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Transport: Introduction

William Lewis and Sanders D. Rosenberg

The propulsion workshop addressed the current status and future requirements for space propulsion by considering the demand for transportation in the three scenarios defined by workshop 1. The low-growth scenario assumes no utilization of nonterrestrial resources; the two more aggressive scenarios include the use of nonterrestrial resources, particularly propellants. The scenarios using nonterrestrial resources demand that tens of thousands of tons of rockets, propellants, and payloads be shipped through cislunar space by 2010. Propellant oxygen derived from the Moon is provided in the second scenario, and propellants from asteroids or the Mars system are provided in the third. The scenario using resources derived only from the Earth demands much less shipping of hardware but much more shipping of propellants.

We included in our examination a range of technologies that could be developed to meet the transportation requirements of

these scenarios. Descriptions of these technologies can be found in the individual contributions that follow this introduction.

It appears that current oxygen-hydrogen propulsion technology is capable of meeting the transportation requirements of all scenarios. But, if this technology is used in conjunction with advanced propulsion technology, a much more efficient space transportation system can be developed. Oxygen from the Moon promises to significantly reduce the yearly tonnage on the transport leg from the Earth to low Earth orbit (LEO). Hydrogen from Earth-crossing asteroids or from lunar volatiles (in cold-trapped ices or the lunar regolith) would offer further improvement and reduce propulsion technology challenges. Mars missions are supportable by propellants derived in the Mars system, probably from Phobos. Unfortunately, these opportunities cannot be taken at current funding levels.

The NASA baseline scenario is shown in figure 1. This scenario assumes the development of a space transportation network without utilization of nonterrestrial resources. The space station is developed first and used to support development in geosynchronous Earth orbit (GEO), manned exploration of the Moon, and unmanned exploration of the solar system. Beyond the timeframe considered, the space station can serve as a base for lunar settlement and manned Mars exploration.

The nonterrestrial resource scenarios, figures 2 and 3, initially follow almost the same path but, after the space station is established, move less toward GEO and more toward the Moon. In addition, these scenarios consider selective mining of asteroids that cross the Earth's orbit. Nonterrestrial resources are used to reduce transportation and construction costs for projects in cislunar space. Eventually, the space station and lunar base serve as production and staging areas for manned Mars exploration.

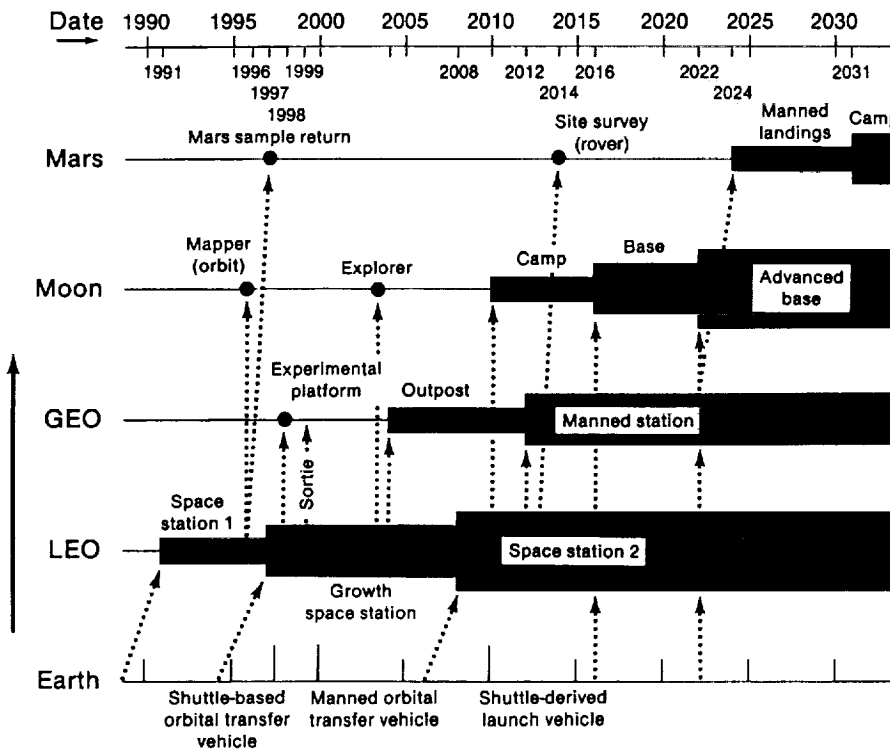


Figure 1

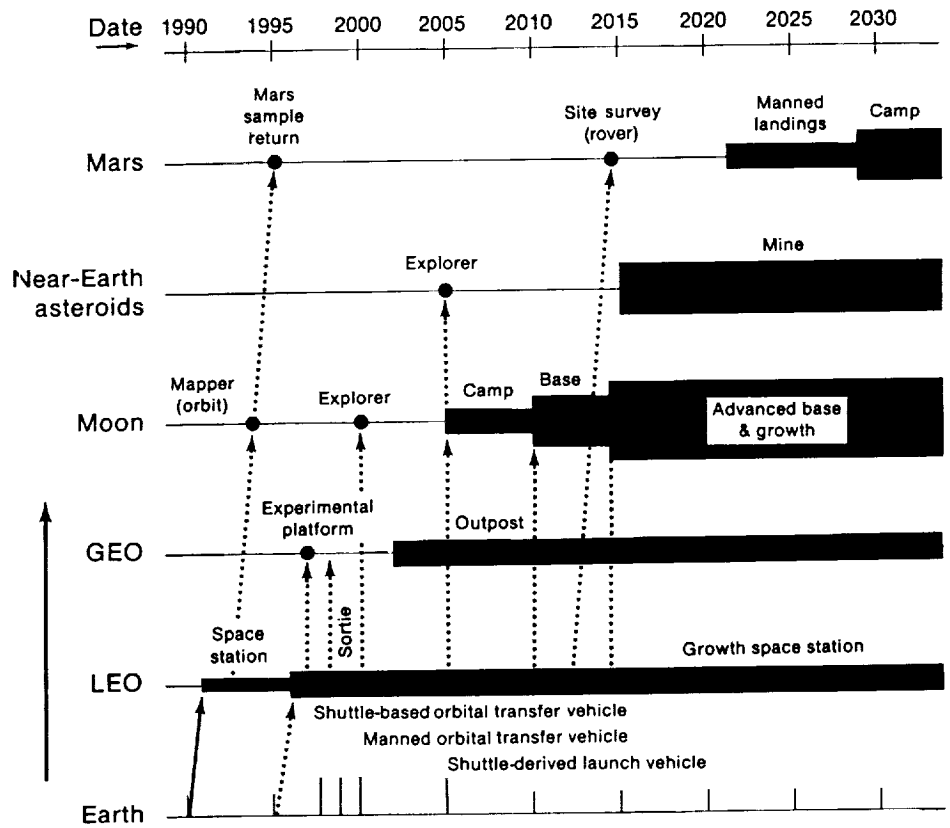
Baseline Scenario

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.

Figure 2

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.



Transportation System Requirements

Table 1 lists the principal routes between nodal points in the Earth-Moon-asteroid-Mars system and identifies technologies for each of the legs. The principal distinctions between categories of space propulsion are related to whether significant gravitational fields are involved. Leaving a gravitational field requires a high-thrust propulsive system. Orbit-to-orbit trips can be made with fairly low thrust, though such trips take longer and are less efficient because gravity reduces effective thrust. If a planet has an atmosphere, atmospheric drag

(aerobraking) can be used to offset requirements for inbound propulsion. Because of differences in mission duration and in the accelerations achievable using various techniques, some transportation modes are more relevant to manned flights and others to cargo flights. Manned flights require fast and safe transportation to minimize life support requirements and radiation exposure. Cargo flights can be slower, less reliable, and thus cheaper. We also discussed to a limited extent transportation on the surface of the Moon, which will require quite different technologies.

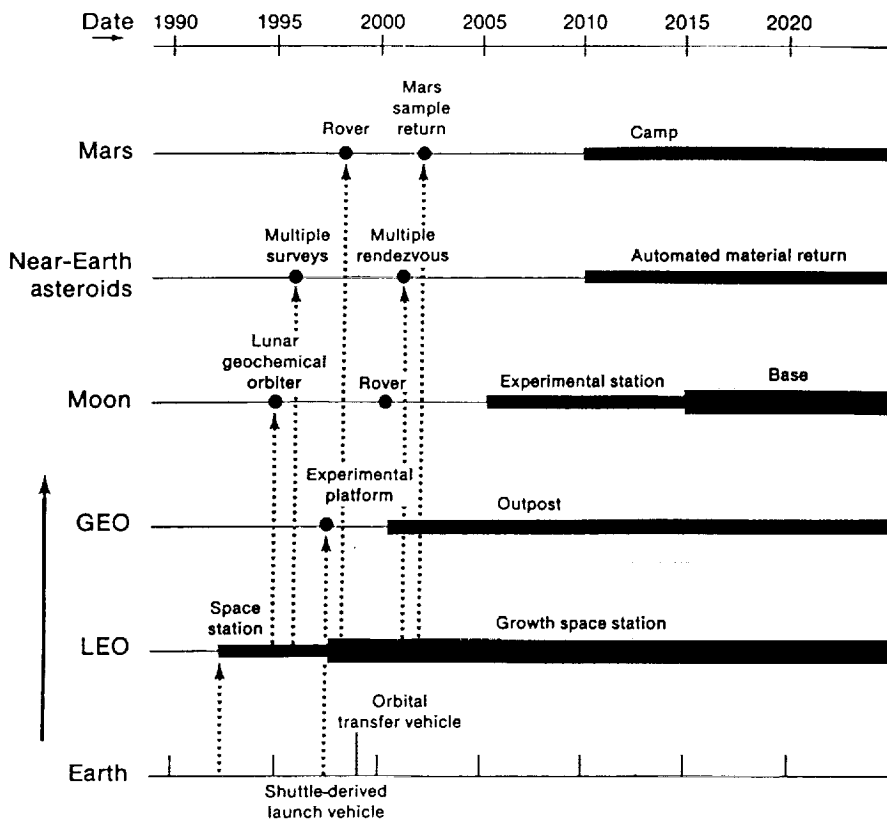


Figure 3

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.

TABLE 1. *Principal Routes Between Transportation Nodes*

(a) Nodes and their locations	
Node	Location
1. Earth	Kennedy Space Center
2. Low Earth orbit (LEO)	Space station
3. Geosynchronous Earth orbit (GEO)	Shack
4. Lunar orbit	Shack
5. Moon	Advanced base
6. Earth-crossing carbonaceous chondrite asteroid	Mining base
7. Mars orbit	Shack
8. Mars	Advanced base

(b) Routes and modes of transportation for them	
Leg	Transportation mode options
Earth to low Earth orbit	Chemical rockets
LEO to LEO (plane changes)	Chemical rockets Low-thrust orbital maneuvering vehicles (OMVs) Tethers
LEO to GEO, lunar orbit, asteroids, Mars orbit	Chemical-rocket-propelled orbital transfer vehicles (OTVs) Low-thrust propulsion
GEO, lunar orbit, asteroids, Mars orbit to LEO	Aerobraked chemical rockets Low-thrust propulsion
Lunar orbit to Moon	Chemical rockets Tethers
Moon to lunar orbit	Chemical rockets Electromagnetic launch Tethers
Mars orbit to Mars	Aerobraked vehicles
Mars to Mars orbit	Chemical rockets

The baseline scenario could be implemented with the Space Shuttle, Shuttle-derived launch vehicles (SDLVs), and orbital transfer vehicles (OTVs). The nonterrestrial resource scenarios require the development of additional systems. While it is technically possible to establish the transportation network for these scenarios with oxygen-hydrogen (OH) rockets alone, the expense of operating the transportation network, even for the baseline scenario, could be reduced by the introduction of non-OH rocket technologies. Let us consider briefly the technologies that could be used for three categories of transportation: surface-to-orbit, orbit-to-orbit, and surface.

Surface-to-Orbit Transportation (Earth to Orbit, Moon to Lunar Orbit, Mars to Mars Orbit)

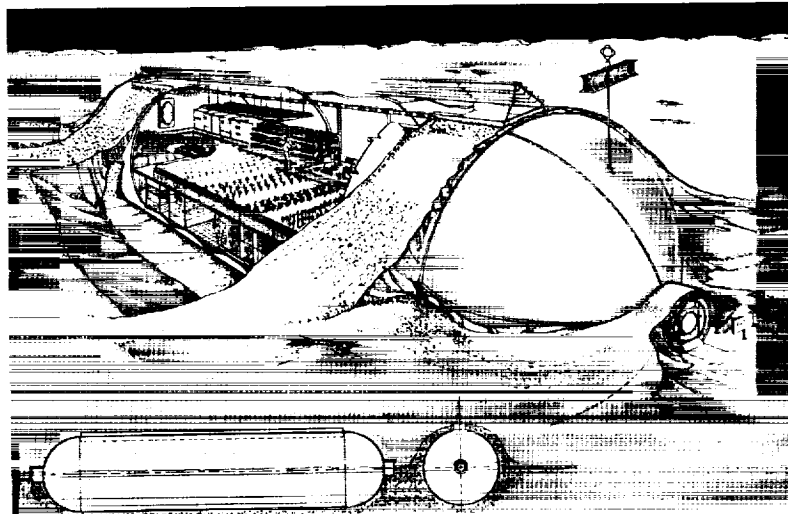
Transportation from the Earth's surface to orbit is conventionally accomplished using chemical rockets. There seems no readily available substitute for such rockets on this leg. Shuttle-derived launch vehicles or, if traffic becomes heavy enough, heavy lift launch vehicles (HLLVs) could provide Earth-to-orbit transportation at a lower cost than does the current Space Shuttle

system. (See Salkeld and Beichel 1973, Eldred 1982 and 1984, and Davis 1983.) These systems gain efficiency by eliminating man-rated elements and reducing system weight, rather than by improving the rocket engine (although some improvements in rocket engines are still attainable). It may be worthwhile to develop such vehicles for cargo transport in the baseline scenario over the next 20 years. And the scenarios using nonterrestrial materials require such vehicles for cost-effectiveness.

Transportation from the lunar surface to orbit could be accomplished using OH rockets. The advantages of choosing OH rockets are summarized in table 2 by Sandy Rosenberg, who points out that oxygen-hydrogen propulsion is likely to persist simply because the large amount of effort that has gone into its development has led to a level of understanding which surpasses that of any alternative propulsion system. In a separate paper, Mike Simon considers the use of OH rockets in a systems sense, showing how the introduction of nonterrestrial propellants can affect the overall system performance and, eventually, reduce the cost.

TABLE 2. Selection Basis for Oxygen-Hydrogen Propulsion

Factor	Rationale
1. Common use of water to support human activity in space	The exploration and exploitation of space is based on a water economy because of the presence of humans. Water and oxygen are required for life support. Therefore, use of oxygen and hydrogen in propulsion systems will benefit from synergism with other parts of the space system.



A Plant-Growing Module at a Lunar Base

Plants will require a considerable stock of water, but nearly all the water can be recycled in a properly designed controlled ecological life support system (CELSS).

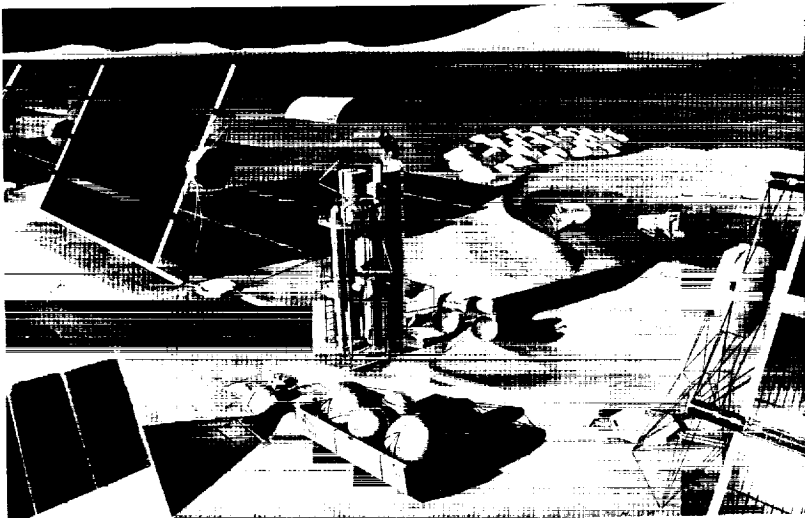
2. High performance

The bipropellant combination of liquid oxygen (LO₂) and liquid hydrogen (LH₂), operating at a mixture ratio of 6:1, offers a vacuum specific impulse of 460 to 485 sec, with an environmentally acceptable exhaust.

The LO₂/LH₂ bipropellant propulsion system offers a high thrust-to-weight ratio, an acceptable fraction of propellant mass to propulsion system mass, a short trip time (an important factor for all manned missions), and a firmly established technology base.

TABLE 2 (concluded).

Factor	Rationale
3. Technological feasibility	The technology for the long-term storage and transfer of cryogenic fluids in a low-gravity environment, which will enhance the efficient management of LO ₂ /LH ₂ propellant, is being actively pursued by NASA's Office of Aeronautics and Space Technology (OAST). Aerobraking is also being actively studied and appears promising.
4. Benefit from nonterrestrial resources	LO ₂ /LH ₂ propulsion benefits directly from the utilization of nonterrestrial resources; e.g., the manufacture of O ₂ on the Moon and O ₂ and H ₂ on Mars. Earth-crossing carbonaceous asteroids may be a source of O ₂ and H ₂ .



Oxygen Manufacturing Plant on the Moon

This plant uses a fluidized bed to reduce lunar ilmenite with hydrogen and produce water. The water is electrolyzed, the oxygen is collected, cooled, and cryogenically stored in the spherical tanks, and the hydrogen is recycled into the reactor. The plant is powered by electricity from the large solar cell arrays, each of which can generate 56 kilowatts.

Artist: Mark Dowman

5. Programmatic support	LO ₂ /LH ₂ propulsion gets more than 90 percent of the investment that NASA's OAST is currently making in its research program. No change in the current NASA program is required when LO ₂ /LH ₂ propulsion is selected.
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Specific Impulse (I_{sp})

Specific impulse (I_{sp}) is a measure of the performance of a rocket engine. It is equal to the thrust generated F divided by the weight flow rate w of the propellant used:

$$I_{sp} = F / \dot{w}$$

Its units turn out to be seconds. In the English system, pounds of force (mass times acceleration or lb ft/sec²) divided by pounds of weight (mass times gravity or lb ft/sec²) per second equal seconds. In the metric system, newtons (kgm/sec²) divided by kilograms (kg) times gravity (m/sec²) per second equal seconds.

Specific impulse is also equivalent to the effective exhaust velocity divided by the gravitational acceleration. This relationship can also be derived from a consideration of the units. Force, or mass times acceleration, can be seen as mass per second times velocity. Weight flow rate, or mass times gravity per second, can be taken as mass per second times gravity. Thus, specific impulse equals velocity (m/sec) divided by gravity (m/sec²), or seconds again.

Other rocket propellants derived from nonterrestrial materials could also find use in the future. Andy Cutler considers an oxygen-hydrogen-aluminum engine as a possibility. Such an engine could use oxygen and hydrogen derived from lunar or asteroidal materials and could also provide a second use for the Space Shuttle's aluminum external tanks, which are currently thrown away.

Among the alternative technologies that may be useful are electromagnetic launchers capable of launch from the Moon to low lunar orbit and of propelling vehicles in space. The Department of Defense is funding a program of significant size in electromagnetic

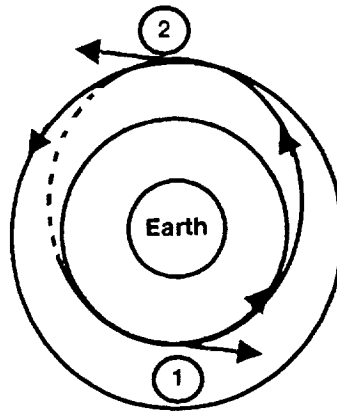
launch; the results of this program might be fairly cheaply adapted to the space environment. This concept is considered in a paper by Bill Snow.

Several other technologies may be of value in surface-to-orbit transportation. Tethers, in particular, can permit an orbiting station to acquire momentum from a high I_{sp} propulsion device over long periods of time and quickly transfer it to a vehicle that needs the momentum to gain orbital velocity on launch from the Moon (Carroll 1984 and 1986, Carroll and Cutler 1984). In effect, high I_{sp} is combined with high thrust, although only briefly. Andy Cutler discusses this idea.

Orbit-to-Orbit Transportation (LEO to GEO, Lunar Orbit, Asteroids, or Mars Orbit and Back)

Orbit-to-orbit transfers within cislunar space can be handled by OH rockets. See figure 4. A series of space-based orbital maneuvering vehicles (OMVs) and orbital transfer vehicles (OTVs) is now being considered by NASA.

Aerobraking, which uses aerodynamic effects to lower orbit, may be significant in cislunar space transportation. This technology will be used primarily with high-energy systems, such as OH rockets, to slow spacecraft returning to the Earth (or entering the Mars atmosphere), reducing their need for propellant. See figure 5. This technology is under development



but has not been tested in the context of GEO, lunar, asteroid, or Mars missions. No paper on aerobraking was produced during the workshop, but the principles and prospects of aerobraking have been discussed by Scott and others (1985) and Roberts (1985).

Figure 4

Orbital Transfer Maneuver

A spacecraft orbiting the Earth can raise the altitude of its orbit by firing its engines to increase its velocity in a series of two maneuvers. In the figure, the spacecraft in a low circular orbit fires its engines at point 1. Its new velocity causes an increase in orbital altitude on the opposite side of the orbit. When the spacecraft reaches the high point of this new elliptical orbit, at point 2, the engines are fired again to increase its velocity. This increase in velocity raises the low point of the elliptical orbit and in this case results in a circular orbit at a higher altitude than the original orbit. An orbit can be lowered by following this procedure in reverse.

Taken from AC Electronics Division, General Motors Corp., 1969, *Introduction to Orbital Mechanics and Rendezvous Techniques, Text 2*, prepared under NASA contract NAS 9-497, Nov.

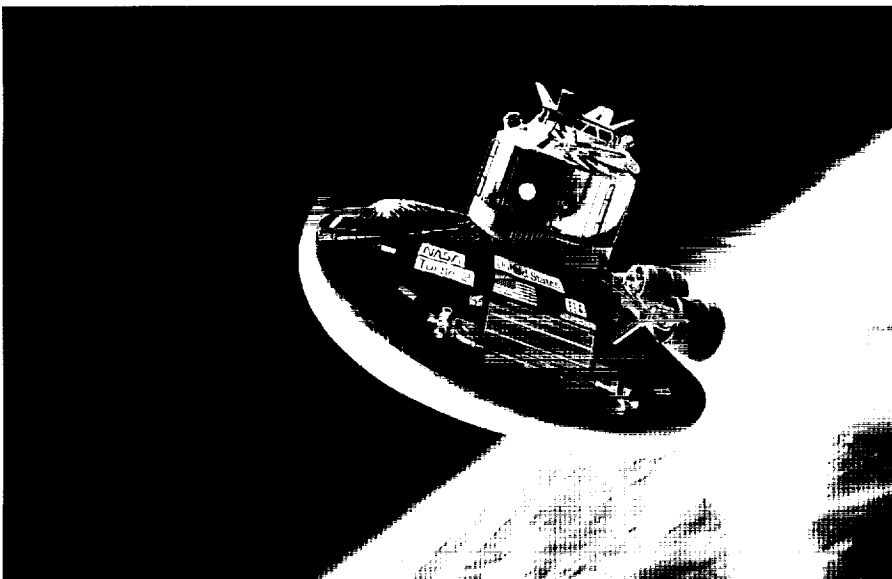


Figure 5

Aerobrake Used To Slow Down Unmanned Spacecraft Returning From Mars

Aerobrakes can reduce or eliminate the need for retrorockets because they use aerodynamic forces in the upper atmosphere of the Earth to slow down spacecraft for orbital insertion or for reentry. Aerobraking could also be used on the Mars end of a voyage to slow down spacecraft.

Artist: Pat Rawlings

Because high gravitational fields do not have to be surmounted, there are additional approaches to orbit-to-orbit propulsion. Electric propulsion, which has a high I_{sp} but low thrust, can be applied to orbit-to-orbit transfers of cargo. Trip time from LEO to lunar orbit, for example, is about 100 days, as opposed to 3 days for rocket propulsion. And loss of effective thrust (gravity loss) is experienced in the vicinity of the planets (causing most of the trip time to be spent near the planets). But specific impulses of 1000 to 3000 seconds for advanced electric thrusters still give the systems high fractions of payload mass to starting mass. Electric propulsion is discussed by Phil Garrison.

Tethers could be used to supply some momentum to orbit-orbit transfers. Near-Earth orbit-orbit transfers might be accomplished without propellant by using conductive, or electrodynamic, tethers. This method is especially good at changing the inclination of

orbits and could, for example, change an equatorial orbit to a polar orbit in about a month. This idea is discussed by Andy Cutler.

It is possible that a beamed power system could be used to provide either thermal or electric power for an orbit-orbit transfer. Beamed energy is considered in the paper by Jim Shoji in this propulsion part of the volume and in a paper by Ed Conway in the part on power.

Orbit-orbit transfers outside cislunar space can benefit from alternative technologies, because the trip times are long and, for manned missions, the payloads required for safe return to Earth are large. For these missions, electric propulsion, nuclear propulsion, or, for cargo, light sails (Sauer 1976 and 1977) may become the technology of choice for economically feasible payload-to-starting-mass fractions. Beamed power over these distances is infeasible with antenna sizes suitable for power sources in Earth orbit.

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**Surface Transportation
(On the Moon)**

Surface transportation technology on the Moon resembles that on Earth (see fig. 6). The major difference is that radiation protection must be provided for personnel. Among other things, this implies that base modules will be connected by trenches and tunnels. The machinery to produce these must be part of the base construction equipment. It also implies intensive use of vehicle teleoperation for activities on the lunar surface (see fig. 7). Teleoperation was not treated in detail by our group but has been considered by Rob Lewis in workshop 4.

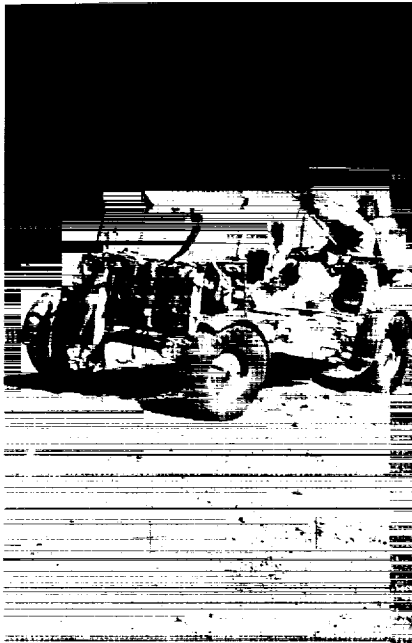


Figure 6

Rover Used on the Apollo 16 Mission

The astronaut is aiming the antenna toward Earth at one of the stops. This rover offers no radiation protection other than the space suits of the astronauts.



Figure 7

Teleoperated Rover at a Lunar Base

The rover in this artist's conception is powered by batteries which are recharged by the solar cell panels. While designed mainly for teleoperation, the vehicle has a cab so that it can be used for manned operation or human transport.

A second difference is that lunar surface vehicles must function in a vacuum. Besides the obvious requirement for passenger life support, there is the requirement that external mechanisms be successfully lubricated, in a dusty vacuum, without significant outgassing. The technical difficulties involved have yet to be seriously addressed.

It should be noted that logistics support will be required at each node. This logistics support is itself an important transportation technology; it absorbs the lion's share of transportation funding.

The logistics support at all nodes will contain some kind of repair and maintenance facilities and will make provision for refueling, including storage and handling of cryogenes. Neither has yet been done routinely by NASA in space. In the short run, there will have to be major facilities only on the Earth's surface and in LEO. In the long run, facilities will probably be placed on the Moon and at other nodes as well (see fig. 8). These facilities will contribute a considerable portion of the system's operating cost. To our knowledge, the technology of logistics support has not received the attention it is due.

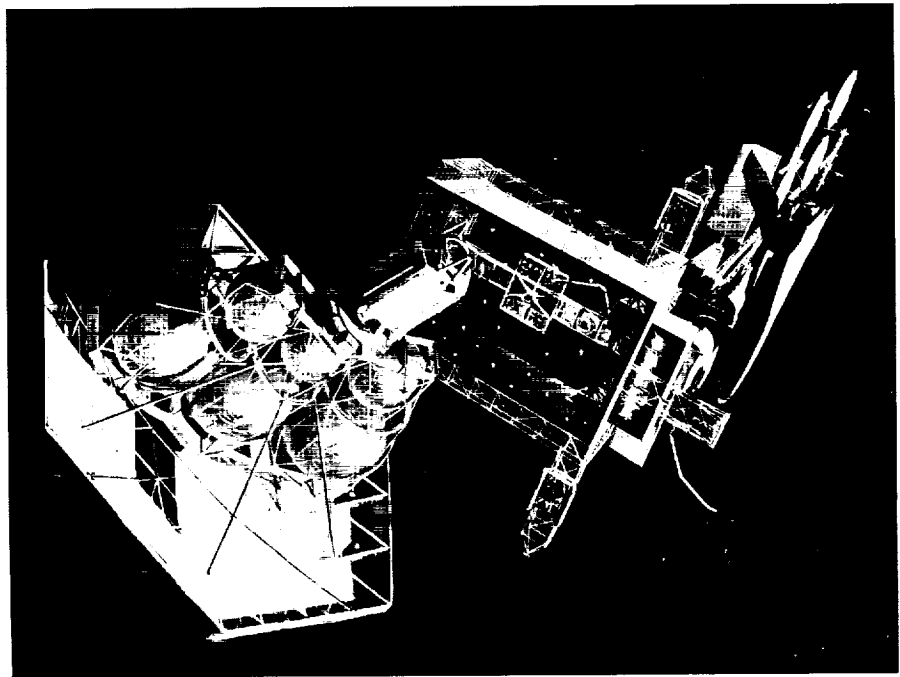


Figure 8

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.

Effects of Developing Nonterrestrial Resources

The development of nonterrestrial resources will have mixed effects on the space transportation system. On the one hand, the establishment of nonterrestrial manufacturing facilities will increase the load on the transportation system early in the program. On the other hand, once these facilities are established, they will reduce transportation requirements by providing propellant at various transportation nodes. This propellant can then be used to support cis- and translunar missions.

Intensive development of GEO could also make good use of nonterrestrial resources, in much the same way as would a Mars expedition. In addition, structural members of a GEO platform could be fabricated on the Moon.

Intensive use of cislunar space for the Strategic Defense Initiative (SDI) would almost demand use of lunar or asteroidal materials for shielding. And the transportation requirements of the SDI would probably be large enough to merit use of nonterrestrial propellants.

Remarks

Because of our assumptions, we have overlooked some technologies. We have not considered nuclear propulsion in cislunar space, for example, as it does not seem advantageous over such short distances. We have not considered several very speculative forms of transportation, such as fusion power and antimatter, because they seem technically uncertain or simply inapplicable. A good overview of advanced propulsion systems may be obtained from work by Robert L. Forward (1983) and a Jet Propulsion Laboratory report edited by Robert H. Frisbee (1983).

Some privately funded groups are apparently interested in funding specific experimental work in certain advanced propulsion technologies. NASA should consider cooperation with such groups as a way to extend seed money.

In summary, it seems likely that OH rocket engines will be indispensable for the foreseeable future. It is at least possible that such rockets are best used in conjunction with other technologies. It is therefore advisable to spend enough seed money to ensure that these other technologies are available when needed.

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