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Manned Mars Missions

**Working Group
Summary Report**

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MANNED MARS MISSIONS

A WORKING GROUP REPORT

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Based on

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PREFACE

In 1984, three important factors modified the NASA planning environment. That year the Space Shuttle became operational, the Space Station program received strong presidential support, and Congress mandated the creation of a National Commission on Space to survey the space program and recommend future strategies and missions. In this environment, a study of manned Mars missions was initiated at the suggestion of former astronaut, H. H. Schmitt.

This study was undertaken by NASA Centers and the Los Alamos National Laboratory, assisted by experts from university and governmental organizations (Appendix A). The purposes were to update earlier Mars mission study data, to examine the impact of new and emerging technologies on Mars mission capabilities, and to identify technological issues that would be useful in projecting scientific and engineering research in the coming decades. In the first half of 1985, the study team held meetings at Los Alamos National Laboratory, Johnson Space Center, Kennedy Space Center, and Marshall Space Flight Center. The final meeting was held at the Marshall Space Flight Center, June 10-14, 1985, as a workshop entitled "Manned Mars Missions." Over 90 invited and contributed papers were presented at the workshop to elaborate on scientific and technical opportunities and issues. This report was produced from the findings and conclusions deliberated by the study team at the workshop. The papers will be published separately as NASA Report M002, Manned Mars Mission Working Group Papers. They contain more detailed descriptions and literature references than are given here.

At the end of the study, all participants recognized that many unanswered questions remain and more complete integrations would result from further work. This report provides a basis for furthering that process.

The original drafts of this report were prepared by the following working group members: Report Overview, M. Duke; Science Objectives and Operations, P. Keaton; Mars Surface Infrastructure and Activities, J. Blacic; Transportation Trade Studies, B. Roberts; Space Vehicle Concepts, J. Butler; Subsystems and Technology Considerations, J. French; Life Sciences, J. Sharp and J. Mason; Impacts on the Space Infrastructure, B. Askins; Costs, Schedules and Organizations, K. Cyr. The editors of this report take full responsibility for any errors or changes in emphasis and style that occurred during the editorial process.

The Marshall Space Flight Center and personnel of the University of Alabama in Huntsville hosted the meeting and provided logistics support for this report.

1. REPORT OVERVIEW

INTRODUCTION

The Space Shuttle and the low Earth orbit (LEO) Space Station (SS) constitute two elements of a space infrastructure capable of supporting a permanent human presence in space. With the addition of Orbital Transfer Vehicles (OTVs) to the SS, reusable transport will be used to carry cargo – and eventually people – to the edge of the Earth's gravitational influence. Although in one respect the OTV is simply an advanced upper stage, its existence will admit the possibility of permanent space depots at the Moon, geosynchronous Earth orbit (GEO), or the libration points of the Earth-Moon system. With the transcendence of terrestrial gravity, manned flights to the planets – particularly to Mars – fall within the reach of state-of-the-art propulsion engineering.

More than 15 years have passed since manned Mars Missions (MMMs) were seriously considered by the National Aeronautics and Space Administration (NASA). In that period, the space program has changed dramatically, and space technology has made significant advances. At a time when long term goals are being critically reexamined, it is appropriate to review the issues associated with Mars missions in the context of contemporary technology.

This report summarizes the discussions of the Working Group, based in large part on working papers, which will be published separately. These papers cover a broad range of subjects which need to be addressed in the formulation of such a formidable enterprise as a manned Mars program. Although the study was intended to be a limited reassessment of work initially done over ten years ago, new insights were gained this time through the interplay of the diverse backgrounds of the participants, some of whom had not considered MMMs previously. In addition, new perspectives arose from recent advances in space systems and technology, including the planned SS, Earth-to-orbit (ETO) launch vehicles, and orbit-to-orbit (OTO) vehicles. Still, all participants recognize that many unanswered questions remain and that this work is subject to considerable refinement. Much of the information is in the form of general estimates rather than detailed breakdowns. Other options could be developed, and results could be

more completely integrated. Consequently, the value of this report may be as a basis for elaboration of basic concepts.

RATIONALE FOR GOING TO MARS

An opportunity to conduct the first manned visits and to establish the first settlement on another planet in the solar system is within the grasp of humans on Earth. Initiation of this historic enterprise will require a national commitment.

It is believed that most Americans would find it unacceptable for political, economic, scientific, or intellectual reasons for some other nation to dominate this effort. Politically, U.S. leadership would insure a stable and open program with a wide variety of international participants. Economically, the development of the technology and the space operations base necessary for these missions would bring new commercial opportunities to Americans in a growing space-oriented enterprise. Scientifically, leadership in planetary and space sciences brings benefits with better understanding of the planetary processes (atmospheres, oceans, tectonics, and the origin of life) on other planets as well as on Earth. Intellectually, "going to Mars" is an endeavor that can captivate and motivate a generation of young people from throughout the world, just as the American frontier motivated generations past.

It must also be emphasized that the potential for international cooperation on a Mars venture is real and has far-reaching implications. Other nations with similar space capabilities and motivations also envision a prosperous future in space. Sharing the costs and benefits of a Mars program with other nations in a project of this magnitude which has only peaceful objectives could also increase cooperation and decrease antagonism on other issues.

SCIENTIFIC OBJECTIVES OF MARS MISSIONS

Past unmanned Mars missions have studied the geological, geophysical, and climatological state of that planet and have addressed the

question of whether life has existed or currently exists on Mars. Considerable information is available from these efforts, which include Mariner 4 and 9 flybys and the Viking I and II missions as well as Earthbound telescopic observations. To date, the U.S. is the only nation to fly a totally successful mission to Mars, although the Soviet Union intends to send an orbiter to investigate Mars and Phobos in 1988. The U.S. currently is developing the Mars Observer, an orbiting remote sensing mission, to fly to Mars in the late 1980's. Other orbiters to explore the atmospheric and geophysical properties of the planet have also been proposed. The U.S. planetary exploration program has also intensively studied the possibility of sending a mission to Mars that could collect surface rocks and soil and return them to Earth for analysis.

Mars is best studied by comparing it to Earth. Mars has sustained volcanic activity that may continue to this day, but it does not exhibit the plate tectonic activity shown by Earth. Its atmosphere is carbon dioxide-rich rather than oxygen-rich. Viking was unable to discover evidence of existing life and demonstrated that the current surface environments at the landing sites are quite hostile to life as known on Earth. On the other hand, Mariner and Viking data show extensive fluid-cut channels which suggest that Mars was wetter in the past than it is now, and that it may have been more hospitable to life. These limited views have excited people with the possibility that extended habitation on Mars could be feasible, that eventually self-sufficient colonies could be maintained, and that there may still be special local environments on Mars that support life.

It is unlikely that any of the major scientific issues will be resolved prior to the first human exploration of the planet. However, unmanned "precursor" missions can provide vital information about Mars and its vicinity that increase the probability of success of the first manned missions. Thus, the decision to go ahead with a manned program would likely change the emphasis of the unmanned probes currently being planned toward resolving crew safety and other operational issues.

Intensive and extended observations made possible by human expeditions will be a major focus of early missions. These will continue the exploration of the geological, climatological and biological states and evolution of the planet by

extending the range of action and providing additional tools to the explorers not feasible on unmanned missions. In addition to research in planetary science, some investigations must be planned which are directly related to our ability to sustain and protect people on Mars for long periods of time. These include exploration for readily recoverable supplies of water, development of the capability to monitor solar flare activity from Mars, general engineering geology studies to support surface operations, and study of the performance of closed ecological life support systems.

The extended space flight to and from Mars will provide opportunities for astronomy and life sciences, among other studies, not previously afforded on space missions. These investigations will contribute substantially to the total scientific return of the manned missions.

MARS SURFACE ACTIVITIES

The nature of activities planned for the surface of Mars on any MMM is a major factor in determining the scale of the mission. For missions that land only automated instruments – for example, flybys or Mars moon missions – the spacecraft and instrument packages are typically small and self-contained. For missions that land people on the surface, two major requirements must be met – habitation (life support) and surface transportation (mobility). For exploratory missions with short stay-times on the surface, the landing craft itself would probably provide the habitable volume and a short-range (25 km) roving vehicle might be included, similar to the approach of the Apollo lunar missions.

For a permanent outpost that can sustain people for years at a time, habitations, power supplies, and life support systems will be more complex. For example, in initial visits, the surface transportation system will provide for local investigations of the landing area. At a Mars outpost, more extensive exploration will be permitted by the use of long range pressurized mobility systems. Eventually, airplanes that can fly in the thin Martian atmosphere may be used for reconnaissance purposes.

At a relatively early time in a permanent base program, the use of indigenous Mars resources for support of the base will be tested intensively and

then integrated into the development of the infrastructure. Although initial habitats will undoubtedly be taken entirely from Earth, they may eventually be constructed in part or entirely of Martian material. To reduce the need for base resupply, a life support system will be needed which has a high degree of closure, makes use of Mars atmospheric constituents, and may eventually use Mars soil for agriculture. Propellants manufactured from the atmosphere or surface materials will reduce or eliminate the need to bring rocket propellants from Earth. Tunneling may be used to protect the long term habitation and work space which must be shielded from energetic radiation penetrating the thin atmosphere. These concepts and others will add to the capability of the base for self-sufficiency in some of the basic elements necessary for planetary living.

MISSION CONCEPTS

Depending on the motivation for undertaking Mars missions, different classes of missions, or scenarios, can be developed. If people are flown to Mars and back without landing or even orbiting the planet, in order to demonstrate some aspects of technology or to get there first, a "flyby" mission scenario can be developed which requires a minimum investment, but has small perceived return. Most participants in this study would not consider such a Mars strategy desirable, because of the limited scientific and technological payoff compared to the cost and risk. With a little more effort, the benefits might be significantly enhanced.

For expeditions to Mars that carry large crews and are equipped to intensively study Mars orbital space, its satellites Phobos and Deimos, and the surface of Mars, two somewhat different scenarios are considered. These scenarios, based on the opportunities allowed by efficient orbital mechanics techniques, are called conjunction-class and opposition-class missions. The opposition-class missions require about two years total mission duration and allow stays at Mars of about 60 days, but require relatively more energy and mass in LEO at the start of the mission. Conjunction-class missions require about three years, allow a little over a year at Mars, and require less propellant than the opposition-class missions. Both classes

of missions might be useful in a manned Mars program, the shorter-duration type for early missions or for unmanned cargo missions, and the longer-duration type for more extensive surface exploration and base buildup activities.

It was generally agreed by the working group that the exploration of Mars will require multiple flights and that one of the objectives of a manned Mars program should be the establishment of a permanent scientific base, or "outpost," on Mars. Planning and designing for an initial mission should not be so austere or unique that follow-on mission evolution or overall program benefits would be impacted significantly. A comprehensive and efficient overall program should stress the development of the infrastructure in space to provide routine travel to and from Mars (as well as to other in the solar system) and the technology for the Mars base. Technology developments such as high performance propulsion systems, the development of lunar, Phobos/Deimos, or Mars resources for propellants and life support, the utilization of permanent Earth-Mars SSs in repetitive transfer orbits or libration points, and expanded Mars surface infrastructure concepts have been or will be considered. Many interesting technological developments, which are qualitatively different than those required for short duration space flight, are emphasized in this report.

TRANSPORTATION TRADES AND OPTIONS

Once a series of objectives for initial and growth stages of a Mars program are selected, the requirements for the transportation system will be established. This study was primarily focused on transportation systems needed for use between LEO and Mars. Other transportation systems, such as ETO and OTO vehicles, are also needed in a Mars program. Reference versions of such vehicles from other studies were used here. Various vehicles placed in opposition-class or conjunction-class trajectories designed for orbiting or landing missions create many options from launch to recovery. Many of them are described in this report.

Several tradeoffs are considered to be especially important. First, the selection of orbits at Mars and on return to Earth has a strong effect on the initial mass required in LEO – the basic

figure of merit for many trade studies. Higher, more elliptical orbits require less energy and less propellant to achieve but require that capabilities for staging from the planet to the orbiting spacecraft be available. At Mars this could be influenced by a local source of propellant. At Earth, recovering the returned spacecraft with a separate vehicle launched and recovered from the SS could affect the selection.

Another key consideration is aerobraking, in which the spacecraft uses atmospheric braking as it passes through the planetary atmosphere to remove energy. Aerobraking at Mars and Earth can reduce mission performance requirements considerably compared to propulsive braking, and can reduce much of the mission performance requirement differential between opposition and conjunction class missions. However, for some trajectories, aerobraking creates problems of excessive acceleration levels for human crews, uncertainties in the performance of thermal protection systems, and guidance and control reliability at planetary entry.

Because chemical propulsion technologies are mature, substantial performance improvements are not expected. However, non-chemical systems provide increased performance which can be traded against concepts such as aerobraking or in-situ propellant production. The principal non-chemical systems studied in the past have been nuclear thermal and electric propulsion. Electric propulsion systems are efficient but have low thrust and take relatively long times to climb out of a planetary gravitational field. However, they can yield rather short Earth-Mars transit times if launched from the edge of a planetary gravity field, for example from a libration point. Nuclear thermal systems with higher thrust offer a means of improving overall system performance, providing the same performance as an all-propulsive (non-aerobraking) mission with about half of the required propellant mass. The utilization of nuclear stages requires different endpoint trajectories so as to avoid the risk of potential nuclear contamination of Earth or Mars in case of a failed entry, which may add to the development costs. In general, the non-chemical systems are more likely to be beneficial the greater the number of missions intended, because of the extra opportunity provided to recover the development costs.

The production of propellants on the Earth's Moon, on Phobos/Deimos, or on Mars potentially can provide very large performance benefits. If hydrogen can be produced on the Moon, a lunar site may become the favored place to produce both hydrogen and oxygen for cryogenic propellants. Mars, Phobos or Deimos appear to offer the greatest performance advantage if only one propellant depot is developed. Scenarios utilizing non-terrestrial propellant production do not tend to provide cost benefits unless a significant number of missions is undertaken, due to the cost of emplacing and maintaining the production equipment at the remote site. Hybrid systems, for example, a nuclear thermal system utilizing propellants derived from Phobos for the return trip, could provide even better performance than any of the cases studied. No attempt has been made to "stack" technologies in the studies reported here.

Special orbits, such as repetitive Earth-Mars orbits, and special properties of transfers between Earth-Moon, Earth-Sun and Mars-Sun libration points, utilizing lunar and planetary gravity assists, also can influence total mission performance significantly.

SPACE VEHICLE DESIGN

The space vehicle (SV) designed for Mars missions must be sized to the number of crew personnel and the operations intended. For a typical Mars mission, the basic Spacecraft elements are: (1) a Mission Module (MM), which provides the habitable volume during transit to and from Mars and in Martian orbit; (2) the Mars Excursion Module (MEM), which travels between Mars orbit and the surface; (3) scientific equipment operated in transit, in Mars orbit, and on the surface; and (4) the rocket stages required to propel the SV to and from Mars. The need to provide artificial gravity is subject to further research and has considerable impact on vehicle design. For example, if habitats must be deployed on the ends of very long booms which are rotated to provide artificial gravity, aerobrakes may be precluded or retractable booms might be needed to bring the habitats within the aeroshell envelope.

SUBSYSTEM CONSIDERATIONS

Subsystems for Mars missions should be able to evolve naturally from existing space systems and emerging SS and propulsive vehicle technologies. Many of these development areas are enabling and/or could be significant in enhancing the Mars Program, including propulsion, power, closed ecological life support systems, structures, materials, and other areas. One subject worthy of special mention is the area of autonomy of operations. Because of the communications delay time between the Mars elements (SV and/or surface elements) and Earth, and because at some times there can be no direct communication, attention must be paid to making operations essentially autonomous and not dependent on immediate communications with Earth. Many of the technology and subsystem areas will be stretched by a Mars program. Some, such as the extraction and utilization of Mars resources, have not yet been explored in any detail.

LIFE SCIENCES AND LIFE SUPPORT ISSUES

Crew safety and performance on Mars missions provide many of the most difficult constraints on the mission design. The adaptation of the human body to extended durations of weightlessness diminishes its capability to respond when returning to a gravity field. Although the Soviets have flown people in space for over seven months, approximately the duration of some flights to Mars, their ability to perform after such exposure unaided by a ground crew is questionable. Readaptation to the gravity field apparently occurs when it is restored; however, the restoration may be too slow. Also, it is not yet clear that readaptation will occur for more extended weightlessness exposure. However, neither is it clear that artificial gravity is the only solution. Combinations of diet, medication, exercise, and short duration exposure to acceleration regimes may be alternatives. All of these questions need to be addressed in a long term research program studying people in zero gravity.

Medical support for a two to three year mission will provide new challenges and will put constraints on selection, training, and skill mix of the crews. Psychological support of small crews for missions of these durations will need to be

studied thoroughly before embarking on the missions.

The radiation environment of space beyond LEO is hazardous. Solar flares of brief duration can provide fatal radiation doses in the absence of sufficient radiation protection. One option for flare protection is to provide "storm shelters" of minimal, but sufficient volume to hold crew members for periods of about 24 hr during peaks of solar flare activity. Because of communication distances between Earth and Mars, it will be necessary for solar flare monitoring to be performed on board the SV and on the surface of Mars. Cosmic ray protection cannot be provided without extreme amounts of shielding mass; in fact, modest amounts of shielding worsen the effects due to secondary radiation emitted from the shielding. The accumulated dose expected on a three-year mission is about half of the current lifetime limit for workers in industrial radiation jobs. Thus, it appears that this risk may have to be accepted in early Mars missions.

IMPACTS ON THE SPACE INFRASTRUCTURE

Impacts on existing or planned space systems, including the ETO transportation system, the SS, and OTVs, need further study. For a typical scenario in which 545 metric tons of SV weight in LEO is required at the start of the mission, the existing or planned Space Transportation System (STS) capability would be insufficient. At SS altitudes, where the STS can presently deliver about 18 metric tons per mission, approximately 30 flights would be required, ignoring the additional flights which would be needed to restore cryogenic propellants that would boil away during the assembly and fueling phase of the mission. A heavy lift launch system capable of carrying several times the STS load is required for such scenarios.

The SS program is expected to contribute significantly to a manned Mars program. Its technology base, systems designs, and the utilization of its in-orbit operational capability for test beds will be enabling and enhancing. The early phases of assembly of an SV can probably take place at the SS. However, since a typical Mars mission would have a mass on departure from the orbiting SS that is larger than NASA's reference growth SS,

this could stress significantly the capabilities and functions of the SS, suggesting a co-orbiting rather than an attached mode for final phases of assembly activities. The SS also may have to provide temporary quarters for assembly and/or flight crews brought from Earth before departure to Mars, and facilities, including quarantine facilities, for holding the crew and samples when they return. Storage areas and maintenance facilities, including machine shops, also would be desirable.

Orbital Maneuvering Vehicles (OMVs) operating from the SS may be important in providing assistance in assembly and transportation between the SS and the Mars SV if they are co-orbiting. OTV capability appears necessary for the recovery of the crew and modules from elliptical orbit on return from Mars. In some scenarios envisioning the availability of an assembly and launch platform at an Earth-Moon or Sun-Earth libration point, heavy use would be made of OTVs to transport equipment from LEO to the assembly platform, and OTVs could also be used as propulsion stages for the Mars SV.

A lunar base is a possible element of the space infrastructure that could exist at the time MMMs are initiated. Although it is not essential to a manned Mars program, a lunar base might influence the development of a Mars program by providing a source of propellant and radiation shielding, making launch from a libration point

platform feasible. In addition, many of the technologies needed for Mars surface activities might be developed and tested (at least partially) on the Moon, and extended operations in a reduced but not negligible gravity field could be tested at a lunar base. If a Mars program came prior to the existence of a lunar base, technology useful on the Moon likewise might be derived from the Mars program. The potential for mutually common elements and activities of lunar base and Mars programs should be examined further.

COSTS AND SCHEDULES

A preliminary analysis has been made for the cost of an initial mission to Mars in the year 2000, suggesting costs on the order of 30 to 40 billion dollars. This amounts to about half of the cost of the Apollo program which took place when the U.S. Gross National Product (GNP) was one-third as large as it is now. It is concluded that such an initial flight could be accomplished within a NASA budget that grows, along with the historical U.S. GNP growth rate, at 3 percent per year from its current level. Without significant budget growth or international sharing of the project, other MMMs would have to be deferred beyond the year 2000.

2. SCIENCE OBJECTIVES AND OPERATIONS

SCIENCE STRATEGIES

NASA's basic charter for space exploration includes three principal scientific mandates: (1) to determine the origin and evolution of the solar system, (2) to determine the origin and evolution of life, and (3) to clarify the nature of the processes that shape the Earth's terrestrial environment. These goals have been used as templates to devise basic scientific programs that can be carried out by scientists on a sequence of MMMs. In addition, it is known that certain basic science inquiries, such as assaying resources, can have a major impact on the growth rate and operations of a manned Mars outpost. Therefore, science programs have been developed along two tracks — basic science and operational science.

This section is primarily concerned with the extra dimension that the human presence brings to scientific investigation. It is in spontaneous observation, integration, interpretation, and calculated response that people exhibit their ultimate role as explorers. For example, a simple job, such as effectively positioning seismic stations in noise-free and well-coupled environments, involves choosing the optimum specific location in a general vicinity, drilling and carefully backfilling deep holes, and erecting towers so that telemetry will not be disturbed by the landscape. Furthermore, experience has shown that the ability to check out, calibrate, and repair research instruments in situ can make the difference between the success or failure of major costly experiments. In an unexplored environment such as Mars, all this can only be done well by people.

Manned research on Mars will feature activities that require adaptation to new findings. Such activities include field geology observations and sample selection. With a reasonably complete set of instruments for geological and petrological analyses, the crew can provide an initial screening of the samples — or discover unexpected clues in the search for water. These analyses will direct further sampling activities or scientific sorties, and this whole process could be essential to finding and utilizing Martian resources. Furthermore, by pre-identifying unique or anomalous rocks, only the most important specimens will be

brought back to Earth. The science return from Mars missions will be enhanced by providing a basic analysis of a large number of samples from a large number of sites, along with a detailed analysis of specific rocks of special importance.

Many important insights about the chemical precursors of life and the conditions necessary for life to evolve can be obtained by studying the surface of Mars. Some suggest that the surfaces of Earth and Mars had similar environments 4.6 to 3.0 billion years ago when life began to evolve on Earth. Those people concerned with understanding how life evolved must know how a planet's environment has changed with time. This requires a knowledge of the composition of rocks and minerals on and near the surface, the nature and history of the atmosphere and climate, and the status and intensity of different geologic processes. All of these factors will be investigated within a manned Mars scientific program. Should evidence of past or present life be found on Mars, further investigations will become of paramount importance, and subsequent missions will be altered to meet those needs.

Typical one-way transit times for manned missions to Mars are on the order of one year. Astronomical observations during this period will be important to science and can provide the crew with mental challenges. The crew should have on board both long-wavelength and short-wavelength detectors to allow some very fundamental measurements of the heavens in any and all directions, unencumbered by a near-by planet. In addition, a small solar observatory will permit both fundamental and operationally necessary measurements of the Sun's activity to be made.

Some scenarios of manned missions leave a crew of two or more in orbit in a command module around Mars for the duration of the manned landings. This could afford an excellent opportunity to visit and explore the two moons of Mars — Phobos and Deimos. Phobos and Deimos are large "rocks" 21 km and 13 km in diameter, respectively. Several lines of scientific evidence indicate that they may have compositions similar to carbonaceous chondrites — meteorite types that are rich in water and organic compounds. The investigation of Mars' two

satellites could be important operationally as well as scientifically.

And finally, the manned spacecraft missions may be complemented by unmanned spacecraft missions to make some of the more systematic observations and routine measurements. This would involve obtaining global morphological and low-resolution compositional map data, making gravity-field observations, conducting magnetic-field, nuclear particle, and aeronomy measurements, and observing the global weather system. With systematic mapping, many of the landing site and traverse route options could be studied prior to the launch of the first manned mission to Mars. Additionally, synchronous satellites could serve as early-warning solar flare observation platforms and communications links to Earth. By making the routine observations with unmanned spacecraft, the scientific payoff is greater because people are free to engage in the kind of scientific activities for which they are best suited.

A DESCRIPTION OF MARS

Mars, the fourth planet from the Sun after Mercury, Venus, and Earth, has been studied more thoroughly than any other planet except Earth. Spacecraft exploration began in 1964, when Mariner 4 flew by Mars and sent back to Earth several indistinct pictures of a cratered surface. This was followed by two additional U.S. flybys in 1969 and by the Mariner 9 flyby in 1971. The Soviets sent to spacecraft to Mars in 1971 and four additional vehicles in 1974. Then, in the summer of 1976, the Viking project placed two elaborately instrumented vehicles on Mars' surface and left two others in orbit to make global observations.

Mars Atmosphere and Climate

Mars' equatorial radius of 3,390 km is a little over half that of the Earth and close to twice that of the Moon. The axis of rotation is inclined 25 deg to the ecliptic, giving the planet seasons. Because of the relatively high orbital eccentricity (0.097), there is seasonal asymmetry, with summers in the south being shorter and hotter than those in the north.

The atmosphere is composed of 95.3 percent CO₂, 2.7 percent N₂, and 1.6 percent Ar, with

lesser amounts of O₂, CO, H₂O, and noble gases other than argon. It is thin, about 1 percent as dense as that on Earth, and a significant fraction of the CO₂ condenses on the polar caps in winter. This results in atmospheric pressure variations from 7 mb at zero elevation in southern winter to 9 mb at zero elevation in southern summer. Because the atmosphere is thin, temperatures at the surface have wide diurnal and seasonal ranges, varying from as low as 140°K (in winter) on the southern polar cap, to as high as 290°K (at mid-day) in summer in mid-southern latitudes. At no time or place is liquid water stable at the surface; it either evaporates or freezes.

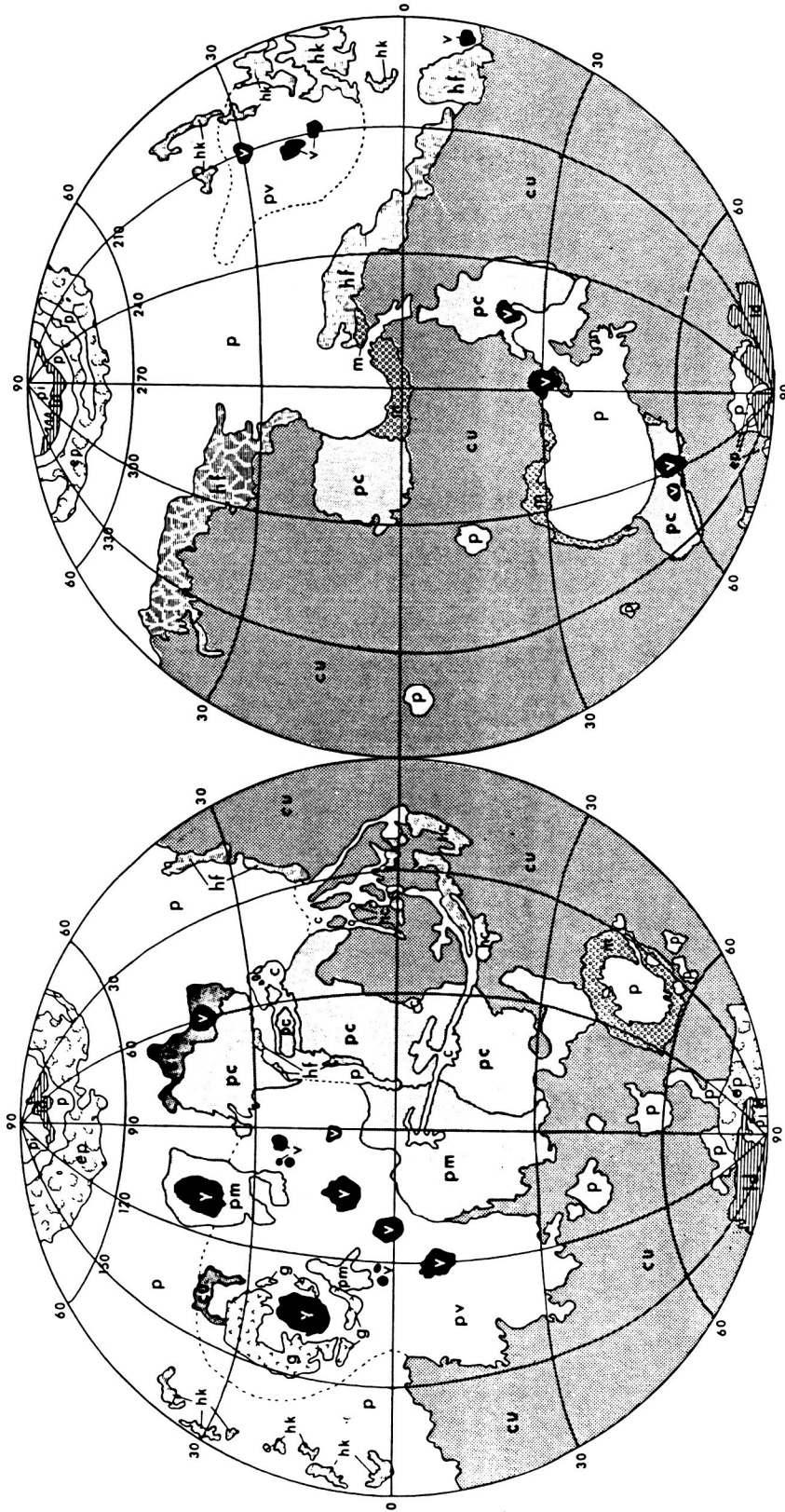
At midsummer in the south, local dust storms are common and a feed-back mechanism between the amount of dust in the atmosphere and the magnitude of the tidal winds can result in a runaway effect, causing most of the planet to become engulfed in gigantic dust storms. The dust raised by the storms generally settles out in about 3 months, but the atmosphere always retains a significant dust component.

General Terrain

Mars is markedly asymmetric in the distribution of its surface features and in its geologic evolution. It can be divided into two hemispheres by a plane dipping 50 deg to the equator and oriented so that it intersects the 50°N latitude parallel at 330°W. This division results in nearly all the most ancient and most densely cratered surfaces falling on the more southerly hemisphere and in most of the lightly cratered plains and large volcanoes falling on the northerly hemisphere (Fig. 2.1). In many parts of the northern hemisphere, however, remnants of old craters protrude through the plains to the surface, which indicates that the old cratered terrain, albeit considerably disrupted, underlies the plains.

Mars possesses a variety of impact craters and large basins. These features are not only interesting for what they can tell about the effects of planetary variables in the impact (e.g., Martian atmospheres and target volatiles), but also provide natural "drill-holes" into the Martian crust that enable a three-dimensional reconstruction of crustal stratigraphy and composition.

Mars has many discrete volcanoes. The most spectacular are large shield volcanoes several



THE MARTIAN SURFACE PLOTTED ON A LAMBERT EQUAL AREA BASE. POLAR UNITS INCLUDE P1 (PERMANENT ICE), LD (LAYERED DEPOSITS), AND EP (ETCHED PLAINS). VOLCANIC UNITS INCLUDE V (VOLCANIC CONSTRUCTS), PV (VOLCANIC PLAINS), PM (MODERATELY CRATERED PLAINS), AND PC (CRATERED PLAINS). MODIFIED UNITS INCLUDE HC

(HUMMOCKY TERRAIN, CHAOTIC), HF (HUMMOCKY TERRAIN, FRET-TED), HK (HUMMOCKY TERRAIN, KNOBBY), C (CHANNEL DEPOSITS), P (PLAINS, UNDIVIDED), AND G (GROOVED TERRAIN). ANCIENT UNITS INCLUDE CU (CRATERED TERRAIN, UNDIVIDED) AND M (MOUNTAINOUS TERRAIN).

Figure 2.1. Geological map of Mars.

hundreds of kilometers across, but numerous smaller volcanoes a few hundred meters across are also present. Most of the large volcanoes are in two broad provinces: Tharsis, centered in the equator at 112°W , and Elysium, centered at 25°N , 214°W . The largest volcano, Olympus Mons, is located at the northwest edge of Tharsis, towering 25 km above the surrounding plains and circled by a peripheral plateau 550 km across; lavas drape over the cliff that defines this plateau and extend far beyond, and thus the true diameter of Olympus Mons is closer to 700 km (Fig. 2.2). By comparison, the largest volcanoes on Earth – those in Hawaii – only grow to 120 km across and 9 km above the ocean floor.

The numerous channels on the surface of Mars present some of the most perplexing problems of Martian geology, because liquid water is unstable at the surface under present conditions.

The channels can be divided into three main types: runoff, fretted, and outflow. Runoff channels resemble terrestrial river valleys and appear to have been formed by the slow erosion of running fluids such as water (Fig. 2.3). Fretted channels are special erosional features which may be accounted for by freeze/thaw processes coupled with scarp recession. Outflow channels start full size, bearing as striking resemblance to the large Pleistocene flood features of eastern Washington, which suggests formation by catastrophic floods.

Some of the youngest features on the planet are at the poles. A sequence of layered deposits at least 102 km thick extends from each pole out to the 80 deg latitude circle. The deposits are almost devoid of impact craters, suggesting either a young age or some efficient self-annealing process. The succession almost certainly records variations in aeolian deposition, and hence climates, in the

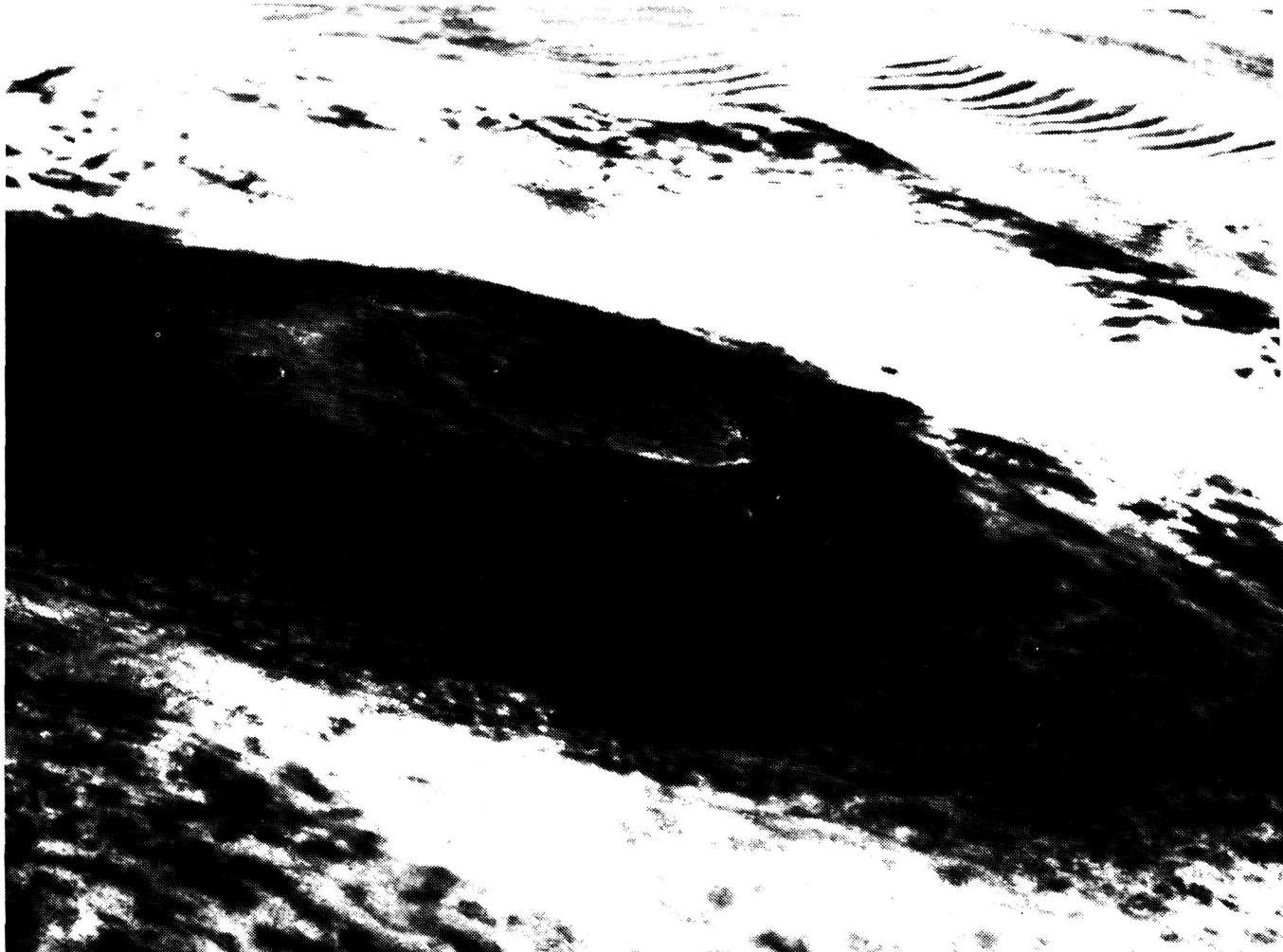


Figure 2.2. Portrayal of the great Martian volcano, Olympus Mons, prepared from photographs taken by Viking 1.

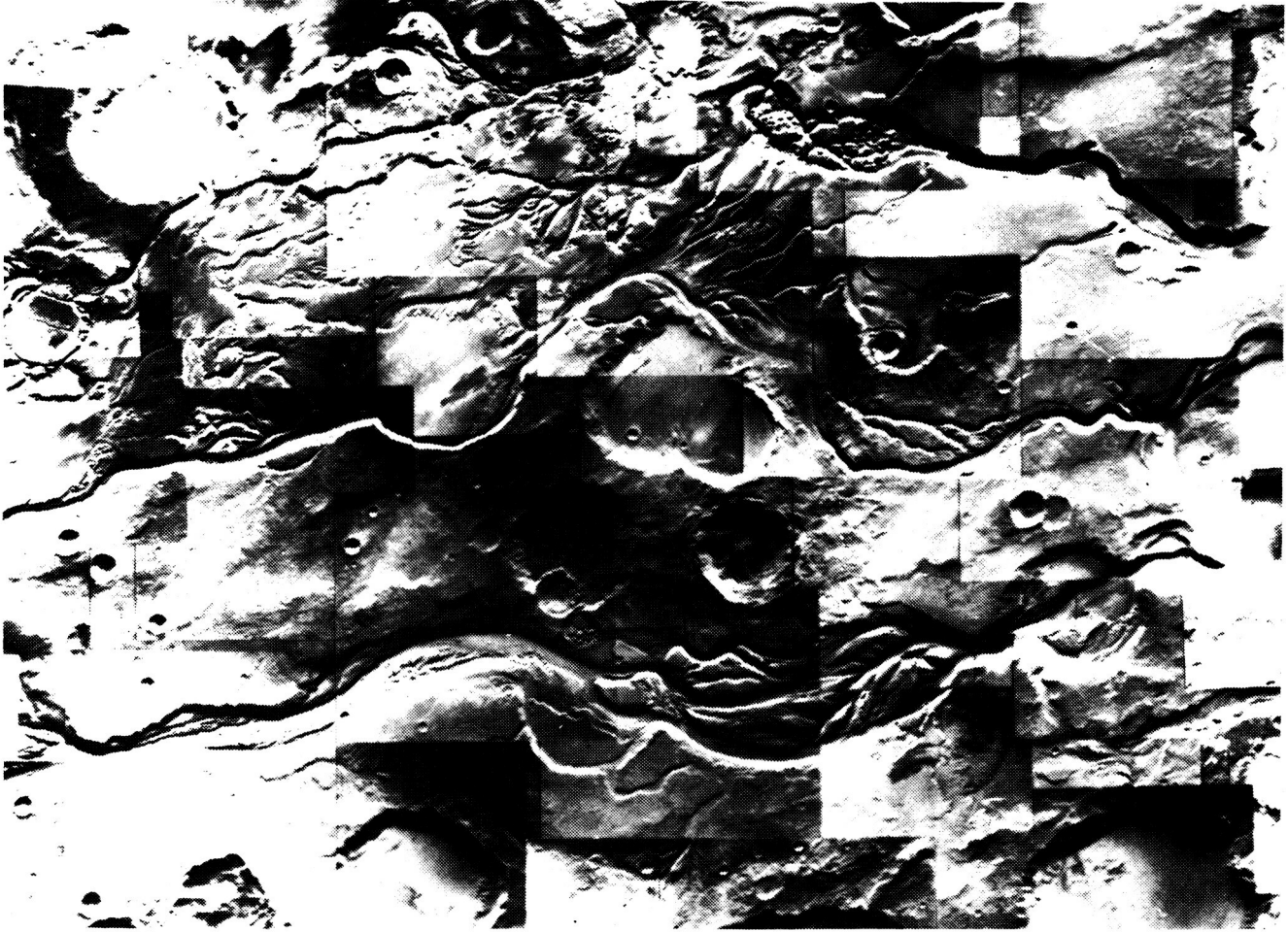


Figure 2.3. Viking mosaic showing features interpreted to be runoff channels resulting from an early history of fluvial activity on the Martian surface.

recent geologic past. In fact, the layering and partial dissection of the deposits suggest that periods of deposition have altered with periods of erosion.

Earth and Mars Comparisons

Mars, like Earth, is a volcanically and tectonically active planet, whose surface has been affected by the action of wind, water, and ice. However, Earth's surface is dynamic: the lithosphere is continually being recycled through subduction and spreading on the ocean floor, and materials within the lithosphere are being altered, transported, and reformed by processes of weathering, erosion, and metamorphism. In contrast, while

there is volcanism on Mars, the products simply accumulate, almost unaltered, at the surface. Fluvial erosion has occurred but has had only a trivial effect on the redistribution of materials across the surface. Weathering takes place extremely slowly because of inefficient removal of the weathered products. Mountains form, as do canyons, basins, and impact craters, but because of the thick, rigid lithosphere and the absence of running water at the surface, they survive almost unchanged, even though they are billions of years old. The result is a spectacular planet on which geologic features of enormous scale and a wide variety of origins and ages are almost perfectly preserved.

MARS SURFACE SCIENCE

Geology

Geologic analysis provides a conceptual framework to guide surface-exploration planning, and to integrate the scientific results into a coherent picture of Martian history, evolution, and resource distribution. Volcanism, tectonism, impacts, erosion and fluid deposition have played varying roles in forming the geologic units observed on Mars. Further field geologic investigations are necessary to understand how these processes operated in detail, individually and in concert, to form the Martian landscape and subsurface structures.

Viking orbiter photographs display various apparently overlapping units that are representative of many periods of Martian history. These units include probable sections of the primordial crust, volcanic flows, ancient sedimentary layers, eolian deposits, and ice rich polar deposits. At least a component of each major period must be studied in detail to collate with other Martian data into a regional and global context.

A few manned landings in carefully selected regions cannot provide all the answers to the history and evolution of a planet as complex as Mars, but an experimental matrix can be formulated that will provide a series of answers at increasing levels of detail. In this way, the geologic history and evolution of Mars ultimately will be deciphered. By understanding the geology of Mars, the processes and history of the Earth will be better understood, potentially including the most intriguing of cosmic questions — how did life begin?

Geochemistry

MMMs allow direct and complex geochemical investigation of historical geologic record in local areas and of units formed by contemporaneous global processes. Especially important is understanding the interaction of the atmosphere and the Mars surface soil. Determining the composition of surface materials, their mineralogy, and their relative ages, is essential to infer the geochemical evolution of Mars. The chemistry and mineralogy of young basalts, for example, provide information

on the composition as well as chemical and isotopic evolution of the planetary interior and its thermal history. Similar data on ancient highland rocks will probably give information about the formation and subsequent modification of the Martian crust. But, above all, detailed chemistry of the rocks yields their ages and places the events in proper sequence that have resulted in the present configuration of the planet.

Investigators on Mars can make measurements of the delicate equilibria among co-existing soils, volatiles (including water), and the atmosphere. Measurements of relative acidity, temperature, pressure, volatile components of soils, oxidation potential, and phase equilibria data on hydrated and clathrated minerals, are best made in aggregate by human explorers who can view these data in the context of their detailed interrelationships.

The interactions of the present atmosphere with the Martian surface will be studied by in-situ measurements and interactive physical experiments. The history of the atmosphere and possible oceanic precursors will be deduced by studying historical geologic materials. Samples recovered by drilling will be especially valuable for these studies. Isotopic measurements of volatiles in ancient geologic materials will provide the data to infer formational and evolutionary processes of the Martian atmosphere and potentially how those processes related to early Martian life.

Geophysics

Geophysical investigations on Mars will closely parallel similar observations that are performed on the Earth. These investigations will include: seismic (both passive and active), heat flow, electric and magnetic fields (including active electromagnetic sounding), paleomagnetic imprints, and gravity measurements. The presence of investigators on Mars will enhance these scientific activities by allowing precise instrument set-up procedures, real time adjustment of their operating parameters, and repair of failed instruments.

Geophysical investigations will help to determine the interior structure of Mars. Measurements of heat flow will place limits on the amounts of radionuclides within Mars as well as place limits on models for its thermal history. Gravity measurements will answer questions about variations in

sub-surface density distributions and will be used in the interpretation of sub-surface structures as well as surface features. Electric and magnetic field measurements will place constraints on any internally generated Martian magnetic field, its time variations and its relation to any fields induced by the solar wind. These measurements will be important for studies of the Martian deep interior, crustal structure, and the potential for the survival of ancient life forms. The response of the Martian surface to artificially induced electric fields will be important for investigating the shallow structure of the crust and, most importantly, for locating sub-surface deposits of ice. The passive seismic experiment will monitor naturally occurring Marsquakes and will be used to establish boundaries of the Martian core, mantle, and crust. Combined with the other surface geophysical observations and orbital gravity observations, these investigations will allow a thorough understanding of the large scale structure of the Martian interior. The active seismic experiments will provide data on density variations in the near surface regions, layering, regolith thickness, sub-surface ice deposits and geologic structures. Long-term monitoring of natural seismic activity by carefully emplaced instruments, including induced free oscillations, will gradually define the internal structure of Mars, the relations between crust and mantle and, potentially, the existence of atmospheric gravity waves.

Atmospheric Science

Among the planets, the Martian atmosphere is most similar to Earth's (Fig. 2.4). Although the Mars atmosphere is much less massive than Earth's atmosphere, it has an underlying solid silicate-dominated surface, similar chemical elements and compounds, a nearly identical rotation rate, and solar energy input that varies with latitude and season. On the other hand, Mars has no modern oceans or vegetation, far fewer clouds, and more widespread dust storms. The similarities suggest that much can be learned about the terrestrial atmosphere by studying the Martian atmosphere. Understanding the differences will require realistic modeling of these atmospheres to simulate the somewhat different dynamical regimes.

Orbital imaging of cloud motions over a long time period will provide global information on the

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Figure 2.4. Viking picture of Mars showing a thin atmosphere in the distance, with cratered terrain and lava basin in the foreground.

bulk motion and temperatures of the atmosphere. Selectively positioned surface instrumentation will provide local pressure and vertical profile of temperature, wind velocities, and composition. These observations will help to determine the mean state of the Martian atmosphere, its seasonal variations, the nature of the interactions between the atmosphere, surface topography and the ice caps, as well as the origin and evolution of dust storms. In addition to these, and other basic scientific questions, the atmospheric observations will also be needed for day-to-day human operations on the Martian surface. The onset of dust storms and the possible presence of strong wind shears must be accounted for in planning traverses and spacecraft launches and landings.

Because the modern atmosphere, and any ancient atmospheric components trapped in the polar ice or other local situations, may contain a product of ancient biological activity, atmospheric studies will be a fundamental science priority for early missions to Mars.

Water

A major objective of a manned mission to Mars will be to determine how much water the planet has and where it is now located. The total water inventory provides clues to the planet's thermal history, the history of the atmosphere, possibly its impact history, and the amount of volatiles incorporated into the planet during its formation. Knowledge of the present location of this water is, of course, essential for permanent human habitation of the planet.

The atmosphere currently contains only minute amounts of water but there is strong geologic evidence that water is abundant in the ground as ice near the surface and as liquid at greater depths. The near surface distribution of water probably depends strongly on latitude. The near-surface materials at latitudes less than 30 deg may contain very little water ice because at these latitudes water is unstable and will tend to sublime and diffuse into the atmosphere. Water or water ice may, however, be present anywhere at depths in excess of a few hundred meters. At latitudes higher than 30 deg, water ice will probably be found at depths of a few tens of centimeters. Liquid water could occur at depths in excess of 1 to 2 km.

To assess the amount of water on the planet, the amount present in each of the various reservoirs must be estimated. The major suspected reservoirs are the permafrost zone, the ground-water system below the permafrost, the polar layered deposits, the permanent polar cap, and hydrated minerals in the regolith and in rocks. Theoretical considerations and observations suggest that the near surface is ice-free at latitudes less than 30 deg. This could be confirmed by drilling and performing seismic and electromagnetic sounding. At high latitudes, where ice is expected, similar techniques could be used for determining the fraction of ice in the permafrost zone and the depth of the base of the permafrost. The porosity and water content of deep rocks might also be

assessed by examination of impact ejecta excavated from these depths. The inventory at the poles is readily determined by direct sampling of the layered deposits and the permanent ice cap and seismic surveys to determine their thicknesses. The fraction of bound water in the regolith and other rocks can be measured directly from samples and estimated globally by geological extrapolation. The main uncertainties in assessing the amount of water tied up in these minerals will be in measuring the proportions of different components such as clay-rich regolith, hydrous sedimentary rocks, and altered or unaltered igneous rocks. This could be determined by direct examination where sections are exposed as in canyon walls, deep drilling and by various geophysical techniques.

Other Resources

The Martian atmosphere, regolith, polar caps, igneous rocks, and its moons can provide materials to improve performance, increase reliability, and expand opportunities for Martian exploration and settlement. Existing technologies can be adapted to provide useful production rates for nominal plant masses and energies. The most likely early uses of Martian materials are: (1) propellants obtained by decomposing CO_2 collected from the atmosphere or electrolyzing water from the soil (water or hydrocarbons may also be extracted from Phobos and Deimos); (2) radiation shielding with excavated soil or crushed rock; (3) structural materials, such as iron metal from carbon reduction of iron oxide; and (4) breathable air, which can be produced from the Mars atmosphere by refrigerating Martian air to remove CO_2 and then catalytically separating out O_2 . Buffer gas for a breathing mixture such as N_2 or a nitrogen-argon mixture can also be produced from Martian air.

The global distribution of the potential resources is largely unknown. Before Mars resource utilization becomes feasible for products other than those derived from the atmospheres, additional data are required. Outside of the remnant polar caps which are water ice and probably accessible, current understanding of the location of liquid water and water ice on Mars and the moons is meager, as discussed in the previous section. Understanding of the clay, carbonate and

hydrous constituents of Martian rocks and soil and the moons is also poor. Before Mars resource utilization becomes feasible for products other than those derived from the atmosphere, additional data are required. Analysis of selected samples of Martian rock and soil is necessary to define the resource availability and economics of Mars. Orbital remote sensing could define the global distribution of key rocks and minerals and the distribution of ice. These could be done on precursor automated missions or on early manned missions.

Search for Life

Understanding the potential for past, present, and future life on Mars is the major scientific question for the Mars biology analysis program. Viking experiments showed that, at present, life probably does not exist on the surface of Mars (Fig. 2.5). Furthermore, conditions there are harsh and unfavorable to life as we know it. If life is present on Mars, it is most likely hidden in protected environments where conditions are more favorable.

The requirements of biology profoundly affect plans for a manned Mars mission. If Mars has not already been contaminated by unmanned probes, it could be locally contaminated by Earth life forms (e.g., spores, bacteria, viruses, etc.)

when humans land on Mars. Since this is inescapable, steps must be considered prior to human landing on Mars to ensure that humans will not endanger the survival or identification of Martian species. Once humans land, the search for extant and extinct life forms will be an important objective. Life is unique because it is so diverse that it can only be defined in terms of a set of attributes, rather than as a physical or chemical entity. Thus, human intelligence and the ability to make on-site decisions could be critical for the recognition of present or past Martian life forms. Furthermore, scientists on Mars with simple equipment have the greatest flexibility in searching for Martian life. It will be easy to look under rocks and in crevices for protected Martian environments. Less simple will be subsurface examination. Scientists can search for possible biological oases including areas of higher atmospheric pressure and possible liquid water. If no indigenous life is found on Mars, the potential exists for purposely introducing Earth life on the planet. By studying the adaptive strategies of terrestrial organisms, perhaps one could engineer the planet for more comfortable human habitation.

Paleontology

While present Martian surface conditions provide little opportunity for indigenous life,

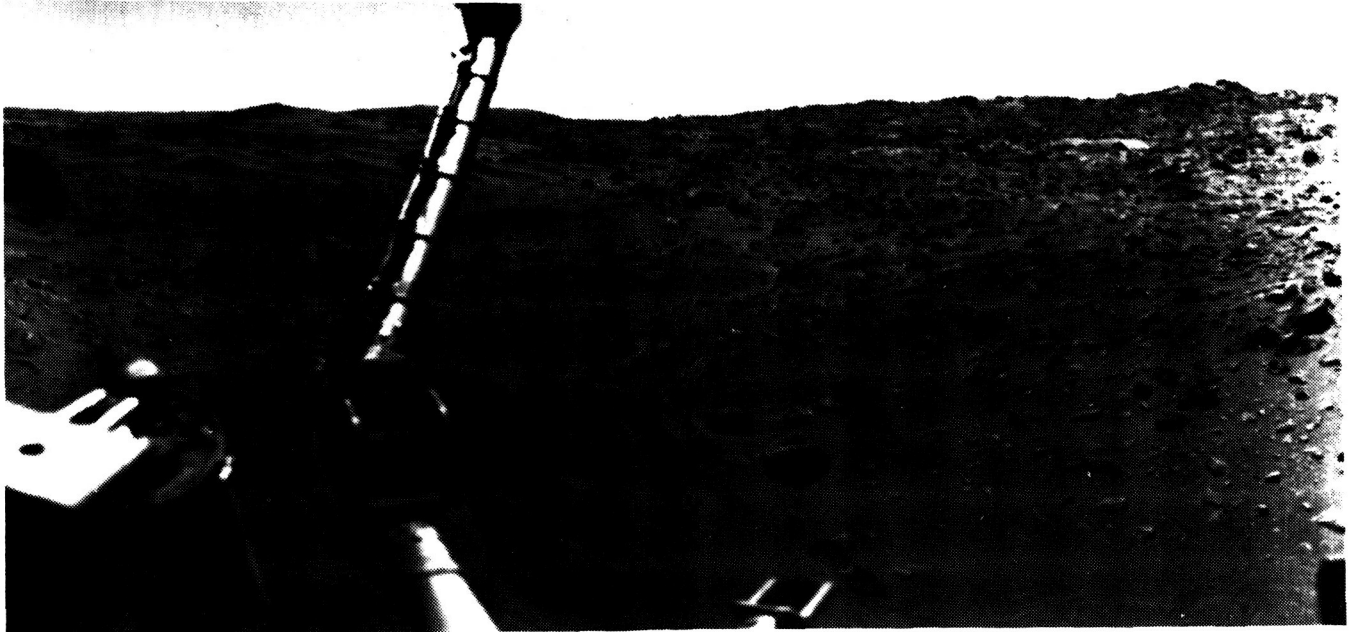


Figure 2.5. Viking spacecraft gathering Martian samples to test for signs of life.

geologic and climatologic evidence suggests that conditions early in the planet's history were far more hospitable. The presence of sinuous channels indicate that liquid water was once readily available. The isotropic composition of the atmosphere suggests that it was once considerably denser, perhaps as high as 3 bars. This thick atmosphere would have provided considerably more protection from ultra-violet radiation than the present one, and the enhanced greenhouse effect would have made the surface of Mars warmer. During this early era, probably from 4.5 to 3 billion years ago, conditions on Mars and Earth may have been very similar.

Life appears to have started on Earth prior to 3.8 billion years ago since the geologic record from that time includes fossil life forms as well as banded iron formations and some carbonate rocks which are believed to have required organic intervention for their formation. It is not unreasonable therefore that life could have evolved on Mars when conditions were similar. These life forms were probably very primitive, as was the case on Earth. The search for evidence of ancient life should concentrate on sediments from water-rich environments. Such sediments may be common. Lakes probably occurred, if not on an oceanic scale then at least at the termination of large flood features, within the canyons, and in local foci of convergent drainage systems. Those lakes could

have been stable early in Mars' history and would have provided a safe haven for development of life as did the Earth's proto-oceans. Information derived from the study of now extinct life forms on Mars would be of extreme importance in understanding the origin and early evolution of life in the solar system.

MARS ORBIT ACTIVITIES

As with the Moon, the first missions to Mars may leave some of the crew in orbit around the planet while the rest proceed to a surface landing. The crew members in orbit could also play an important scientific role.

Phobos and Deimos

Asteroids are potentially a significant extra-terrestrial source of materials. Retrieval of Earth-crossing asteroids has been suggested to provide resources of strategic metals, carbon, nitrogen, and possibly water and its constituents, oxygen and hydrogen. Based on spectral characteristics observed from Earth, both of the Martian moons appear to be representatives of the most common class of asteroids (C Class), which are interpreted as carbonaceous chondrites (Fig. 2.6). A series of MMMs would provide opportunities to (1) closely

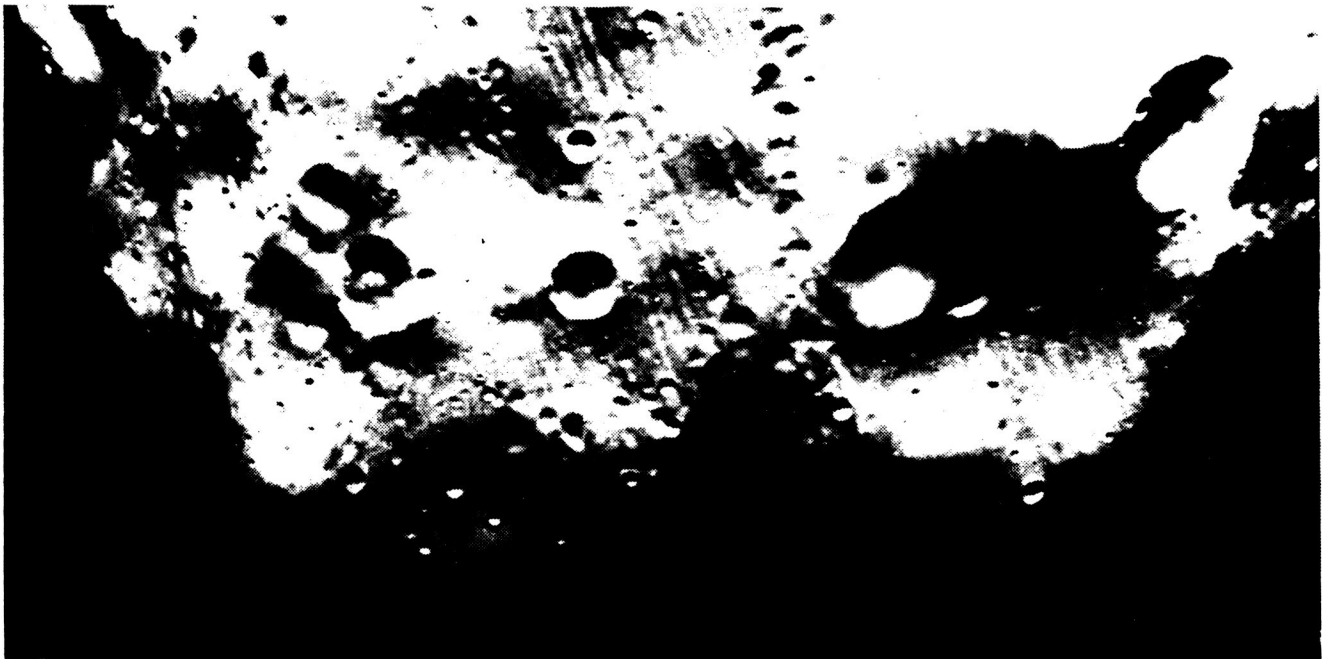


Figure 2.6. Viking photograph of Phobos, the largest moon of Mars.

examine these objects to better characterize their chemistry and structure, and (2) determine their potential as resources for support of Mars missions or lunar base activities.

The objectives at the Martian moons will be to determine their chemistry and mineralogy, their internal structure, and the thickness and nature of their regolith. These objectives can be accomplished by the following approaches: (1) determination of the satellite figure in order to interpret gravity and seismic data (this may be possible by a combination of photographic and laser ranging techniques); (2) measurements of absolute gravity at a few dozen locations; (3) performance of active seismic experiments to determine the internal structure of these satellites; and (4) acquisition of samples at several surface sites and of cores from drill holes for precise chemical and mineral analysis.

Weather

The most important on-orbit weather observations are global synoptic imaging of cloud motions with high time-resolution, which could best be done by unmanned spacecraft in Martian synchronous orbit. But there are other weather observations that could benefit from the presence of an on-site or in-orbit human observer. These would involve high resolution observations of localized, time-variable phenomena where the human observer would be required to identify the phenomena and control the observing program in real-time in response to the specific nature of the phenomena. These could include observations of the generation, movement, and decay of local and global duststorms, fogs, storms, fronts, weather systems, and individual clouds.

Site Selection

Scientific desirability will be one of a variety of factors considered in site selection. Other factors include safety, energy requirements, resource availability, communication needs, and local trafficability. During early missions it will be necessary to traverse and sample terrain offering the widest possible diversity. Later missions may focus on more specific problems, such as the nature and origin of the polar layered deposits,

once the main scientific questions have been defined.

To assess the relative merits of different sites, consideration will include: (1) global geologic maps based on remote sensing data and any data previously acquired from the surface; (2) global maps of chemical and mineralogical variability; (3) trafficability maps showing surface roughness and obstacles at the scale of the rover; (4) radar reflectivity and thermal inertia maps to indicate variations in properties of the near surface material and possible presence of water; and (5) radar sounding profiles to indicate regolith thickness and other sub-surface structures, including those caused by ground-ice.

These scientific planning observations would allow the science community to refine its understanding of Mars and then identify those areas that would require detailed on-site human investigation to further enhance present knowledge of that world. The on-orbit observations would provide the knowledge needed to attempt landings at future sites.

IN-TRANSIT ACTIVITIES

The crew will have a unique opportunity to make scientific investigations while they are traveling from Earth to Mars and return. Two obvious research endeavors will be astronomy and solar physics.

Astronomy

The MMM vehicle will serve as an excellent and unique platform from which advanced astronomical observations can be performed in transit. Fundamentally new data on the universe can be gathered. Three experiments which either operate on a long Earth-Mars baseline or take advantage of interplanetary space serve as examples.

First, a 50-cm aperture optical ultraviolet-infrared telescope, similar in design to the Hubble Space Telescope (HST), can more than triple the volume of stars with accurately measured distances. Such a telescope can: (1) accurately measure the distance of stars using stellar parallax techniques and thereby provide a firmer foundation for the extragalactic distance scale (i.e., expansion rate of the universe); (2) provide high linear

resolution (possible stereoscopic) views of asteroids; (3) perform deep sky imaging on a background that is nearly 1 astronomical magnitude darker than that near the earth; (4) examine the inflow of the interstellar medium into the solar system by studying backscattered solar Lyman-alpha emission; and (5) aid navigation.

Second, a gamma ray burst detector (or series of detectors deployed along route) will add an important new dimension in understanding the source of these high energy photon emissions. There are no such detectors at present outside the Earth's orbit. By comparing the times of arrival of a burst at different detectors spread throughout the solar system, one can accurately determine the position of the radiating object. A Mars baseline will increase the position accuracy by a factor of 2 to 10 and, therefore, lead to identification of specific optical objects.

Third, a 10 to 15 m aperture radio telescope on the mission could be used for telemetry of data from the surface to the mother craft, to probe the interplanetary medium plasma, and as an element in a synthetic aperture radio interferometer. Such a Mars-Earth baseline will produce a resolution of 4×10^{-9} arcsec at a wavelength of 1 mm, limited by scattering of the radio waves by the interstellar medium. The corresponding linear resolution is 0.8 km at the distance of the nearest star, 6000 km at the distance of the nearest galaxy (resolving individual stars), and 3×10^{16} km at the distance of the nearest active galaxy (resolving the inner accretion disk near a 10^6 solar mass black hole that powers the galactic activity).

Solar Physics

Solar observations must be obtained as part of the day-to-day operation of a MMM (Fig. 2.7). Energetic particles generated by solar activity present specific risks to the crew of such a mission (See Life Sciences section on radiation exposure). The prediction and warning of threatening activity cannot be performed from Earth because it will face the opposite side of the Sun during much of the mission. A second operational need for solar observations may be for forecasts of solar interference with radio communications between the manned Mars mission and Earth. These two tasks can be conducted with a small solar observatory used during the transit and orbital phases of the

mission. H-alpha and x-ray images of the Sun made several times per hour, together with magnetic field maps, can be used to monitor for the likely occurrence of solar activity and the onset of proton events.

In addition to these operational tasks, this facility can be used for basic scientific studies that will benefit from observations covering more of the surface of the Sun than just the portion facing the Earth. These observations can give a more complete picture of the time evolution of active regions, coronal holes and the solar magnetic field.

PRECURSOR MISSIONS

Despite two decades of Mars exploration by Mariner and Viking Spacecraft, there remain many unanswered questions about Mars that can be answered by unmanned precursor craft. The efficiency of the operation of manned missions and the quality of their science investigations will be enhanced if the data to answer these questions are obtained prior to the manned missions.

The precursor missions will provide important information in three primary areas. First, they will provide the information needed to plan the operations of the manned missions. This will initially involve verification of the safety and trafficability of potential landing sites and traverse routes. They will aid in characterizing details of the environmental factors such as radiation and atmospheric factors as needed to refine the design of manned missions. For example, the present understanding of the vertical structure of the Martian atmosphere and its diurnal variation introduces uncertainties in planning aerobraking maneuvers for manned missions. Precursor missions are needed to obtain this information for pre-mission planning, and additional probes may be needed to obtain updates immediately before the manned mission aerobraking activities.

Second, the precursor missions will provide the information to assist the early science planning of manned missions. This will involve determining the scientific desirability of the selected landing sites and traverse routes. Additionally, these observations will provide data needed to interpret the detailed, but necessarily highly localized, surface observations made by manned missions.

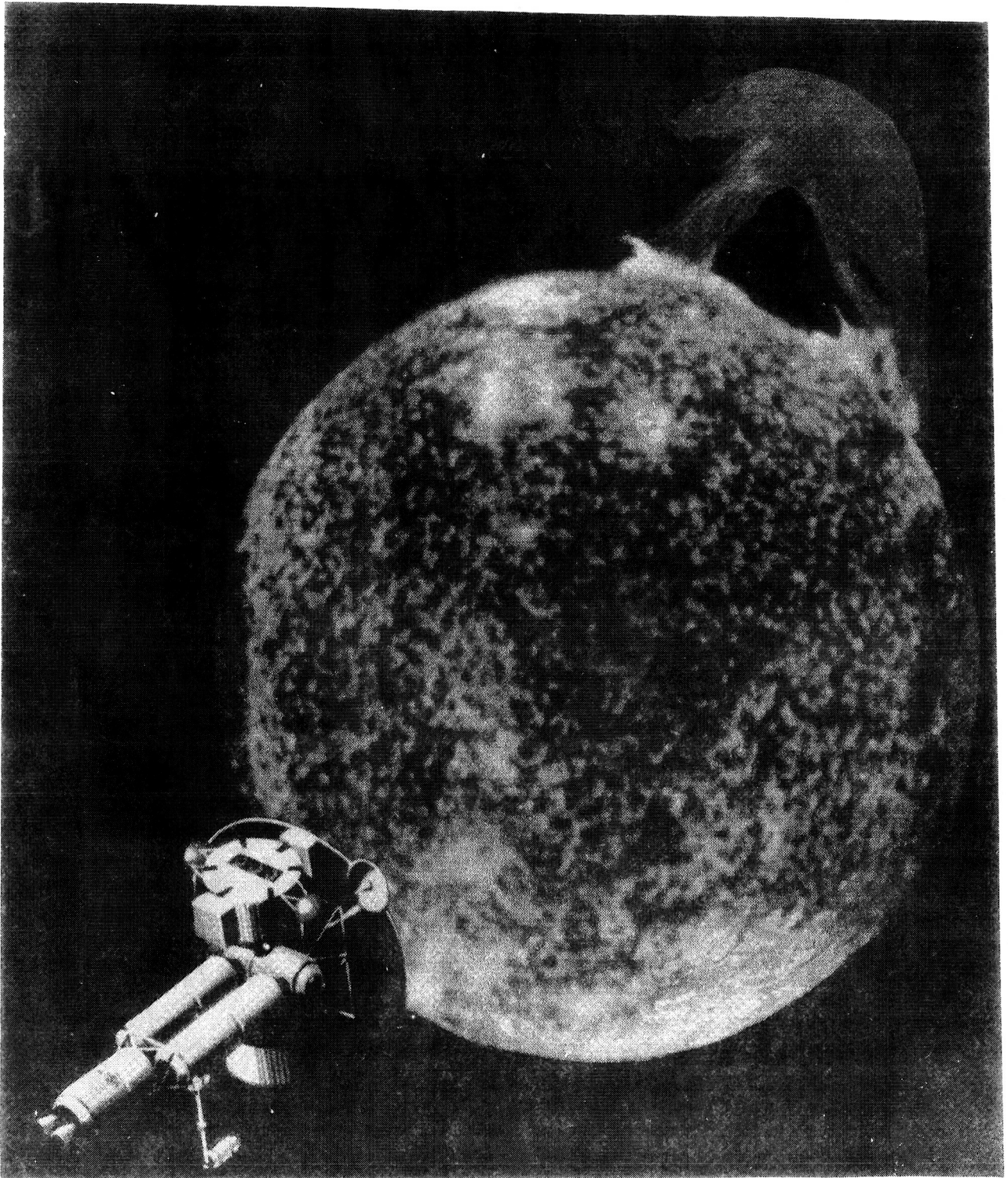


Figure 2.7. Solar physics observations enroute to Mars.

Third, if these spacecraft are still operating during the time frame of the manned missions, then they could provide real-time support for these missions. These activities could include imaging support for the surface operations, synoptic observations of Martian weather systems and communications relays.

Six specific mission types, typically requiring more than one spacecraft, should be considered. They are: (1) Global High Resolution Mapper; (2) Global Synthetic Aperture Radar (SAR) Mapper; (3) Global Geochemical and Climatological; (4) Fields and Particles Environment Mapper; (5) Advanced Aeronomy Observer; and (6) Phobos/Deimos Resources Reconnaissance.

The precursor missions must be started well before the manned missions so that there will be

sufficient time to acquire the data and use it to influence the manned missions.

Sample return missions have been proposed as unmanned missions in the Planetary exploration program. Manned Mars landings can provide better sampling capability; however, if manned missions cannot be mounted in the next 20 years, unmanned sample return missions should be considered to advance man's understanding of the planet. Such missions, by advancing the understanding of Mars petrology, surface soil composition, and rock ages, can significantly clarify science issues and ease operational problems for the subsequent manned missions.

3. MARS SURFACE INFRASTRUCTURE AND ACTIVITIES

In early exploratory missions, the fundamental requirements for life support on the surface of Mars will be met by including the necessary equipment as essential elements of the SV itself, and the range of operational capabilities on the surface will be limited. However, the eventual development of a permanent, more robust "surface infrastructure" is envisioned, consisting of life support systems, transportation, processing, and other elements which will become a Mars outpost (Fig. 3.1). A possible infrastructure is examined in this section. This indicates the type of development feasible, and provides a basis for understanding the characteristics of the space system needed to deliver Mars surface infrastructure elements.

HABITAT STRUCTURES

A permanent shelter that provides space in which the crew can live and work in a shirt-sleeve environment (habitats) must also protect against lethal solar flare radiation and continuous cosmic-ray radiation exposure on the Martian surface. The latter requires substantial shielding, which can be accomplished by burial or emplacement beneath the Mars surface to a depth of 1 to 2 m. For smaller habitat volumes, especially for early missions in multiple landing scenarios, the approach probably will be to land prefabricated modules (e.g., SS modules) that can be moved together for assembly into a base configuration and then covered with Martian soil. This approach implies a soil-moving and module-placing capability using landed equipment (bulldozer, trailer, drag line, crane, etc.). The need for this equipment could possibly be reduced by using explosive trenching and casting techniques to cover the modules. Examples of these long-term habitat concepts are illustrated in Figure 3.1.

Short-term, transportable structures are needed for protection from potentially lethal solar flare radiation storms that may occur while crew members are away from a base. Controlled excavation of a trench using explosives, then driving a rover vehicle with shielding in its floor over the trench to produce a protected volume, can be accomplished within the approximate one-hour warning time, if solid rocket exhaust

jet-piercing technology is used to rapidly produce the holes into which the explosives are placed. For larger facilities, explosive tunneling techniques, well developed for Earth applications, can provide a safe, reliable, and efficient construction method. Inflatable or collapsible structures can be erected within the tunnels to provide pressurized and conditioned living space.

LIFE SUPPORT

An environmental control/life support system (ECLSS) is vital for any manned activity on the Martian surface. Table 3.1 summarizes the functions and equipment required for an ECLSS, and Table 3.2 lists the average ECLSS design loads. For extended operation, this ECLSS should require minimal replenishment with terrestrial supplies; however, not all the ECLSS loops must be closed since the Mars surface and atmosphere can provide useful materials, particularly oxygen, water and carbon dioxide (for plant growth). A typical system for a permanent Mars base would consist of water, oxygen and CO₂ extracted from the atmosphere or soil, enclosures (greenhouses) in which plants could be grown, and an advanced ECLSS. The only resupplies necessary might be supplemental food, nitrogen, argon, or some other pressure-maintaining gas (eventually, these could be obtained from the Martian atmosphere), and equipment repair or refurbishment items. Although much development must be done to accurately size the ECLSS that is needed for a Mars base (see Section 4c), mass, volume, and power requirements are estimated in Table 3.6.

TRANSPORTATION

Surface transportation vehicles are essential to transport both men and scientific instrumentation to sites not within walking distance of the landing craft or base, as well as to expedite the return of samples. Since a number of missions are envisioned, with explorations ranging from within a kilometer of the landing site to as far as the nearest pole, the optimum configurations and technologies are not obvious.



Figure 3.1. Artist's concept of a Manned Mars Scientific Outpost.

TABLE 3.1. ECLSS SYSTEM FUNCTIONS

<u>ECLSS Function</u>	<u>Major Equipment</u>
Atmospheric pressure and composition control <ul style="list-style-type: none"> - Total and partial pressure control and monitoring - Fire detection and suppression 	Pressure regulation Portable oxygen system Smoke/fire detectors Fire suppression system
Module temperature and humidity control	Dehumidification Ventilation fans Air cooling heat exchangers
Atmosphere revitalization <ul style="list-style-type: none"> - CO₂ control/removal/reduction - O₂ and N₂ makeup - Trace gas monitoring and control 	CO ₂ removal and collection CO ₂ reduction Contamination control Odor control Atmosphere monitoring Oxygen generation Emergency O ₂ and N ₂ storage
Water management <ul style="list-style-type: none"> - Waste water collection/processing - Water quality monitoring - Storage and distribution of recovered water 	Evaporation purification Water quality monitoring Water storage
Waste management <ul style="list-style-type: none"> - Collect/process urine - Collect/store fecal matter 	Waste collection and storage Emergency waste collection Hot/cold water supply
Extravehicular activity (EVA) support <ul style="list-style-type: none"> - Provide expendables/support to EMU and MMU - Provide life support services to airlock/hyperbaric facility 	Suits and backpacks Recharge stations Air lock support

The most likely candidates for Mars transport vehicles are: (1) a direct derivative of the lunar EVA rover; (2) an advanced-design, long-range EVA rover equipped with a portable, inflatable life-support tent; (3) a large, self-contained mobile lab capable of sustaining a shirt-sleeve environment; (4) rocket-propelled flying vehicles; and (5) a remotely-piloted, unmanned long-range airplane.

Wheeled vehicles have the largest data base and are best understood. Although they are probably the lightest options, a simple wheeled vehicle has reduced capability in terms of climbing obstacles and operating on soft soils. Obstacle

climbing capability can be enhanced by segmented flexible chassis and/or active suspension.

Tracked vehicles are usually represented as using the flexible loop wheel rather than the much heavier conventional tracks seen on tanks and other heavy machinery. While heavier than conventional wheels, these devices offer lower load per unit area which may be advantageous in soft soil. The track length offers better capability in crossing ground openings, and, with proper suspension design, substantial obstacle climbing ability may be achieved.

TABLE 3.2. ECLSS AVERAGE DESIGN LOADS

Metabolic O ₂	0.83 kg/man day
Leakage Air	2.27 kg/day total
EVA O ₂	0.55 kg/8 hr EVA
EVA CO ₂	0.67 kg/8 hr EVA
Metabolic CO ₂	1.00 kg/man day
Drink H ₂ O	1.86 kg/man day
Food preparation H ₂ O	0.72 kg/man day
Metabolic H ₂ O production	0.35 kg/man day
Clothing wash H ₂ O	12.47 kg/man day
Handwash H ₂ O	1.81 kg/man day
Shower H ₂ O	3.63 kg/man day
EVA H ₂ O	4.39 kg/8 hr EVA
Perspiration and respiration H ₂ O	1.82 kg/man day
Urinal flush H ₂ O	0.49 kg/man day
Urine H ₂ O	1.50 kg/man day
Food solids	0.73 kg/man day
Food H ₂ O	0.45 kg/man day
Food packaging	0.45 kg/man day
Urine solids	0.06 kg/man day
Fecal solids	0.03 kg/man day
Sweat solids	0.02 kg/man day
EVA Wastewater	0.91 kg/8 hr EVA
Charcoal required	0.06 kg/man day
Metabolic sensible heat	2.05 kW-hr./man day
Hygiene Latent H ₂ O	0.44 kg/man day
Food preparation latent H ₂ O	0.03 kg/man day
Wash H ₂ O solids	0.44 percent
Shower/hand wash H ₂ O solids	0.12 percent
Air lock gas loss	0.60 kg/use
Trash	0.82 kg/man day
Trash volume	0.0028 m ³ /man day

Walking vehicles are a currently developing technology. For certain situations, e.g., very irregular terrain, walkers offer substantial advantages. Walkers, usually hexapodal, offer excellent stability in traversing irregularities and in climbing obstacles. Disadvantages include the complexity of control involved in placement, force sensing for each leg, and the inherent inefficiency of oscillating versus rotary motion. Because of this, walkers are less efficient on hard, smooth surfaces. However, in soft terrain the walker may be more efficient since it compresses less of the surface material. Examples of vehicles using the mobility concepts discussed above are shown in Figure 3.1.

Surface vehicle power conversion studies indicate that conventional or alkali metal conversion of radioisotope heat to electricity using Radioisotope Thermoelectric Generators (RTGs) is the method of choice for small vehicles. Large manned rovers that have the possibility of periodic refueling may favor H_2/O_2 fuel cells as an appropriate source of motive power. Estimates of mass, volume, and power specifications for the EVA and shirt-sleeve classes of rover vehicle are indicated in Table 3.3.

Rocket propelled flying vehicles, either manned or unmanned, would offer advantages over surface vehicles in extremely rugged terrains. These vehicles could range in size from one-man, EVA platforms to mobile bases; provide range capabilities of a few kilometers to several hundreds or thousands of kilometers; and deliver payloads of a few hundred kilograms to many metric tons. For example, a vehicle patterned after the Apollo Lunar ascent module could carry two astronauts in a shirt-sleeve environment with several metric tons payload over a round trip range of several hundred kilometers. To be widely useful, these rocket propelled vehicles would probably need to be

refueled with locally produced propellants (see in-situ production of propellants discussed below).

The Mars airplane offers particular advantages as an adjunct to MMMs. Operating as an unmanned remotely piloted vehicle (RPV) using guidance and control technologies in current operational use with Earth-bound RPV's, the Mars airplane can: (1) perform medium to high resolution geophysical surveys of large areas using cameras and other remote sensors; (2) deliver (via airdrop or landing) remote weather, seismic, or compositional measuring instruments; and (3) perform detailed atmospheric measurements. The development of landing and take off capability at remote sites would make sample acquisition and return possible. Local airfields could be cleared using a bulldozer (Fig. 3.1). As an engineering/operational tool, the airplane can: (1) survey and provide detailed photographic maps of proposed surface rover routes; (2) function as a communications relay; and (3) deliver supplies to rover crews. Other applications will suggest themselves in practice. Range and payload will vary inversely and depend on whether remote landings are used. Mars airplane characteristics are indicated in Table 3.3.

PROCESSING AND CONSTRUCTION

Significant reductions in Earth launch mass can be achieved by in-situ production of propellants (ISPP) and life support consumables using indigenous resources on Mars. For example, oxygen/methane propellants can be produced from atmospheric CO_2 and water or ground ices. Since ISPP performance, in terms of the ratio of useful mass to system mass, improves as surface stay time increases, the technology is an important element in the infrastructure for a manned Mars outpost.

TABLE 3.3. MARS SURFACE AND AIR VEHICLE CHARACTERISTICS

<u>Vehicle</u>	<u>Mass (kg)</u>	<u>Packaging Volume (M³)</u>	<u>Payload (kg)</u>	<u>Range (km)</u>
EVA Rover	700	15	800	10 - 20
Shirt Sleeve Rover	5000	100	2000	100
Airplane (unmanned)	300	20	40 - 100	1000 - 4000

Table 3.4 summarizes estimates of system masses and power requirements for two types of Mars surface ISPP processor systems. The system masses include all machinery except storage tanks and electric power generators. If electric power generators can be produced that require one kilogram of system mass per watt of electric power, ISPP total system masses would range from 600 kg to 4630 kg. It is possible to define a break-even point where the produced consumable mass equals the ISPP hardware mass.

Construction of habitats, tunneling, and scientific exploration activities will require rock drilling and coring capabilities. These needs imply specialized drill rigs (Fig. 3.1) and ancillary equipment such as air compressors for drilling fluid and refrigerators for environmental storage of geologic samples. Table 3.5 summarizes the mass, volume and power requirements for the equipment.

Integration of Infrastructure Elements Into A Manned Base

Integration of the surface systems into the manned base facility requires a specific mission plan. At this stage of the conceptual analysis of MMMs it is useful to develop several scenarios and investigate their potential advantages and disadvantages. Design of a Mars lander and ultimate Earth orbit mass requirements will depend on the surface infrastructure mass and volumes that need to be landed.

For the purpose of investigating scenarios and evaluating trade-offs, a systems engineering methodology was developed during the study based on a top-down functional decomposition approach. Infrastructure functions were first defined based on specific mission requirements. The subsystems and hardware needed to accomplish the specified functions were then determined and the interrelations among elements specified by rules. Calculation of total masses and other attributes of the integrated surface infrastructure system was automated in order to quickly assess the overall system impacts of evolving mission requirements and increased capabilities (e.g., closed loop ECLSS systems). Table 3.6 is an example of the results of this approach that shows the basic properties of the surface infrastructure of a generic mission scenario. This scenario emphasizes scientific investigation and the establishment of a permanent outpost. The scenario illustrated is not optimized and does not explicitly address questions regarding radiation protection, integrated surface habitation modules, or trade-offs of SS module derivatives versus inflatable or other surface structures. It indicates that the order of magnitude of equipment mass and volume is consistent with the one-way delivery capability of one mission of the type described in Section 4 (Table 4.1).

TABLE 3.4. SUMMARY OF ISPP SYSTEM ESTIMATES

<u>Product</u>	<u>Raw Materials</u>	<u>Production Rate</u>	<u>Est. System Mass</u>	<u>Electrical Power Requirements</u>	<u>Break Even Point</u>
O ₂ , CH ₄	CO ₂ , H ₂ O	20 kg/day	350 kg	3 kW	30 days
O ₂ , CH ₂	CO ₂ , H ₂ O	40 kg/day	700 kg	5.5 kW	30 days
O ₂	CO ₂	10 kg/day	300 kg	3 kW	60 days
O ₂	CO ₂	100 kg/day	1630 kg	30 kW	45 days

TABLE 3.5. ROCK DRILLING AND CORING EQUIPMENT CHARACTERISTICS

<u>Type</u>	<u>Mass (kg)</u>	<u>Packing Volume (M³)</u>	<u>Total Power (kWe)</u>
100 m-deep core drill	1150	125	37
10 m-deep core (mobile) drill	120	15	5
Rotary percussion explosive shot drill	30	8	2
Solid rocket exhaust rapid drill	15	1	—

TABLE 3.6. EXAMPLE MARS SURFACE INFRASTRUCTURE
ELEMENT INTEGRATION

<u>Function</u>	<u>Subsystem</u>	<u>Packing Volume (M³)</u>	<u>Mass (kg)</u>
Life Support	Habitat (includes ECLSS for 4 people)	130	17,200
Greenhouse	Prototype	50	150
Transportation	EVA rover (2-person)	7	700
	Shirt-sleeve rover (2-person)	110	5,000
	Airplane (unmanned)	50	300
Construction	Crane	100	5,000
	Trailer	75	3,000
	Bulldozer	50	5,000
Surface Science	Lab Equipment	15	1,100
	100 m core drill	125	1,150
	10 m core drill	15	120
Power	100 kWe nuclear generator	100	3,000
Manufacturing	ISPP	90	600
Totals		<u>917</u>	<u>42,320</u>

4. MISSION AND SYSTEMS CONCEPTS AND CONFIGURATIONS

The exploration of Mars will require multiple manned and unmanned missions. The utilization of Mars as a science outpost, a resource production site, and a site for colonization experiments requires a significant increase in the quantity and sophistication of space missions beyond that required for exploration. Some of the key, top-level considerations which will determine the nature of missions and SV systems concepts for MMMs are discussed below.

4a. TRANSPORTATION TRADE STUDIES

INTRODUCTION

The analysis of a manned Mars program involves a vast network of system trade studies. There seems to be an almost limitless list of combinations and permutations of configurations, propulsion systems, propellant sources, orbits, transfer trajectories, mission goals, infrastructures, landers, ascent vehicles, etc. The following is a summary of considerations which seem more

important at this time for MMMs. The summary describes MMM opportunities, Mars vicinity transportation issues, impact of aerobraking, impact of extraterrestrial propellant production, impact of advanced propulsion options, and impact of lunar base support. Potential impacts to ETO and OTO vehicles are discussed in Section 6.

MISSION DESCRIPTION AND OPTIONS

Three classes of MMMs are technically feasible near the turn of the 21st century using near-term cryogenic (chemical) propulsion concepts. These are (1) manned Mars "flybys," (2) conjunction class, and (3) opposition class missions (Fig. 4.1). Several of these concepts were examined in detail, based on LH₂/LO₂ propulsion, and sized to near-minimum requirements for brief and impermanent visits to Mars.

A Mars flyby mission can be accomplished with a total mission duration of one year by placing 400 to 800 metric tons of SV and propellant mass into LEO. The mission is spartan and yields only a few minutes of high speed passage

MARS FLYBY FOR 1999 OPPOSITION ONE YEAR MISSION

- 1 EARTH DEPARTURE, APRIL 2, 1999
- 2 MARS PASSAGE, AUGUST 8, 1999
- 3 EARTH ARRIVAL, APRIL 2, 2000

OUTBOUND VENUS SWINGBY 1999 OPPOSITION

- 1 EARTH DEPARTURE, JAN. 26, 1998
- 2 VENUS PASSAGE, JULY 9, 1998
- 3 MARS ARRIVAL, JAN. 16, 1999
- 4 MARS DEPARTURE, MARCH 17, 1999
- 5 EARTH ARRIVAL, NOV. 18, 1999

CONJUNCTION CLASS MISSION 1999 OPPOSITION

- 1 EARTH DEPARTURE, DEC. 17, 1998
- 2 MARS ARRIVAL, SEP. 28, 1999
- 3 MARS DEPARTURE, JAN. 25, 2001
- 4 EARTH ARRIVAL, SEP. 2, 2001

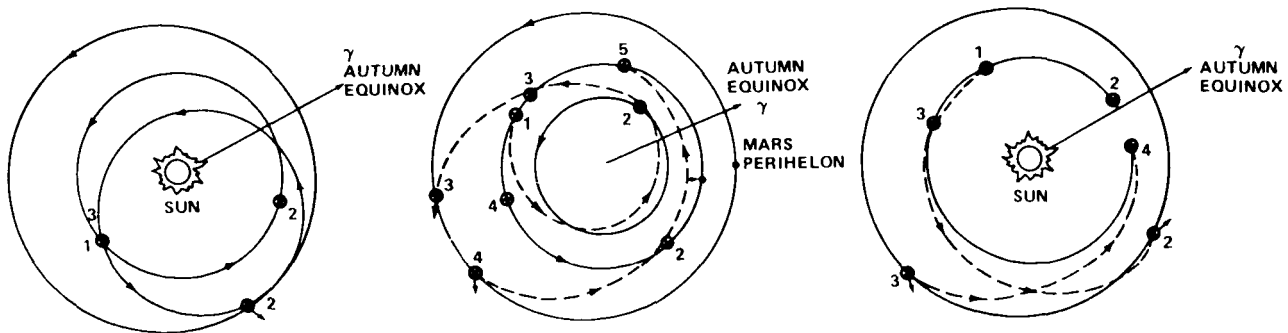


Figure 4.1. Representative mission profiles for 1999 opposition.

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near the planet Mars, with no opportunity for a surface visit by the crew members.

Figure 4.2 compares conjunction- and opposition-class missions which utilize propulsive braking at Earth and Mars. The conjunction-class missions require about 450 metric tons in LEO, with departure mass relatively insensitive to launch year. These missions remain at the surface or in orbit about Mars for 10 to 18 months with consequent high scientific potential and the possibility of replanning to maximize the mission return. Conjunction-class missions, however, require approximately three years mission duration from launch through crew recovery.

Opposition-class missions utilizing all-propulsive vehicles require on the order of 680 to 1800 metric tons of SV weight in LEO, and are quite sensitive to launch year. The opposition-class Venus-swingby missions shown in Figure 4.2 require less total mission duration (2 to 2 1/2 years) than conjunction missions, but provide at most 60 days of activity in orbit or on the surface of Mars.

Other types of trajectories and orbits can be contemplated for systems that go beyond the cryogenic O₂/H₂ systems in technology or operational complexity. For example, development of continuous low thrust propulsion systems (e.g.,

nuclear-thermal or electric) allows reductions in trip time or increases in delivered mass for the same initial mass in LEO. Mission performance may be enhanced in some cases by use of innovative orbital characteristics or staging. For example, periodic Earth-Mars transfer orbits exist which would allow a transfer vehicle to repeatedly visit Earth and Mars with very little propulsive maneuvering. Thus, the transfer vehicle mass would only need to be launched once, then crews and new equipment could rendezvous with the transfer vehicle as required. Such strategies have increased value when repeated trips are intended. Another class of performance enhancements is possible if libration points in Earth-Moon, Earth-Sun and Mars-Sun systems are all utilized as staging points. Such orbits minimize transfer energy but tend to increase trip time and to complicate orbit phasing maneuver timing. They may be attractive in scenarios that utilize in-situ propellant production on the Moon or at Mars. These staging points permit innovative use of momentum exchange between the SV and the Moon that may further decrease the propulsive delta-V requirements. Although recent studies have yielded new insights, much work remains ahead before a manned Mars landing and return program can be planned.

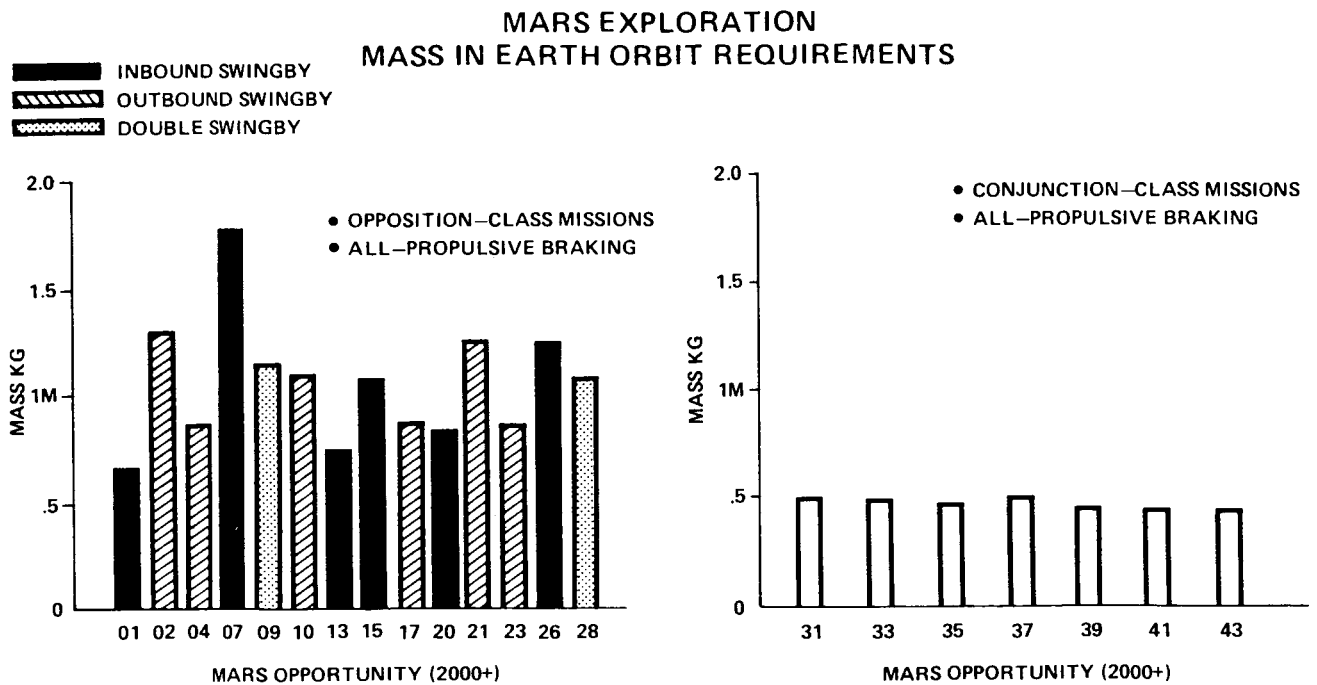


Figure 4.2. Typical MMM opportunities.

IMPACTS OF AEROBRAKING

The dissipation of the entry vehicle's kinetic energy to orbit Mars and/or Earth and/or to land on Mars represents significant vehicle design requirements for MMMs. For conjunction-class missions, the departure mass of an all-aerobraking system will be 20 percent to 30 percent less than that of an all-propulsive system (Fig. 4.3). Opposition-class missions become more attractive in terms of departure mass when aerobraking systems are used, because mass reductions of approximately 60 percent can be achieved compared to propulsive braking systems. The use of aerobraking adds some complexity to the vehicle design, but may allow deletion of an entire propulsive stage, compared to all-propulsive mission designs.

External configurations may need lift/drag (L/D) equal to 0.6 or greater with ballistic coefficients less than 2400 kg/m^2 to provide adequate performance for all mission opportunities. This may require an ablator or an advance in the state-of-the-art of thermal protection system (TPS),

and attention to external configuration of the SV. The primary uncertainty in aerobraking manned vehicles is the capability of the crew to function in a possibly severe g-load environment after long periods in zero gravity. The g-loads encountered during descent to the Mars surface defines the minimum that the crew must be able to tolerate on aerobraking into Mars orbit. These are similar to Earth-entry g-loads for typical conjunction-class missions. Aerobraking at Earth for opposition-class missions is a more severe requirement and a propulsive system may be required to decrease the entry velocity to reduce g-loads to levels that can be tolerated by the crew. Vehicle design, appropriate selection of launch dates, and careful trajectory design will be required to make aerocapture a viable alternative for opposition-class missions. Aerobrake configurations, TPS, and thermal environments for Mars and Earth entry must be studied for all aerobraking applications.

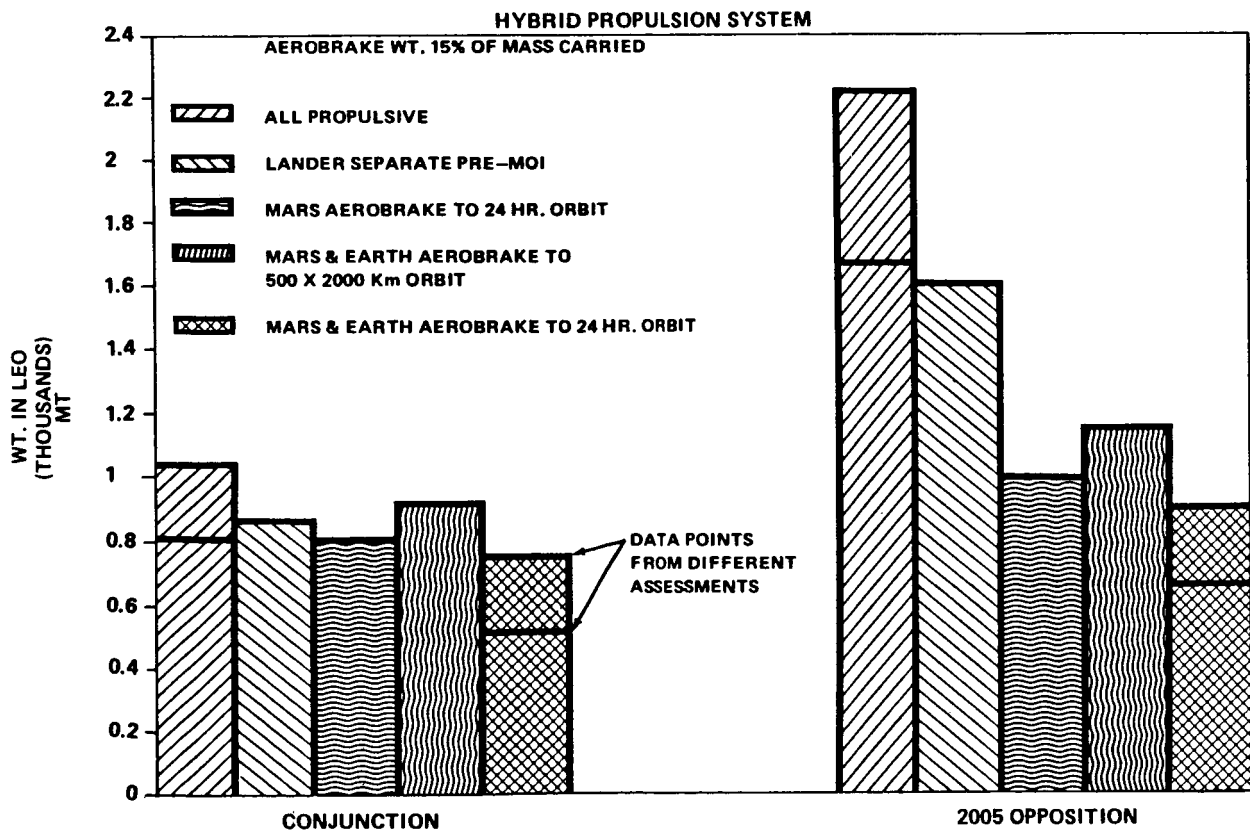


Figure 4.3. Aerobraking comparisons.

ADVANCED PROPULSION OPTIONS

A manned journey to Mars using chemical propulsion requires that many hundreds of tons of mass be assembled in LEO. Advanced propulsion systems can reduce that mass substantially. The Nuclear Thermal Rocket (NTR), which was developed in the Nuclear Engine Rocket Vehicle Application (NERVA) program (1962-1972), and the electric thruster – magnetoplasmadynamic (MPD) or electrostatic ion accelerator – are the two major possibilities.

The most thoroughly tested NTR produced a peak specific impulse (Isp) of up to 850 sec, and thrust of 330,000 N for an inert mass of 12,000 kg including an EVA-compatible radiation shield. In general, for a given payload, the NTR's vehicle mass will range between 50 percent and 35 percent of the comparable chemically-propelled and propulsively-braked vehicle's mass for opposition-class missions to Mars, depending on the launch year. For conjunction-class missions, the ratio of NTR vehicle mass to chemical-vehicle mass is about 60 percent and 75 percent for propulsive

braking and aerobraking, respectively (Fig. 4.4). Aerobraking chemical propulsive concepts are shown here, also, for comparison.

Nuclear powered electric propulsion (NEP) systems require about the same mass in Earth orbit as the nuclear thermal systems, which is about half of the mass of the equivalent chemically propelled, propulsively braked system. For a NEP mission of the same mass as a chemically propelled mission, the total transit time of Mars missions could be reduced. The time required to leave the Earth's gravity field is long, and as much of this transit would be through the Van Allen radiation belts, the nuclear electric system is not suitable for carrying humans from LEO. However, if the crew is placed on board the Mars vehicle at the Earth-Moon L₂ libration point, substantially shorter Earth-Mars transit times result for smaller propellant masses than for other propulsive missions. Development of multi-megawatt nuclear power sources which have inert specific power levels between 100 and 200 W/kg, will make electric thrusters attractive.

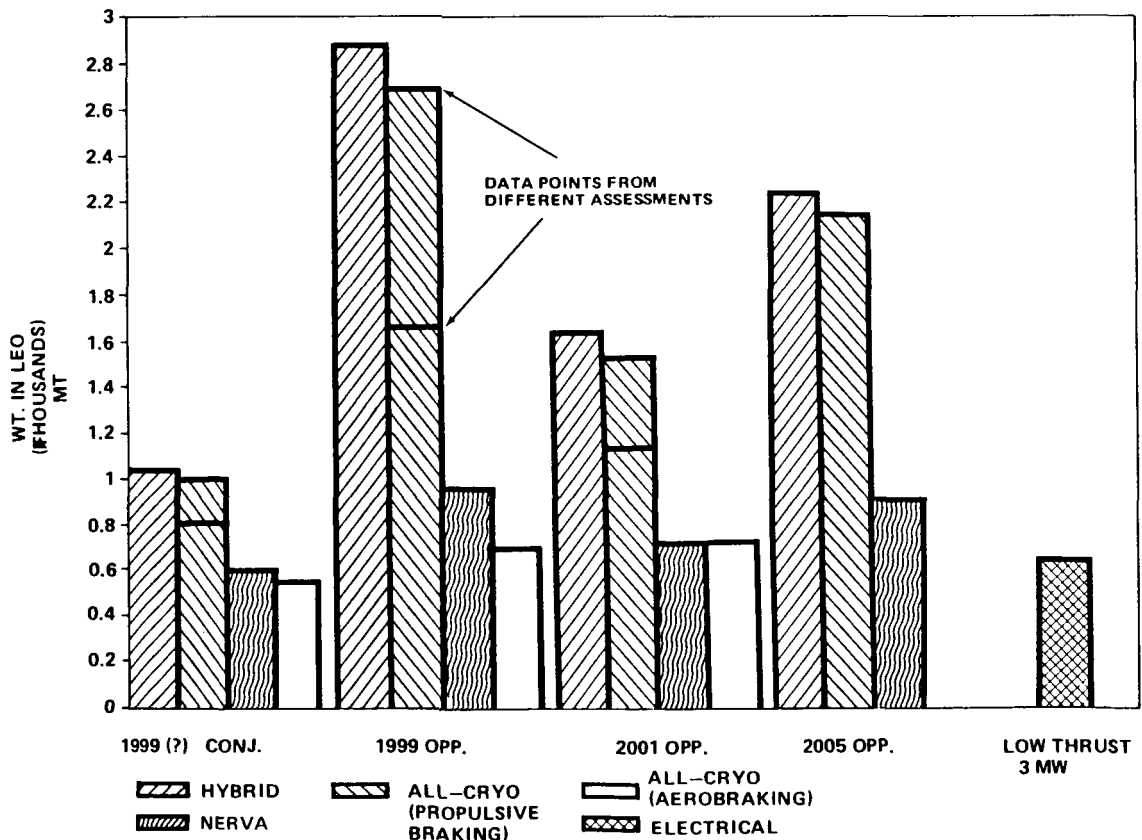


Figure 4.4. Potential missions comparisons.

If the initial MMM is not planned until the year 2010 or later, the possibilities of using more advanced propulsion concepts such as beamed-power or, in the more distant future, the mass conversion of anti-protons must also be considered. Such systems would allow transit times of three to four months each way and would require much less mass in LEO than that required for chemical propulsion/aerobraking systems. Technological advances over the next 30 years required to fill other needs may make such systems feasible. Currently, support of the computational ability to calculate anti-proton interactions is needed. Research to learn how to store low energy anti-protons for use in the laboratory environment is presently underway. Support of efforts to study low momentum anti-proton interactions is recommended.

The potential payback of an advanced propulsion system is greatest for large programs with multiple MMMs and warrants a strong research effort. The possibility of one-year round trips to Mars with vehicles whose mass ratio is less than 10 make advanced propulsion research worth investigating if an evolutionary expansion into space is foreseen.

MARS VICINITY TRANSPORTATION ISSUES

For propulsive-braking cases, the propellant requirements for capture into orbit about Mars and departure from Mars are dependent on the choice of orbit. Low circular orbits will require larger amounts of propellants for braking than elliptical orbits and require significantly more propellants for the return trip. Using a highly elliptical orbit can reduce the Mars orbit insertion (MOI) and the trans-Earth injection (TEI) delta-Vs by more than 1,200 m/sec each over the delta-Vs required for low circular orbit, and can decrease initial LEO mass by factors of 1.3 to 2.0, if chemical propulsion is used. The optimum ellipse should have a periapsis as low as possible without creating atmospheric interference or orbital stability problems. A periapsis of 500 km satisfies this requirement. Such a choice will permit aerodynamic entry of a landing craft to the Martian surface with only a very small delta-V input at the apoapsis of the elliptical orbit. MOI and TEI delta-Vs continuously decrease as apoapsis

altitude is increased, although little gain is seen beyond a 48-hr orbit (57,000 km apoapsis) (Fig. 4.5).

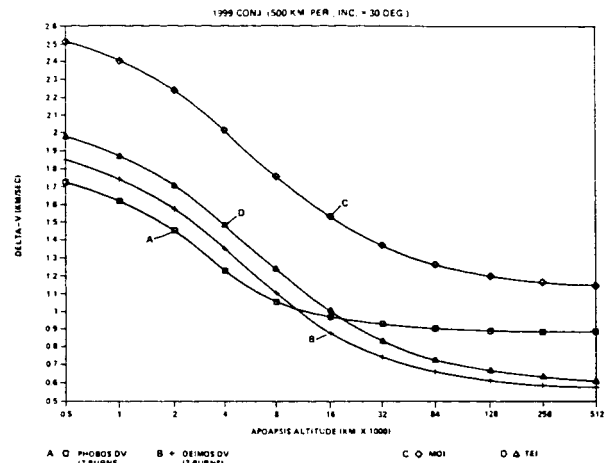


Figure 4.5. Mars Moon visits from elliptical orbits.

Parking orbit inclinations in the range of 20 to 30 deg will reduce the delta-V requirements necessary for alignment with the arrival and departure asymptotes. For an inclined parking orbit, transfer delta-Vs to either of the Martian moons also continuously decrease with increasing apoapsis altitude. All of these considerations drive the Mars parking orbit to as high an apoapsis as possible.

Orbits with 500 km periapsis and 24 to 48 hr periods (33,000 to 57,000 km apoapsis) allow plane changes to be made quite inexpensively at apoapsis and minimize Martian moon visit, MOI, and TEI delta-Vs. The 24-hr orbit (500 x 33,000 km) is reasonable and practical because its period is not excessive and it is not so high that serious stability problems would be expected.

If orbit insertion at Mars is to be accomplished via aerocapture techniques, then the high apoapsis (33,000 km) is very sensitive to atmospheric exit conditions and, therefore, is difficult to achieve. The primary controlling parameters are the navigation errors and atmospheric inhomogeneity and uncertainties. Vehicles with greater atmospheric maneuvering capability are better able to "trim" these errors prior to atmospheric exit. The vehicles chosen for these trade studies could adequately target for, and achieve, a 15,000 km apoapsis. A higher L/D than considered in these trade studies would probably be required to achieve an apoapsis of 33,000 km. Aerocapture

allows the opportunity to insert the entire incoming vehicle into low Mars orbit at no mass penalty compared to the propulsive braking option. Also, some plane change can be accomplished with aerocapture. However, propulsive requirements are still greater on departure. All of these considerations warrant further studies on aerocapture of the vehicle into Martian orbit.

RETURN TO EARTH VICINITY TRANSPORTATION ISSUES

Upon return to Earth, the spacecraft and crew have several alternative procedures for capture and subsequent return of the crew to the ground. These alternatives involve propulsive and/or aerodynamic capture into either high or low energy Earth orbits and may or may not utilize LEO-based OTVs for either crew or the Mars vehicle return to the LEO SS: (1) Direct entry to the Earth's surface results in the minimum initial LEO mass, but can result in high g levels and there is no possibility of crew quarantine or hardware reuse. (2) Propulsive return to orbit. Conventional chemical propulsive insertion of a 50 metric ton crew module into elliptical Earth orbit requires initial LEO mass increases of hundreds of metric tons as the period of the elliptical return orbit drops below 6 hr (500 x 20,000 km) (Fig. 4.6). These orbits require an Earth-orbit based vehicle to retrieve the returning spacecraft. (3) Aerobraking directly from the interplanetary trajectory offers the potential for inserting large masses into LEO. This would be highly advantageous for hardware re-use or return of Mars moon propellants. The g-levels uncountered may be high, however. The g-level a returning Mars crew can safely tolerate (to be determined) must be over 2 g to make this option viable. (4) Advanced nuclear thermal (e.g., NERVA) propulsion. Such missions seem to be insensitive to Earth parking orbit and may enable the vehicle to park propulsively in LEO for no great cost in initial LEO mass. However, concern with nuclear contamination on Earth in the event of unforeseen system failure may dictate that nuclear stages park in a high circular Earth orbit, for instance at the Earth-Moon L_2 libration point. The crew will then be retrieved by a single LEO-based OTV, leaving the stage to be

prepared for re-use, stored, or sent into heliocentric orbit for disposal.

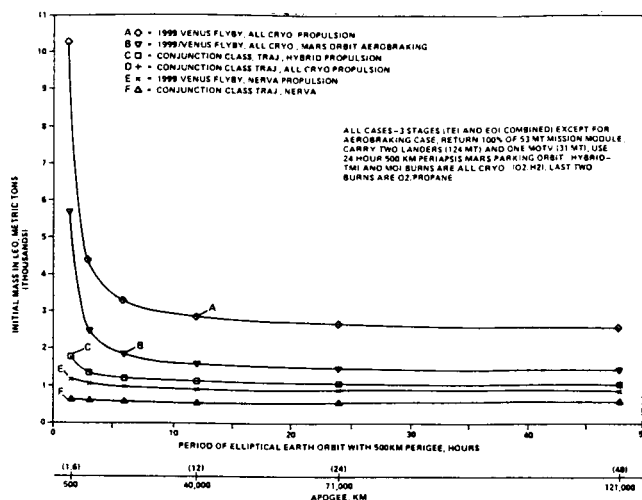


Figure 4.6. Initial mass in LEO versus return orbit.

The Mars program might be best served by parking the crew module in a highly elliptical 24-hr orbit (500 x 71,000 km) from which the crew, and possibly the module itself, is retrieved by a LEO SS-OTV. Retrieval must take place quickly to avoid high radiation doses to the crew from the Van Allen belt.

The crew or crew plus module can be recovered in several different ways: (1) An OTV can deliver an aerobrake, retrieve the crew, and return to LEO. The crew module may then utilize the aerobrake to return to LEO; (2) An OTV might deliver sufficient propellant to the returning spacecraft and the Earth Orbit Injection (EOI) stage to permit propulsive return to LEO; or (3) OTVs can push the entire Mars spacecraft to LEO. Such use of the OTV, for the case of chemical propulsion, results in savings in initial Earth orbit departure mass of from 6 to 30 metric tons for each ton of crew module recovered from the 24-hr ellipse. The exact savings are a function of the propulsion technologies employed for the Mars SV, the specific trajectory, and the specific recovery scheme employed. Recovery of the entire crew module, and perhaps the EOI stage, to the LEO SS may become economical as the number of missions grows.

Issues that require further study include the economics of crew module reuse and recovery costs, and the crew g-levels allowed at the end of a mission with and without artificial gravity.

IMPACTS OF EXTERRESTRIAL PROPELLANTS

For conventional chemical Mars spacecraft, extraterrestrial propellants from the Earth's Moon, the Martian moons, and the surface of Mars offer potential savings in initial LEO mass ranging from around 30 percent for oxygen only to as much as 70 percent for hydrogen plus oxygen (Fig. 4.7).

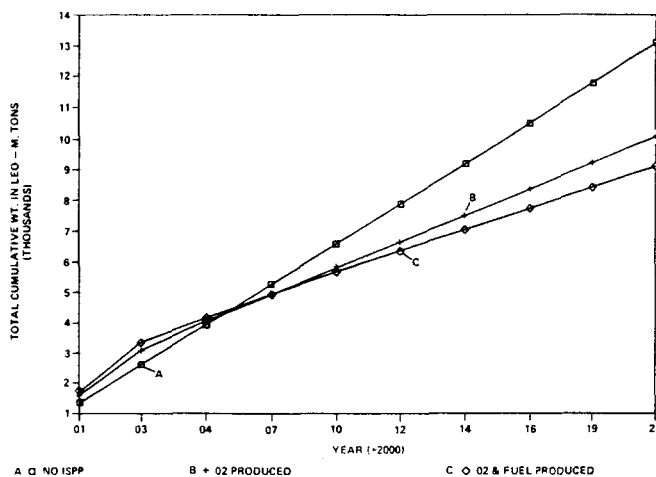


Figure 4.7. Phobos and surface I.S.P.P. all stages fueled - (best case).

A long-term Mars program utilizing extraterrestrial propellant will lower LEO mass compared to delivering propellants from Earth. However, the propellant demand must be large enough such that the costs saved are enough to develop and operate the extraterrestrial propellant production and delivery system. Extraterrestrial propellant cost typically must be compared to the cost for propellant launched from Earth with a heavy lift launch vehicle (HLLV), which may be 1/3 to 1/5 that of a Shuttle launch. A reduction of mass on the order of 30 percent could be enough to merit a lunar oxygen plant, if the Mars mission did not have to be charged for the entire lunar surface infrastructure. Lunar surface propellant production has the highest potential benefit in reducing Earth launch mass but requires that hydrogen be made available on the Moon for delivery of the oxygen produced there. If hydrogen must be delivered

from the Earth, a significant overhead is imposed on the propellant delivery system. If it can be produced on the Moon, it becomes practical for the Mars vehicle to depart from a lunar vicinity transportation node. If lunar propellants can be delivered to the lunar vicinity transportation node at 1/4 of the cost of propellants delivered to LEO, then the Earth-to-LEO costs for the MMMs may be reduced by about 40 percent. Also, under these circumstances, lunar propellants would be generally competitive for other uses in LEO.

Given no other infrastructure in place, the Martian moons have some advantages as a propellant source. Because of the small size of the moons, launch from their surface has negligible propellant requirements. Utilizing Mars moon propellants can result in LEO launch cost savings of around 30 percent. Zero-g mining on the Mars moons may be difficult, however, and requires further study. Mars surface propellant production may result in savings of less than 10 percent in initial LEO mass for a conventional propulsion, conjunction-class program over a 20-year period. However, in a mission scenario involving vehicle ascent to hyperbolic rendezvous with a passing crew module, surface propellant can save 50 percent of the initial LEO mass.

Future work should include an attempt to estimate lunar surface launch and Earth-Moon cargo OTV costs. Mars orbit operations with Martian moon propellant requires more study and costing. The mass and cost (including operations cost) of Martian moon and surface propellant plants should be estimated. The development and production costs of a lunar propellant plant should be determined.

MMM'S SUPPORTED BY A LUNAR BASE

There are several areas in which a manned Mars program can potentially profit from a lunar base: (1) lunar-produced propellants, (2) construction of some or all of the vehicle utilizing lunar materials, and (3) the development of technologies and life sciences for extraterrestrial habitation.

Most of the benefits accrue from the basic fact that the Moon is on the outer edge of the Earth's gravity well. Therefore, much less propellant is required to place mass in lunar orbit and send it on its way to other places in the solar

system than for departure from the Earth. The opportunity to develop the technologies for, and gain experience in, extraterrestrial habitation at a Moon base is a desirable objective, because the Moon is only three days away in transport time and a few seconds in communication time. Mars, however, is months away in transit time and approximately eight minutes, at best, in communication time.

Should a Mars program precede a lunar program, many Mars program developments would likewise benefit the lunar program. Both should continue to be studied together, and mutual benefits examined further.

4b. SPACE VEHICLE CONCEPTS

Several types of vehicles are required in a manned Mars program: ETO's, SV's, and OTO vehicles. SV's are discussed in this section and the others are discussed in "Impacts on Space Infrastructure" (see Section 6).

SPACE VEHICLES

General Considerations

The capability to perform an early manned Mars flyby mission may be a key ingredient in a manned Mars program. Also, the capability to utilize both opposition- and conjunction-type trajectories may be desirable, the former for initial short-term manned missions and for cargo missions throughout the program, and the latter for more extensive science/exploration and Mars base buildup activities. Such a variation in trajectories, coupled with the variation in energy requirements across the spectrum of flight opportunities, imposes a fairly wide variation in SV sizing.

Additional variations are imposed by the desire to be able to fly manned missions, cargo missions, and hybrids as part of the program. SV sizing implications result also from the desire for a capability to land crew or cargo in almost any region of the Martian surface or on the moons.

The greatest contribution that the systems designers might make to the program is to provide a high degree of versatility to accommodate various

mission and program options at reasonable cost. A system that allows an early flyby mission to be accomplished readily, but also serves efficiently for follow-on exploration and utilization, would be highly desirable.

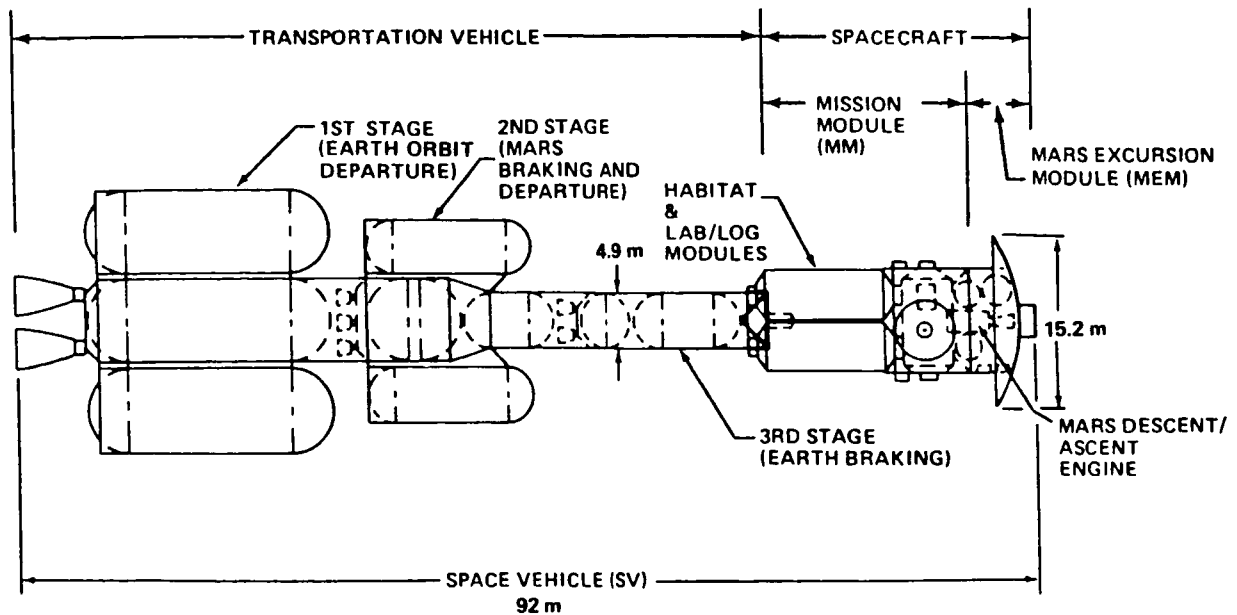
Some of the critical ingredients of such systems designs would be modularity and "technology transparency." Vehicle designs, for example, would have multiple stages, add-on tanks, etc., to accommodate greater payloads (or the same size payloads in years offering less-favorable mission opportunities), and would be able to incorporate newer-technology systems as they become available, with minimum impact on the rest of the vehicle. Vehicles should have adaptability to either manned or unmanned (cargo) missions and should accommodate various landing sites with minimum impact.

General Description

The SV concepts provided herein are not optimized designs, but rather are typical options which were generated to facilitate mission analysis and costing activities.

Figure 4.8 identifies the terminology used for SV elements. This figure depicts an all-propulsive SV which utilizes cryogenic chemical propellants. The term SV refers to the total complement of equipment assembled in LEO and launched toward Mars. This includes a transportation vehicle (TV), which usually includes several propulsive stages, and a spacecraft. The TV is used for transport of the elements to and from Mars (including braking for some SV options). The spacecraft provides living quarters in Earth-Mars transit and in the Mars vicinity, and transportation (if required) to the Martian surface and/or to Phobos or Deimos. The spacecraft consists of a MM, a MEM, and scientific equipment. The MM consists of several habitable modules which remain in Mars orbit. The MEM has a habitable volume, ascent, and descent propulsion elements, and storage volume for transporting equipment to the surface of Mars and surface samples back to Earth. Subsystems which utilize existing or near-term technology/designs were used for chemical-propulsion TVs and for the spacecraft elements in this study, for sizing and costing purposes.

Transportation vehicles which have been examined in this study include chemical, nuclear,



	<u>PROPELLANT WEIGHT* (KG)</u>	<u>TOTAL WEIGHT* (KG)</u>
1ST STAGE	1,027,602	1,083,127
2ND STAGE	305,313	328,409
3RD STAGE	72,995	79,674
SPACECRAFT	32,661	132,088
TOTAL	1,438,571	1,623,298

* REFERENCED TO EARTH

Figure 4.8. MMM 1999 opposition all-propulsive option.

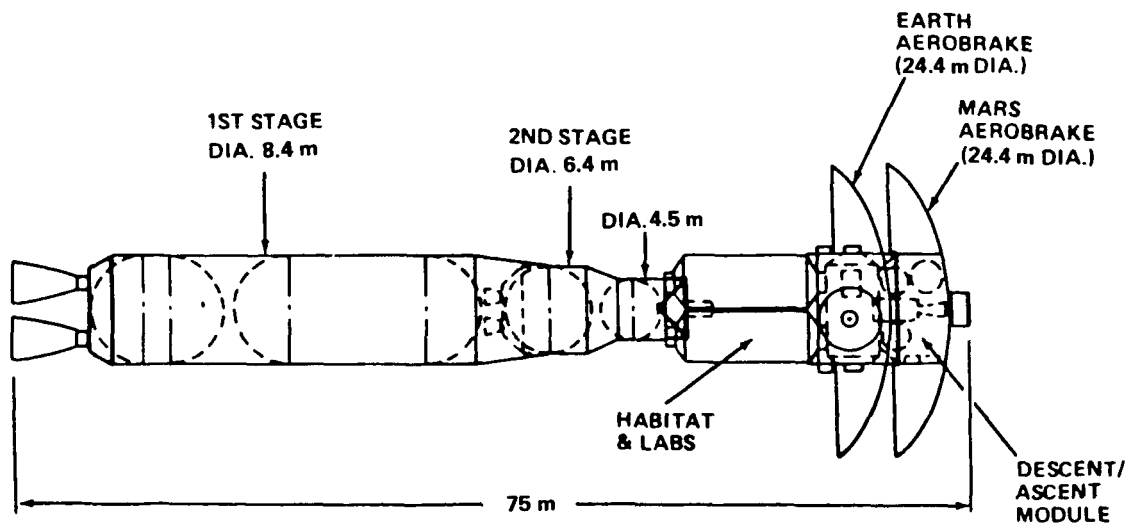
and electric concepts, and hybrids of these. The chemical types have been dealt with more extensively than the others. Most of the work on them has been done assuming the performance of LO_2/LH_2 propellants, although storable propellant options have also been addressed.

The concept shown in Figure 4.8 is an "all-propulsive" SV, which utilizes propulsive capture at Mars and Earth. An all-propulsive SV concept utilizing storable propellants for the propulsive vehicle was sized during the study, but the total weight (near 400 metric tons) was considered to be beyond practicality. Figure 4.9 is an "all-aerobraking" concept which utilizes aerobraking for capture at both planets. Both vehicles utilize a MEM concept which has a combination propulsive/aerobraking system for descent to the Martian surface. Other than the aeroshells, the difference in physical size and mass of the two vehicles is mainly in the propulsive stages.

These vehicles are designed so that their normal orientation during the Earth-Mars transit phase of the mission is "long-axis along the solar vector." This allows the sides of the propellant

tanks to see deep space, thus keeping propellant boiloff losses very low. Other orientations can be effected occasionally during the transit phase, as long as they are kept within reasonable limits. These vehicles could utilize solar, nuclear, or other types of power systems. Boiloff of cryogenics must be kept very low for cryogenic concepts to be practical. Boiloff in transit to and from Mars can be kept extremely low (0.05 kg/hr) by using insulation and preferential initial orientation of the SV. In the vicinity of Mars, however, boiloff could be on the order of up to half a kilogram per hour and at Earth could range up to several kilograms per hour, if only passive means are used (10 cm of insulation). Present reliquification technology requires enormous amounts of energy, but improved insulation and reliquification technology areas should be pursued.

In the concept shown in Figure 4.8, three propulsive stages are necessary for the total mission. The outboard tanks are jettisoned from stage 2 when empty, to save weight. The Earth-departure stages makes use of Shuttle-derived engines and tanks, and the second and third stages



	<u>PROPELLANT WEIGHT* (KG)</u>	<u>TOTAL WEIGHT* (KG)</u>
1ST STAGE	445,359	484,691
2ND STAGE	72,474	78,951
SPACECRAFT	32,661	149,729
TOTAL	550,494	713,371

* REFERENCED TO EARTH

Figure 4.9. 2001 opposition MMM aerobrake option.

use OTV-derived propulsive elements. The concept shown in Figure 4.9 requires only two stages and these are of much smaller size than those shown in Figure 4.8. The first stage is a Shuttle-derived vehicle and the second stage can be an OTV.

The large difference in LEO SV weight (0.7 M kg for the all-aerobraking case, compared to 1.6 M kg for the all-propulsive case) translates into significant benefits in cost, vehicle complexity, delivery time to LEO, assembly time in LEO, etc. Although some vehicle complexity is added for the aerobraking case, an entire propulsive stage can sometimes be deleted as in this case. Aerobraking also reduces the mission-to-mission variation of required SV LEO mass for different opposition-type launch opportunities, with these masses becoming only slightly larger than those for conjunction-type missions. Because of such reduced mass values and reduced mass variations for different opportunities, this class of design has the potential of performing either opposition-type or conjunction-type missions at any opportunity.

Modular propulsive elements could be used to adjust to the mass variations from one opportunity to another, or payload delivery capability could be varied.

The all-aerobraking concept can be available for flights in an early time frame (before 2000). Some of the required propulsive and aerobraking technology is being pursued in the course of the SS, OTV, and other development activity (the SS is currently planned for operational status in the early-to-mid 1990's, and the OTV is planned to be operational in the mid-to-late 1990's). The potential for utilization of these large aeroshells on the surface of Mars for storage, habitation, or other purposes has been assessed briefly and appears promising.

During some opportunities, the trajectory flown by an all-aerobraking SV would produce g-loads unacceptable to the human body, especially one which has possibly not experienced a significant gravity field in months. These g-forces must be reduced to acceptable levels. In such cases,

the vehicles would have to be designed to reduce g-forces to an acceptable range by use of a propulsive burn late on the return trip, instead of utilizing aerobraking at Earth. This could be implemented by either (1) adding a modular increment to the propulsion system, or (2) hauling additional propellant along to use with the MEM ascent stage engine which could be retained on the return trip. The propulsive elements can be kept small if it is acceptable to jettison the MM before the propulsive braking operation. Table 4.1 provides a summary weight statement for the spacecraft in Figure 4.9.

One of the key configuration-related issues for the SV is whether or not an artificial-g design will be required. Figures 4.8 and 4.9 are SV concepts having no overall vehicle artificial-g capability, although internal systems, such as centrifuges and exercise equipment, could be included in these concepts to provide limited g-fields.

If alternative means are not found to ameliorate the deleterious effects on the crew of long-term weightlessness, the SV may have to provide a "gravity" field. While not impossible to do, this adds complexity to the SV which should be avoided unless absolutely necessary. This has been considered for two levels of artificial gravity, obtained by rotating the SV (Figs. 4.10, 4.11, and 4.12). The physiological response to coriolis forces necessitates that rotating g-field systems have a rotation rate of no more than 2 to 4 rpm. Figure 4.10 depicts a rotating SV (all-propulsive) which provides a 1-g field in the modules and has an arm radius of 61 m (based on 4 rpm). In comparison to the non-spin SV, mass must be provided for: (1) the reaction control system (RCS) required for spinup and maintenance of the spin rate; (2) the truss structure supporting the modules; (3) the tunnels and their ECLSS equipment, additional shielding weight, etc.

Design and operational complexities are introduced, since: (1) efficient utilization of the habitable environment is difficult due to the distances involved; (2) frequent traversing between modules would tend to produce sickness due to the varying g-levels experienced; (3) systems and living quarters would have to operate and be functional in zero-g, partial g, and 1-g environment (with the latter two involving two different g-force directions); (4) some of the modules and other elements would have to be relocated to the region behind

the aeroshell of an all-aerobraking concept for capture at Mars and Earth; (5) EVA activities would be difficult without stopping the rotation; (6) The booms may have to be of adjustable length to balance the changing masses as the configuration changes over the two- or three-year length of the mission; and (7) Some elements of the SV (astronomy instruments, guidance sensors, etc.) would have to be de-spun to allow their proper operation while others (appendages, etc.), would have to be stiffened to withstand the g-forces.

A 0.4-g concept is shown in Figure 4.11. The required module separation distances here are much less than those for the 1-g concept. This concept would have essentially the same types of problems as those mentioned for the 1-g concept, but to a smaller degree.

The concept shown in Figure 4.12 was designed for a conjunction-class mission which permits long (10 to 15 months) stay-time in Mars orbit. Cryogenic propulsion is provided for the first two stages to acquire a Mars orbit having a one-day period. Two landing vehicles are provided for dispatch to separate sites on the Mars surface. The long residence in Mars orbit could be employed for manned visits to the surface of both Mars moons. Laboratory facilities are provided to permit some analysis of the data and mission replanning during the mission, as information from Mars or moon exploration is received.

Aerobraking is not employed in this early design, resulting in a relatively high departure mass of above 1250 metric tons with a total MM mass of 80 metric tons and with two 75 metric ton MEMs. Four manned Mars maneuvering vehicles are provided for the moon visits and retrieval of the MEM ascent stages from 500 km circular orbits. Sufficient flight performance reserves are provided so that a single SV design can accomplish any of the Mars conjunction-class missions.

The trans-Mars insertion (TMI) stage propellant requirements were found to be very close to the Space Transportation System (STS) External Tank (ET) capacity. Thus, a ground-assembled TMI stage can be designed which could be launched as an STS ET to LEO for the largest single element of the SV. Further studies are needed for this class of vehicle employing aerobraking at Mars arrival and increased payload, utilizing the ET-OTV concept for the TMI stage.

TABLE 4.1. WEIGHT* SUMMARY (kg)
MANNED MARS SPACECRAFT FOR 2- AND 3-YEAR MISSIONS

<u>SUBSYSTEMS</u>	<u>HAB MOD # 1 (KG)</u>	<u>HAB MOD # 2 (KG)</u>	<u>LAB/LOG MOD (KG)</u>	<u>MEM (KG)</u>
STR. MECHANISMS	680	680	454	680
PRESS. STRUC. (3)	2381	2381	2155	1871
SECONDARY STRUC.	680	680	454	680
MICR/INSULATION	408	408	318	213
INTERFACE STR/SHELLS	544	544	3084	1860
AIRLOCK/HEAT SHIELD	—	—	680	1814
STRUCTURES SUBTOTAL	4693	4693	7145	7118
THERMAL CONTROL	534	534	23	693
ELECTRICAL POWER	1361	1361	54	2483
COMM. & DATA	919	919	68	1007
GN&C	378	—	—	378
CREW SYSTEMS	2487	1332	1932	2969
ECLSS	3322	3322	106	1240
PROPULSION SYSTEM W/CONTIN.				3155
CONTINGENCY (15%)	2054	1824	1399	2383
SPARES (3%/YEAR) (NON-STRUCT.)	621	515	151	605
SUBTOTAL (DRY)	16369	14,500	10,878	22,031
FLUIDS, THERMAL	64	64	—	64
FLUIDS, ELECTRICAL	25	25	—	—
ECLSS CONSUM.	2447	2447	—	871
CREW SYS. COMSUM.	2177	2177	4407	517
PROPULSION DEORBIT & PLANE CHANGE CAPABILITY				3534
PROPELLANTS DESCENT & ASCENT				32,661
MISSION/SCIENCE	2009	2009		671
CREW (6)	1034			
TOTAL (LAUNCH)	24,125	21,222	15,285	60,349
SCIENCE PROBES			11,104	
TOTAL MISSION MODULE (LAUNCH)			60,632	
TOTAL MEM (LAUNCH)			60,349	
TOTAL SPACECRAFT (LAUNCH) 2 YEAR MISSION		132,085		
ADDITIONAL MISSION/SCIENCE EQUIPMENT		4,953		
ADDITIONAL CREW SYSTEMS, ECLSS, & CONSUMABLES		23,507		
ADDITIONAL STRUCTURES AND SUBSYSTEMS		13,409		
TOTAL SPACECRAFT (LAUNCH) 3 YEAR MISSION		173,954		

* REFERENCED TO EARTH

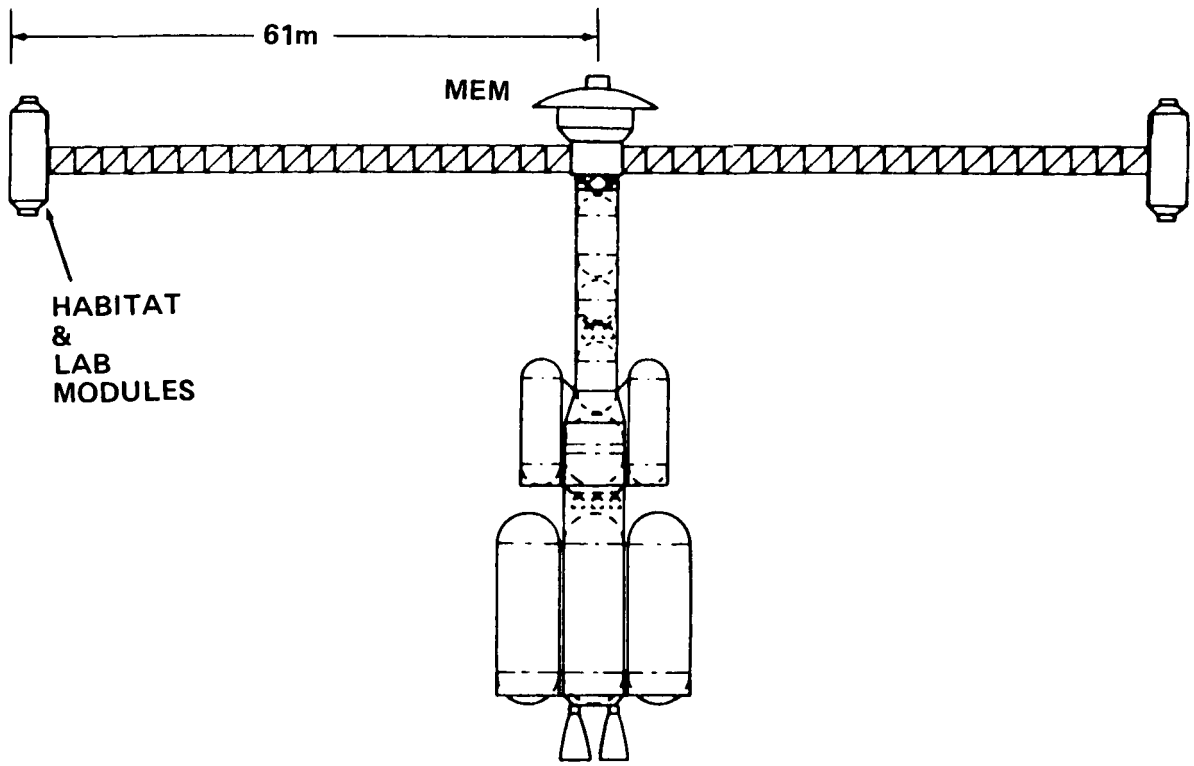


Figure 4.10. MMM 1-g option.

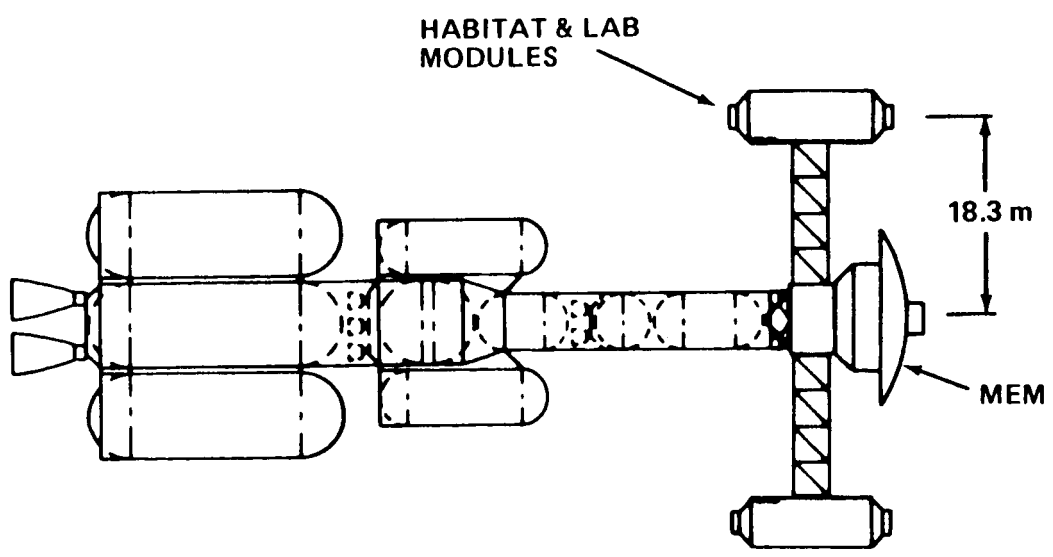
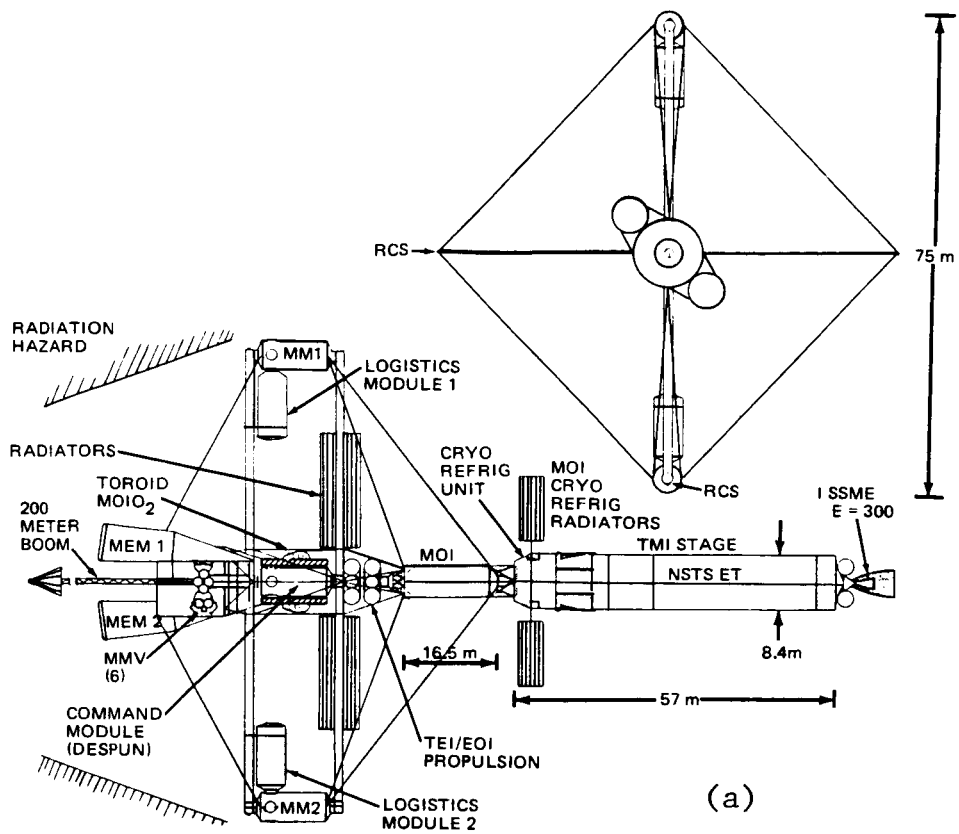
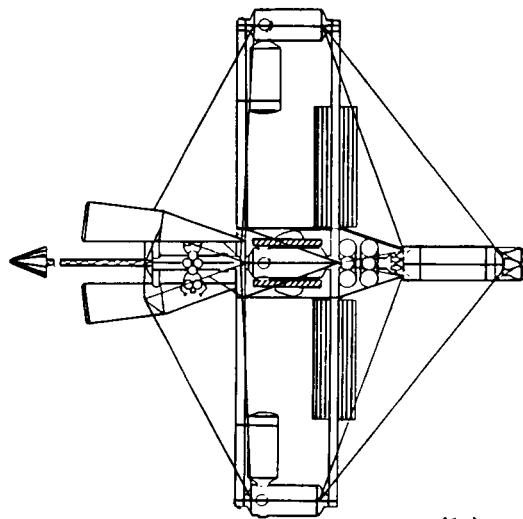


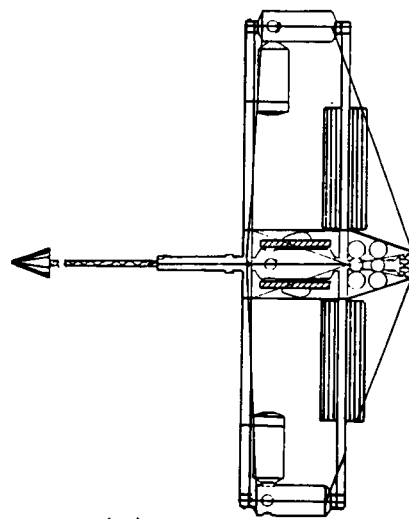
Figure 4.11. MMM 0.4-g option.



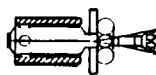
(a)



(b)



(c)



(d)

Figure 4.12. (a) MMM conjunction class near term technology option hybrid chemical propulsion 1400 metric ton class. (b) Initial Mars orbit configuration. (c) Trans-Earth configuration. (d) Earth orbit configuration.

Figures 4.13 and 4.14 show vehicles having electric propulsion and nuclear-thermal propulsion concepts. These vehicles may offer reductions in LEO SV mass compared to all-aerobraking vehicles. Electric and nuclear-thermal vehicles will require more extensive propulsion system development programs than chemical propulsion concepts. These will be difficult to justify in a short program, but may be attractive in a long-term program requiring transport of large masses to Mars. These should continue to be studied, along with others, as candidate vehicle concepts. Some discussion is provided on these in the Transportation and Subsystems sections.

Space Vehicle Size Considerations

Figure 4.15 shows comparative weights for 4 SVs. As noted previously, the all-aerobraking concept (e.g., bar No. 2) can be considerably smaller than the comparable all-propulsive concepts (e.g., bar No. 1). Bar No. 3 shows the effect

of scaling up the SV in bar No. 2 to allow an increase in residual payload on the surface of Mars (payload delivered to the surface and left there) of a factor of 8 on manned flights. The increase in total SV weight is about a factor of 2; hence, there is a net 4-to-1 benefit-to-cost ratio. By comparison, if two identical SVs like bar No. 2 were flown, only a 1-to-1 ratio would be achieved (although twice as many crewmen could be taken on the mission). Bar No. 4 shows weights for a typical conjunction mission. Increases in systems weights, consumables, and experiments for the 1-year-longer mission are more than compensated for by the lower propellant requirements, and the conjunction mission thus requires less weight in LEO than the comparable opposition mission in bar No. 2. The capability for delivery of only cargo, shown on these bars, is approximately equal to the total spacecraft weight on the manned flights.

Figure 4.16 shows the potential cumulative buildup of weight of equipment left on the surface of Mars for manned and unmanned missions, using

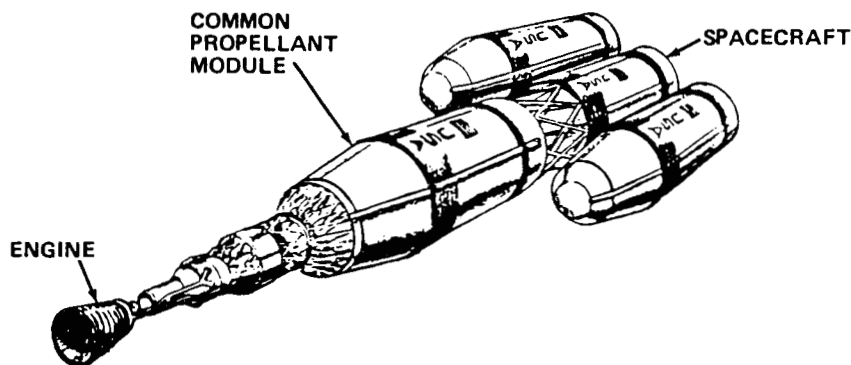


Figure 4.13. Nuclear Engine Rocket Vehicle Application (NERVA) vehicle.

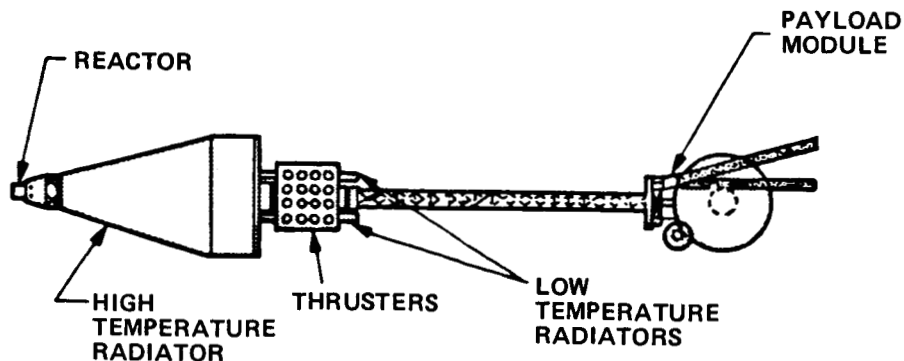


Figure 4.14. Nuclear Electric Propulsion (NEP) vehicle.

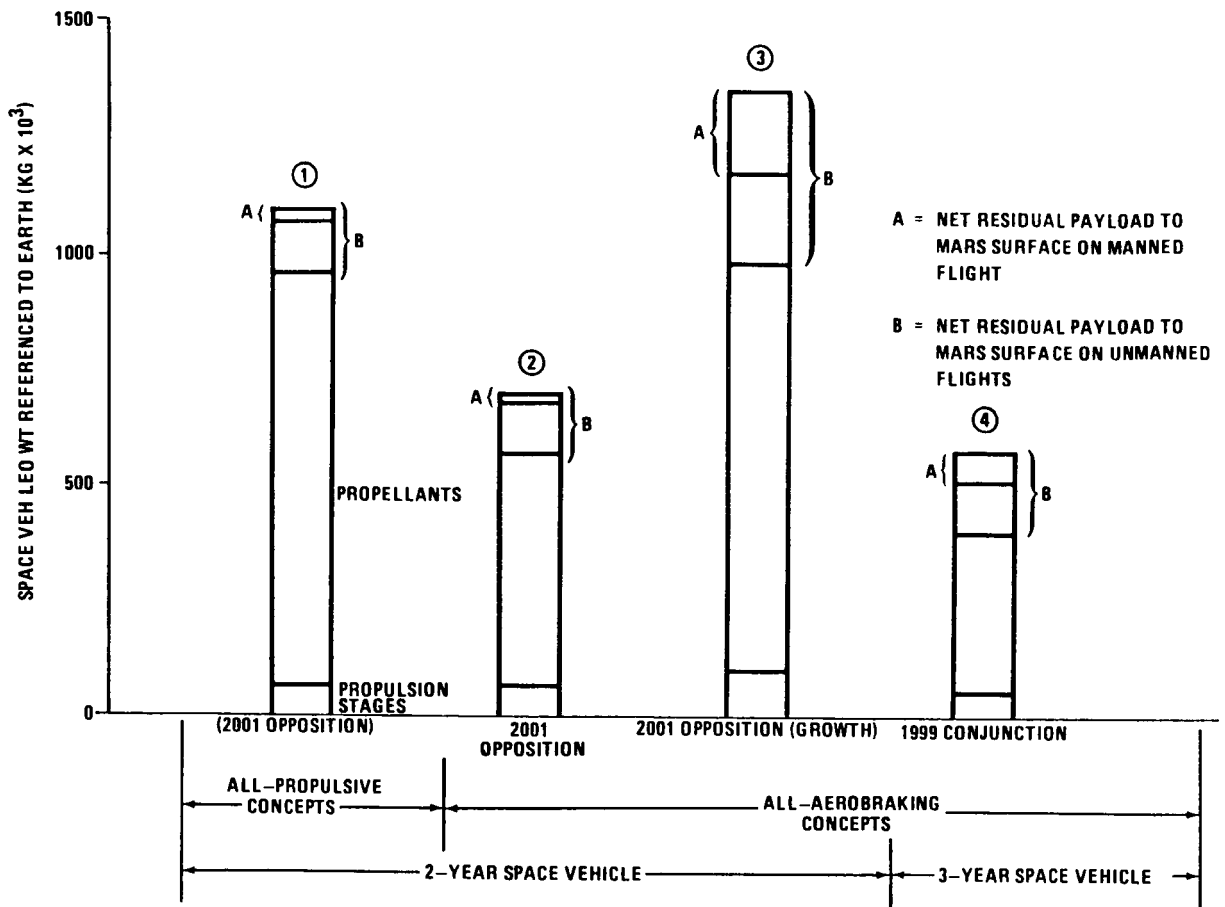


Figure 4.15. Space vehicle weight breakdown (cryo propulsion).

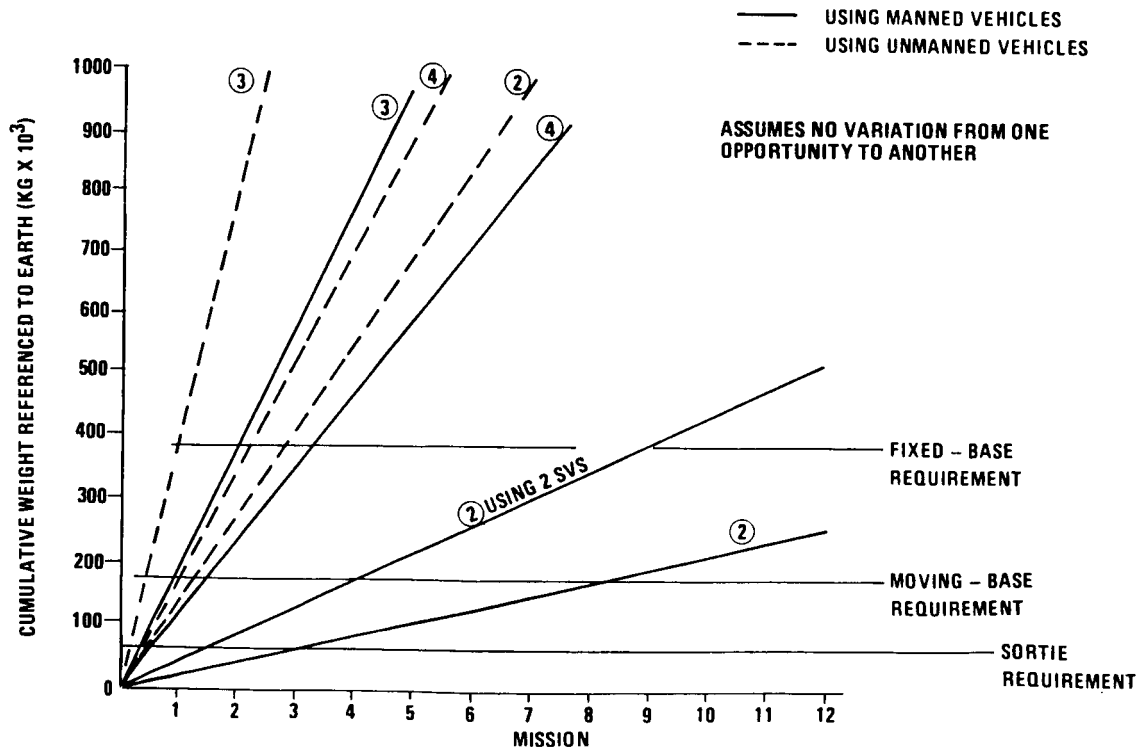


Figure 4.16. Cumulative buildup of payload weight on Mars surface.

different propulsive vehicles of the types shown on previous charts. The circled numbers refer to bars on Figure 4.15, and indicate which type of vehicle and mission was used for each line on Figure 4.16. The degree of improvement in buildup rate can be seen for cases using growth versions of the propulsive vehicle compared to cases using two vehicles, and compared to cases using just one vehicle. Unmanned vehicle cases allow rapid buildup, also. The assumption made here is that propulsion requirements for every opportunity are the same. As previously mentioned, considerable differences exist between opportunities (the SV sizes and/or payload capabilities vary from one opportunity to another), and the curves would not be as smooth as shown. The horizontal lines shown on Figure 4.16 represent weight necessary for different types of bases.

Figure 4.17 shows the cumulative weight required in LEO to accomplish the buildups shown in Figure 4.16. Here, the effect can be seen of the more efficient trajectory of the 3-year conjunction mission (curve No. 4) compared to the 2-year opposition mission (curves No. 2 and No. 3). The ordinate axes on the right-hand side of this

chart show rough estimates of the quantity of Shuttle Derived Vehicles (SDVs) or HLLVs required, depending on which of these concepts is used. No detailed "capture" analysis was done here, so the data shown by these axes may be overly optimistic in terms of estimates of packaging efficiency in the SDV-3R and HLLV.

SPACECRAFT

The spacecraft subsystem elements were identified as MM, MEM, and science equipment. The MM and MEM are discussed below. Much of the science equipment is located inside the MM and MEM. External science equipment consists of large telescope assemblies for astronomy and solar observation, probes for release in the vicinity of Venus and Mars, and other equipment.

The spacecraft must provide at least two separate habitable volumes for the crew during all mission phases for safe haven purposes. Adequate shielding must be provided for protection from natural radiation sources, solar flares, and on-board nuclear elements. Preliminary indications

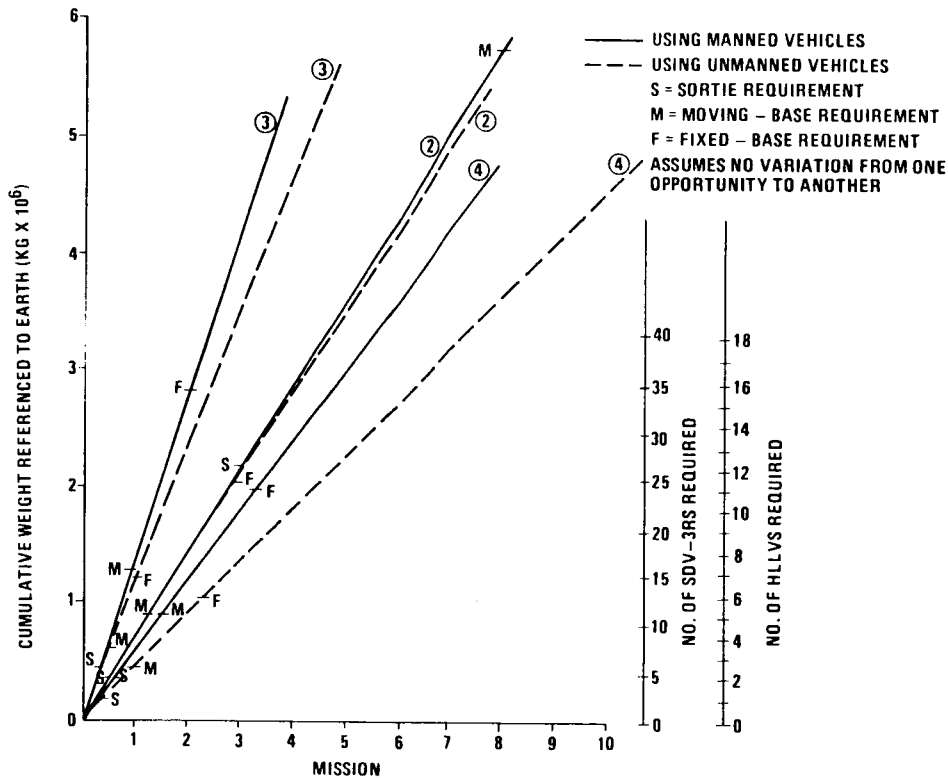


Figure 4.17. Cumulative buildup of LEO weight.

are that there will be sufficient mass in the basic structure and other systems of the spacecraft to provide the required shielding from background and solar flare radiation. Detailed packaging assessments must be made to ensure that effective use can be made of this mass. Otherwise, shielding mass of several thousand pounds may have to be added to the concepts.

Most spacecraft subsystems technology/designs were assumed to be the SS-type for sizing and costing purposes. Although SS modules and subsystems are still in a very early stage of definition, it appears that a closed-loop (except for the food loop) ECLSS will be used there. The spacecraft power source was assumed to be an isotope-Brayton power system (non-SS type), operating at a power level of 25 kW during the transit phases with MEM and MM systems active, and having 10 kW for the surface phase (MEM active). A crew size of six people was assumed for early missions: four crewmen would descend to the surface in the MEM during opposition-type missions, and two would remain in the MM in orbit about Mars; all six would descend during conjunction-type missions. Aerobraking concepts were assumed to be derivatives of those utilized for the OTV, which is anticipated to be derived from Apollo, Viking, and STS concepts.

Mission Module (MM)

The MM consists of one or more habitable modules in the spacecraft. The MM provides part of the habitable volume during the trip to Mars and back, and provides all the habitable volume in Mars orbit after the MEM descends to the surface of Mars. The design of the MM will be a function of the mission requirements. Crew-related requirements such as crew size, degree of ECLSS loop closure, consumables sizing and storage, habitable volume, safe haven, and redundancy will have a major effect on MM design. However, at this time, further effort is needed to define these in sufficient detail to enable MM preliminary design.

The design of the pressurized module(s) for the MM could employ SS-derived modules (4.3 m diameter by 10.7 m long), as shown in Figure 4.18. The SS module designs are expected to be quite mature in the near term. Adaptation and use of them in the MM design may be the lowest-cost solution. An alternate option is the use of large

diameter pressurized modules in the design of the MM, also shown in Figure 4.18. These could be launched with the SDV or HLLV. Possible advantages are weight, internal packaging, and simpler on-orbit assembly of the MM. The choice of an artificial gravity concept for the mission may influence design of the MM, the choice of power systems, etc. Trades are needed to evaluate options of pressure volume designs.

The MM might serve as a strongback for other mission equipment. Components such as the MEM, propulsive stages, and other equipment could be attached to the MM for the transit to Mars.

Mars Excursion Module (MEM)

A number of MEM conceptual designs exist (Fig. 4.19). The major divisions are: (1) low L/D concepts as shown in the two upper sketches, and (2) high L/D concepts as shown in the two lower sketches. The large aeroshell option has advantages for packaging various cargos and will provide very versatile lander delivery systems if further study substantiates its viability.

The low L/D designs are approximately 10 percent lighter than the high L/D designs and are simpler and less expensive. They may not be capable of direct entry to a specified recovery area (e.g., the Mars base) from the trans-Earth trajectory.

The high L/D designs appear to be capable of direct entry, have a wider entry corridor, a much larger footprint, and may be easier to spot-land. There is a problem keeping the g-forces in the preferred direction for human physiological considerations during both entry and ascent, however. In each concept, a portion of the MEM (ascent stage) returns to orbit, while the remainder (descent stage) is left on the surface.

CONTAMINATION CONSIDERATIONS

In addition to the usual concerns of contamination due to the natural and induced environments associated with the mission and systems, there are several special areas of concern which can have far-reaching impacts. These are discussed in Section 5. Potential impacts to vehicle concepts are mentioned briefly here. The potential for

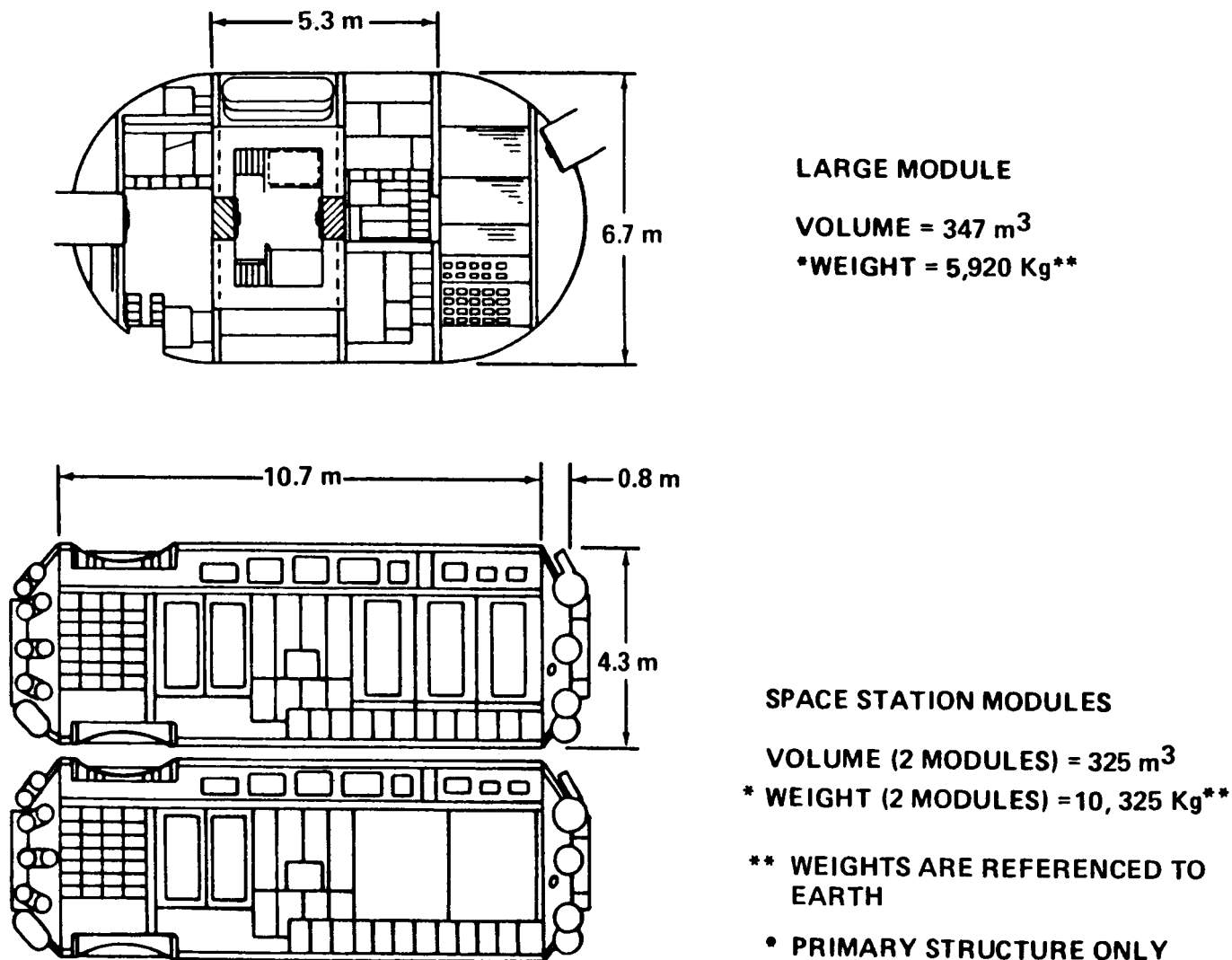


Figure 4.18. Mission module options.

biological contamination of Mars and Earth imply potential impacts such as sterilization of equipment, use of bio-locks, and quarantine areas. The potential for radiological contamination of Earth or Mars may be of concern if nuclear power and/or nuclear propulsion concepts are used. Convincing the general public of their safety is an important consideration.

4c. SUBSYSTEMS AND TECHNOLOGY CONSIDERATIONS

Technology developments in major spacecraft/base subsystems generally fall under the category of enhancing rather than enabling for MMMs.

Such a mission could be mounted with technology in hand today or very soon at some penalty in mass and possibly in risk. A number of technical developments can be identified which can substantially reduce the required mass departing LEO and/or reduce the risk. Technology status and developments are discussed in this section grouped by major subsystem. A final subsection discusses other technology needs which do not conveniently fit into the above categories.

ELECTRICAL POWER

The possible power requirements for this mission range from tens of kilowatts for an initial Mars base to multimewatts for an electrical

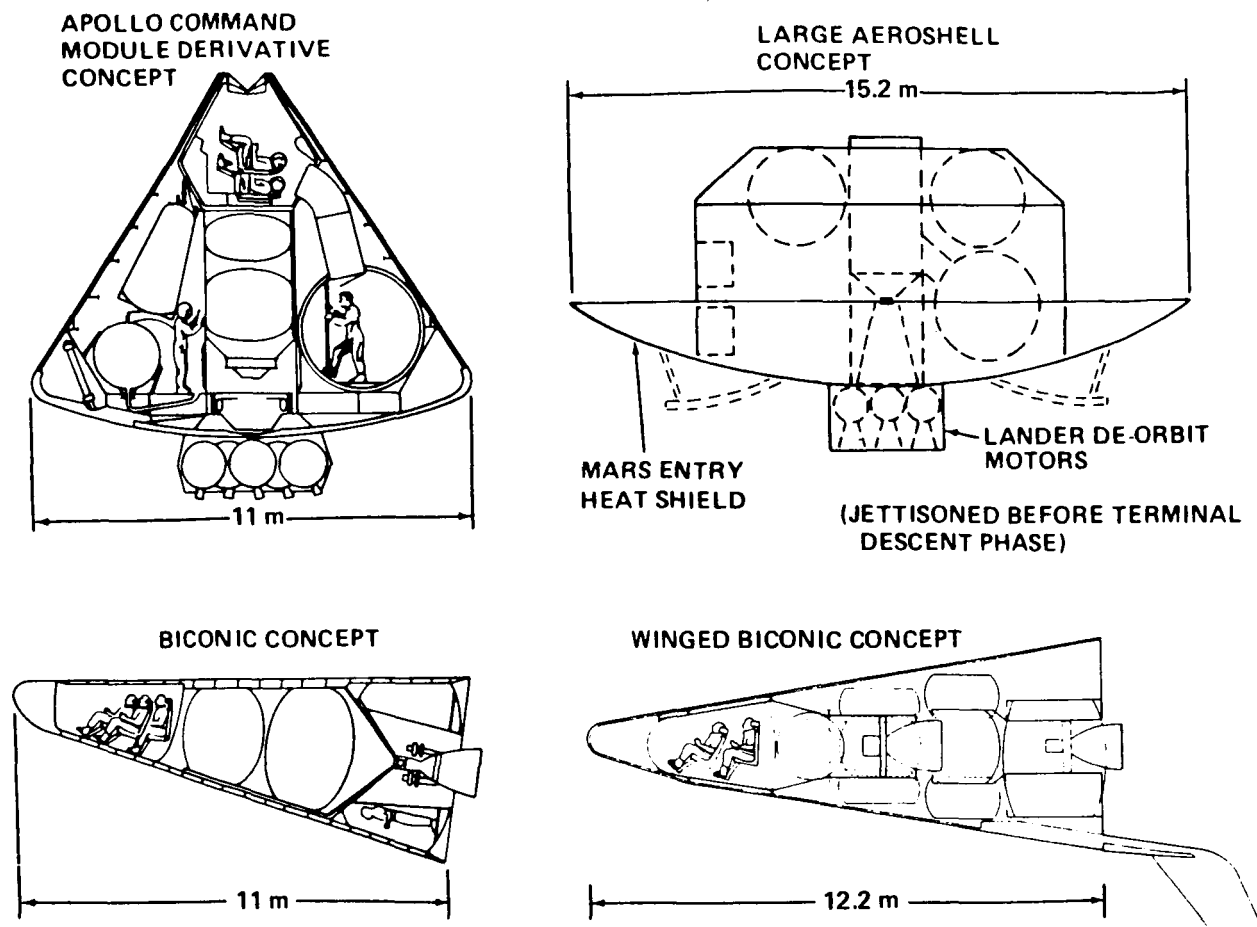


Figure 4.19. Mars Excursion Module (MEM) concepts.

propulsion transit vehicle. A number of power system options were assessed to ascertain which technologies are applicable to these various needs. They include nuclear reactor (RX), photovoltaic (PV), solar thermal (ST), isotope power sources (IPS), and open loop conversion of Mars resources. Regenerative fuel cells were considered for storage, where required. Fuel cells were also considered as a power source for a long range inhabited surface exploration vehicle.

Mission Module

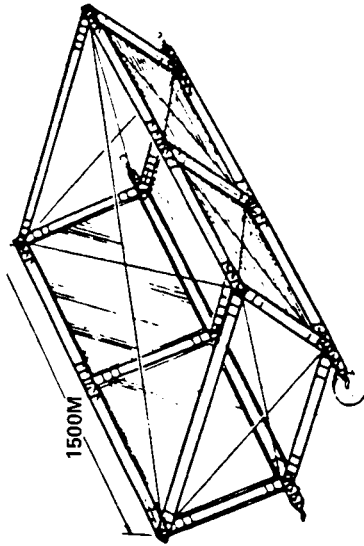
Power requirements, based on crew size, are estimated to be 25 kWe for six-person crews, assuming relatively moderate science activity during the interplanetary flight phase. Power requirements based on electrical propulsion are estimated to be 3 to 6 MWe. It may be desirable

to provide power to the surface base by placing the transit vehicle in Mars synchronous orbit and beaming power to the surface. For example, if laser transmission systems achieve an 8 percent end-to-end efficiency, 500 kWe could be supplied to a Mars base by utilizing surplus power available from a 6 MWe electric propulsion power system. Figure 4.20 shows possible transit vehicle concepts employing a variety of power system options. The actual system chosen will depend on final mission scenarios and power levels.

PV and ST systems were considered to be leading power source candidates for the transit vehicle even though lower solar intensity at Mars (0.43 relative to Earth orbit) doubles solar array or mirror size. Energy storage requirements have an even stronger influence on system weight. Power system performance for mission concepts, requiring energy storage at Earth and/or Mars orbit

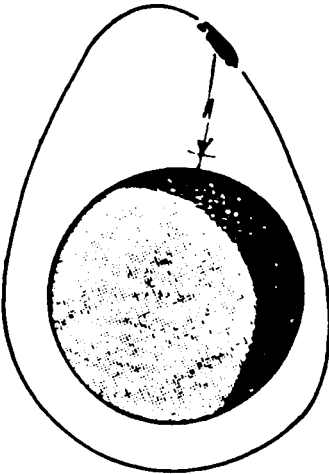
ELECTRICAL PROPULSION

300 MW PHOTOVOLTAIC

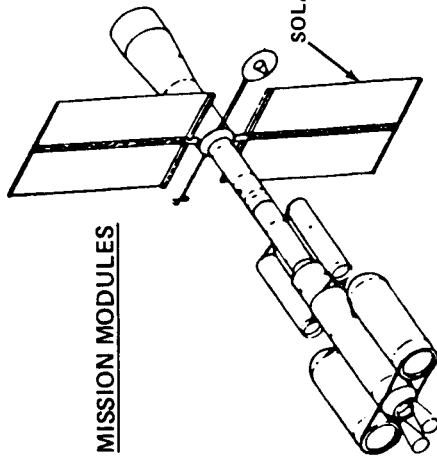


THRUSTERS

LASER TRANSMISSION



SOLAR ARRAY



6 MW NUCLEAR

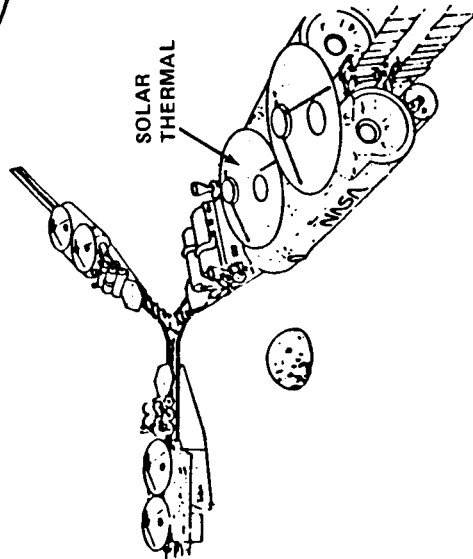
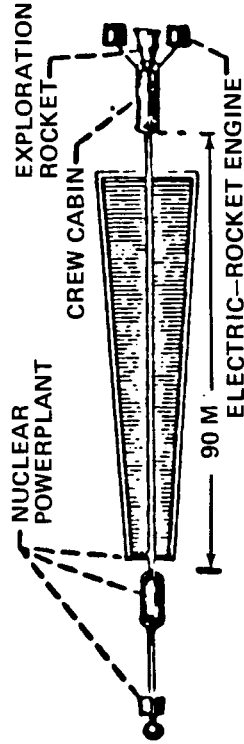


Figure 4.20. Electrical power systems.

(4 hr worst case) is estimated to be 13 W/kg referenced to Mars orbit. Throw-away energy kits at Earth departure and favorable Mars orbit conditions (5 to 15 min occultation) increase performance to 35 W/kg. Megawatt solar power systems with a performance of hundreds of W/kg may be available in the future and if so would be viable candidates for electrical propulsion. Energy storage technologies to support PV systems include regenerative fuel cells, NaS or Li batteries and flywheels. ST systems would utilize thermal energy storage.

Nuclear reactor power sources at the turn of the century, for 5 or 6 MWe electric propulsion missions, could achieve specific weights of 80 W/kg (lithium cooled-uranium nitride fueled reactors). Technology advancements (cermet fuels, boiling liquid metal cooled reactors, advanced heat rejection concepts, etc.) could increase this to 140 W/kg by the early decades of the next century. Man-rated shielding, a major portion of the weight for 10 to 100 kWe class systems, is a weak function of power level. Thus, performance at 25 kWe is 1.4 W/kg but is 13 W/kg at 300 kWe.

Isotope power systems were considered to be inappropriate for the 10 to 100 kWe power range due to cost, availability, and safety reasons. However, weight is comparable with solar power options.

Energy converters are required by ST, RX and IPS systems to convert heat energy to electrical energy. Dynamic conversion system technologies include Brayton, Rankine, and Stirling cycles, and static conversion systems include conventional thermoelectric, thermionic, and Alkali Metal Thermal Electric Conversion (AMTEC).

Mars Base

The term "Mars Base" could include fixed or mobile bases at Mars or on Phobos or Deimos, having objectives of exploration and exploitation of natural resources leading to permanent bases or even colonization of Mars. This discussion concentrates on early manned bases to be located on the surface of Mars. The Mars surface base power requirements will depend upon the level of manning and the functions to be performed. This will vary for the different phases of a program. An intermittently manned base is postulated to consist of a small contingent, possibly four persons, with a

minimum of operational power requirements and may include an in-situ propellant production plant (ISPP) or an in-situ water production plant (ISWP). Such a plant would remain operating during the interval between missions, producing propellants or other consumables, in preparation for the next mission. Because of the low production rate required (two years between missions), the power requirements are modest (5 to 25 kWe). In the subsequent phases of the program, as the base is expanded in size and functions, the power requirements could increase to possibly hundreds of kWe, or even to the megawatt range, especially if large ISPPs and/or ISWPs evolve toward self-sufficiency. Power source capacity could be increased by: (1) adding modules to existing power systems (2) large step increases from the introduction of larger power units; or (3) conversion of Mars resources into electrical energy.

Initial requirements in the 10 to 25 kWe range may be met by PV or ST systems augmented by an isotope system for night time operation (6 W/kg). However, the Mars environment (dust, wind, reduced solar intensity, 0.3 g, deployment over rough terrain, 12-hr nights, and the CO₂ atmosphere) poses severe design challenges. Nuclear reactors, buried for radiation shielding (15 to 25 W/kg), are an attractive option and are not affected by long night periods or reduced solar intensity. However, the inherent long range advantage of utilizing solar energy or other natural Martian resources, such as wind, Mars-thermal, and superoxides, deserve further study. Figure 4.21 depicts the options investigated for the Mars surface base power.

For a fixed base with expanded sortie operations, Mars surface exploration via surface vehicles or possibly airplanes will be needed. One concept for a large inhabited mobile laboratory with 100-km range and 5-days duration capability suggested that H₂-O₂ fuel cells are viable options to power such a vehicle. The H₂-O₂ fuel cell system may be integrated with the vehicle life support system to provide breathing and cabin makeup oxygen for the crew from the O₂ reactant tanks. Other fuel cell options or open loop engines may also be viable for this application pending further study.

The power systems for Mars include high performance conditioning and distribution equipment to support megawatt size electric propulsion

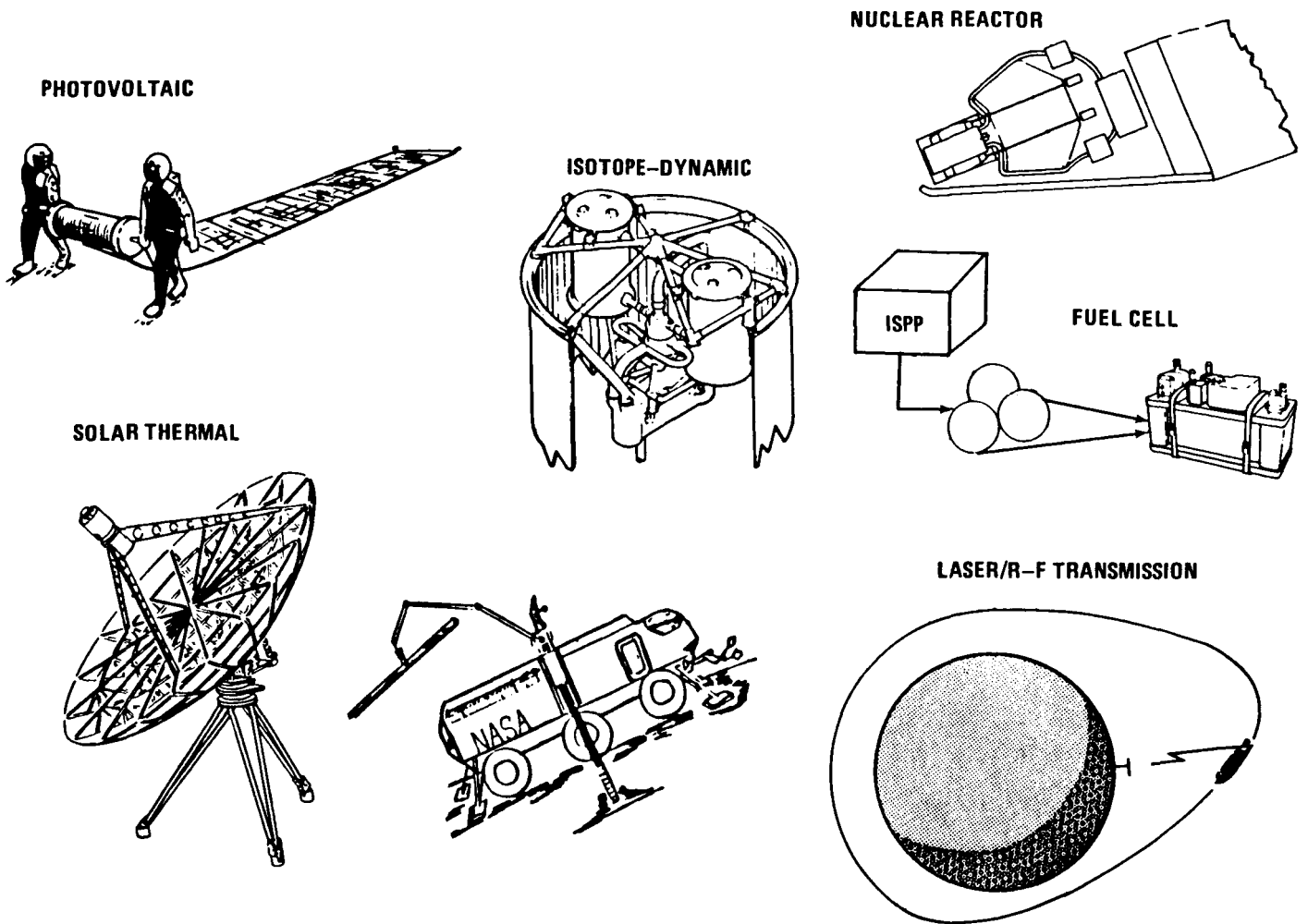


Figure 4.21. Electrical power systems for Mars lander.

systems and autonomous power management systems to support long unattended operations on the Mars surface.

PROPULSION

The ability to move payloads from place to place in space is fundamentally dependent on the capability to control and apply energy. The practicality of any propulsion concept is determined by the size, mass, efficiency, and cost of the method of energy conversion from its initial form, such as high-temperature combustion gases or high-energy nuclear reactions, to the production of force or thrust. The historical dependence of transportation progress on advancements in propulsion technology also has its analog in space.

The nature of a manned Mars program will no doubt require advancement in chemical and other propulsion concepts. Chemical propulsion is presently the most mature propulsion technology.

Because of this, present expectations are that advanced all-chemical concepts will be the basis for the primary propulsion systems of the early Mars SVs. Other advanced propulsion concepts (nuclear, electric, etc.) are desirable for improved SV efficiency, but their development will be more extensive and will require more time and funding than that for all-chemical concepts. Advanced all-chemical propulsion concepts are needed for ETO vehicles, for some OTO vehicles, and for Mars ascent and descent vehicles, no matter what technology is used for primary propulsion of the SVs. Figure 4.22 shows a relative performance comparison of propulsion concepts with respect to important vehicle design parameters.

In most cases, propulsion concepts to the left of the dashed line result in unsatisfactory trip times for a MMM because of insufficient vehicle acceleration. However, these advanced propulsion concepts could be enhanced if combined with a nuclear or chemical boost from LEO.

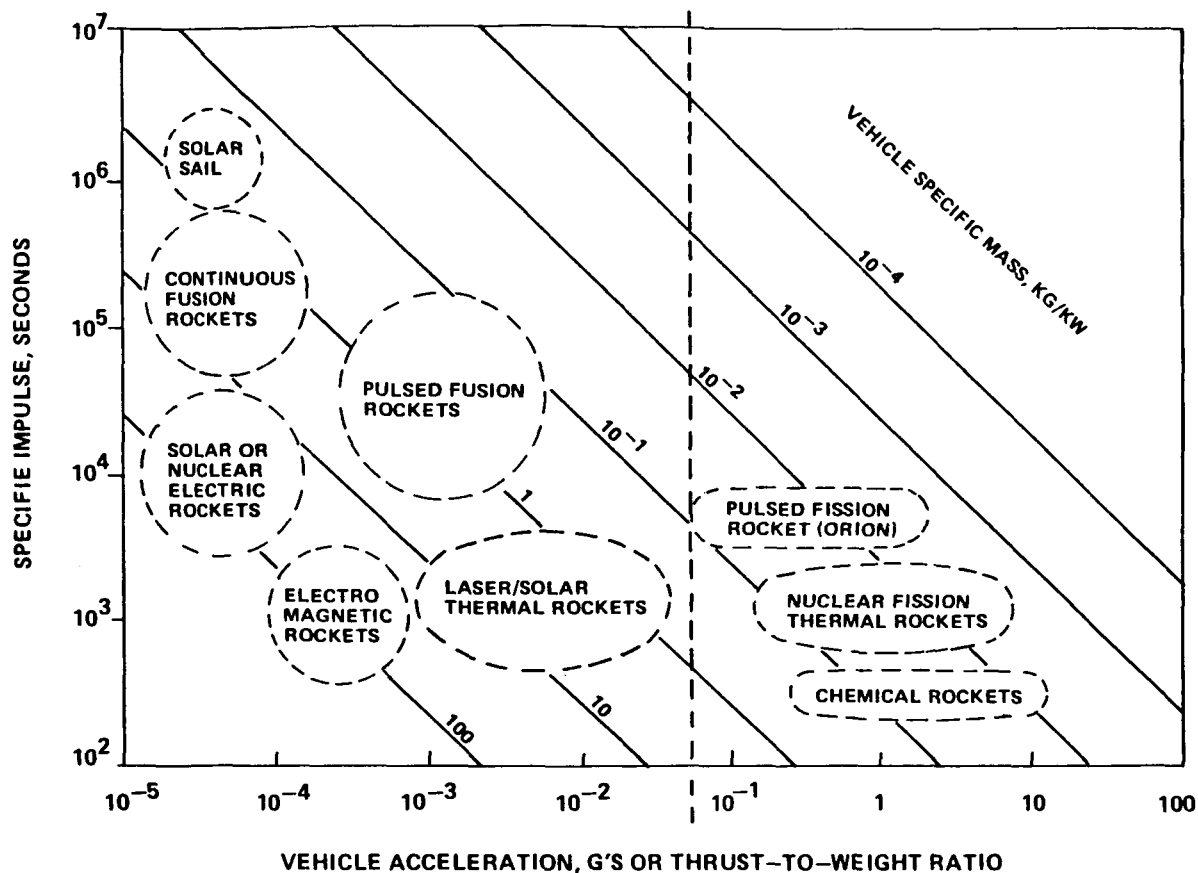


Figure 4.22. Propulsion concepts.

Therefore, the major propulsion options could be reduced to the following: (1) Chemical; (2) Nuclear fission (thermal or electric conversion); (3) Chemical boost with advanced upper stage concepts; and (4) Pulsed nuclear fusion or anti-proton concepts (for longer-term development). (Note: High energy concepts still require chemical ETO and Mars landing/ascent propulsion.)

Advanced non-chemical propulsion concepts fall into two categories: (1) those that can be developed in the near future using today's design level technology, and (2) those appearing to be physically realizable extrapolating from today's technology, but for which detailed design data do not exist. The first category includes nuclear thermal, nuclear electric, and MPD concepts. The second category includes the solar sail, pulsed fission rocket, pulsed fusion and antimatter concepts.

CHEMICAL PROPULSION

The chemical rocket engine is about 50 years old. Its latest application in the Shuttle Orbiter requires that its near ultimate theoretical potential

be realized in practical application, especially with respect to efficiency and endurance.

Chemical propulsion technology as manifested in actual hardware such as the Space Shuttle Main Engine (SSME), the RL-10 (Centaur), the throttleable Lunar Module Descent Engine, and others are adequate to support MMMs today. Specific new developments involving the latest technology but derived from these antecedents would be desirable for the all-chemical or chemical boost. New developments in chemical propulsion would be powerful enhancements. Alternative propulsion options of higher performance are also of interest.

Recent all-chemical propulsion system design work for Mars SVs has centered primarily on cryogenic concepts, utilizing liquid oxygen/hydrogen as propellants. Advanced engine candidates include the Space Transportation Main Engine (STME) 625 (Space Shuttle Main Engine (SSME) derivative) for Stage 1 engines and the advanced expander cycle engine (RL-10 derivative) for Stage 2 and Stage 3 engines. Advancements incorporated in these engines include longer lifetime, higher Isp (up to 482 sec), and extendable nozzles.

A storable propellant option utilizing nitrogen tetroxide/monomethyl hydrazine propellants has been pursued as a potential approach for alleviation of the cryogenic propellant boil-off problem: however, the storable propellant option has a significantly greater vehicle weight (about a factor of 3) than the cryogenic option, due to the lower Isp (up to 346 sec).

Recent studies of MEM descent/ascent propulsion systems has centered around engine types and propellant combinations which are close to the state-of-the-art. Two engine designs were evaluated, both utilizing two-position nozzles. A LOX/MMH concept which had an Isp of 361 sec and a vacuum thrust of 40K lbf was examined. Quantities of LOX boiled off in the vicinity of Mars and on its surface can become sizeable over a period of time (although the LOX boiloff is not as great as the LH₂ boiloff associated with all-cryogenic vehicles). Consequently, an all-storable-propellant MEM concept was examined, utilizing N₂O₄ and MMH. Here, an Isp of 329 sec and a thrust of 178 kN was utilized. This concept, of course, is heavier than the first concept, because of the lower Isp. The MEM engine, whether for storable or cryogenic propellants, would be a new development, but would make use of existing or near-term technology.

The use of aerobraking on Mars missions would allow significant reductions (up to 60 percent) in SV weight compared to all-propulsive cases, hence, this technology should be pursued. Aerobraking technology is expected to be advanced as part of the OTV development activity, and this will be supportive of the needs of MMMs.

Nuclear Thermal Propulsion

The ability of the United States to field manned missions to Mars will be greatly enhanced if an advanced propulsion system can be utilized. Substantial advantages such as reduced vehicle mass or transit times can be realized by use of the NTR.

The NTS was thoroughly tested in the NERVA program in the 1960's. Consequently, a large data base exists which would allow a rebuilding of the NTR so that new development could be kept to a minimum. Development of the flight-ready engine was just beginning in 1972 when the NERVA program was discontinued.

The NTR operates by passing liquid hydrogen through an operating nuclear reactor where the hydrogen is heated and ejected out through a nozzle as shown in Figure 4.23. Temperature differences and chemical effects of the different phases of hydrogen are major difficulties of NTR operation. Major objectives of a new program would be to re-examine (1) the corrosion of the nuclear fuel elements due to hydrogen interactions, (2) hot, hydrogen gas-driven turbopumps for the LH₂, and (3) hydrogen-nozzle interactions.

The other major area of development would be in the nuclear fuel. The original fuel of uranium carbide in a graphite matrix had an operating temperature limit of just over 2000°C and tended to abrade into the hydrogen stream. The possible use of uranium carbide/zirconium carbide fuel was conjectured in the early 1970's and may possibly allow higher operating temperatures (peak Isp equal to 975 sec) and reduce the corrosion problem. Reduction of the corrosion rate will reduce the radioactivity in the exhaust stream which will aid in the testing of the engine.

Most of the testing of a new NTR could be performed at a revitalized Nevada Rocket Development Station (NRDS). Substantial facilities such as the post-burn processing building and large 500,000 gal LH₂ tanks still exist and can be refurbished. Due to constraints on radioactivity emissions, however, actual full power tests will probably be performed more easily at the Johnston Atoll in the Pacific Ocean.

The Johnston Atoll offers a remote test area removed from human settlements, an existing infrastructure in the form of a military base, an active airstrip and shipping port, and less stringent radioactivity release limits. The costs of developing a Johnston test facility (5 billion dollars, 7 to 10 years) do not appear to substantially increase the total program cost of rebuilding a NERVA type engine. A more thorough study of the possible economic gains, the space operations requirements, space and Earth safety provisions, and materials availability constraints should be completed before a decision on using an NTR is made.

Another technological development with a large potential payback is the concept of using the NTR in the dual mode, that is using the NTR reactor to produce electricity for vehicle power during the flight. Furthermore, sufficient power could possibly be generated to power electric

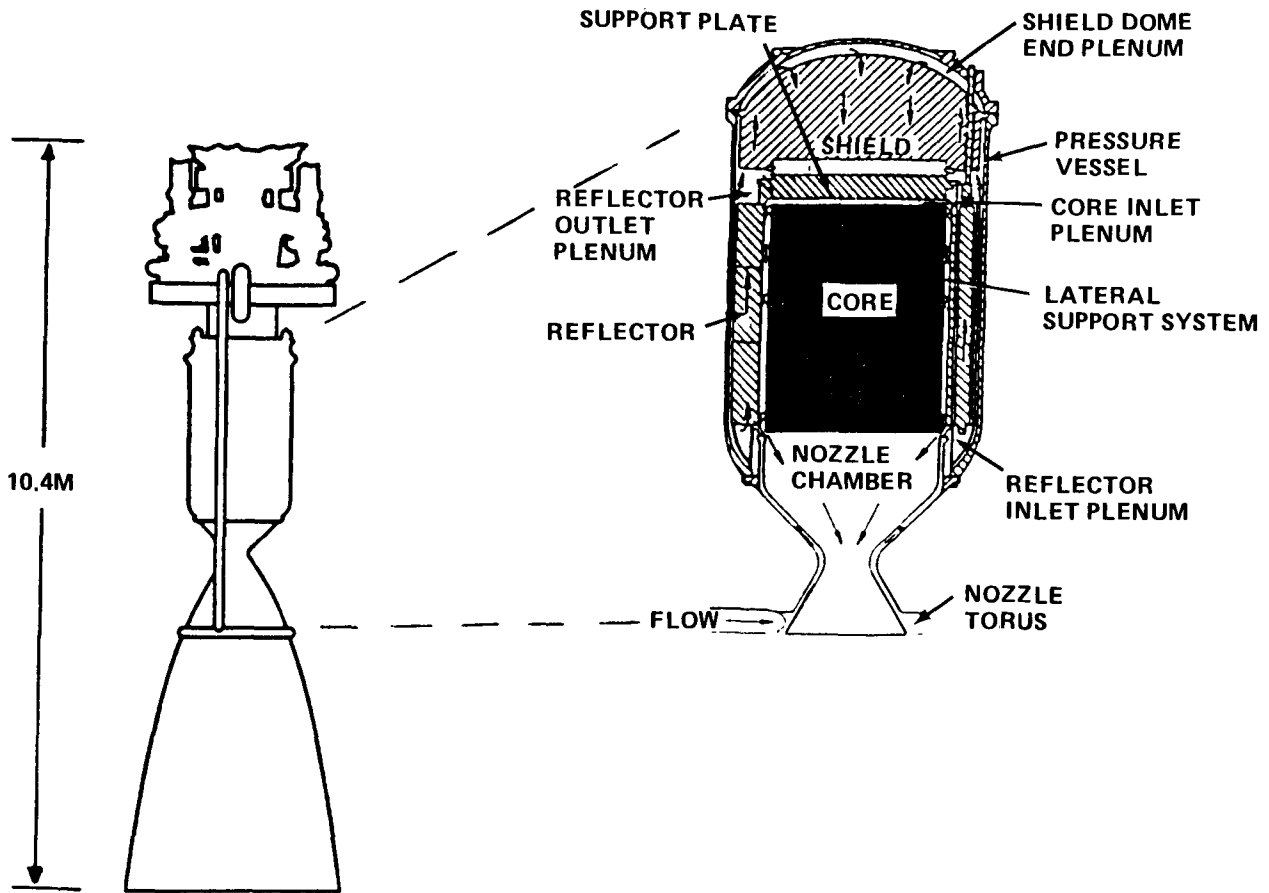


Figure 4.23. NERVA engine.

thrusters. The combination of impulse and electric propulsion may provide the lightest and fastest trip to be made to Mars.

Nuclear Electric Propulsion

Electric propulsion systems have not been seriously considered for use with large spacecraft due to the lack of a suitable electric power source to drive them. However, recent efforts to develop megawatt-class space power sources show such systems to be technologically feasible. A multi-megawatt lightweight nuclear electric power plant driving an electric propulsion system, such as a MPD or ion thruster, make this an attractive propulsion system. Pegasus, a power generating system for use in space, is one such multimegawatt power system that would enable missions of almost any conceivable duration and scope, including MMMs.

Pegasus, the proposed power source for this electric propulsion system, employs a direct Rankine power cycle with an output of 8.5 MWe and a total mass of 36,500 kg. The power system

is designed to meet the electric power requirements of up to 6 MWe available for mission specific tasks and experiments. This system is expected to have a specific power density of approximately 5 kg/kWe. The size and mass limitations of the STS are a prime consideration in the design of this system to allow the collapsed system to be placed in LEO by two shuttle missions. Once in orbit, the system would be deployed to its full dimensions. Development of this power system could be completed by the mid 1990's and the system could be available near the turn of the century. Being an advanced system concept, some development efforts are still needed in the reactor fuels, heat rejection, and turbo-alternator areas. The five major components of Pegasus are: (1) a cermet fueled, boiling liquid metal fast reactor producing 30 MWt; (2) a four-pi contoured man-rated reactor shield; (3) two 5 MWe axial flow turbines and superconducting alternators for power conversion; (4) a series of transformers and rectifiers for power conditioning; and (5) a heat rejection system that employs a bubble membrane radiator. A schematic diagram of the system is shown in Figure 4.24.

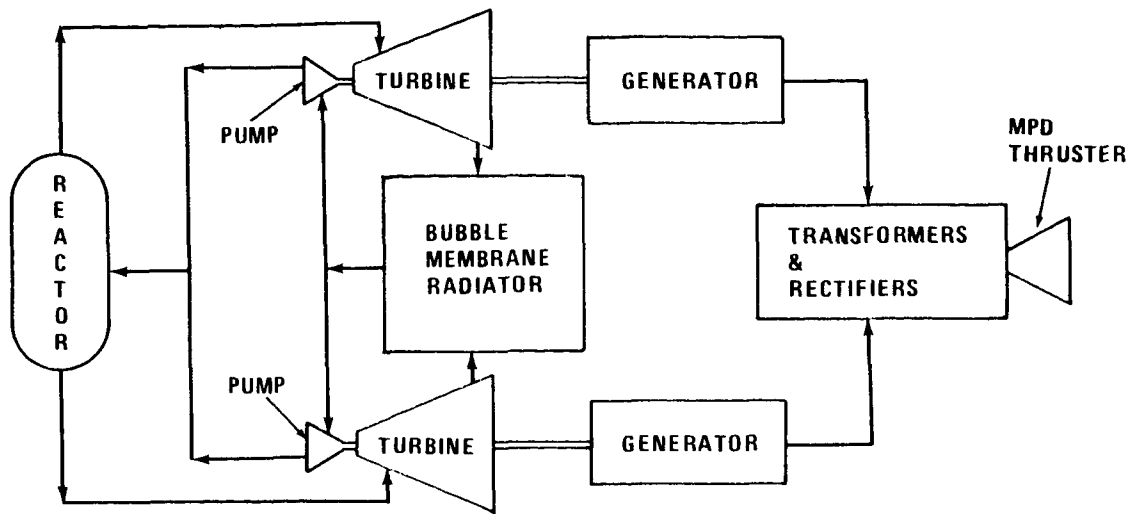


Figure 4.24. Pegasus schematic diagram.

Magnetoplasmadynamic Thruster

The MPD thruster system (Fig. 4.25) is a multimewatt, steady-state propulsion device providing 50 to 150 Newtons of thrust at specific impulses of 1500 to 8000 sec. When driven by a light-weight power supply, this engine can transport a large payload to Mars and, due to the high specific impulse, use from 1/3 to 1/10 as much propellant as a conventional all-propulsive chemical system. The MPD thruster uses a magnetic body force induced by a large radial current to

accelerate an ionized propellant to high speeds. Present experiments demonstrate a 35 percent conversion efficiency of input power to direct kinetic energy in the exhaust at 3000 sec specific impulse, while analyses show that 50 to 60 percent is ultimately possible. The difference between 35 percent and 60 percent efficiency primarily affects the burn time required to conduct Mars missions. Since burn time is roughly inversely proportional to efficiency for a given mission, efficiency improvements can (1) reduce lifetime requirements, and (2) shorten trip times to Mars.

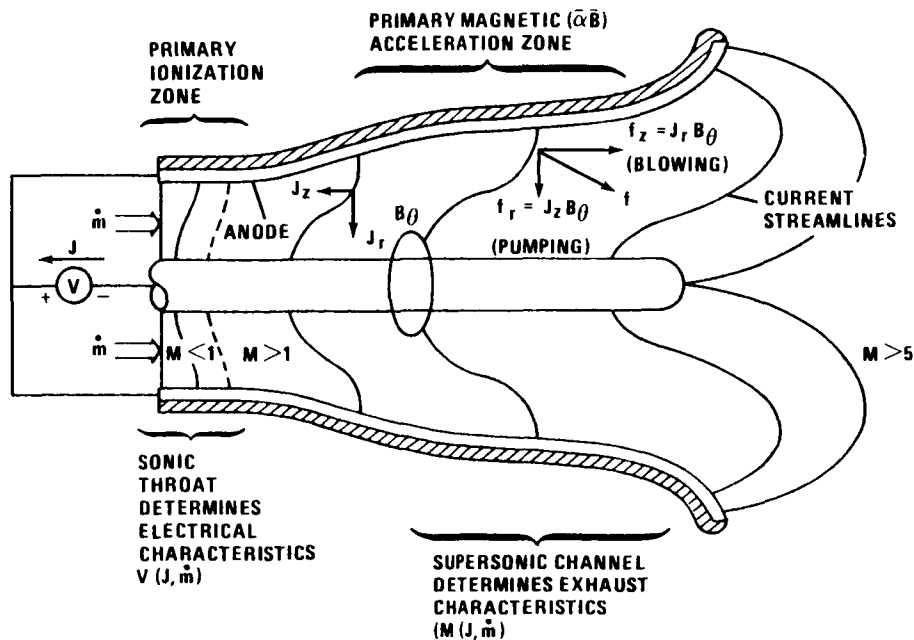


Figure 4.25. MPD thruster.

The lifetime requirements for MMMs are thousands of hours but no data yet exists to permit projections of the life of an engine. Erosion of the insulator and electrode material by the hot plasma exhaust is a concern that is under study. At present, the efficiency and lifetime of the MPD thruster are either undetermined or insufficient to support Mars missions. A well-planned development program should correct these deficiencies in time to support the mission.

Engineering requirements for the MPD thruster system include power conversion equipment and heat removal from the 1600°K anode. The anode dissipates about 300 kW of heat either to radiators or fluid that is recycled to the thermal-to-electric conversion system. The MPD thruster requires about 240 Vdc and 25,000 Adc. Multi-megawatt nuclear power supplies with rotating machines are well disposed to produce 1500 Hz, 3 phase, 10 to 20 kV power. The high voltage power may be distributed with relatively low mass cables to transformer and rectifier, both of which need to be developed.

Anti-Proton Propulsion

Within the next 20 to 30 years, the concept of using an anti-proton engine should begin to be considered. Projections suggest that perhaps one gram of anti-protons per year could be produced world wide by the year 2010 (Fig. 4.26). With priority effort, this milestone could occur earlier. Since estimates suggest that about 100 mg could perform the currently envisioned Mars scenario, the problem is not one of production but one of storage.

Anti-proton engines rely upon the large energy release when anti-protons interact with normal nuclei. High pressures, temperatures, and radiation fields will be inherent in such an engine. Intense magnetic fields will also be necessary for containment of the plasma. The plasma is generated by heating a LH₂ mass to a few eV temperature using the anti-proton interactions. Within the next two years, an experiment will be performed which is designed to trap and store over 10¹⁰ anti-protons in a Penning trap. The Penning trap has been used successfully for containment of other nuclear particles and eventually may provide a source of low energy anti-protons for researchers in laboratories. Storage of anti-protons is clearly

the first major technological development required for development of a propulsion system.

Another major objective is to utilize the anti-proton efficiently in an engine or to enhance the amount of energy deposited in the propellant for each anti-proton used. One technique, recently proposed, is to use the concept of muon-catalyzed fusion in conjunction with the anti-proton energy release. Negative muons will result from the decay of the pions produced in the anti-proton interaction. Experiments have shown that the muon will catalyze fusion of deuterium and tritium atoms. Employing this phenomenon in the anti-proton engine may yield five times as much energy per incident anti-proton than the annihilation reaction alone. Techniques such as this require complex computer code development and experimental work to determine their feasibility. The possible advantage of an anti-proton engine are so great that support of research in this area is clearly justified.

LIFE SUPPORT

For long missions, a reliable integrated life support system can enhance crew safety and survival and also reduce the amount of consumables that must be carried from Earth. The ability to close or partially close the system by recycling air, water, and possibly food is of great importance.

Four major components and two developmental areas are recognized as vital to the creation of a regenerative life support system. Components include: (1) atmospheric regeneration, (2) food production, (3) waste management, and (4) food processing. Development areas include (1) engineering and control technologies, and (2) analytical and monitoring capability.

A Controlled Ecological Life Support System (CELSS) development program is required that will not only build on the active basic research conducted over the past several years but will also fabricate, test and operate ground-based facilities to accomplish proof-of-concept testing and evaluation leading to flight experimentation.

This systems level test and development should include three phases. The first phase would include integrated system development in a closed chamber. In phase two, a new facility capable of

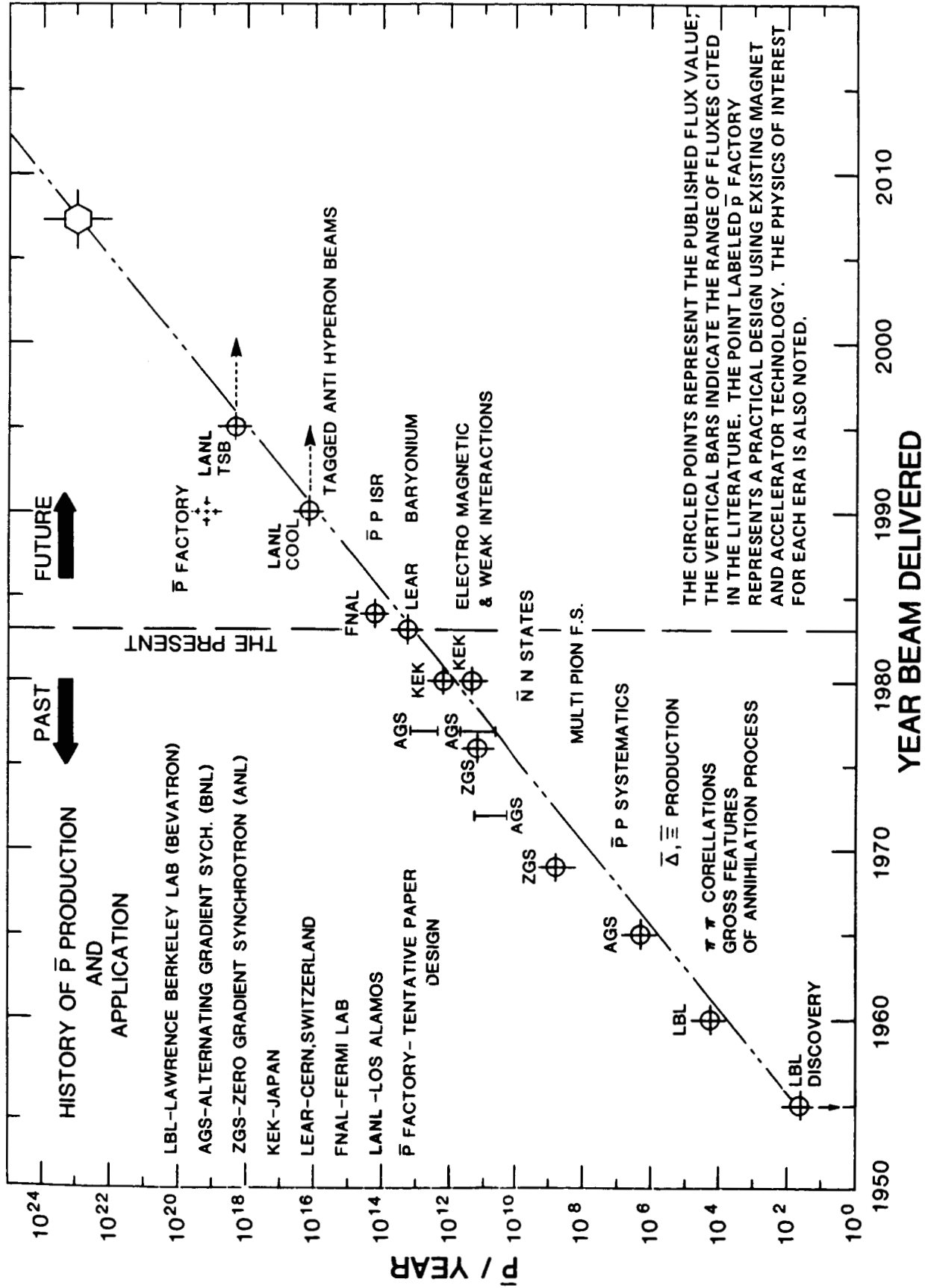


Figure 4.26. Annual antiproton production versus year for most high-energy physics facilities around the world.

integrated manned testing would be developed. The final phase would center on the construction of a CELSS module to be flight tested.

In the first phase, candidate technologies and systems should be tested and refined until a system is proven effective and feasible to continue to the next phase. Examples of technologies for development include supercritical water oxidation technology and plant growth in space environments. Supercritical water technology can be used in a CELSS for carbon dioxide removal, partial humidity control, trace contamination control, water reclamation, nitrogen generation, and ultimately trash and garbage reduction. Plants can be used as a source of food and for carbon dioxide removal and oxygen generation. Other physiochemical subsystems will also be necessary to close the system as much as possible.

In phase two, two six-month tests are proposed with man in the system. At the conclusion of this testing, a refined CELSS should be developed that has the efficiency and reliability to make it a candidate for space use.

The final phase would be manned flight testing of a full blown CELSS supported module. The ultimate product of this phase (and the entire program) will be a functioning, reliable, and useful CELSS that will play a central role as man attempts to extend his presence in space.

COMMUNICATION AND DATA MANAGEMENT

The requirements for the communication and data management systems to support MMMs are largely dependent on the ultimate mission objectives, mission duration, and the number of vehicles involved. Key issues regarding the space communications system include data rates, frequency, communication coverage, security and the distribution of audio, video, and other high rate data internal to the vehicle.

The data rate requirement is a major factor in determining the total communication system architecture, the sizing of the spacecraft antenna and RF power systems, and appropriate technologies. Data compression should be used to avoid the transmission of redundant or unneeded data. Depending on data rate, frequency options for communication links between the Earth and Mars

include S/X band, Ka-band, and optical frequencies. At present, a Ka-band system appears the most attractive for moderate data rates in the 50 to 100 Mbps range.

Depending on communication coverage requirements, communication links between a Mars base and the Earth may be direct or relayed. Direct links between Mars and the Earth provide approximately 50 percent coverage. Alternatives for providing more coverage include the establishment of a network of communication relay satellites in orbit around Mars and use of a combination of direct and relayed links.

Data system issues include the degree of automation/autonomy and the data system architecture. MMMs will involve small crews and many complex tasks. The productivity of the crew and the entire mission will depend to a large degree upon the effective automation of these tasks and the ease with which the crew can interface with the automated processes. The selection of a data system architecture involves many options and trades in the following areas: processing architecture, number and functional use of the physical data buses, bus or network topology, data bus medium, and on-board data bases.

The communication and data system technology required to support MMMs exists today; however, the evolution of software and electronic technology is making available many interesting options with a potential for increased mission productivity and safety while reducing life cycle cost. These advanced technology areas include fault and damage tolerant distributed data systems, on-board data reduction/processing techniques, man-machine interfaces, laser communications, and reliable high-power RF amplifiers.

STRUCTURE AND MATERIALS

SV structural systems, with the possible exception of aerobrakes, are well understood and do not represent limiting technology for MMMs. The overall structural challenge is to provide structural designs that are light in weight with high strength and reliability, and to develop and utilize better and faster analytical capability. Table 4.2 shows the relative ranking for some of the structural elements of a MMM, with 10 indicating the area where technology improvement is likely to

TABLE 4.2. TECHNOLOGY EMPHASIS

<u>Item</u>	<u>All Propulsive</u>	<u>Aerobraking</u>
Trans-Mars injection stage	3	2
Mars braking stage	5	7
Mars departure stage	6	6
Earth braking stage	9	10
Mission Module (MM)	10	10
Mars Excursion Module (MEM)	10	10

provide the greatest benefit to the program. The areas of greatest dynamic interaction, such as aero-brake structure, will benefit greatly from new materials and structural design and analysis techniques.

Much advancement with composite materials has been made recently that allows for lighter and stronger structures. Figure 4.27 shows a projection of weight reductions that can be expected through the year 2000, due to the introduction of new materials. This suggests that improvement in performance can be expected over that shown in analyses presented in earlier sections of this report.

THERMAL CONTROL AND THERMAL PROTECTION

Cryogenic Systems

The Mars mission transit vehicle experiences several different environments. They include LEO buildup, interplanetary transit, and Mars orbit and surface environments. The thermal protection system (TPS), thermal control system (TCS), and fluids acquisition system of a cryogenic vehicle must withstand each environment. Active and passive TCS are available to minimize cryogenic boiloff.

Minimizing cryogenic propellant boiloff in all mission phases is an important issue. Insulation performance, active TCS support structure requirements, and zero-g propellant transfer are major issues in LEO. Cryogenic boiloff will be relatively high in LEO (based on current technology systems) due to environmental heating and vehicle tank sizes. Figures 4.28 and 4.29 show heat flux versus multi-layer insulation (MLI) thickness (passive system) and MLI optimization for all the cryogenic stages in LEO (MLI optimization may vary with vehicle configuration). During vehicle transit and Mars orbit, reduction of environmental heating through preferred orientation is a key issue. Vehicle orientation may need to be varied to meet

STRUCTURAL WEIGHT REDUCTION

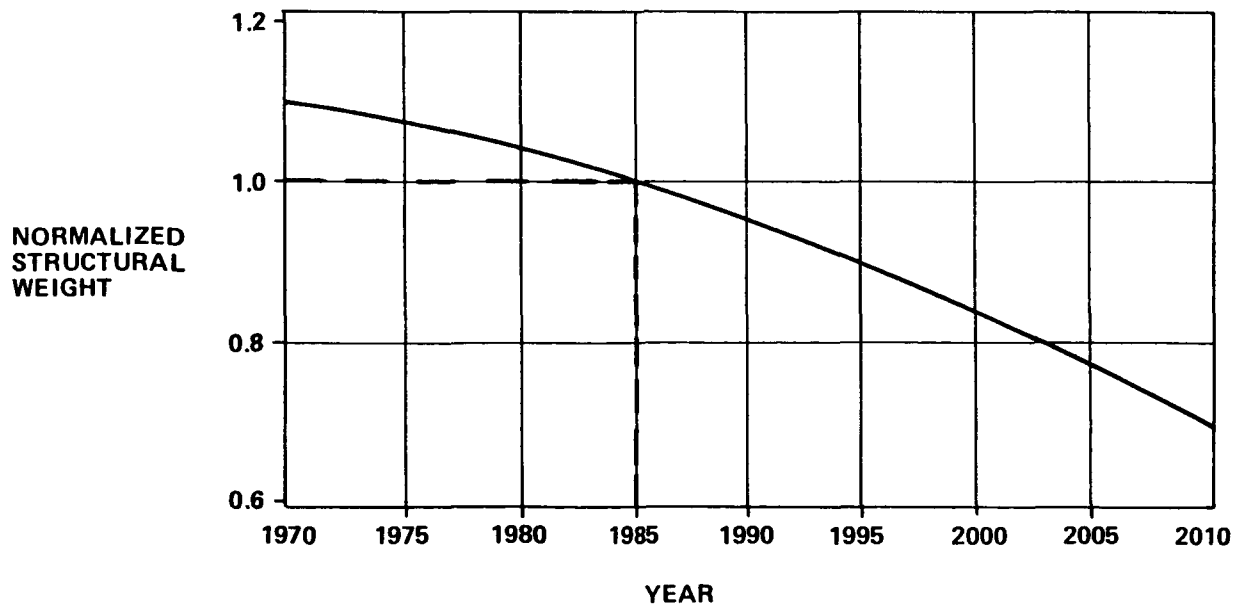


Figure 4.27. Projection of weight reduction.

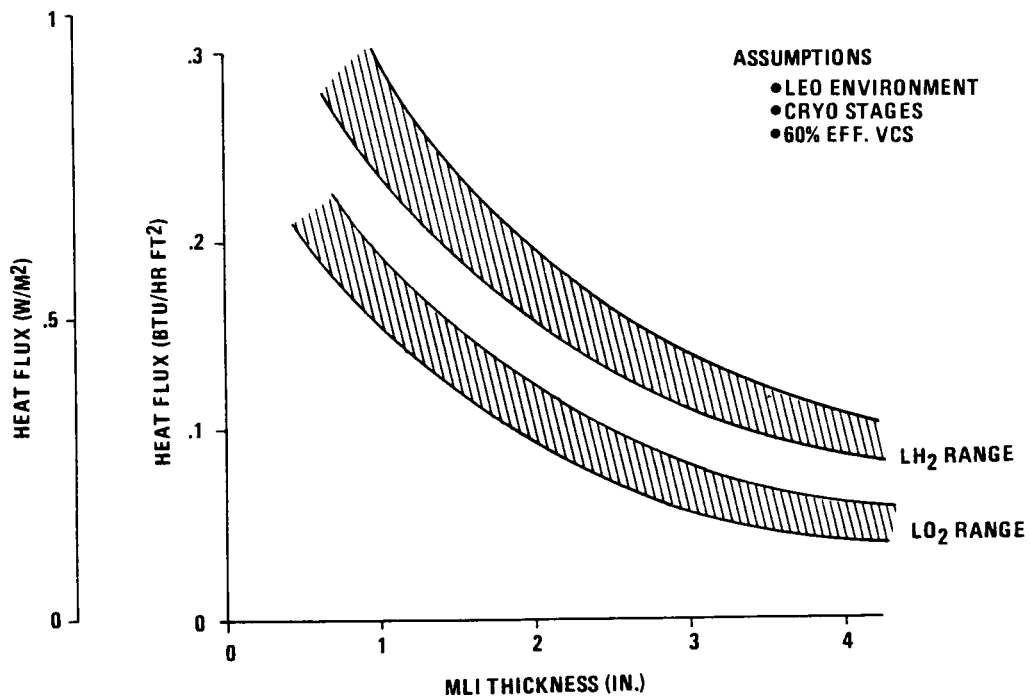


Figure 4.28. Mars transit vehicle heat flux versus MLI thickness.

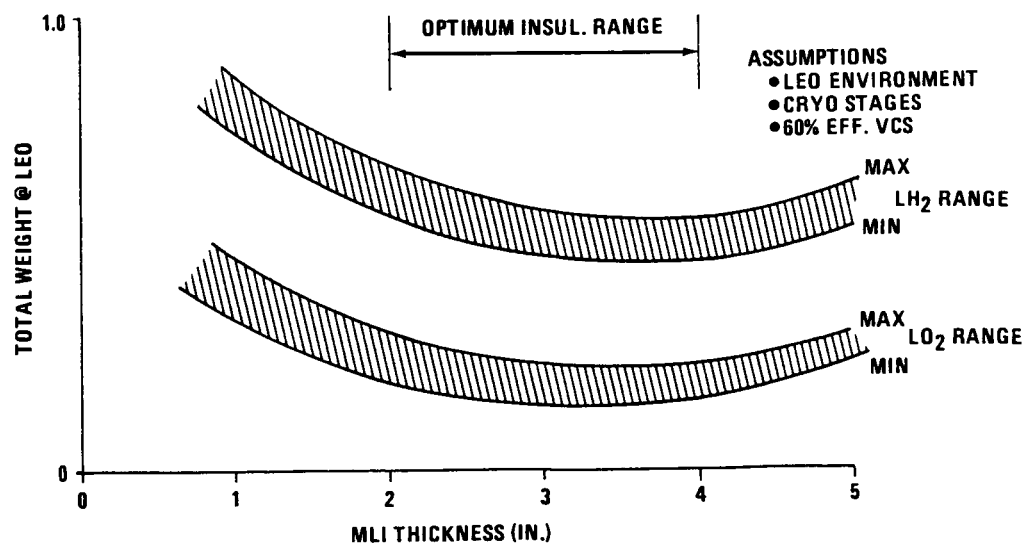


Figure 4.29. Mars transit vehicle typical insulation optimization.

mission requirements and must be considered in overall TCS design.

Advanced active TCS and the utilization of it, and further development of passive TCS and fluid systems for zero-g fluid transfer represent technology drivers in the development of all-cryogenic MMMs.

Spacecraft and Base Thermal Control

In general, thermal control of the spacecraft proper (environment for crew and electronics) will employ SS and Space Shuttle techniques. Operations on the surface of Mars will differ from those in space and must take into account convective cooling by the atmosphere as well as radiation for heat rejection. The reduction in the ability to reject heat by radiation during dust storms must be considered in the design of the system. Possible degradation from dust on heat rejection surfaces must be considered.

Entry System Thermal Protection

Systems which enter the Martian atmosphere out of Mars orbit can use light ablator material or possibly reusable insulation (Shuttle technology). For aerocapture from a hyperbolic trajectory at minimum energy, current technology ablators and possibly advanced reusable insulation could be used. Aerocapture at Earth from minimum energy trajectories will probably require denser Apollo-type ablators. Some proposed mission profiles involve quite high entry velocities for aerocapture at one or both planets. Such operations would probably require new developments in entry thermal protection.

Radiators

Rejection of waste heat to space via radiators is normal practice and for moderate heat flux and temperature, current technology will suffice. The problem is entirely different for high energy and/or high temperature systems. Spacecraft system studies have shown that heat rejection systems are a major weight and volume contributor to any thermal management or power system. The amount of waste heat that can be radiated by these systems is directly proportional to the fourth power of the absolute temperature of the radiator.

Future heat rejection radiators will strive to increase their efficiency through higher operating temperatures, while decreasing system masses and size, and improving deployability. One innovative approach to the problem of space based heat rejection is a class of radiators referred to here as Rotating Bubble Membrane Radiators (RBMR) as shown in Figure 4.30. The RBMR is an enclosed two-phase direct contact heat exchanger and consists of a thin film envelope rotating about a central axis.

The development of the RBMR will require new light-weight, high-strength membrane and structure materials, meteoroid protection and tear mitigation techniques, and selection of working fluids to optimize the radiator design to its particular application.

ADDITIONAL TECHNOLOGY

Technologies related to the Mars Airplane, such as improved low Reynolds number aerodynamics, improved performance non-airbreathing engines, and enhanced guidance capability (e.g., landmark recognition and correlation tracking) could greatly enhance the capability of this most useful vehicle.

Rover development, eventually trending towards longer duration sorties in shirt-sleeve environments, is of great interest. Wheeled or tracked vehicles are and probably will remain superior for most terrain. However, walkers may offer considerable enhancement in soft or very steep or rough conditions.

Better understanding of the behavior of spacecraft connected by long flexible structures (light-weight beams or tethers) will be very helpful if rotation-induced artificial gravity is required.

Further study is needed for aeromaneuvering capabilities and capabilities and requirements for guidance and control of aerocapture and aeromaneuvering vehicles as well as target planet centered navigation of such vehicles. This is crucial to ability to hit very tight entry corridors as well as to accurately hit desired surface landing targets within 2 to 5 km accuracy. An allied issue is that of aerodynamic design of such vehicles.

The ability to produce propellants and life support consumables from Martian resources is vital to long-term habitation and free access to the

entirety of Mars, and will substantially reduce mass departing Earth orbit. Even highly efficient nuclear deep space transport concepts can benefit from Mars-produced propellant used by Mars ascent

vehicles. Development of highly efficient, reliable and long-lived systems, starting with systems to derive water and oxygen from materials of Mars and Phobos/Deimos, is required.

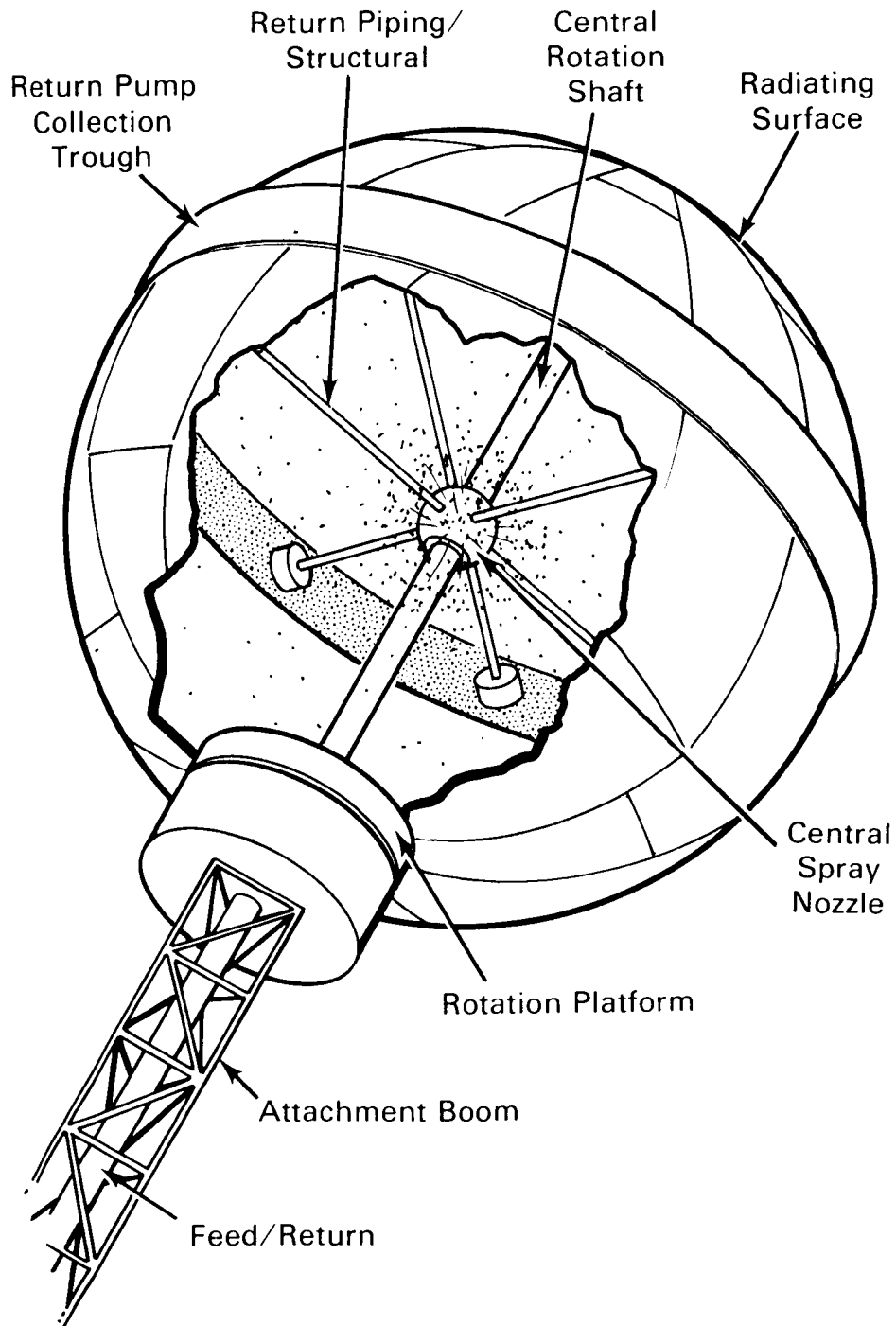


Figure 4.30. Rotating bubble membrane radiator.

5. LIFE SCIENCES

INTRODUCTION

A manned mission to Mars will challenge the human capacity to solve problems and cope with extreme environments. Such long durations of weightlessness have not yet been experienced. Never before has medicine been called upon to certify that an individual will be healthy enough to perform full duty for two years following the examination. Life support systems must prevent the long-term buildup of toxic chemicals. Psychological issues and man-machine interfaces may emerge as important considerations. Radiation exposures could exceed those on the Apollo missions by orders of magnitudes. These subjects are all addressed in this section, but it should be emphasized that before proper engineering tradeoffs can be made, more information is needed. The SS will provide an ideal laboratory in which to conduct most of these investigations.

The biomedical problems that need to be addressed for missions of 600 days or more are ultimately related to crew performance and safety. The minimum acceptable standards should insure survival; however, the system should promote enhanced crew productivity and adaptability along with a safe return to the gravity of Earth. A workable approach must incorporate design characteristics that will both sustain the crew and optimize performance. The Soviet Union, having by far the greatest experience with long duration missions, has integrated human factors considerations into their space program. The major challenges to the space medical community are to determine both the significance of human psychological and physiological issues and to incorporate their consideration into early design phases of the mission. In the past, many of the elements that are required to provide for crew productivity and psychological well-being have been considered as low priority items. For long-duration missions, this may no longer be feasible. It is difficult to prove that crew performance factors are equal in importance to power or structural factors, but such factors must be part of the early design process.

Indications from the U.S. and Soviet manned programs show that medical issues include: cardiovascular deconditioning; muscle atrophy; vestibular

and neurological changes; microbiological concerns; conservative toxicologic strategies, and nutrition. A strong case can be made that all these issues must be better understood to guarantee productive Mars surface missions and to return healthy people from such a mission. Can some of these concerns be resolved by providing gravity-like accelerations throughout the trip? Fortunately, many of the answers, and some of the countermeasures, can be developed aboard the STS and the SS if a firm and sustained commitment is made to do so.

MEDICAL ISSUES

The most significant areas which are of medical concern during a MMM are: (1) adaptation and readaptation, (2) health maintenance capability, (3) toxicological safeguards, (4) psychosocial issues and crew factors, and (5) radiation risk assessment and risk management.

To certify that an individual will be healthy enough to perform full duty, it is desirable that long term health prediction techniques be developed for a mission that could last in excess of two years. Middle-aged humans tend to be relatively free of disease processes for long periods of time, and the problems they do develop are usually not so severe that they cannot continue to function for a period of time long enough to complete an important task. However, the disabilities of aging may have time to become asymptomatic during a trip to Mars. This is particularly true of osteoarthritis of the spine, which may be exacerbated by changes in spinal dynamics resulting from microgravity. Previously undiagnosed malignant disease may have time to become clinically significant during a Mars trip. Radiation exposure, combined with the compromised immune system, could combine to increase the rate of formation and the growth of malignancies.

ADAPTATION AND READAPTATION

During a prolonged mission, atrophy of bone, otoconia (small inner ear calcium grains), and muscle may occur. Learning how to prevent or

ameliorate these changes is an important medical prerequisite for a Mars mission. Such changes and their countermeasures are best studied in microgravity, suggesting that long duration U.S. missions be undertaken at the SS to obtain more data. The Soviets require long duration crews to spend several hours each day in body conditioning maneuvers. Bedrest studies indicate that it takes four hours of vigorous exercise, each day, to prevent negative calcium balance. Drugs are being looked at as a possible way to prevent bone atrophy. However, there are problems with drugs which could stimulate areas of the skeleton where increased calcium deposition is harmful, or would interfere with delicate homeostatic mechanisms of calcium balance resulting in hypo- or hypercalcaemia. It is not known if a partial or intermittent gravitational field will control the loss of calcium, although it is clear that a one-g field will.

Another aspect of cellular atrophy is being observed in cardiovascular adaptation (i.e., reduction in heart mass) and in the hematopoietic adaptation with a reduction in red blood cell mass. A potentially significant operational aspect involves the changes in heart size and cardiac dynamics of microgravity. This may increase the propensity for electrical instabilities and arrhythmias during prolonged EVA, although data are not yet statistically reliable.

The crew, living in what amounts to an isolated state, would have fewer problems with infectious diseases except those brought with them. Preflight quarantine could mitigate this problem. Some investigators feel that humans adapt to isolation by a gradual decrease in the immune system which is not called upon to respond to new disease challenges. It has been learned from the Antarctic experience that symptomatic respiratory virus infections regularly appear among the station complement months after the start of isolation. The same situation exists for bacteria and bacterial diseases. In general, the crew will probably not be free of infectious diseases, and opportunistic infections may occur if the immune system is depressed.

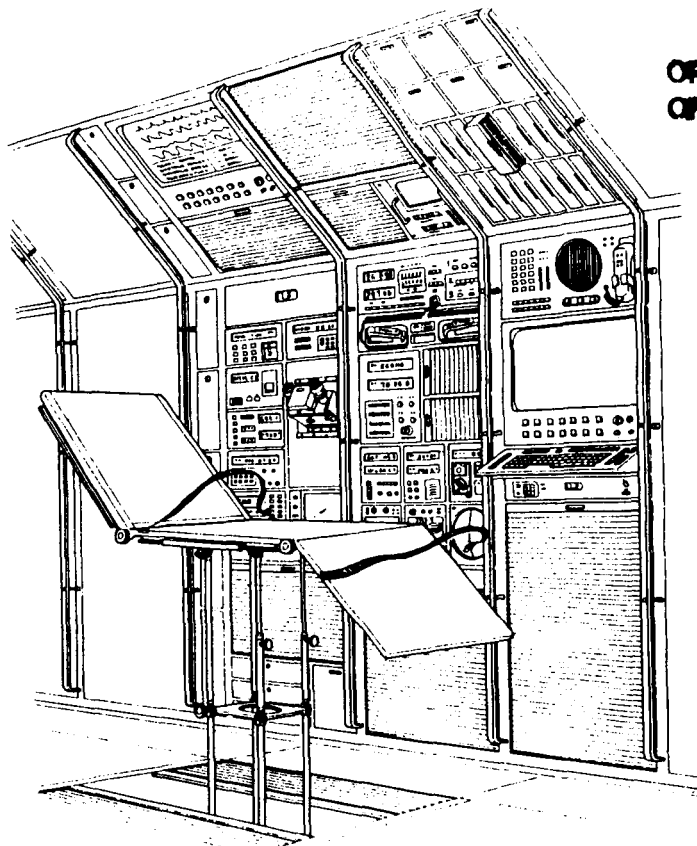
The unloading of the otolith, as well as other possible vestibular factors which occur in microgravity, is followed by what is known as the space adaptation syndrome. Shuttle crews report that the acute symptoms disappear in two to three days. Long duration USSR crew members report

annoying returns, at random times, of the disorientation which they felt on entering microgravity. Although it is important that this problem eventually be understood, the solution of the space adaptation syndrome problem is not yet seen as a prerequisite to a MMM.

HEALTH MAINTENANCE

The establishment of a permanently manned Mars outpost creates an unprecedented state of crew isolation with no immediate nor near-term return capability to Earth. Thus, for some few years into the program, crew members will not have access to the full spectrum of health care support and the same standards of health care available on Earth. In other words, as in all exploration, certain risks may have to be accepted by NASA and the crew. The medical screening of the crew participating in such a mission will need to be somewhat more extensive than for previous missions. Fortunately, the Antarctic experience (as well as NASA's own experience) has demonstrated that medical problems are relatively infrequent among properly screened individuals. Two situations seem to occur, the first being one in which the medical contingency is of such a benign nature (e.g., a cold in a crew member) as to present no significant health hazard, the second being of such catastrophic dimensions (usually secondary to accidental trauma) as to result in death even with Earth-bound medical support. Since serious medical events are relatively infrequent, a substantial portion of the resources assigned to health maintenance, including the time spent by the physician, will address the long term medical monitoring of the crew, and the practice of preventive medicine, particularly with respect to deconditioning countermeasures.

Based upon designs of the SS Health Maintenance Facility (HMF) (Fig. 5.1), the therapeutic/diagnostic/preventive modalities of the HMF must satisfy the following four general requirements: (1) The mission surgeon and HMF can reasonably handle most common non-surgical medical problems. (2) The mission surgeon and HMF can reasonably handle minor surgical problems and possesses limited capabilities to deal with major surgical events. (3) The mission surgeon and



HEALTH MAINTENANCE FACILITY (HMF) FOR SPACE STATION. HMF FOR MARS MISSION WILL CONSIST OF A SIMILAR MODULAR ASSEMBLY OF VARIOUS UNITS FOR DIAGNOSIS AND TREATMENT. ADDITIONAL SPACE WILL BE REQUIRED FOR STORAGE OF SUPPLIES FOR A LONGER MISSION. ALSO, THE MARS MISSION HMF WILL REQUIRE A SUBSTANTIAL AMOUNT OF SPACE FOR EXERCISE EQUIPMENT NOT INCLUDED IN THE 3-RACK SYSTEM FOR SPACE STATION

Figure 5.1. Health Maintenance Facility (HMF) for Space Station.

HMF can obtain a predefined (as well as undefined) array of medical data on the crew members in order to follow the effects of long-term exposure in microgravity as well as on the surface of Mars. (4) The mission surgeon and the HMF can provide a scheduled conditioning program in order to maintain cardiovascular and musculoskeletal function at optimum levels during the mission.

The HMF, during transit from Earth orbit to Mars orbit, would be identical with the one on the surface of Mars, since it must satisfy the same basic requirements. A major design difference will be that the transit HMF will need to incorporate hardware and techniques which will function in microgravity (in an emergency mode, even if artificial-g is provided). Such considerations are being incorporated into the design of the SS HMF. The presence of one-third gravity on the surface of Mars will facilitate the use of off-the-shelf medical hardware in the HMF. It will also simplify medical procedures, such as surgery, which would otherwise be very difficult to perform in microgravity.

TOXICOLOGICAL SAFEGUARDS

Toxic exposures during a manned Mars mission are of great concern because of the long trip duration. New spacecraft maximum allowable concentration (SMAC) limits will have to be established for potential contaminants during the mission. In addition, safeguard against excessive crew exposure include proper materials selection with regards to off-gassing, heat stability and flammability, and early testing of the Martian soil. Toxicological safeguards that should be instituted include proper containment of bulk chemicals, alarms warning of chemical release in the atmosphere; the wearing of protective clothing, goggles and masks, the use of fume hoods, if it is necessary to handle toxic chemicals; and the availability of safe havens in which the crew can take refuge in the event of high levels of toxic chemical contamination of their living environment. Atmospheric contaminant levels in all compartments of the transit spacecraft and the Mars outpost should be monitored at frequent intervals with a real-time analyzer.

PSYCHOSOCIAL ISSUES AND CREW FACTORS

Psychosocial issues and crew factors may emerge as important considerations during a MMM. Crew factors, or integrating the human system with the engineering system, relate to the goals and priorities determined for the Mars trip as well as the design of the vehicle for that journey. As much as possible, the engineering system must adapt to the needs of the human system.

The acceptable range of crew performance will vary from non-negotiable criteria for survival to the criteria for high productivity during the mission. The approach will be to examine areas such as crew size, composition, nationality, and leadership structure, which is susceptible to planning and design, so as to sustain the crew as well as optimize its performance. Other important habitability factors include food, sleep and privacy. Meals, for example, are an important time of the day to both enjoy food and to fulfill some social needs. Consideration should be given to growing vegetables and flowers onboard. To reduce the costs of later "fixes," early inputs relative to performance factors and crew support must be considered.

RADIATION RISK ASSESSMENT AND RISK MANAGEMENT

A manned mission to Mars will be confronted with radiation exposure that is two orders of magnitude greater than that encountered on the Apollo lunar missions. With nominal spacecraft shielding (2 g/cm^2 Al) astronauts could receive a dose of 45 Roentgen equivalent man (rem)/year from galactic cosmic radiation (GCR) at solar minimum. Most of this dose is from heavy ions, such as iron (Fe). In addition to the GCR dose, it is likely that during a two-year mission astronauts will receive an integrated dose in excess of 100 rem from solar particle events (SPE) with the possible exception of quiet periods during solar minimum. These figures indicate that adherence to the proposed career dose guideline for SS astronauts (200 rem) will necessitate specific consideration of radiation shielding. Further, there is some possibility of an anomalously large solar particle event (ALSPE) similar to the solar flare of August, 1972. Consideration of shielding strategies early in the design

of the Mars spacecraft and its habitat is strongly urged.

The dose equivalent from GCR has been modeled with a 30 cm diameter spherical water phantom. This baseline dose is 50 ± 10 rem/year. Shielding by 1.5 cm (4 g/cm^2) Al reduces this dose by only 15 percent. At solar maximum, the dose is about 1/2 the baseline dose. On the surface of Mars, the dose equivalent at solar minimum is 12 ± 3 rem/year assuming a 10 g/cm^2 atmosphere of CO_2 . This value is considerably less than 1/2 the baseline dose. For comparison, Table 5.1 shows the proposed radiation exposure limits for the SS.

SPE are the most serious radiation threat on the MARS mission because skin doses up to (and perhaps greater than) 2600 rem and doses to blood forming organs (BFO) of up to 500 rem may be rapidly absorbed. Such an event would be lethal. A series of flares occurring in 1959 and again in 1972, would have delivered such dosages (behind shielding). Relatively benign flares, such as the 10 percent worst case, can result in 100 rem absorbed dose behind 2 g/cm^2 Al shielding. Shielding thicker than this nominal value is required to provide 99 percent probability that current dose guidelines are not exceeded. Stowage, water, and liquid waste could contribute to the shielding requirements.

Exact shielding requirements for SPE are not known. The proton dose in the August 1972 event is reduced to 15 rem by 20 cm of water shielding. At the same time, neutrons build up in the shielding material. Several neutrons are produced when a proton fragments a target nucleus. The neutron dose rises dramatically in 10 cm or so of shielding. Neutrons have fewer interactions at higher energies but a large dose can be built up in thick shielding material. An example of this buildup occurs under the lunar surface, where neutrons build up in 30 g/cm^2 and maintain a high cosmic ray dose to 500 g/cm^2 (1 m depth). Since neutron build-up depends both on the incident particle energy spectrum and shielding composition and thickness, the lunar results should not be extrapolated to ALSPEs on the Mars mission.

It is concluded that radiation shielding will impact the design of Mars spacecraft and habitats if current dose guidelines are to be met. The degree of this impact on spacecraft weight and crew procedures can only be answered by thorough

TABLE 5.1. IONIZING RADIATION EXPOSURE LIMITS
PROPOSED FOR SPACE STATION (rem)

<u>Constraint</u>	<u>Bone (5 cm)</u>	<u>Skin (0.1 mm)</u>	<u>Eye (3 mm)</u>
1 Day (1 yr. avg.)	0.2	0.5	0.3
30 Day Max.	25.0	75.0	37.0
Quarterly Max.	30.0	80.0	40.0
Yearly Limit	60.0	170.0	85.0
Career Limit	200.0	600.0	300.0

rem – Radiation absorbed dose in rad times a quality factor (Q) to account for the different relative biological effectiveness (RBE) of different radiations. For planning purposes, Q = 1.2.

scientific and engineering analysis. As a first step, a detailed study is recommended of neutron build-up in water, aluminum, and Martian soil, subject to SPE and GCR irradiation.

Predictions of solar proton events are required to provide lead time for the crew to seek shelter. These predictions will require data from small on-board solar telescopes. As Mars moves toward the opposite side of the Sun from the Earth, the solar flares that produce SPE of danger to Mars cannot be seen from the Earth. The telescopes must be capable of solar X-ray imaging, hydrogen-alpha chromospheric scanning, and solar magnetographic recording. A small radio telescope would be desirable. The long delay time in sending the solar information to the Earth for analysis and returning a SPE alert to Mars requires that there be on-board computer analysis of the solar data along with some visual observations at times when large events threaten. Reliable predictions of SPE can only be made 20 to 30 min before particle fluxes reach a standard level indicating that an event has begun. An additional 20 to 30 min are available to seek shelter before the SPE increases to hazardous levels. The short-term forecasts are reliable to 95 percent accuracy. Forecasts of SPEs, one to ten days in advance, are made in probabilistic estimates. The forecasts are sufficiently accurate to put the crew on alert, but not accurate enough to make yes/no decisions, which may have major operational impact. Forecasts for periods of 1 to 2 years are not reliable for predicting when a SPE

will occur. Thus, for a Mars mission, on-board capability for solar activity monitoring and prediction will be required. Such predictions may provide an alternative to heavy shielding of the entire spacecraft.

If current radiation guidelines are to be met, high doses can be avoided by providing the crew with a shielding capability that can be used for protection during the few hours of a solar particle event.

A potential means of protecting crew members against ALSPE could consist of water-inflatable, cylindrical shell "storm shelter." One providing 0.85 m³ of space per person assuming a six-person crew and at least 20 g/cm² of shielding would require about 4000 kg of water (about 4,164 l). Such a shield, if needed, should be tolerable for the less than 12 hr of high dose rate which occurred, for example, during the August, 1972 event.

An alternative scheme uses a jacket of shielding around the crew sleeping quarters which not only protects against ALSPE but also provides some reduction in the GCR dose. Assuming 20 g/cm² of water shielding and a six-person crew, the shield will have a mass of ≈ 9980 kg (10,410 l). When all the crew is in the sleeping quarters each person will have 3.4 m³ of space. The reduction in the GCR dose is about 1/3 and if an astronaut spends 10 hr/day (8 hr sleeping + 2 hr reading/leisure) the total reduction in the GCR dose is 14 percent or about 6 rem/year.

The 4 to 9 1/2 metric ton water shield requirements are not unreasonable considering water usage and recycling capabilities. Assuming 4.5 kg of water per person per day for all purposes and 50 percent recycled water, a crew of six requires 8165 kg of water on a 600-day mission.

Table 5.2 presents approximate BFO doses and the projected increases in lifetime risk of cancer incidence per year of mission; a three-year mission during solar minimum would increase the risk of a 35-year-old male's contracting cancer by roughly 6 percent over that expected to occur normally, i.e., without radiation. The above considerations of cancer incidence versus dose-equivalents are based on doses calculated using current quality factors.

Unfortunately, the quality factor (Q) (based on radiobiological effectiveness (RBE)), which converts a dose (energy/tissue mass) into a dose equivalent (rem) measuring biological response, is not well-understood. This is particularly true for neutrons created in secondary interactions in spacecraft material or tissue, and for high-Z elements (HZE, $Z \geq 2$) which account for about 80

percent of the GCR dose behind 4 g/cm² Al shield. Recently, it has been recommended that the Q for neutrons should be raised from 10 to 25. Also, HZE with Linear Energy Transfers (LET) above 200 keV/m (micro meters) show a drop-off in RBE which reduces the dose equivalent from the more slowly moving nuclei. In addition, different parts of the body can tolerate different doses (e.g., skin is less sensitive to dose than the BFO). The situation is further complicated by the fact that many stresses encountered during spaceflight may have synergistic effects on the biological response to radiation. More information is needed to reduce the uncertainties surrounding radiological risk assessment.

Finally, there has been some success in reducing the biological response to radiation through the use of chemical agents. Unfortunately, these agents have side effects at effective concentrations. Recent studies with pharmaceutical agents that act on stages of carcinogenesis, occurring after the initial radiobiological lesion stage, are promising. Nonetheless, the most effective countermeasure is still likely to be some physical shielding.

TABLE 5.2. APPROXIMATE BLOOD FORMING ORGAN DOSE EQUIVALENTS AND RADIATION HEALTH RISK FOR A MANNED MARS MISSION

<u>Radiation Environment</u>	<u>Blood Forming Organ Dose Equivalents (behind 5 g/cm² H₂O)</u>	<u>Health Risk in a 35-year old male*</u>
<u>Galactic Cosmic Rays (Chronic Exposure)</u>		
Free Space (behind 2 g/cm ² Al)		
Solar Minimum	45 rem/yr	≈3 percent/yr increased cancer incidence
Solar Maximum	18 rem/yr	<1 percent/yr increased cancer incidence
On Mars (behind 10 g/cm ² CO ₂)		
Solar Minimum	12 rem/yr	<1 percent/yr increased cancer incidence
Solar Maximum	5 rem/yr	<1 percent/yr increased cancer incidence
<u>ALSPE, Aug 72 (Acute Exposure)</u>		
Free Space (1 A.U.) behind 2 g/cm ² Al	500 rem	>90 percent lethality in 60 days 37 percent increased cancer incidence in survivors
behind 20 g/cm ² Al	11 rem	<1 percent increased cancer incidence in survivors
On Mars behind 10 g/cm ² CO ₂	170 rem	<10 percent lethality in 60 days 12 percent increased cancer increase in survivors
behind 10 g/cm ² CO ₂ + 50 g/cm ² Mars soil	0 rem	<<1 percent increased cancer incidence in survivors

*The percent increased cancer incidence for a 35-year-old female is roughly twice that for a 35-year-old male. Note: LEO phase, Van Allen Belt phase together contribute <4 rem/passage. The percent increase in cancer for a typical Mars mission is obtained by multiplying the yearly percent increase by the number of years of exposure.

6. IMPACTS ON THE SPACE INFRASTRUCTURE

SPACE STATION

Initial Operational Capability (IOC) SS as a Transportation Node

The SS impacts and interactions will be discussed in two parts: the IOC SS and a growth version of the SS. Although the initial SS is being designed with maximum flexibility for growth to support new missions and the assumption is that this growth will occur at the appropriate time, there is always the possibility that schedule problems would dictate that only the IOC station is available at the time of a Mars mission. Therefore, it seems prudent to look first at the possible support to a Mars mission by the initial version of the manned SS.

The initial Mars spacecraft element to be brought to LEO would likely be a MM. The MM could be temporarily berthed at the station where the systems could be activated and checked out. These operations would probably be in conflict with the station's stringent microgravity and pointing requirements, but it may be possible to suspend these activities for a short time. Once the systems have been checked out, the MM could be attached to the station in a quiescent mode or detached and put in a station-keeping mode until additional elements are brought up. Similar station checkout procedures could be accomplished for other Mars spacecraft elements. If the microgravity and pointing stability constraints on the station are still in effect during the Mars mission build-up, it may not be feasible to attach multiple assembled elements on the station. The assembled elements and larger assembly operations could be supported at a station-keeping position 100 m or more from the station.

For a Mars spacecraft which departs from and returns to the SS, the natural parking location would be in an orbit co-planar with the SS. If an OTV is available, it could be used to circularize the elliptical orbit of the returned Mars spacecraft into a co-planar orbit near the SS. The SS OMV could be used to assist in the final positioning of the Mars spacecraft. For maintenance activities, the attitude control and propulsion systems of the Mars spacecraft (partly resupplied after the return to the station) could be used to maintain it in the vicinity

of the station, Isolation quarters or a clean room could be attached to the SS to be used for temporary crew isolation upon return if necessary.

Growth SS as a Transportation Node

There are several possible scenarios for the growth of the SS, including evolution and replication. If replication is the path chosen, there would be in existence two or more stations of size and resource capability similar to the IOC station. These might have a high degree of commonality, yet might be dedicated to different functional capabilities, e.g., one might be a more science-oriented station and another might have a more operations-oriented capability. If evolution is the growth mode, there will be only one station in the mid-to-late 1990's and it will have responsibility for supporting a wide variety of science and operations activities. This station would have larger dimensions and greater resources than the IOC station. Each of these considerations would have a bearing on the way in which the SS would be used to support the MMMs.

There are two basic modes in which either SS could support the build-up of MMMs: (1) by attaching the Mars SV to the SS, and (2) by allowing the Mars SV to free-fly in the vicinity of the SS. There are several ways in which the attached Mars SV modules and systems could be supported by the SS: (1) the Mars program provides a special assembly crew and the Mars SV systems remain dormant while the SS provides all habitability, resources and some additional crew support; (2) the Mars SV crew provides habitability and a special assembly crew and the SS provides resources and some additional crew support; and (3) the Mars SV provides habitability, resources and a special assembly crew while the SS provides some additional crew support. The other support mode, allowing the Mars SV to co-orbit, offers an alternative. In this option there is sufficient isolation and interdependence between the Mars SV and the SS to minimize interference, yet allow the Mars SV to benefit from using some SS resources or equipment. The only significant impact to the Mars SV resulting from the station-keeping option would be the propellant required to maintain proper orbit-phasing. If a nuclear power source is

available, nuclear electric propulsion could be used to substantially reduce the propellant requirements.

The major effect of the SS growth mode on the capability to support the Mars SV build-up is related to the science and microgravity constraints. A "replicated" station devoted to operations would be free of these constraints. An evolutionary station would still have these constraints and operational work-arounds would have to be developed during some periods of the Mars SV build-up phase. The extent to which interruptions to the SS science and microgravity activities would be acceptable depends on many factors, both technical and operational, that cannot be accurately forecast at this time. Another feasible solution is to place most microgravity experiments and pointing instruments on unmanned platforms during this phase.

Both the evolutionary station and the "replicated" operational station would probably include a propellant storage/transfer capability and an OTV support facility; both of these should be useful to MMMs. However, the addition of these facilities to the IOC station will reduce the amount of clear area around the station for attaching the Mars SV elements. The evolutionary station will have greater total resources, including attitude control capability. If science and microgravity activities were temporarily suspended, most of these resources would be available to MMMs.

Space Station/Mars Program Commonality

There are many areas where the manned Mars program could benefit from SS program commonality. The SS common module will include primary structure, power, data, cooling provisions, and environmental control and life support, as well as external interfaces. Use of a modified version of this module may be advantageous to the Mars program. Whether or not the tooling for these modules is still available will depend on the relative timing of the two programs and on the degree and timing of SS growth. Other SS areas of benefit to the Mars program can be broadly listed under "technology" (discussed in the following section) and "experience." The latter includes operations, on-orbit assembly, on-orbit maintenance, crew training, logistics, and payload accommodations. The SS

"lessons learned" in these areas should be very valuable to the Mars program.

Space Station/Mars Program Technology Development

There are a number of advanced development activities and technology and scientific experiments underway or proposed in support of SS or Shuttle that could support key technical and scientific areas of concern for MMMs. A close interaction with these activities by Mars program interests is recommended. Key areas include: long-term weightlessness effects and countermeasures; progress toward a closed environmental control and life support system; development of cryogenic propellant storage, handling, gauging, and transfer capabilities; large space structure assembly and construction techniques; plant growth techniques in microgravity; nuclear power and propulsion studies; laser communications and positioning systems; automation and robotics studies; and inflight training techniques and capabilities. Additionally, the use of the SS as a test bed for Mars mission/systems technology development should be considered. SS missions of this type may be submitted for inclusion in the SS mission data base.

ETO VEHICLES

The Earth launch requirements for executing a program for manned exploration of Mars have not yet been firmly determined. Several trends have emerged from the recent work which provide indications of what will be the general nature of these needs.

First, MMMs will require that on the order of 700 metric tons or more of equipment and propellant be assembled in LEO, in addition to the weight of propellants needed to replace losses from boiloff during assembly and tanking periods. Since the present Space Transportation System (STS) has a performance capability of 15 to 17 metric tons to the LEO SS, a supplemental launch system is a clear necessity to deliver the Mars SV elements to LEO within reasonable time limits.

In addition to the need for a heavy lift capability, the need to reduce launch costs below

current levels is paramount. Two key factors which will contribute to such reduction are increased automation of operations (ground and flight) and increased flight rates. A third type of need in the ETO vehicle area is a capability for delivery of increased crew sizes, particularly in later phases of the program.

Several types of advanced ETO vehicles are under active study by NASA and the Department of Defense. Both manned and unmanned vehicles are being studied, and key characteristics being considered range from partial to full reusability, from Shuttle-derived to advanced technology, and from single to dual stage operation. Delivery capabilities range from about 5000 kg to about 200,000 kg, and propulsion types include rocket and air breathing varieties. Vehicles at the lower end of this performance scale would serve primarily as "people carriers," and those at the higher end would be primarily cargo vehicles.

Critical dimensions and weights of the SV elements will influence ETO vehicle requirements and minimum cargo mass per launch. If aerobraking is used for the SV, and if on-orbit assembly of the aeroshell is difficult, very large cargo diameters must be accommodated by the ETO vehicle. The SV habitable module (orbiter or lander) diameters will directly influence the ETO vehicle payload envelope diameter, and vice versa.

The choice of a cargo ETO vehicle will depend on the number and types of missions to be flown and the launch time frames required. For near-term missions, an ETO vehicle derived from the present STS could launch approximately 100 metric tons per flight, with unit launch costs of 1/2 to 2/3 of STS costs (Fig. 6.1). If other large

cargo needs emerge from the Strategic Defense Initiative (SDI), lunar base, or other programs, a higher national investment in an ETO vehicle can be justified and vehicles with larger unit cargo mass and lower launch costs will be available to a Mars program.

Typical ETO vehicle concepts are shown in Figure 6.2. The SDV, HLLV, and STS were used as reference ETO vehicles in the MMM study.

ORBIT TO ORBIT VEHICLES

Orbit Transfer Vehicle (OTV)

This class of vehicle is expected to be available in the mid-to-late 1990's and will provide transportation to and from various Earth orbits to supplement the nation's payload delivery and space operations capabilities. Some versions will be compatible with the STS and some will be space-based at the SS. NASA has currently underway three OTV systems studies and several applicable technology studies (an advanced engine technology study, a long-term cryogenic propellant storage study and an Aeroassist Flight Experiment program, etc.). Other related systems studies which are in progress are studies on SS OTV basing, propellant scavenging, OMV studies, STS aft cargo carrier studies, ground operations studies, etc.

A typical space-based OTV is shown in Figure 6.3, along with some of its top-level systems data. Other concepts exist which offer similar sizes and performance ranges; no selection of a preferred option has been made.

The OTV's will be the workhorses of LEO-GEO-Moon orbital space and will find many applications in a MMM. A likely direct use will be to recover the returning Mars vehicle or crew from an elliptical Earth orbit. OTVs may also find use in staging missions launched from high orbit (L_2 , Moon, or GEO) transportation nodes.

Aerobraking

Analyses and conceptual designs for the OTV show that aerobraking is a significant enhancing technology that can reduce the cost of transportation to GEO by almost doubling the delivery capability (compared to an all-propulsive vehicle).

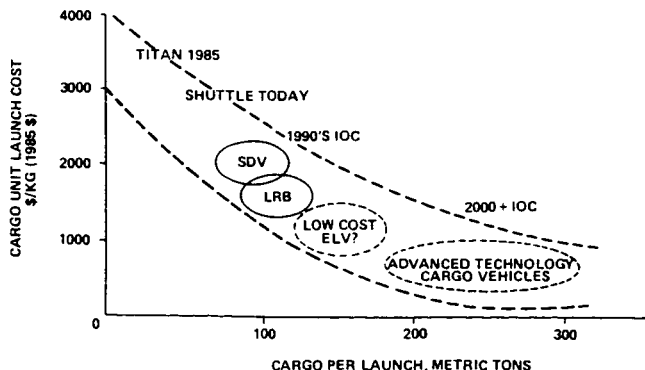


Figure 6.1. ETO vehicle cost/size trends.

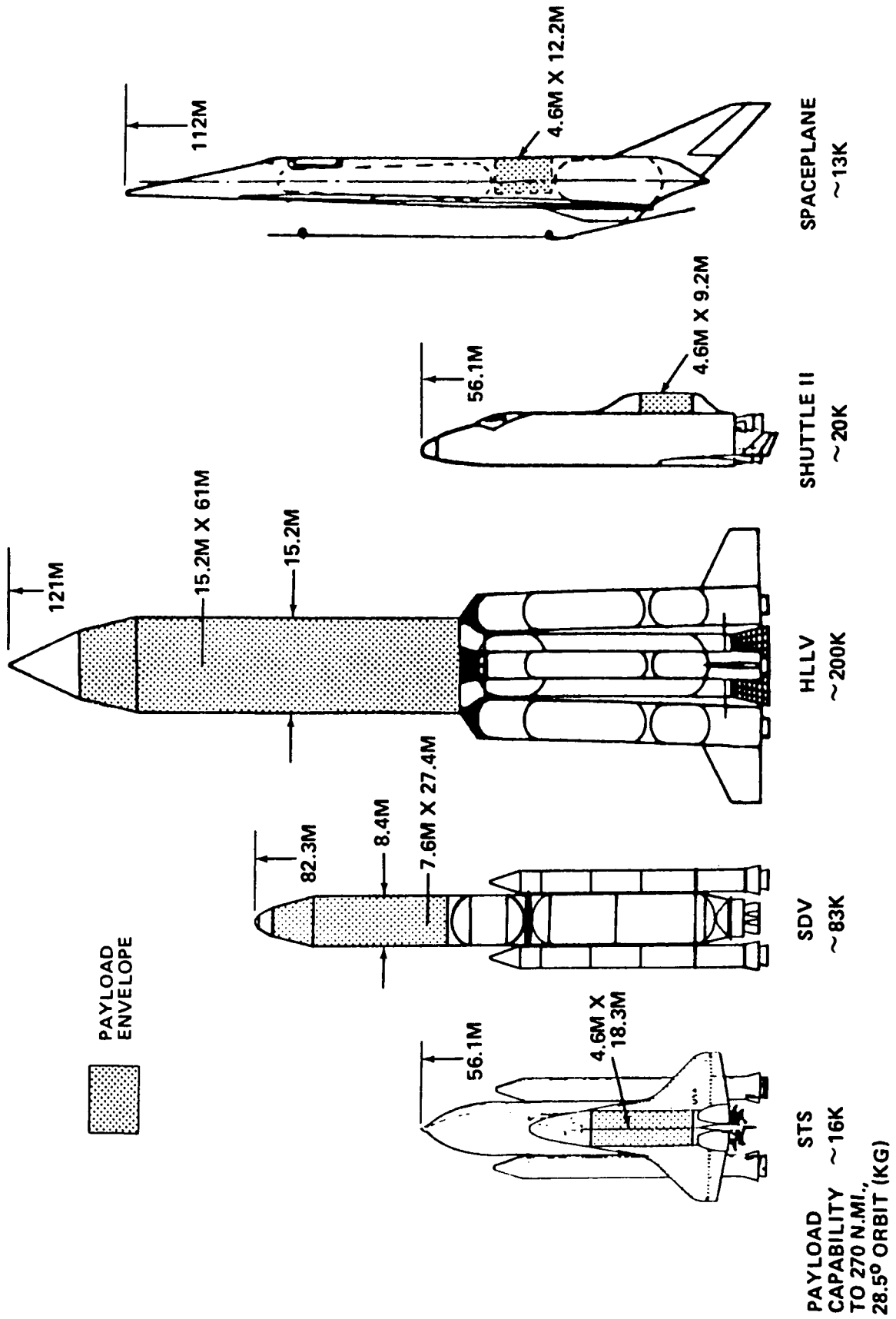
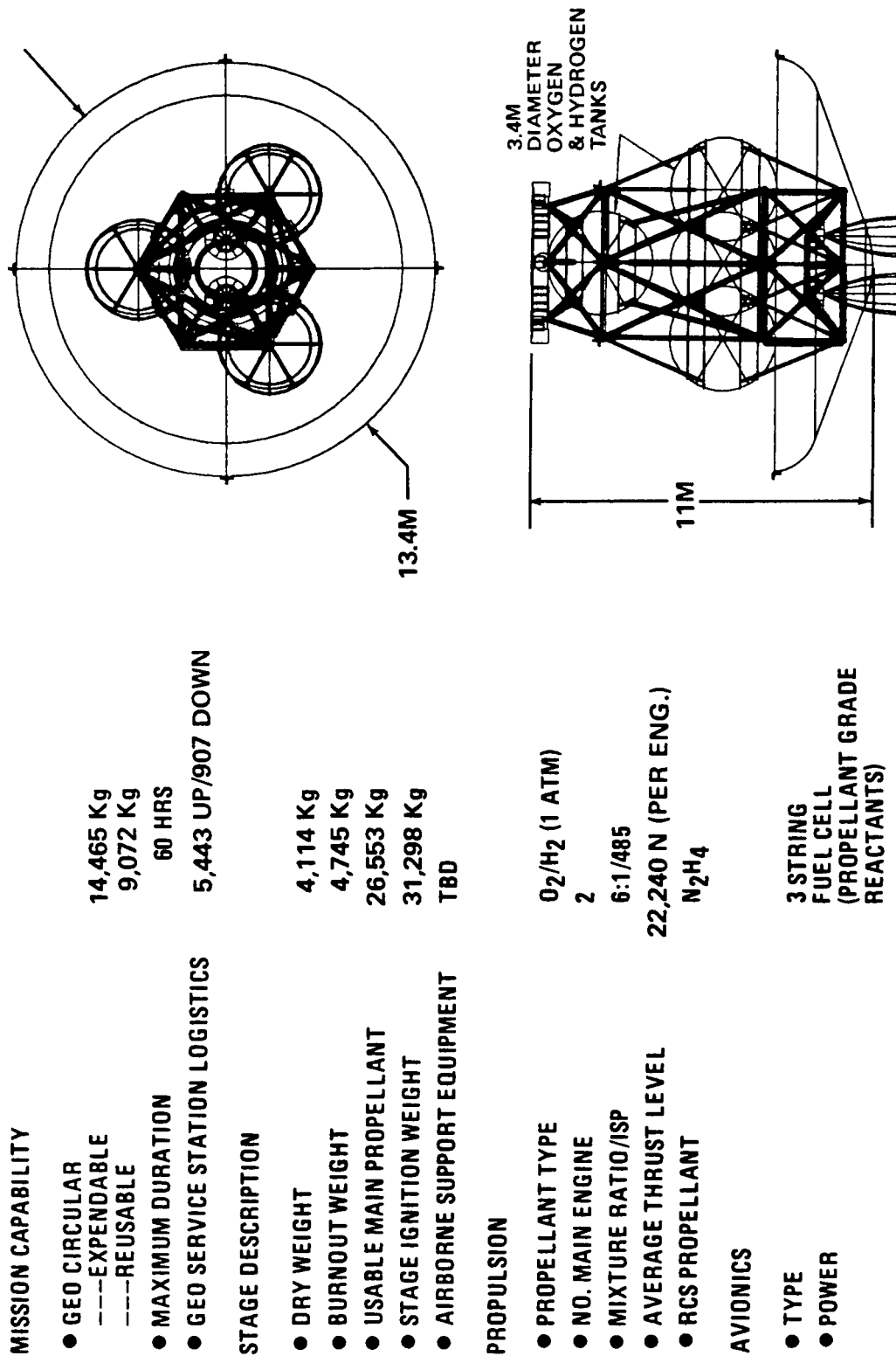


Figure 6.2. Typical Earth-to-orbit vehicles.



MISSION CAPABILITY	
● GEO CIRCULAR	14,465 Kg
---EXPENDABLE	9,072 Kg
---REUSABLE	60 HRS
● MAXIMUM DURATION	5,443 UP/907 DOWN
● GEO SERVICE STATION LOGISTICS	
STAGE DESCRIPTION	
● DRY WEIGHT	4,114 Kg
● BURNOUT WEIGHT	4,745 Kg
● USABLE MAIN PROPELLANT	26,553 Kg
● STAGE IGNITION WEIGHT	31,298 Kg
● AIRBORNE SUPPORT EQUIPMENT	TBD
PROPULSION	
● PROPELLANT TYPE	O ₂ /H ₂ (1 ATM)
● NO. MAIN ENGINE	2
● MIXTURE RATIO/ISP	6:1/485
● AVERAGE THRUST LEVEL	22,240 N (PER ENG.)
● RCS PROPELLANT	N ₂ H ₄
AVIONICS	
● TYPE	3 STRING
● POWER	FUEL CELL (PROPELLANT GRADE REACTANTS)

Figure 6.3. Space-based OTV reference configuration (synthesized version).

Analyses for the MMMs demonstrate the significant advantage of aerobraking on the performance of the Mars spacecraft as well. To handle the thermal environment, an ablative TPS is adequate. Since ablative systems are non-reusable, the technology developments for the OTV must be pushed harder if they are to support reusable vehicle systems for the MMMs. Another technology development related to aerobraking is in the area of guidance through the atmosphere. Current efforts devoted to development of guidance algorithms for the OTV should include the requirement to be able to aerobrake at Mars with little or no alteration.

OTV as a Mars Spacecraft

At least one concept being considered for NASA's OTV could be used for a manned Mars flyby mission. Such a mission would most likely use two of these OTV's, mated to a SS module, to provide the required velocity increment for the mission. In addition, the proposed command module for a manned OTV would also be required for this mission. However, the TPS design proposed for this OTV will not tolerate the entry environment at Earth return and may well have difficulty at Mars also. This shortcoming of the TPS implies the need for more advanced TPS technology than is required for the currently planned near-Earth support. There are also physiological problems that must be considered because high entry velocities associated with some trajectories will subject the crew to high acceleration levels after a very long time in "zero-g." For that reason, the return velocity may need to be propulsively reduced for some trajectories.

Propulsion

NASA is planning the development of an advanced high performance cryogenic engine that is space maintainable, man-rated, and capable of multiple starts. The thrust level of the advanced space engine will be too low for the MMM Earth departure burns; however, the thrust level may be adequate for other portions of the missions, and the technology developments that permit the increase in engine specific impulse may be applicable to the development of a much larger Earth departure engine system. As previously mentioned, this engine is probably suitable for all propulsive

burns except the Earth departure. Pump-fed, high performance, storable propellant engines are also under consideration. The concept of pump-fed storable engines not only results in improved specific impulse for the storable propellant, but also permits greater structural efficiencies in the design of the propellant tankage (due to the greater densities of the storables compared to the cryogenics). Additionally, the use of pumps to directly feed the engines rather than to pressurize the propellant tanks allows lighter tankage designs. These two concepts compete with each other in performance versus boil-off of cryogenics versus lighter and more efficient structures. The winner will be determined by more sophisticated analyses that are currently underway.

Orbital Maneuvering Vehicle (OMV)

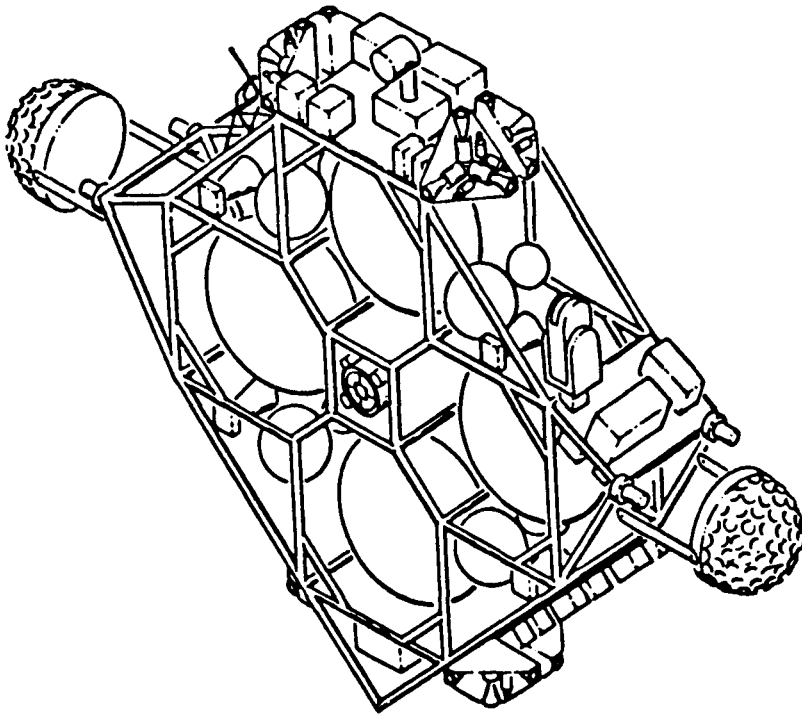
The OMV is a reusable, remotely controlled, free-flying vehicle capable of performing a wide range of on-orbit services in support of orbiting elements. It is projected as an important element of the STS and is designed to operate from either the STS or the SS.

The multiple propulsion systems (orbit adjust, RCS, cold gas) and on-board avionics enable the OMV to economically deliver and retrieve elements at orbits not otherwise achievable by ETO vehicles or the STS. Precision maneuvering for proximity operations, including docking with an orbiting element, is accomplished by man-in-the-loop control from the OMV control station. Remote servicing of orbiting elements, including changeout of modules and resupply of consumables, will become available as the space program advances and OMV kits become available.

Several OMV systems studies and significant related technology work are currently in progress. The OMV is expected to be operational in the early 1990's.

Figure 6.4 shows a concept of a typical OMV, along with a few key parameters. As with the OTV case, other attractive concepts are available, and no preferential selection of concepts has yet occurred.

A SS-based OMV would be valuable for support in on-orbit assembly of the SV, and possibly for ferrying men and equipment between the SS and SV if these are co-orbiting.



DIMENSIONS:

0.94 X 4.5M

WEIGHT LOADED:

4,761 Kg

PROPELLANTS:

3039 Kg NTO/MMH

91 Kg GN₂

Figure 6.4. Typical OMV.

AUTOMATION AND ROBOTICS

The anticipated automation and robotics (A&R) requirements for MMMs are substantially encompassed by the A&R currently under consideration for technology development related to the SS program. The basic A&R implementation of the SS will likely include expert systems for SS systems management and malfunction diagnostics, automation of payload operations, telepresence payload operations (remote operations), some specialized A&R for freeflyer and platform servicing operations, and interactive on-board training systems.

The MMMs will utilize these A&R capabilities and may have requirements which exceed them. A&R implementation for MMMs could include the following: (1) mobile robotics to assist in the assembly, handling and inflight repair of nuclear components and other hazardous system elements, (2) expert systems and artificial

intelligence for automated Mars landing, ascent, and rendezvous operations, (3) mobile robotics on the surface to perform tasks during periods of high solar flare radiation and to help maintain the Mars base during unmanned periods, and (4) a high fidelity "off-line" simulation mode for the MEM (including built-in holographic image projection for out-the-window views) for training on landing, ascent and rendezvous contingencies.

Future MMM studies should include the following activities: (1) identification and prioritization of potential MMM A&R studies and advanced development funding, (2) identification of specific SS A&R activities which should be monitored and influenced to support potential MMM A&R requirements, and (3) a generic feasibility study of utilizing the MEM, coupled with a holographic image projection system for contingency crew training on Mars landing, ascent, and rendezvous.

7. COSTS, SCHEDULES, AND ORGANIZATIONS

This economic analysis is based on one of the mission options described earlier in this report: a one-shot, opposition class mission at the turn of the century using aerobrake techniques with a sixty-day stay time at Mars. Alternative mission scenarios were examined to some extent, but are not discussed in detail here.

SCHEDULE

The estimated schedule for the strawman Mars mission is summarized in Figure 7.1. The authorization to proceed with system studies is assumed to occur in 1986 with definition studies for the major hardware elements also beginning in 1986. LEO assembly operations begin in 1997 and LEO departure occurs in 1998. The arrival at Mars occurs in 1999 with a two-month stay and the return to Earth in 2000. It should be noted that the 1986 start date for hardware definition is due primarily to long lead times for the spacecraft power subsystems. In summary, it appears from a schedule standpoint that a MMM and return is possible by the end of the century. However, considerable planning and early funding will be necessary.

COST

The potential cost of a MMM is summarized in Figure 7.2. Six different cases were studied and all were found to be in the range of \$24 to \$28 billion (FY1985 dollars), which is within the error range of estimates for a conceptual design. A comparison was also made with the cost of the Apollo Program after normalizing the Apollo cost to the environment and ground rules of a MMM, and it was found that the Apollo cost was not significantly different from a MMM. It is concluded that the strawman MMM could be accomplished for under \$30 billion, excluding ETO vehicle development and mission operations.

BUDGET

A forecast of the total NASA budget is presented in Figure 7.3. The NASA base, including administrative expenses, construction of facilities, and research and development other than manned space flight, is assumed to level off at the present (1985) level and remain constant at approximately \$3.5 billion. The budget for Space Transportation Systems, which consists of Shuttle research and development, operations, and tracking and data acquisition costs, is projected to decrease from approximately \$4 billion in 1985 to just under \$2.5 billion by 1989 and then level off. Planning profiles for three new major programs are included: (1) a permanently manned SS, (2) an SDV, and (3) a MMM. It is concluded that all of the new programs can be conducted by the year 2001 with a 3 percent real growth rate at the total NASA budget.

INTERNATIONAL COOPERATION

Recently, many nations have realized that space exploration and science provides a focus and a driver for the development of technology. They have created government-sponsored programs which have developed their industries into strong competitors. Because they are now strong competitors, they are also valuable partners for large ambitious cooperative programs such as the manned exploration of the solar system. There are many examples of international cooperation which involve new and commercially useful technology, including the British-French Concorde, the multi-national production of the F-16 and Boeing's use of Japanese subcontractors to produce sections of fuselages. INTELSAT is a successful commercially oriented user-based organization where various countries with vastly different political systems work together. One possible program for international cooperation in space exploration would be the creation of an international spacecraft, similar

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to the Glomar Challenger or the Calypso, which would explore the planets. In part because of the funding required and the number of countries involved and in part because most governments have a preference in dealing with other governments rather than private firms, an organizational structure which resembles INTELSAT is most likely for such a venture.

INTERNATIONAL MANAGEMENT

Existing international space law as well as the best interests of all nations are consistent with the establishment of a user-based international organization, here called INTERMARS. Such an organization would permit the provision of Martian base facilities, services, and access of high functional potential, quality, safety, and reliability to be available on an open and non-discriminatory basis to all peaceful users and investors.

Through an Assembly of Parties, a Board of Governors, a Board of Users and Investors, and a Director General, INTERMARS would meet its primary goal, as it would be in the self-interest of all members, users, and investors to do so. The internal structure and philosophy of INTERMARS provides for all participants to have representation in decision affecting its activities, thus insuring effective and responsive management.

INTERMARS is an organizational concept modeled after INTELSAT and tailored to provide cooperative international management of a Martian base to the benefit of its members, users, and investors. Most importantly, INTERMARS would provide such management through a sharing of both sovereignty and opportunity rather than unilateral control by any one nation or set of competing nations. We should begin to address such concepts now, because the shores of the new ocean of space are not so far away.

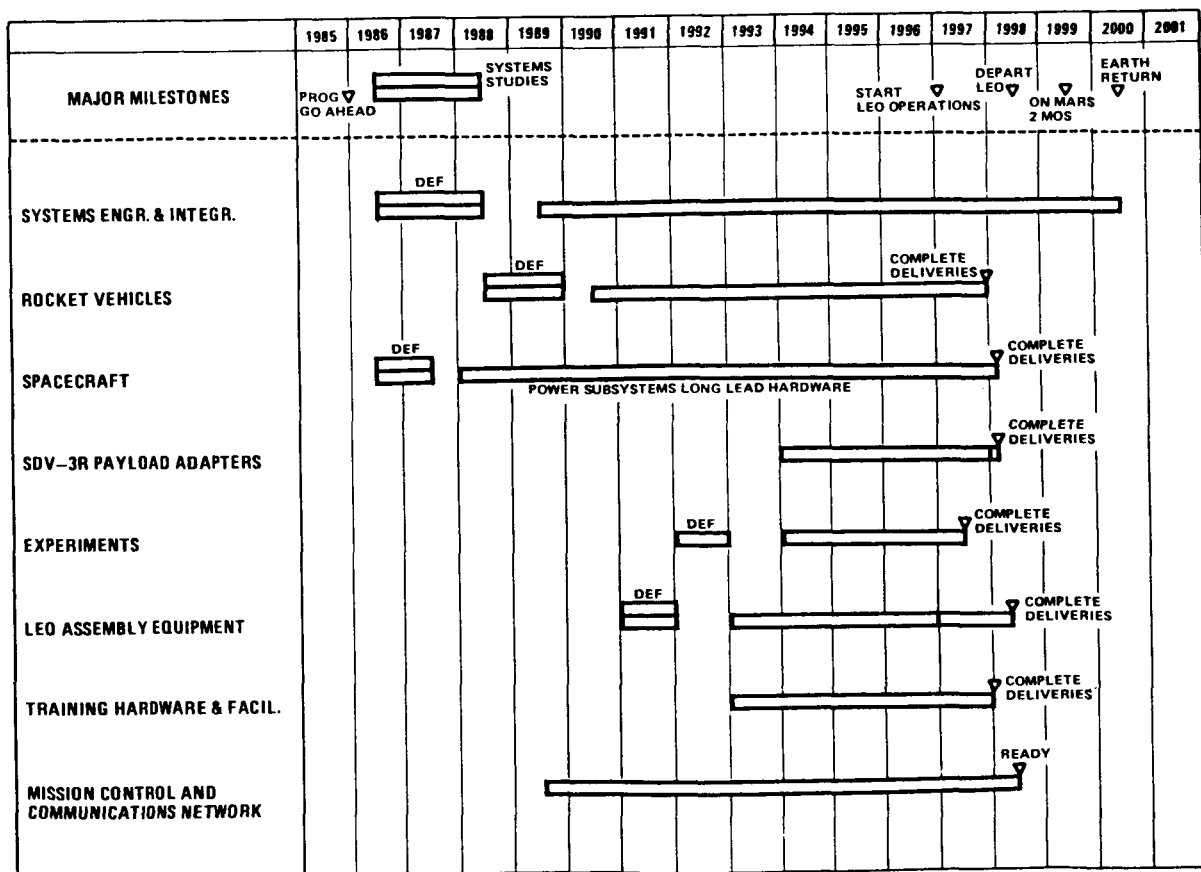


Figure 7.1. MMM summary schedule.

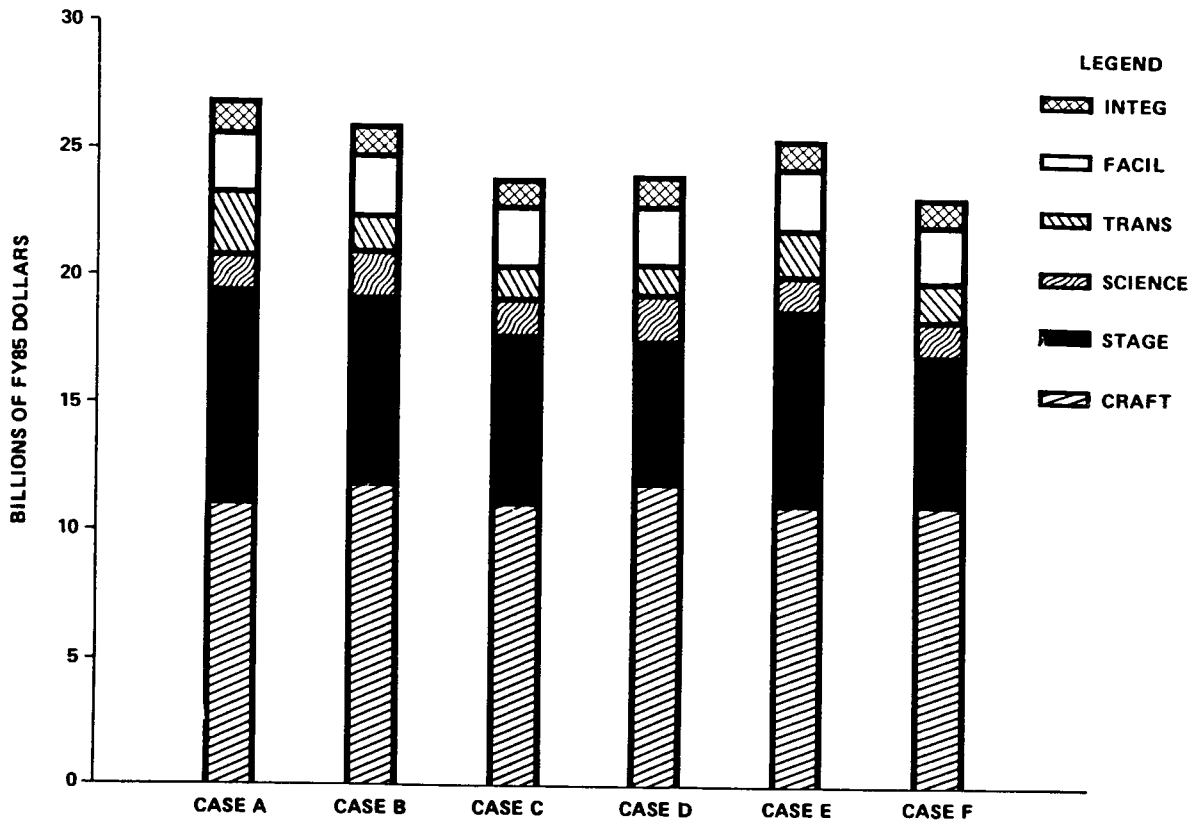


Figure 7.2. MMM cost summary.

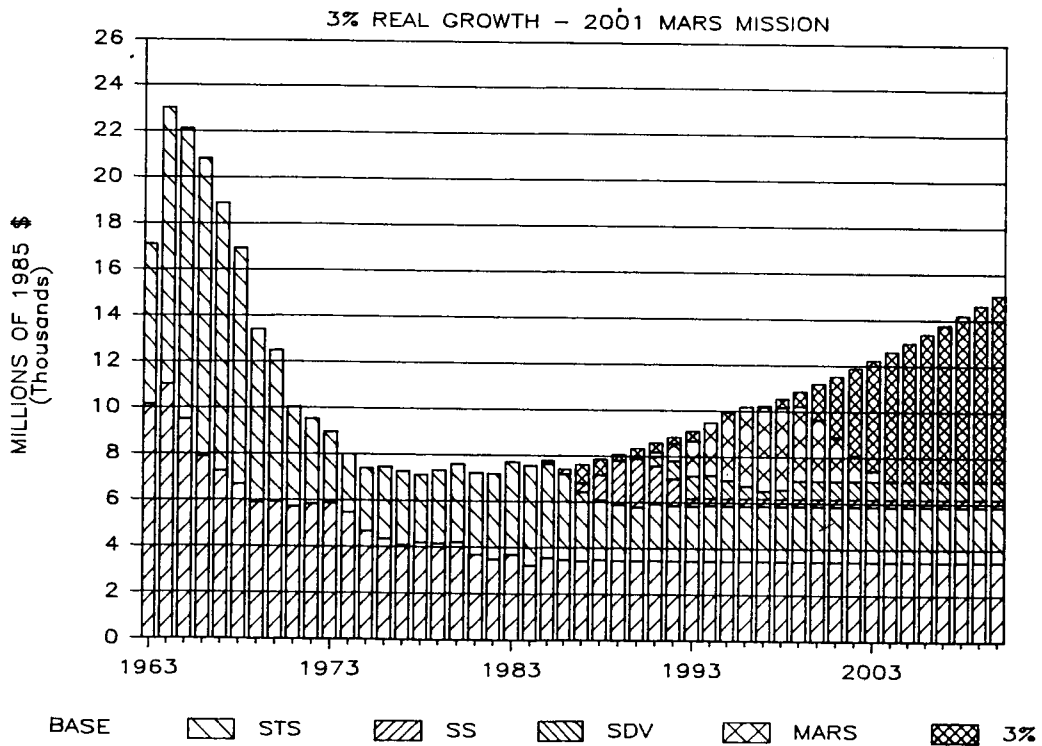


Figure 7.3. Total NASA budget.

APPENDIX A

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ORGANIZATIONS ABBREVIATED IN APPENDIX A

ARC	Ames Research Center
Battelle	Battelle Pacific Northwest Laboratories
CIA	Central Intelligence Agency
CSC	Computer Sciences Corp.
EEL	Eagle Engineering, Inc.
GSFC	Goddard Space Flight Center
HQ	NASA Headquarters
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LANL	Los Alamos National Laboratory
LRC	Lewis Research Center
LSPI	The Large Space Programs Institute
MSFC	Marshall Space Flight Center
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
ODU	Old Dominion University
SAIC	Science Applications International Corp.
TA&M	Texas A&M University
U of Hi	University of Hawaii
U of TX	University of Texas
UAH	University of Alabama in Huntsville
UNM	University of New Mexico
USAF	United States Air Force
USGS	U. S. Geological Survey

APPENDIX B

LIST OF ACRONYMS AND ABBREVIATIONS

A&R	Automation and Robotics
ADC	Amperes Direct Current
ALSPE	Anomalously Large Solar Particle Events
AMTEC	Alkali Metal Thermal Electric Conversion
A.U.	Astronomical Unit
BFO	Blood Forming Organs
CELSS	Controlled Ecological Life Support System
ECLSS	Environmental Control/Life Support System
EOI	Earth Orbit Injection
ET	External Tank
ETO	Earth-to-Orbit
EVA	Extra-Vehicular Activity
GCR	Galactic Cosmic Radiation
GEO	Geosynchronous Earth Orbit
GNP	Gross National Product
HLLV	Heavy Lift Launch Vehicle
HMF	Health Maintenance Facility
HST	Hubble Space Telescope
HZE	High-Z Elements
INTERMARS	User-Based International Mars Organization
INTELSAT	User-Based International Satellite
IOC	Initial Operational Capability
IPS	Isotope Power Sources
Isp	Specific Impulse
ISPP	In-Situ Production of Propellants
ISWP	In-Situ Water Production Plant
K	Kelvin
kV	Kilovolts
kWe	Kilowatts Electrical
LANL	Los Alamos National Laboratory
L/D	Lift/Drag
LEO	Low Earth Orbit
LET	Linear Energy Transfers
LH ₂ /LO ₂	Liquid Hydrogen/Liquid Oxygen

Mbps	Megabyte per Second
MEM	Mars Excursion Module
MLI	Multi-Layer Insulation
MM	Mission Module
MMMs	Manned Mars Missions
MOI	Mars Orbit Insertion
MPD	Magnetoplasmadynamics
MWe	Megawatts Electrical
NASA	National Aeronautics and Space Administration
NEP	Nuclear Powered Electrical Propulsion
NERVA	Nuclear Engine Rocket Vehicle Application
NRDS	Nevada Rocket Development Station
NTR	Nuclear Thermal Rocket
OMV	Orbital Maneuvering Vehicle
OTO	Orbit-to-Orbit
OTV	Orbital Transfer Vehicle
PV	Photovoltaic
RBE	Radiobiological Effectiveness
RBMR	Rotating Bubble Membrane Radiators
rem	Roentgen Equivalent Man
RF	Radio Frequency
RCS	Reaction Control System
RPV	Remotely Piloted Vehicle
RTG	Radioisotope Thermoelectric Generator
RX	Nuclear Reactor
S	Seconds
SAR	Synthetic Aperture Radar
SDI	Strategic Defense Initiative
SDV	Shuttle Derived Vehicle
SMAC	Spacecraft Maximum Allowable Concentration
SPE	Solar Particle Events
SS	Space Station
SSME	Space Shuttle Main Engine
ST	Solar Thermal
STME	Space Transportation Main Engine
STS	Space Transportation System
SV	Space Vehicle

TCS	Thermal Control System
TEI	Trans-Earth Insertion
TMI	Trans-Mars Insertion
TPS	Thermal Protection System
TV	Transport Vehicle
VDC	Volts Direct Current