of aluminum structure available at negligible cost in LEO is simply too valuable to be discarded.

Asteroid Resource Utilization

The first step in asteroid utilization is making an inventory. Advanced Earth-based observation techniques and equipment can be economically fielded to gain quantum improvements in our knowledge of the number, orbits, size, composition, and physical properties of the Earth-crossing asteroids (see table 9). A subset of those asteroids inventoried might be further examined by spaceborne instruments with capabilities similar to those of the proposed Mars geochemical mapper (see fig. 34.). A smaller subset might be identified as candidates for surface exploration and pilot plant operation.

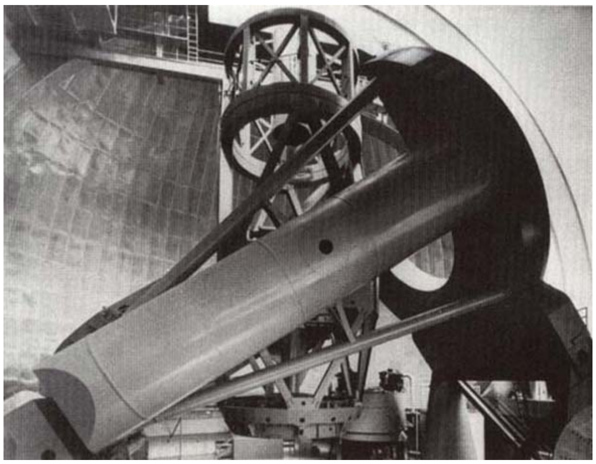
In parallel, advanced space propulsion and mission design techniques should be applied to come to understand the logistics for exploiting this potential space resource.

Space Energy Utilization

The petroleum crisis of the 1970s was not an anomalous, singular event. Even in the face of very effective energy conservation and increased petroleum exploration, the problem will return in the near future. The nearly infinite furnace of the Sun must eventually be used to provide the dominant portion of human beings' energy needs. Space is the best place to harvest and convert sunlight into more concentrated, continuous, and useful forms. Studies on the solar power satellite, a network of solar reflectors, and other means of enhancing the utility of sunlight on Earth should continue. However, the studies should be expanded to include use of such systems to provide energy from space *in* space.

Space "Real Estate" Utilization

If material and energy resources were both abundant and accessible to people, numerous human endeavors exploiting the attributes of space (nearly perfect vacuum, microgravity, and vantage point) would begin and greatly expand.



Mt. Palomar's 200-inch Hale Telescope, pointing to the zenith, as seen from the east side.

TABLE 9. *Physical Parameters of 17 Near-Earth Asteroids**

Name		*Diameter, km*	*Semimajor axis of its orbit, astronomical units*	*Orbital eccentricity*	*Inclination of its orbit, degrees from the plane of the ecliptic*
433	Eros	39.3 × 16.1[a]	1.458	0.219	10.77
887	Alinda	3.6[b]	2.50	.55	9.19
1036	Ganymed		2.66	.54	26.45
1566	Icarus	1.04[d]	1.08	.83	22.91
1580	Betulia	6.3[f]	2.19	.49	52.04
1620	Geographos	2.4[g]	1.24	.34	13.33
1627	Ivar	6.2[h]	1.86	.40	8.44
1685	Toro	5.6[i]	1.36	.44	9.37
1862	Apollo	1.2–1.5 ± 0.1[j]	1.47	.56	6.26
1865	Cerberus		1.08	.47	16.09
1915	Quetzalcoatl	0.14[h]	2.53	.58	20.5
1943	Anteros	2.0[k]	1.43	.26	8.7
2100	Ra-Shalom	>1.4[l]	0.83	.44	15.7
2201	Oljato		2.18	.71	2.5
	1979 VA		2.5	.61	2.7
	1980 AA		1.86	.43	4.1
	1981 QA		2.35	.49	8.95

[a] Lebofsky and Rieke (1979).
[b] Zellner and Gradie (1976).
[d] Gehrels et al. (1970).
[f] Tedesco et al. (1978).
[g] Dunlap (1974).
[h] G. J. Veeder (personal communication).
[i] Dunlap et al. (1973).
[j] Lebofsky et al. (1981).
[k] Revised from Veeder et al. (1981; personal communication).
[l] Lebosky (personal communication).

* After Lucy A. McFadden, Michael J. Gaffey, and Thomas B. McCord, 1984, Mineralogical-Petrological Characterization of Near-Earth Asteroids, Icarus **59**:25–40.

The communication relay function from GEO is only the first of an infinite series of useful and economically valuable activities in space. The ability to observe activities on Earth and, if necessary, to intervene in events may prove to be the means by which nuclear technology is reconfigured to benefit humankind rather than to threaten our existence.

Space as a place to go to and later as a place to live and work in will become of increasing importance in the decades to come. It is not too early to consider growth from NASA's 8- to 12-person space station to communities 2 or 3 orders of magnitude larger (see fig. 35.). Life support technology will need to progress from merely preserving respiratory functions with some small degree of mobility for a handful of exceptional, highly trained people to providing comfortable and even luxurious accommodations for ordinary human beings at work, at school, or at leisure. (See figure 36.).

The potential of personally working and residing in space is perhaps

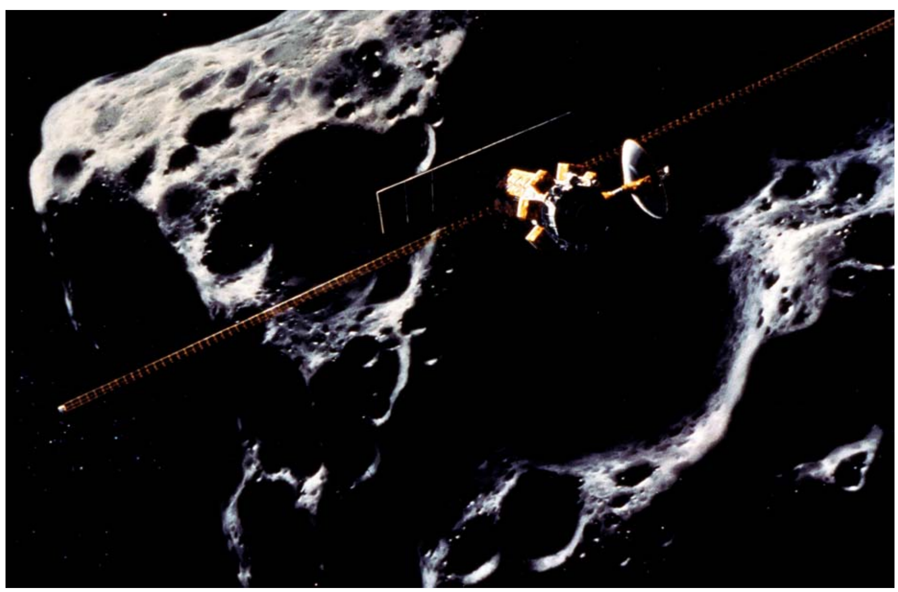


Figure 34

An Artist's Conception of an Unmanned Spacecraft Mission to an Asteroid

An unmanned spacecraft could make detailed photos of an asteroid and chemically map it in preparation for later automated mining missions.

NASA photo: S84-45115

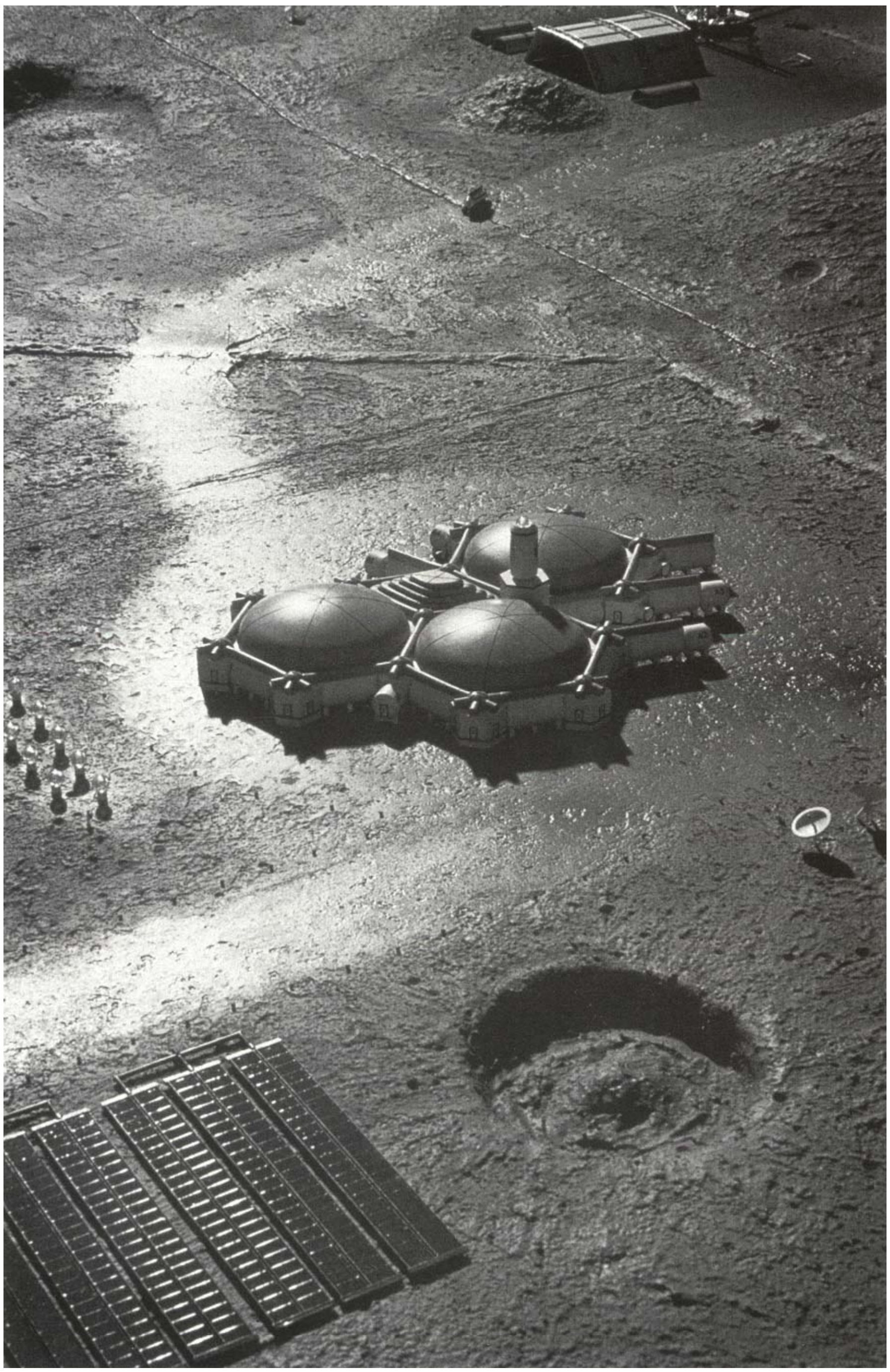


Figure 35

Architectural Model of a Moon Base

This model is the product of a recent study by a group at the University of Houston's College of Architecture. The lunar base, designed for 28 people, includes both inflatable domes and hardened modules. The three functional areas of the base are for habitation, laboratory use, and agriculture.

Figure 36

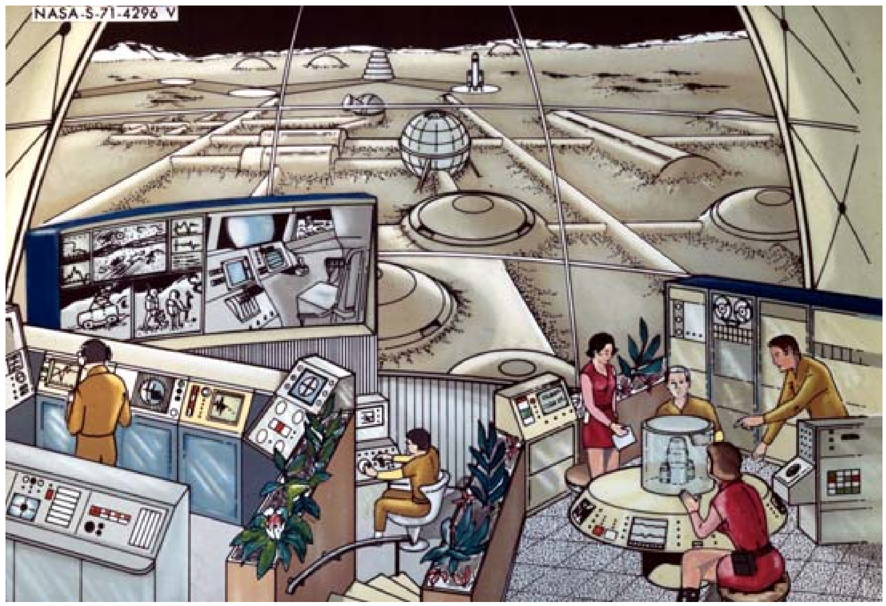
Advanced Lunar Bases

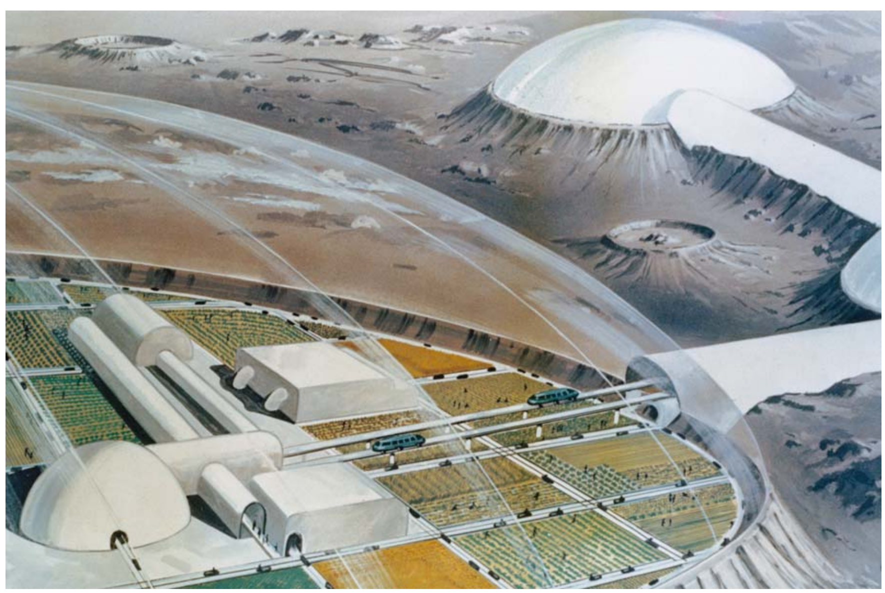
Eventually lunar bases will grow in both the number of people living there and the complexity and diversity of their activities.

In the top illustration, a lunar base capable of supporting several hundred people stretches out across the lunar landscape. This control center can be used to monitor various exploration and transportation activities. Residents may not be satisfied with video images or periscope views of their lunar surroundings and may, like their Mercury astronaut predecessors, insist on windows. Windows could be made thick and dense enough to provide protection from normal radiation, and lead shutters could be used during a solar flare.

In an even more advanced lunar base (bottom), large-scale networks of interconnected domes may house large farms, factories, and living areas. These domes may have Earth-like atmospheres. Currently, radiation hazards from solar flares and cosmic rays would seem to make this kind of planetary engineering for human habitation impractical, but technologies to deflect this radiation or to make humans less susceptible to it may eventually be developed to enable humans to live in large domes on the lunar surface (or on the surface of Mars).

NASA photos: S71-4296V & S76-21109





the strongest single motivation for young people to excel. And it is important to the development of productive future generations—motivated and trained to prove totally incorrect the gloomy "fixed sum game" scenarios for humankind's future. Needed are effective and serious technical and sociological studies, artistic representation of space architectures at both small and large scale, and use of the media to portray people's future in space more realistically as productive and peaceful rather than universally warlike and destructive.

In viewing works like *Star Trek* and *Star Wars,* we must wonder what precursor society and organization *built* the wonderful artifacts so wantonly destroyed in an hour or two. Some of us would be much more interested in the character and adventures of the *builders* than we are in those of the desperate defenders and destroyers. We think many young people might share our preferences.

One final thought: A Space Academy patterned after the military academies might be a very worthwhile national investment (see fig. 37.). This academy might best be a 4- to 6-year institution which took in new students who had successfully completed 2 years of undergraduate work. The last 2 or 3 years might send some of the semifinished products into distinguished universities to gain their Ph.D.s under noted scholars, scientists, and engineers who had contributed to the state of the art in space.

Congressional appointments, paid tuition and salary, assured career entry, and other attributes of the service academies should be characteristics of this institution. A generation of fully prepared people is much more important than hardware or brick and mortar.

Figure 37

Space Academy

A space academy may be an effective way to prepare Americans for living and working in space. Here are views of the Air Force Academy in Colorado Springs and the graduating Air Force cadets. Graduates of a space academy would have the required technical training, the organizational training, and the motivation to be the leaders in future major space projects, including lunar base development, space infrastructure growth, and eventually Mars settlements.

Sightseeing

Other optimistic visions of the future of space activities might include extensive tourism. Here, from a scenic lookout point on Mars, is a tourist's view of the Valles Marineris, the longest, deepest, and most spectacular canyon in the solar system. The idea that much of the solar system might eventually be available for anyone to visit is clearly a visionary one, but one that is not beyond the reach of projected advances in technology.

NASA photo: S80-33906

Addendum: Participants

The managers of the 1984 summer study were

David S. McKay, Summer Study Co-Director and Workshop Manager
Lyndon B. Johnson Space Center

Stewart Nozette, Summer Study Co-Director
California Space Institute

James Arnold, Director
of the California Space Institute

Stanley R. Sadin, Summer Study Sponsor
for the Office of Aeronautics and Space Technology
NASA Headquarters

Those who participated in the 10-week summer study as faculty fellows were the following:

James D. Burke	Jet Propulsion Laboratory
James L. Carter	University of Texas, Dallas
David R. Criswell	California Space Institute
Carolyn Dry	Virginia Polytechnic Institute
Rocco Fazzolare	University of Arizona
Tom W. Fogwell	Texas A & M University
Michael J. Gaffey	Rensselaer Polytechnic Institute
Nathan C. Goldman	University of Texas, Austin
Philip R. Harris	California Space Institute
Karl R. Johansson	North Texas State University
Elbert A. King	University of Houston, University Park
Jesa Kreiner	California State University, Fullerton
John S. Lewis	University of Arizona
Robert H. Lewis	Washington University, St. Louis
William Lewis	Clemson University
James Grier Miller	University of California, Los Angeles
Sankar Sastri	New York City Technical College
Michele Small	California Space Institute

Participants in the 1-week workshops included the following:

Constance F. Acton	Bechtel Power Corp.
William N. Agosto	Lunar Industries, Inc.
A. Edward Bence	Exxon Mineral Company
Edward Bock	General Dynamics
David F. Bowersox	Los Alamos National Laboratory
Henry W. Brandhorst, Jr.	NASA Lewis Research Center
David Buden	NASA Headquarters
Edmund J. Conway	NASA Langley Research Center
Gene Corley	Portland Cement Association
Hubert Davis	Eagle Engineering
Michael B. Duke	NASA Johnson Space Center
Charles H. Eldred	NASA Langley Research Center
Greg Fawkes	Pegasus Software
Ben R. Finney	University of Hawaii
Philip W. Garrison	Jet Propulsion Laboratory
Richard E. Gertsch	Colorado School of Mines
Mark Giampapa	University of Arizona
Charles E. Glass	University of Arizona
Charles L. Gould	Rockwell International
Joel S. Greenberg	Princeton Synergetics, Inc.
Larry A. Haskin	Washington University, St. Louis
Abe Hertzberg	University of Washington
Walter J. Hickell	Yukon Pacific
Christian W. Knudsen	Carbotek, Inc.
Eugene Konecci	University of Texas, Austin
George Kozmetsky	University of Texas, Austin
John Landis	Stone & Webster Engineering Corp.
T. D. Lin	Construction Technology Laboratories
John M. Logsdon	George Washington University
Ronald Maehl	RCA Astro-Electronics
Thomas T. Meek	Los Alamos National Laboratory
Wendell W. Mendell	NASA Johnson Space Center
George Mueller	Consultant
Kathleen J. Murphy	Consultant
Barney B. Roberts	NASA Johnson Space Center
Sanders D. Rosenberg	Aerojet TechSystems Company
Robert Salkeld	Consultant
Donald R. Saxton	NASA Marshall Space Flight Center
James M. Shoji	Rockwell International
Michael C. Simon	General Dynamics
William R. Snow	Electromagnetic Launch Research, Inc.
Robert L. Staehle	Jet Propulsion Laboratory
Frank W. Stephenson, Jr.	NASA Headquarters
Wolfgang Steurer	Jet Propulsion Laboratory
Richard Tangum	University of Texas, San Antonio
Mead Treadwell	Yukon Pacific
Terry Triffet	University of Arizona
J. Peter Vajk	Consultant
Jesco von Puttkamer	NASA Headquarters
Scott Webster	Orbital Systems Company
Gordon R. Woodcock	Boeing Aerospace Company

The following people participated in the summer study as guest speakers and consultants:

Edwin E. "Buzz" Aldrin	Research & Engineering Consultants
Rudi Beichel	Aerojet TechSystems Company
David G. Brin	California Space Institute
Joseph A. Carroll	California Space Institute
Manuel L. Cruz	Jet Propulsion Laboratory
Andrew H. Cutler	California Space Institute
Christopher England	Engineering Research Group
Edward A. Gabris	NASA Headquarters
Peter Harnmerling	LaJolla Institute
Eleanor F. Helin	Jet Propulsion Laboratory
Nicholas Johnson	Teledyne Brown Engineering
Joseph P. Kerwin	NASA Johnson Space Center
Joseph P. Loftus	NASA Johnson Space Center
Budd Love	Consultant
John J. Martin	NASA Headquarters
John Meson	Defense Advanced Research Projects Agency
Tom Meyer	Boulder Center for Science and Policy
John C. Niehoff	Science Applications International
Tadahiko Okumura	Shimizu Construction Company
Thomas O. Paine	Consultant
William L. Quaide	NASA Headquarters
Namika Raby	University of California, San Diego
Donald G. Rea	Jet Propulsion Laboratory
Gene Roddenberry	Writer
Harrison H. "Jack" Schmitt	Consultant
Richard Schubert	NASA Headquarters
Elie Shneour	Biosystems Associates, Ltd.
Martin Spence	Shimizu Construction Company
James B. Stephens	Jet Propulsion Laboratory
Pat Sumi	San Diego Unified School District
Robert Waldron	Rockwell International
Simon P. Worden	Department of Defense
William Wright	Defense Advanced Research Projects Agency

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