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Alternative Scenarios Utilizing Nonterrestrial Resources

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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

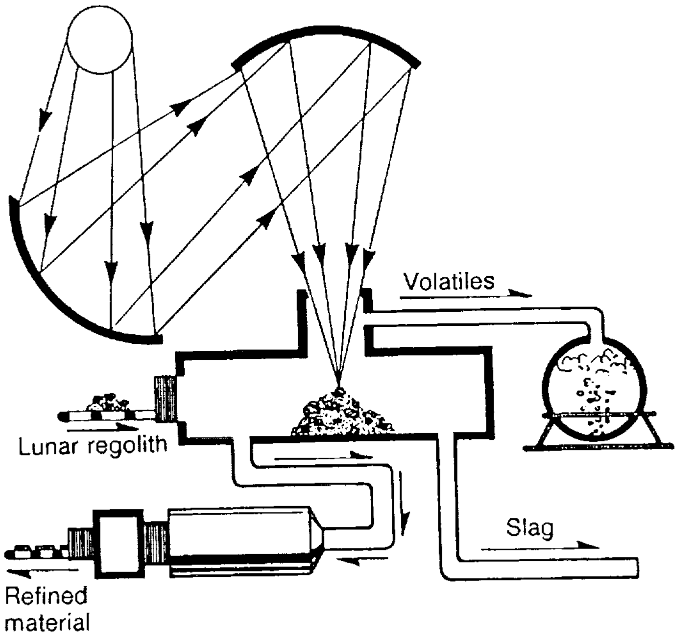

Figure 3

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 The remaining material can be withdrawn as slag, which can be used for construction of buildings and roads or as radiation shielding.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

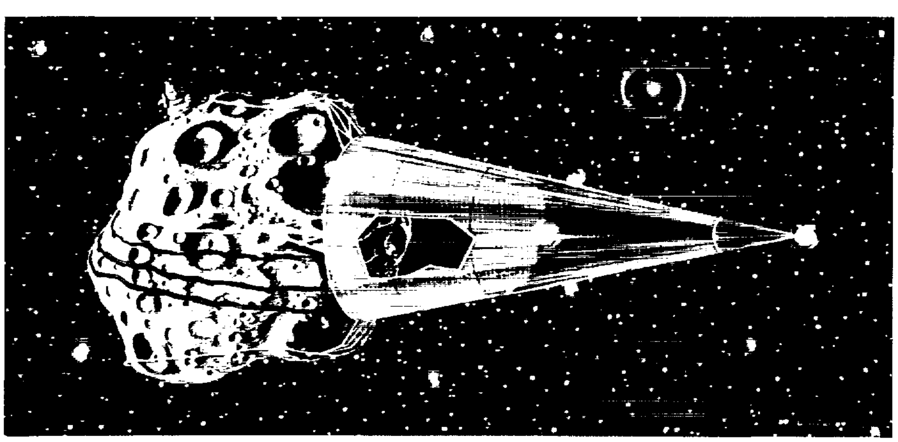

Figure 4

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 1.9 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

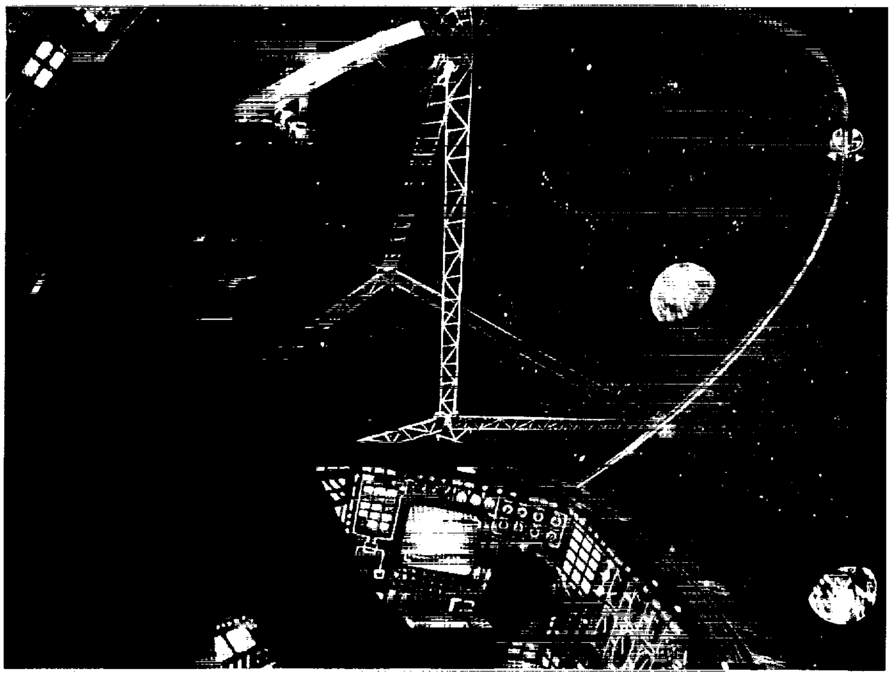

Figure 6

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.

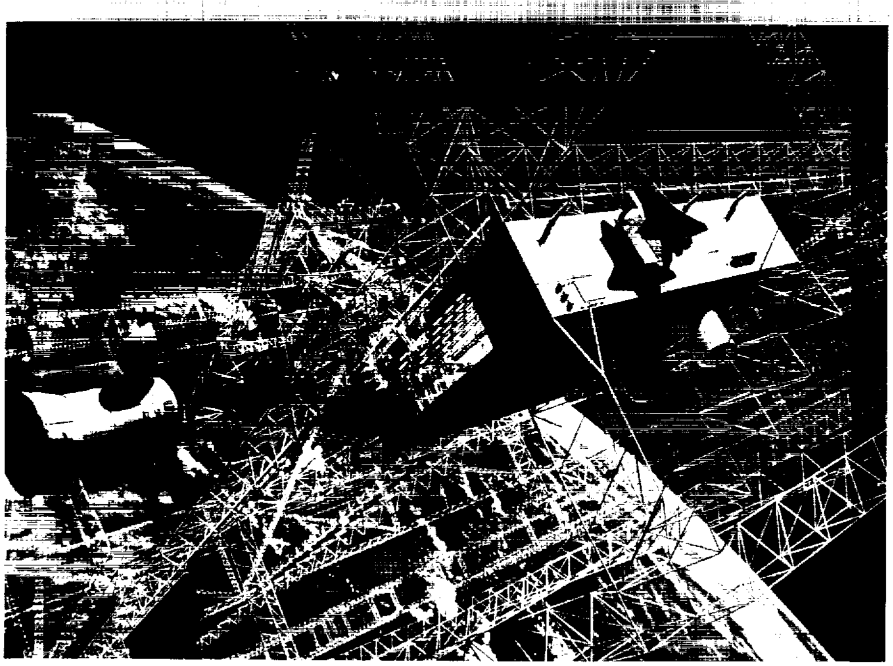

Figure 7

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

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

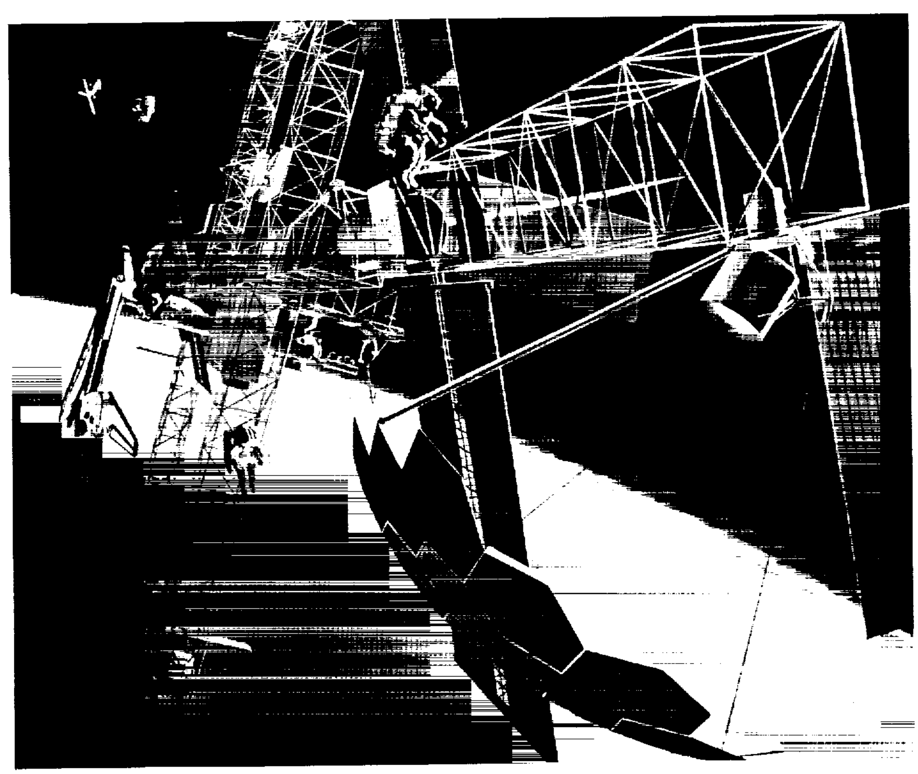

Figure 8

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.

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.

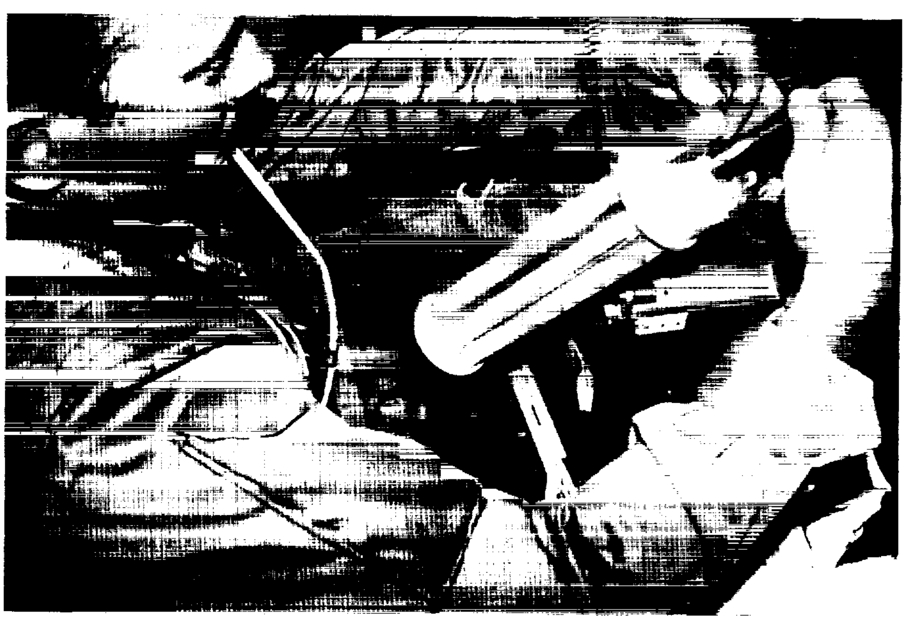

Figure 9

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.

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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.

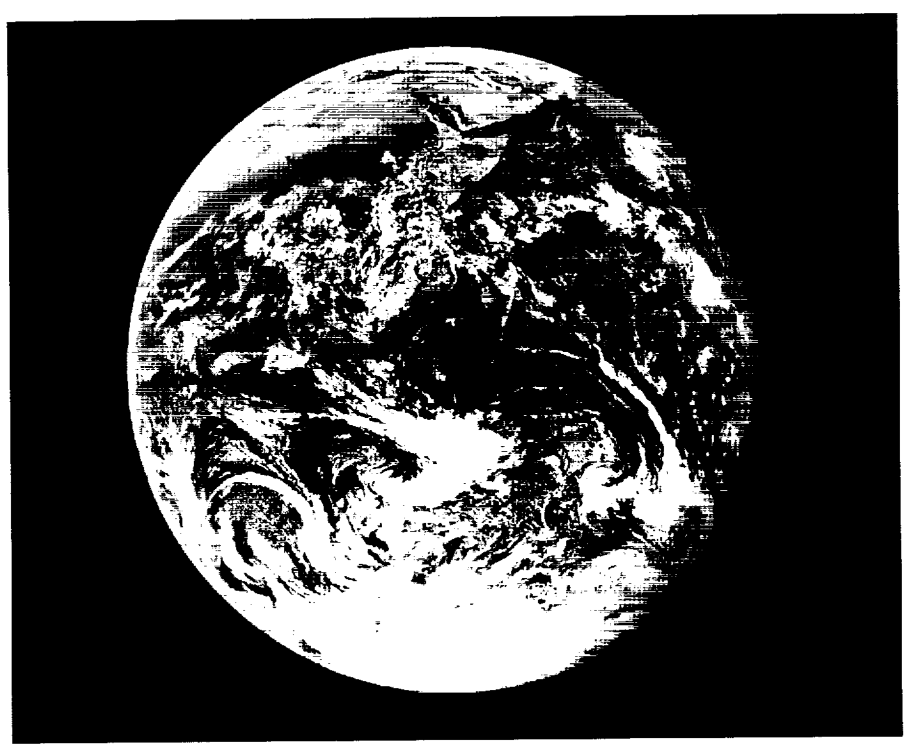


Figure 10

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.

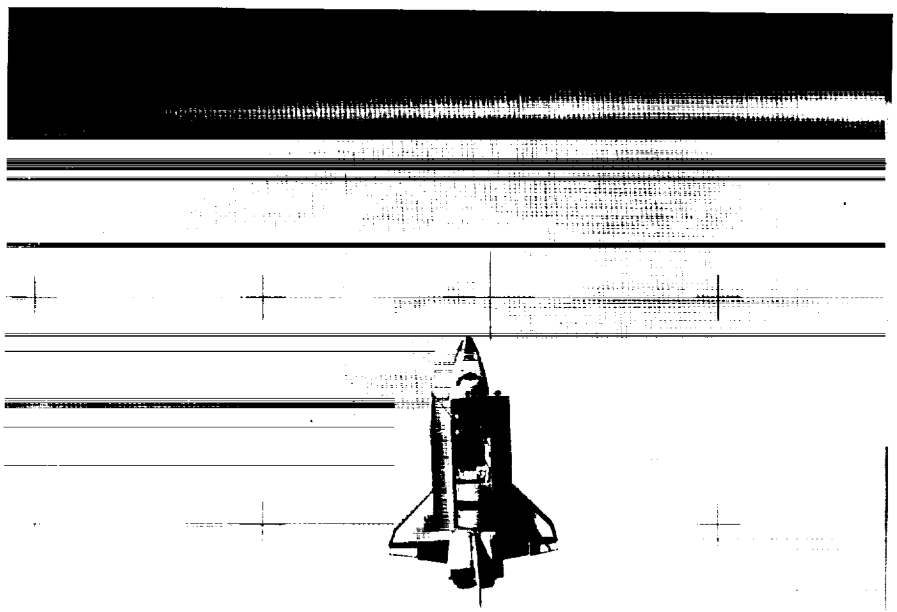


Figure 11

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.

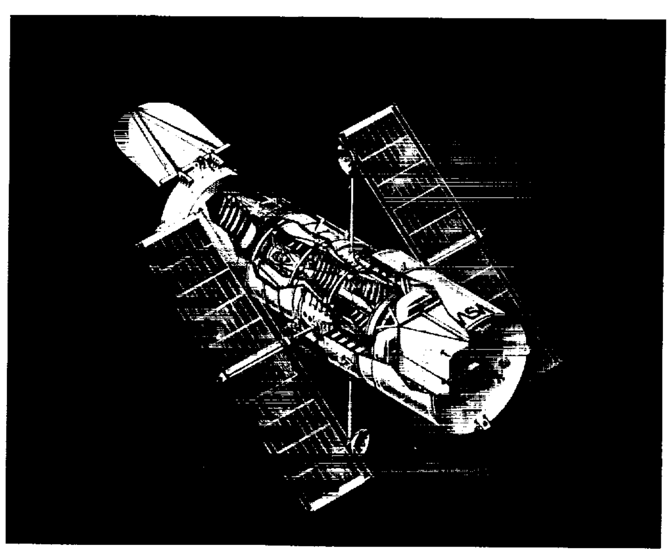


Figure 12

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.

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	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	Planetary bases or outposts

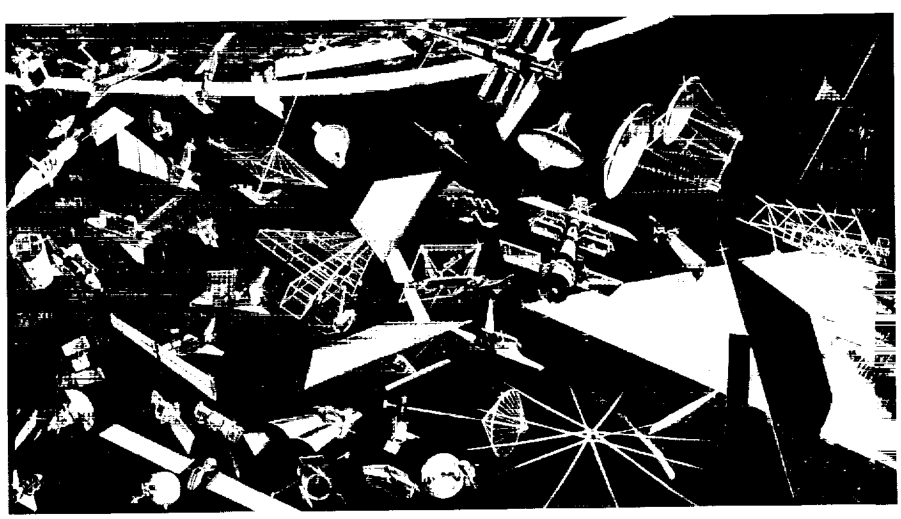
*The columns in this table do not represent related categories but are used simply to enumerate options for each item.

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.

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: Countries:	 Government National	 Government/commercial International	 Commercial		
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: 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 in LEO & GEO		Lunar base Asteroid 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

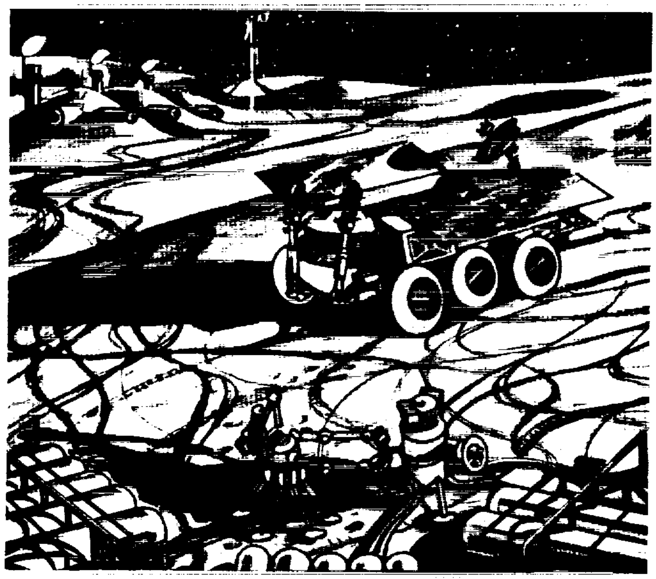


Figure 13

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.

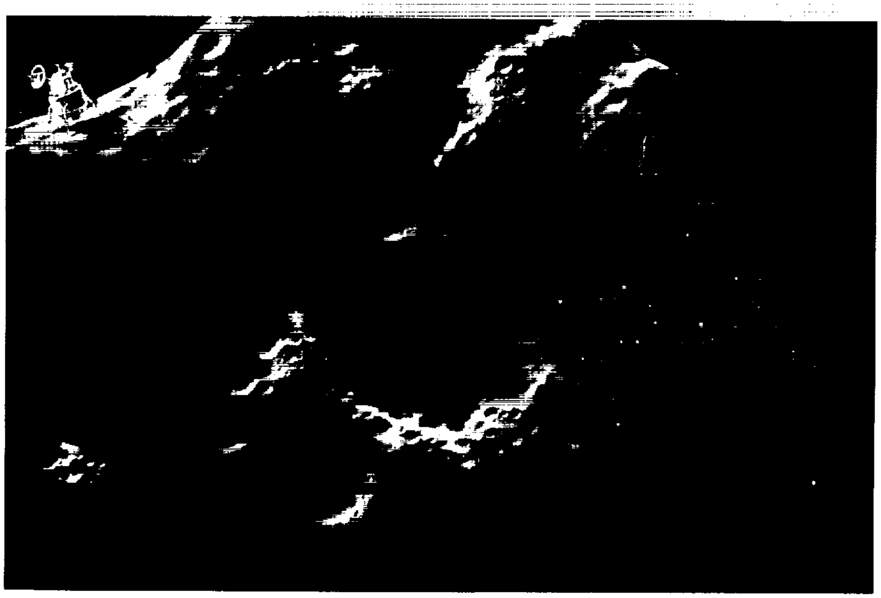


Figure 14

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:				Location/view
5. Resource location:	LEO GEO		Lunar	
6. Product:		Information		Pleasure
7. Processing:				
Location:				
Type:	None			
8. Transportation:				
Resource site / Processing site / Use site	Same			
Mode:	Chemical rocket	Aerobrake	Other	
9. Infrastructure:	Earth-to-orbit transportation Orbital transfer vehicles	LEO space station	Observation instruments in LEO & GEO	Lunar base

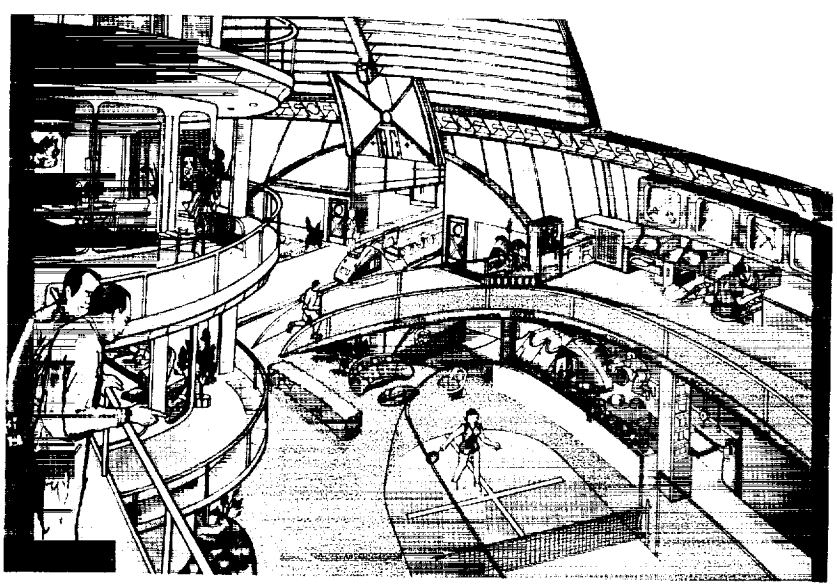


Figure 15

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.

TABLE 5. *Strategic Defense Initiative (SDI)*

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 Asteroid outpost Phobos outpost

Summary: Space Resource Mission Alternatives

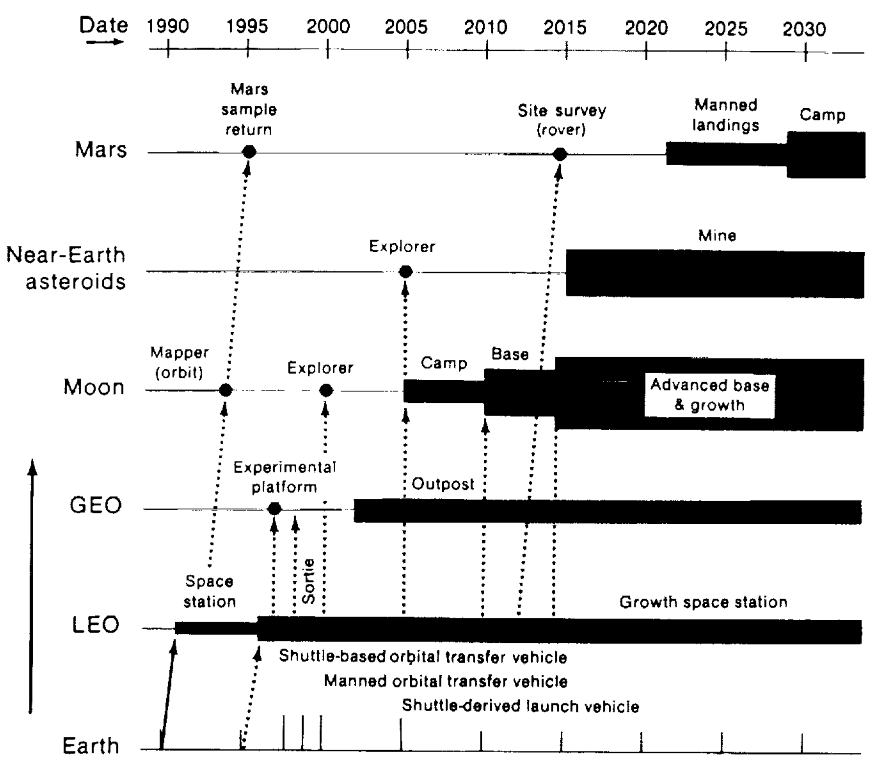
The mission options of table 1 present the basis for the assessment of a broad range of space resource scenarios. The four example missions were selected to illustrate the variety of possible options. Issues, systems, and technologies with common threads in these missions should be of particular interest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



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.

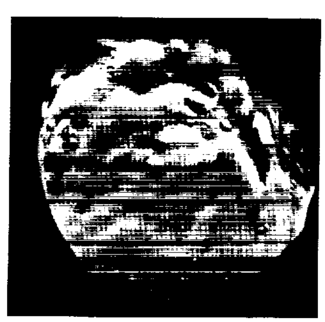


Figure 16

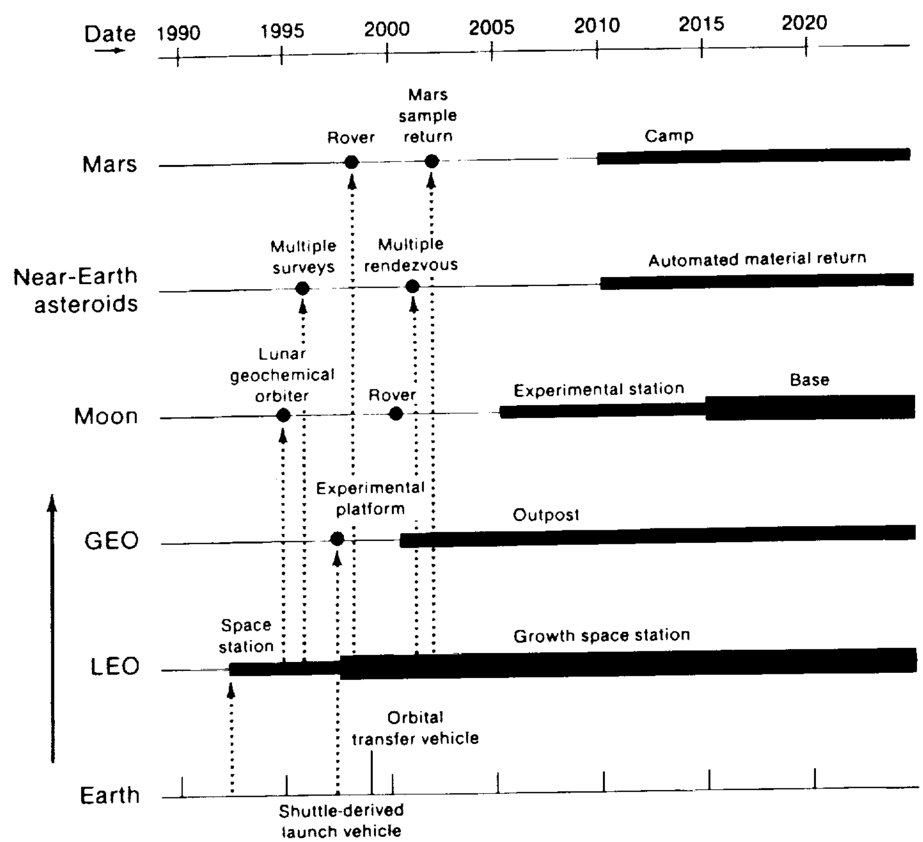
Scenario for Space Resource Utilization

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.

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.