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Final Report

MANNED MARS SYSTEM STUDY (MMSS)

(Mars Transportation and Facility Infrastructure Study)

for

NASA Marshall Space Flight Center

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FOREWORD

This is the Final Report under Contract NAS8-37126. The purpose of the Study was to design and analyze systems for conducting human missions to Mars and the moon, with special emphasis on the transportation and facility infrastructure.

This program was conducted by Martin Marietta Astronautics Group under the direction of **Dr. B. C. Clark**. An important teaming role by Science Applications International Corporation (SAIC), led by **J. C. Niehoff**, included trajectory analyses and contributions to mission design.

Our Contract Officer's Technical Representatives (COTR) at NASA/MSFC were extremely helpful and encouraging in all aspects of these endeavors. For this we must thank **R. H. Durrett, C. F. Huffaker,** and **B. M. Wiegmann**. We wish also to thank **J. M. Butler, C. C. Priest,** and **R. E. Austin** of MSFC and **I. Bekey** of NASA/ Headquarters for their interest, encouragement, and contributions.

Numerous individuals played key roles in the conduct of this effort, which at times assumed a scope of major proportions, under extremely constrained timelines. We wish especially to recognize major contributions by **D. A. Baker, S. A. Geels, R. S. Murray, W. D. Plaster, L. Redd, P. S. Thompson, W. H. Willcockson, R. M. Zubrin** of Martin Marietta and **J. McAdams** and **A. L. Friedlander** of SAIC.

Subcontractors with significant inputs to this work included Life Systems, Inc. (LSI), led by **F. T. Powell**, and Eagle Engineering, Inc., with important work accomplished by **L. Guerra** and **J. M. Stovall** under the direction of **W. R. Stump**. Individually contracted contributions by **E. W. Cliffton, A. A. Harrison,** and **H. H. Schmitt** are greatly appreciated.

We also wish to acknowledge the efforts of the following Martin Marietta personnel: **M. S. Allen, D. Bentley, H. Braun, R. T. Gamber, J. P. Gille, C. M. MacLeod, C. Marshall, L. M. Mason, R. McMordie, J. Molino, R. S. Murray, R. Obermeyer, R. Simms, A. B. Thompson, M. G. Thornton, D. Sosnay, T. Sulmeisters, B. Tobey,** and **B. Woodis**. Personnel from among this group provided much of the in-depth capabilities that were needed at various times, even though the resources available were not such that they could be involved on a continuous basis with the studies. Their efforts and interest were of major contribution to the soundness of the analyses conducted.

Work reported on lunar liquid oxygen (LLOX) utilization and aerocapture sensitivity to Mars atmospheric density variations were developed in part under Martin Marietta internal development projects D-46S and D-33S, respectively.

Finally, it is a pleasure to acknowledge the work accomplished by a group which spontaneously formed to work in parallel to this effort to design a Mars mission (see Appendix C of this report). This group received no compensation because of overall funding limitations, but included over 25 persons during the course of their studies. Led by **D. Seitz**, major contributors have included **J. Danelek, J. Filbert, W. McCarthy, D. Philipp, M. Schloesslin, J. Schulz, G. Thomason,** as well as **D. Greeson, H. Rackely, B. Tuell,** and **J. Zerr**. Early-on , this group selected nuclear thermal propulsion and artificial gravity for their baseline, two technologies that have recently begun to receive more serious consideration in the official studies. Their purely voluntary effort is testimony to the intense grass-roots support for human exploration missions to the planets.

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1.0 INTRODUCTION

This is the Final Report under Contract NAS8-37126, performed for the NASA Marshall Space Flight Center. The purpose of the Study was to design and analyze systems for conducting human missions to Mars and the moon, with special emphasis on the transportation and facility infrastruture. This study was conducted by Martin Marietta Astronautics Group, with an important teaming role by Science Applications International Corporation (SAIC). Subcontractors with significant inputs to this work included Life Systems, Inc. (LSI) and Eagle Engineering, Inc.

The Manned Mars System Study (MMSS) was conducted for the Marshall Space Flight Center (MSFC) during the 35 month period between May 15, 1987 and April 30, 1990. During the course of the study, the NASA Office of Exploration (OEXP; Code Z) was created and MSFC was subsequently designated the Transportation Integration Agent (TIA) for support of the OEXP Mission Analysis and Systems Engineering (MASE) team. This work directly supported the MSFC role as the TIA for MASE through 1989. This work therefore included the studies and separate reports of the Fiscal Year 1988 and 1989 Case Studies, as well as special analyses and parametric studies. The study is reported more fully in Volume II of this report, and in NASA Technical Memorandums 4075 and 4170.

2.0 MISSION OVERVIEWS

2.1 MARS MISSION CASE STUDIES

The Mars human exploration and transportation scenarios that have been studied under this contract are listed in Table 2-1. A synopsis of their individual requirements, generally set by the Mission Analysis and Systems Engineering (MASE) team, and the numbers of Heavy Lift Launch Vehicles (HLLV) determined to be required to accomplish each scenario is given in Table 2-2.

Table 2-1 Mars Human Exploration Scenarios Studied

Scenario	Study Completed
Case Study 1	7-11-88
(Phobos Flags and Footprints; FY88)	
Case Study 2	7-11-88
(Mars Expeditionary trip; FY88)	
Phobos Gateway	11-88
Mars Evolution	6-2-89
(FY89 Case Study 5.0)	
Mars Expedition	6-2-89
(FY89 Case Study 2.1)	

Table 2-2 Summary of Mars Scenario Studies

Scenario	Target	Crew Size	Ave. No. HLLVs per mission
Case Study 1	Phobos	4	25
Case Study 2	Mars, Phobos	8	32
Phobos Gateway	Phobos, Mars	3, 5	5
Mars Evolution	Phobos, Mars	3, 5, 7	8.5
Mars Expedition	Mars	3	7

Case Study 1 was constructed as a high energy trajectory (sprint), but without aerobraking for aerocapture at Mars. These two factors combined to result in an extremely large load of hydrogen/oxygen (H/O) propellants for the trans-Mars Injection System (TMIS) and the all-propulsive Mars Orbital Capture System (MOCS). Although not in the baseline requirements, two alternatives were considered: a nuclear thermal rocket (NTR) propulsion system and a Mars aerocapture brake. Figure 2-1 demonstrates the very major reductions in initial mass in low Earth orbit (IMLEO) that are possible if either or both of these approaches could be adopted for this mission scenario.

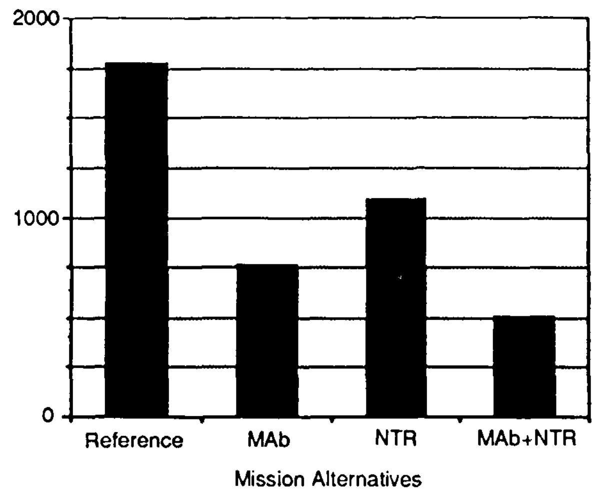


Figure 2-1 IMLEO-Saving Effect of Alternative Approaches for Case Study 1 (MAb = Mars Aerobrake; NTR = Nuclear Thermal Rocket)

Case Study 2 involved a series of three split sprint/conjunction missions to Mars, with a much larger crew complement of eight astronauts per manned mission. Because aerocapture was allowed for both cargo and human flights, it was decided to select a common-sized aerobrake for the designs in order to force a commonality that could reduce implementation costs. The manned interplanetary vehicle is shown in Figure 2-2. During the rendezvous in Mars orbit, the two craft dock as shown in Figure 2-3, allowing a shirt-sleeve transfer of four crewmembers into the lander. In this "clamshell" docking configuration, the trans-Earth injection system (TEIS) is also transferred from the cargo vehicle to the manned vehicle. This TEIS is fully self-contained, with power system, communications, and an all-up propulsion system. Only pyrotechnic mechanical releases and docking latches are required to successfully accomplish the transition; no propellant transfer, electrical, or thermal connection are required in this concept.

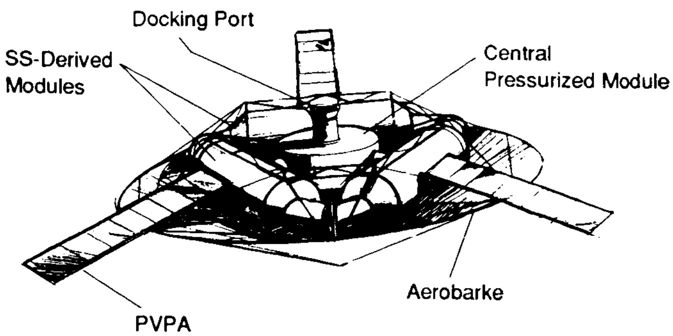


Figure 2-2 Manned Mars Vehicle for Case Study 2

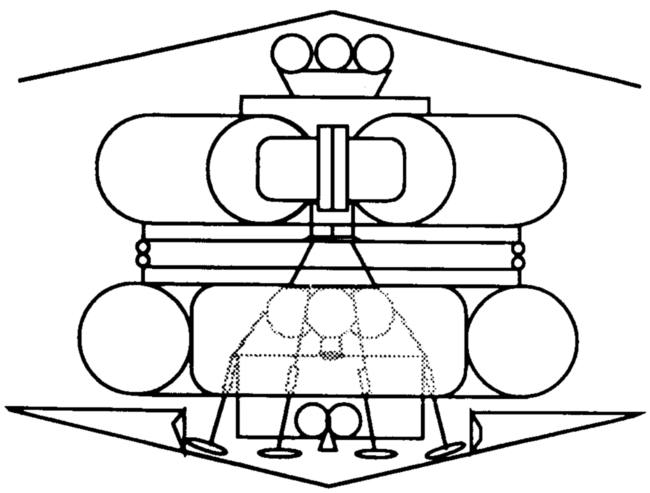


Figure 2-3 Docking Configuration in Mars Orbit

The Mars Descent Vehicle (MDV) includes deorbit propulsion, an entry aerobrake, parachutes, and terminal descent propulsion. It contains a single disk module habitat, Figure 2-4, connected by a shirt-sleeve tunnel to the small conical cabin of the Mars Ascent Vehicle (MAV). During the complex landing sequence, the crew is located inside the MAV and can accomplish a fly-away abort to orbit if a critical fault event occurs.

Major savings can be made in IMLEO if NTR is employed for the TMI, but much less for the TEI stage. In general, the use of NTR for Earth escape will be the highest leverage application, and in many respects the safest use of this technology because once used, the reactor core becomes radioactive but can be jettisoned if further use is not required.

An "all-up" mission flown on a conjunction class trajectory was proposed as an alternative. A comparison of IMLEOs shows that this alternative mission could be performed with almost one-third less mass, yet provide over 70% more habitable volume for the crew, be science-enriched (two pressurized rovers vs one unpressurized rover; a much larger user payload; more than a ten-fold increase in Mars surface staytime), can be recovered into Earth orbit because of the relatively lower encounter velocity, and arrives with humans at Mars at an earlier date without requiring a change in programmatics. However, this alternative has a total mission time of about than 32 months, while the sprint roundtrip is 14.5 months.

The Phobos Gateway was a special study conducted separate from the MASE case studies. This was the first scenario to be baselined with (a) a requirement for artificial gravity (using tethers), (b) to be non-split (i.e., all-up), and (c) to be non-sprint (i.e., to utilize opposition and conjunction class trajectories for crew members). The habitation module cluster is detachable for establishing artificial gravity.

A sequence for launch and assembly of the Phobos Gateway spaceship is shown in Figure 2-5. Compared to the earlier case studies, where 25 to 30 launches of HLLVs were needed for each human flight to Mars, the Phobos Gateway approach was considered a breakthrough into feasibility/plausibility for major manned Mars missions because only 5 HLLV's were required.

The Mars Evolution case study 5.0 was an ambitious combination of missions with Phobos mandated as an operating centrum for on-site production of propellant and anchoring of tethers for momentum transfer. Artificial gravity was also specified as was recovery and reuse of some vehicles. The layout of the interplanetary spaceship is shown in Figure 2-6.

The Mars Expedition, Case Study 2.1, is a three crewmember split sprint/conjunction mission to Mars, but with the TEIS incorporated into the manned vehicle. This case specified that the design include an aerobrake with a lift-to-drag (L/D) ratio of between 0.9 and 1.2. An L/D of 1.0 was selected. The resulting manned vehicle is shown in Figures 2-7 and -8.

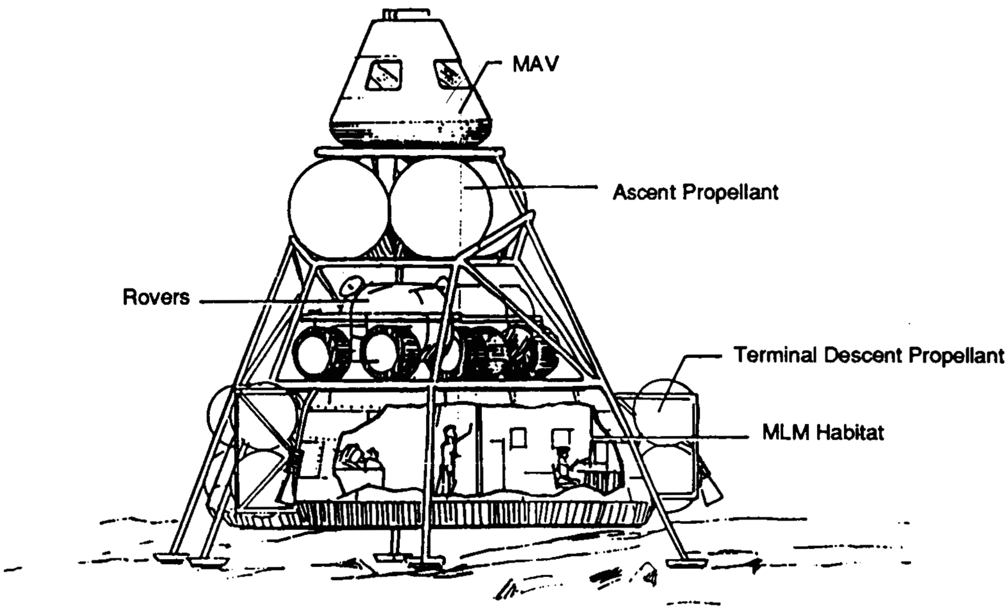


Figure 2-4 Mars Descent Vehicle (MDV)

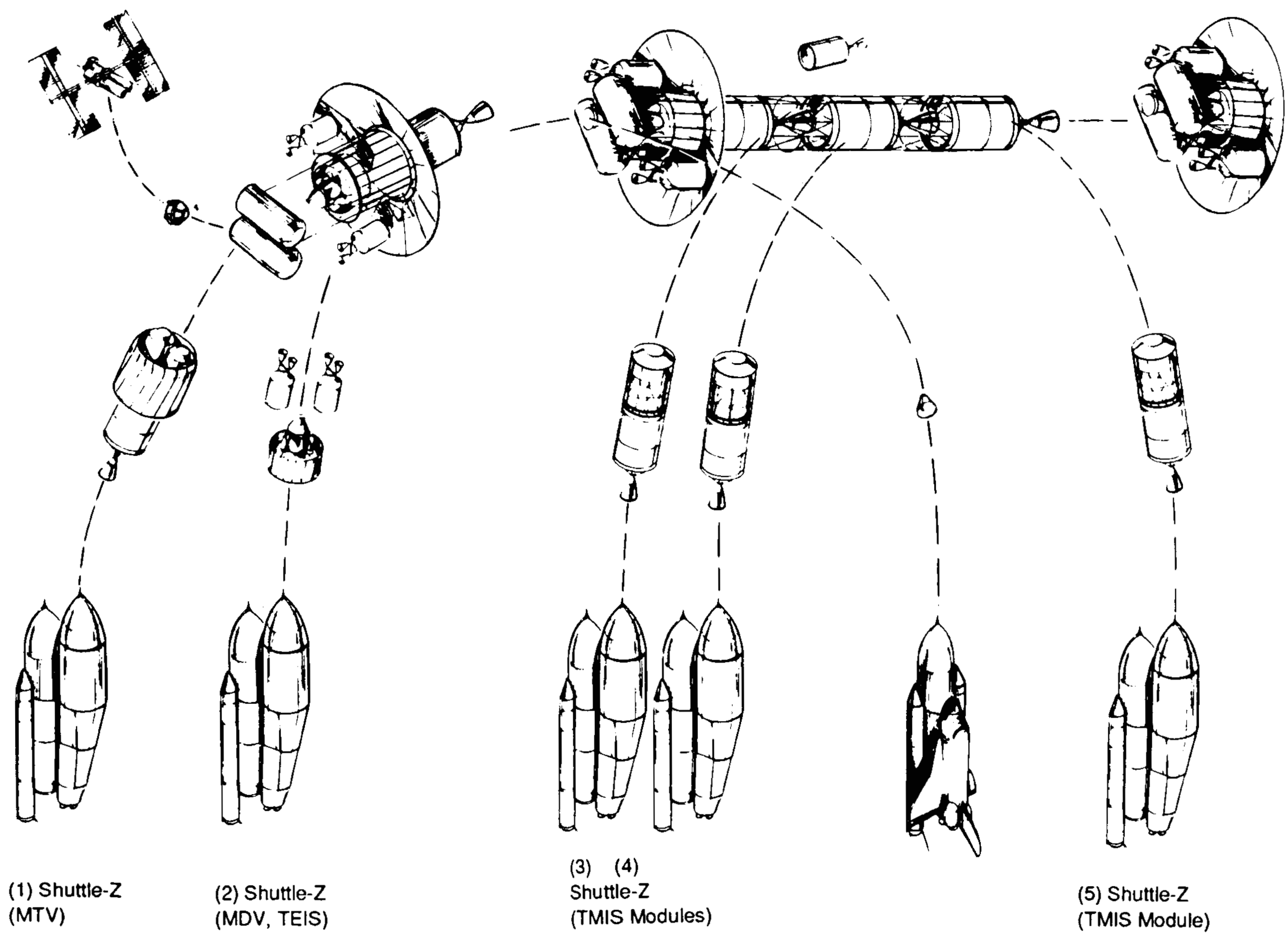


Figure 2-5 Launch and Assembly Sequence for Phobos Gateway Mission

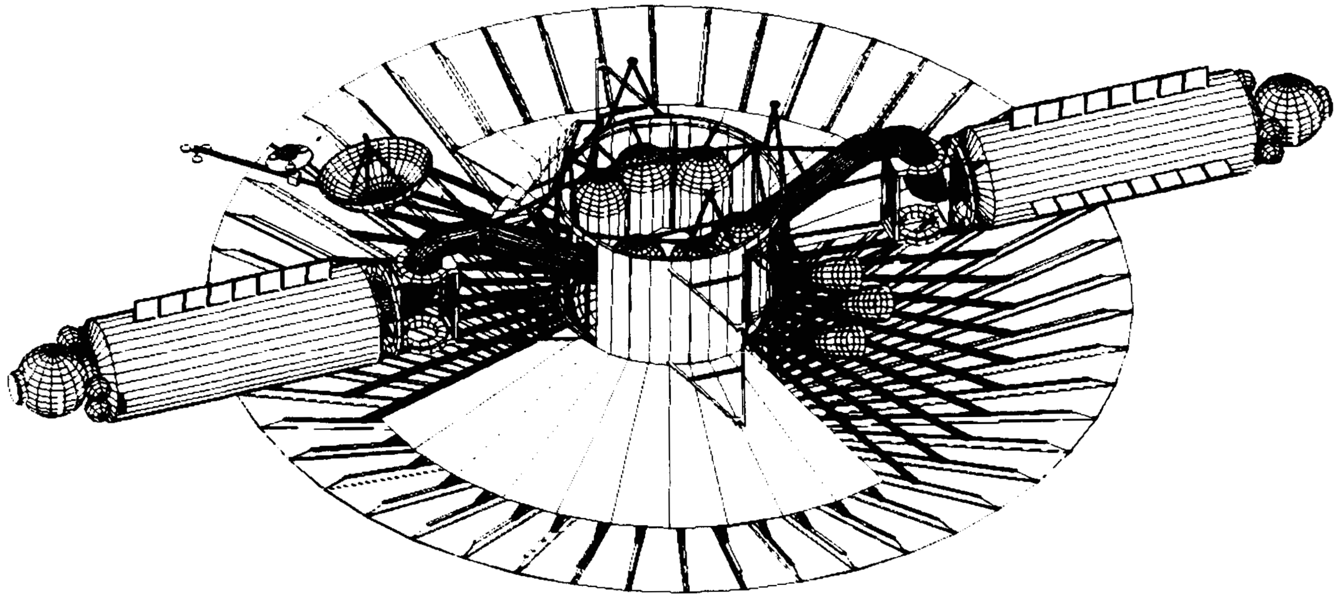


Figure 2-6 Mars Evolution Spaceship (Habitation Modules Deployed)

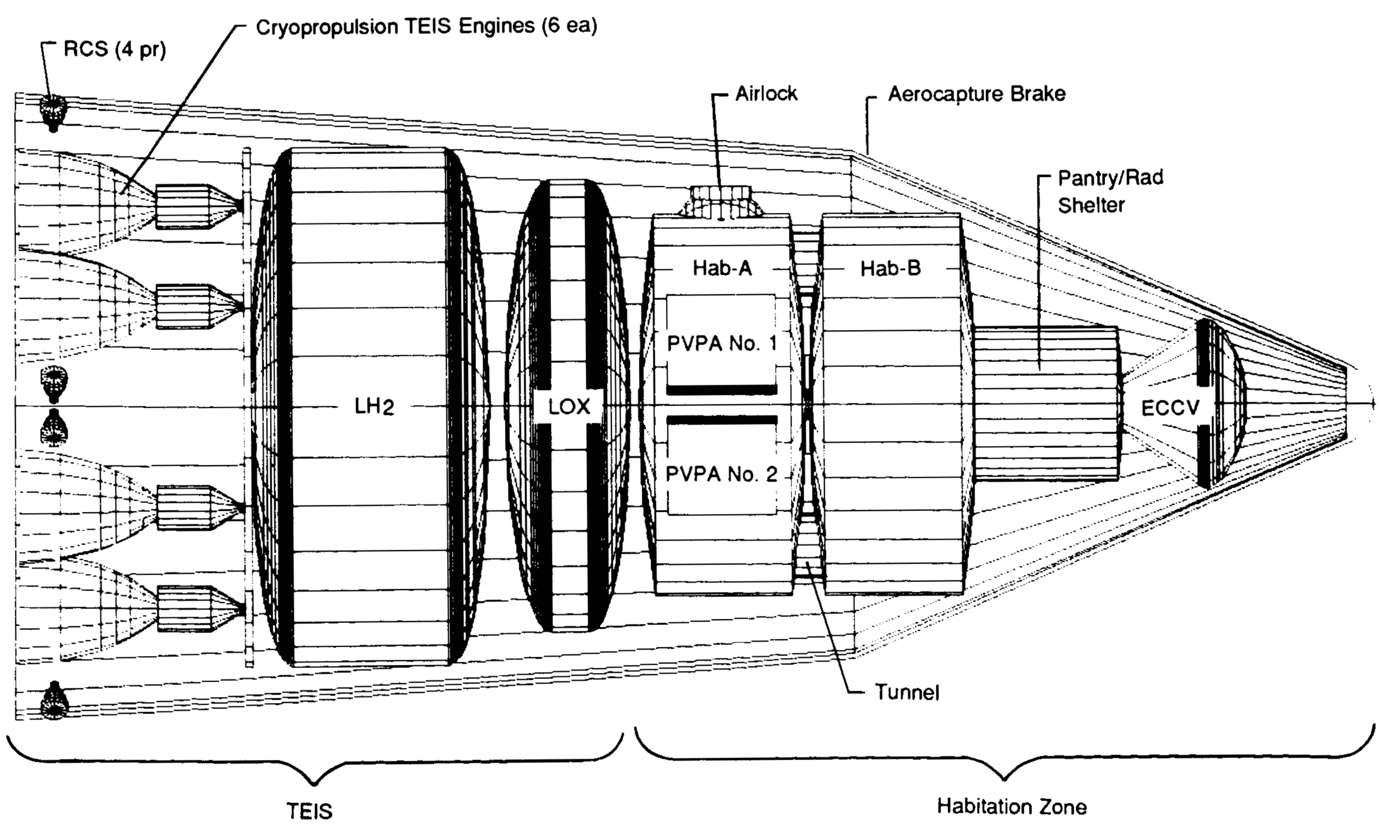


Figure 2-7 Mars Expedition Manned Vehicle, Internal Layout

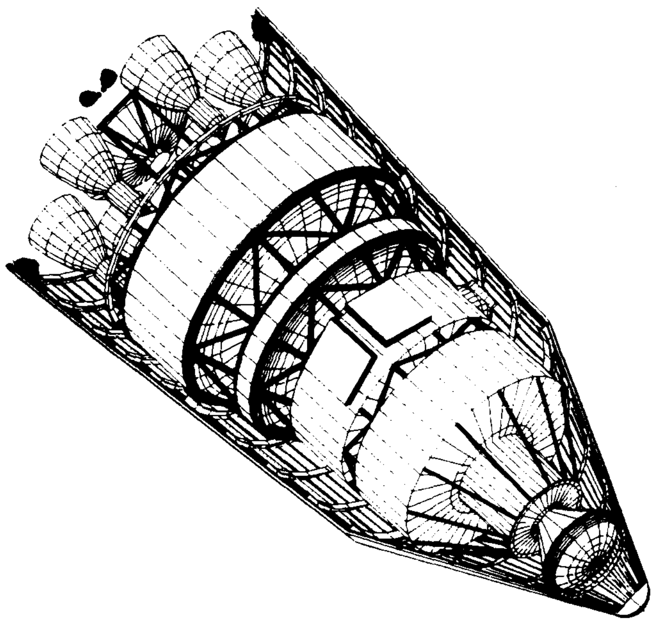


Figure 2-8 Mars Expedition Manned Vehicle, Structural Design

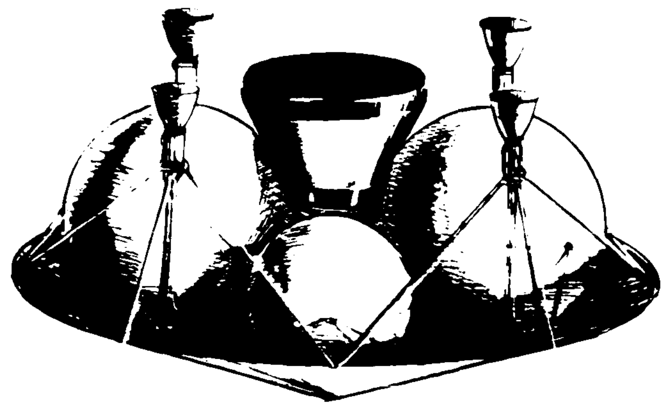


Figure 2-9 Lunar Transfer Vehicle (LTV) for Case Study 3

2.2 LUNAR MISSION CASE STUDIES

The lunar human exploration and transportation scenarios that have been studied under this contract are listed in Table 2-3.

Table 2-3 Lunar Human Exploration Scenarios Studied

Scenarios	Study Completed
Case Study 3 (FY88)	7-11-88
Lunar Gateway	11-88
Lunar Evolution (FY89 Case Study 4.1)	6-2-89
Lunar Evolution Synthesis (Modification of FY89 Case Study 4.1)	6-28-89

Case Study 3 was designed to transfer a crew of four to the moon along with a payload of 6.5 tonnes, but preceded by a cargo mission delivering 17.5 t to the lunar surface. Lunar Descent Vehicles (LDV; landers) were expendable and a separate Lunar ascent vehicle (LAV) was provided, in analogy with the Apollo mission architecture. Cryogenic H/O propellant systems were used throughout. A conically shaped return crew cabin was nestled into the four tanks as shown in Figure 2-9. The cargo vehicle was designed to hold a centrally located cargo bay (Fig. 2-10).

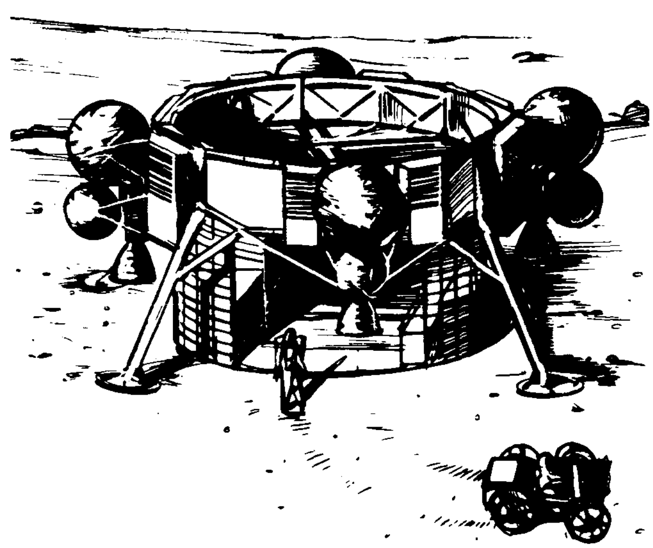


Figure 2-10 Lunar Descent Vehicle - Cargo (LDV-C)

The Lunar Gateway mission design had a requirement of delivering 20 t of cargo to the lunar surface in unmanned missions. It was adopted that the human missions would deliver a habitat, an LAV, the crew, and an amount of cargo that brought the total payload up to 20 t. With this design stratagem, it was possible to design a great deal of commonality into the two systems -- cargo and piloted. Cryogenic H/O was used for all propulsion except lunar ascent. The cargo vehicle (LDV-C) is transported to low lunar orbit (LLO) in the pusher mode, with the lander temporarily attached by ceramic latches at strong-points built into to the aerobrake's rigid core.

The Lunar Evolution case study 4.1 was an extension of the Lunar Gateway concept, but extended the crew size to eight. This study employed "through-the-brake" Advanced Space Engines (ASE). The Lunar Piloted Vehicle, which is the transfer vehicle from LEO to LLO, is shown in Figure 2-11. The reusable lander vehicle, the Lunar Crew Sortie Vehicle (LCSV) is shown in Figure 2-12. In LLO, the two vehicles accomplish docking as seen in Figure 2-13.

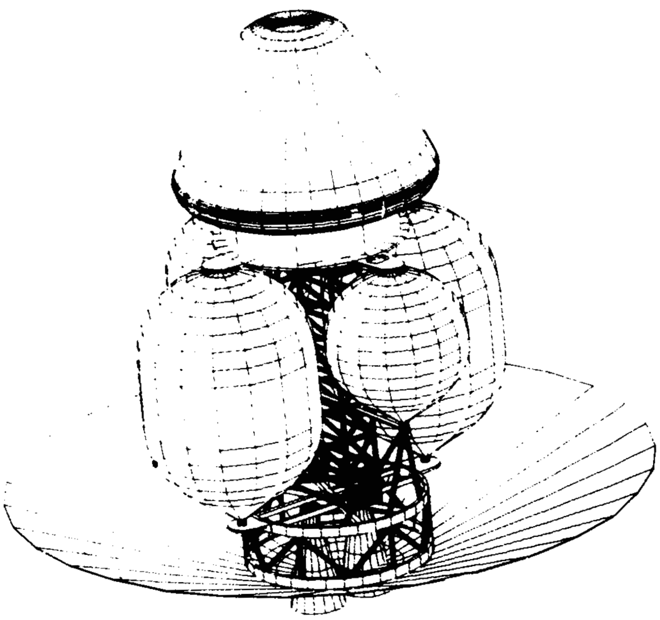


Figure 2-11 Lunar Piloted Vehicle (LPV)

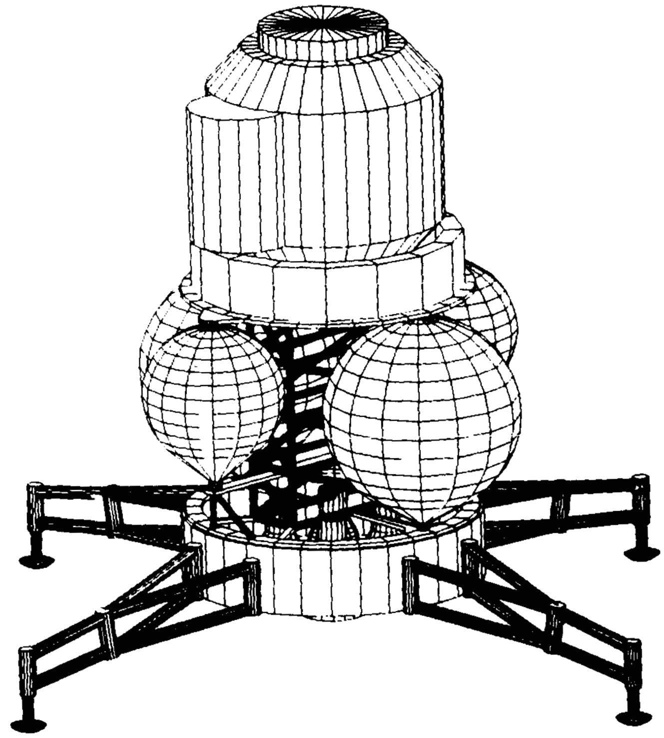


Figure 2-12 Lunar Crew Sortie Vehicle (LCSV) (Lander)

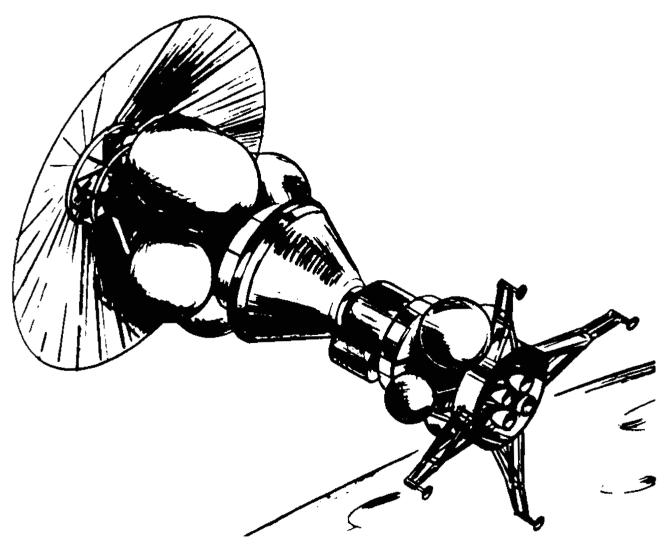


Figure 2-13 Docking in LLO for Transfer of Crew

3.0 MISSION PARAMETRIC AND SPECIAL TOPICS

With the breadth and level of complexity that is invoked by human missions to the planets, there are intrinsically a number of topics of significant importance beyond the obvious transportation issues of propulsion, habitability, node support, and aerodynamic surfaces (aerobrakes). Topics include astrodynamics, radiation protection, artificial gravity, rovers, science and exploration, tethers, habitats, propulsion, and aeroassist. Each are summarized in the following sections.

3.1 ASTRODYNAMICS

Missions to Mars vary as the year of the opportunity, with a 26-month interval between opportunities of like type, and an overall near-identical repeat of the synodic cycle every 15 years. To capture the functional characteristics of these opportunities, results are charted from the data base provided for Mars aerocapture as well as propulsive orbital capture for manned missions by Science Applications International Corporation (SAIC). These data were optimization runs generated with the use of the trajectory analysis tool, Multiple Impulse (MULIMP). Figure 3-1 shows the 17 Mars mission launch opportunities between 2002 and 2013, including conjunction (minimum energy), opposition (medium energy), Venus-swingby, and sprint (highest energy, shortest round-trip) trajectories.

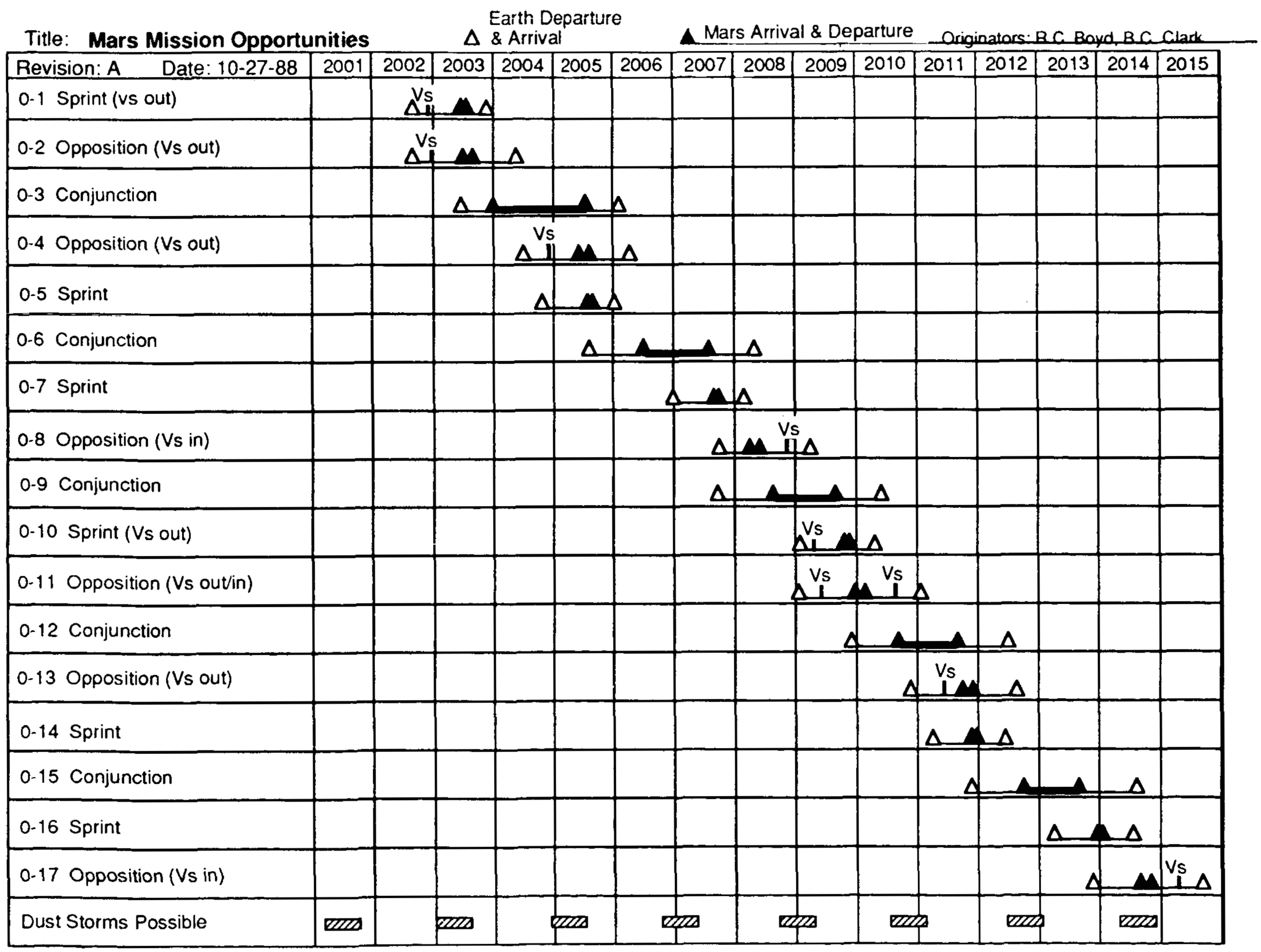


Figure 3-1 Mars Mission Launch Opportunities for 2001 through 2013

3.2 RADIATION

Concern for the radiations in space has been a hallmark of U.S. and Soviet programs since the dawn of the Space Age. Three types of ionizing radiation must be considered: (1) planetary radiation belts, (2) galactic cosmic rays (GCR), and (3) solar particle events (SPE) from flare activity. Neither Mars nor Venus have radiation belts, but the transitions from LEO to interplanetary space and back result in exposure to the Van Allen belts.

Shielding optimization is different for all three types of radiation environments. It appears impractical to provide the mass necessary to significantly reduce the dose that must be taken by GCR. It is likewise unnecessary to provide Mars surface shielding against GCR since the transit times are longer than the surface residence time and the atmosphere provides considerable shielding. Shielding against solar particle event (SPE) radiation can and must be provided. Most SPE energy spectra are such that modest shields are quite effective. However, events rich in relativistic particles can occur and contingencies should provide emergency survival shielding. Food and water provisions, as well as internal flight equipment, can be used for bulk shielding. On-board radiation, such as from radioisotope or nuclear fission power sources, may also be a major concern if such sources are required for success of the mission. The doses from these artificial sources generally are placed under different guidelines than the exposures to natural radiation such as the three sources discussed above.

3.3 ARTIFICIAL GRAVITY

Long interplanetary flight times, combined with possibly protracted stays in Mars orbit, would subject crewmembers to up to three years of weightlessness. In view of the known problems with zero gravity, a spinning spacecraft offers many advantages and may indeed be an enabling technology for human travel to Mars. Five concepts for artificial gravity have been developed during the course of these studies.

Missions in space as well as Earth-based medical studies have clearly demonstrated a number of human physiological adaptations to the absence of normal gravitational forces. Among the effects are the well known (1) progressive losses of skeletal mineral mass, (2) the atrophy of most muscles, including the heart, and (3) the susceptibility to orthostatic intolerance. Potentially serious effects also include alterations in both immunological and pharmacological response. There are also negative aspects of rotational gravity including coriolis effects, gravity gradients, and increased EVA difficulty.

Figure 3-2 illustrates various artificial gravity vehicles. Concepts 1-3 are one-piece vehicles, while concepts 4 and 5 use separate vehicle parts spun around each other on tethers to create the pseudo-gravity acceleration environment.

3.4 ROVERS

A major objective of missions to Mars and the moon will be to accomplish reconnaissance and exploration of the surface. To realize the potential of cognition, serendipity, generalization, opportunism, and those other uniquely human attributes that so importantly contribute to the exploration of uncharted territory, it will be necessary to provide systems that allow astronauts to operate freely in the Martian environment. These systems include transportation, life support, environmental control, and portable equipment. Strategic planning of objectives and means is of utmost necessity in the design of this infrastructure of equipment in order to maximize efficient utilization of the invaluable time on Mars. Table 3-1 summarizes the rover concepts, while Figures 3-3 to 3-5 illustrate the various rovers.

3.5 SCIENCE AND EXPLORATION

The most visible purpose for human exploration of the planets, other than the adventure of exploration and the political and social benefits, will be to make scientific discoveries and enhance our knowledge of the universe. Of great potential direct benefit is learning new aspects about Mars and possibly other planets that will improve our understanding of key processes on Earth, such as geological episodic events and climatological trends. Surrounding these missions will be a multitude of opportunities for endeavors which have the potential to encompass nearly every major scientific discipline.

An Interplanetary Science Experiment (ISE) set of packages can include instrumentation for all of the scientific disciplines listed in Table 3-2.

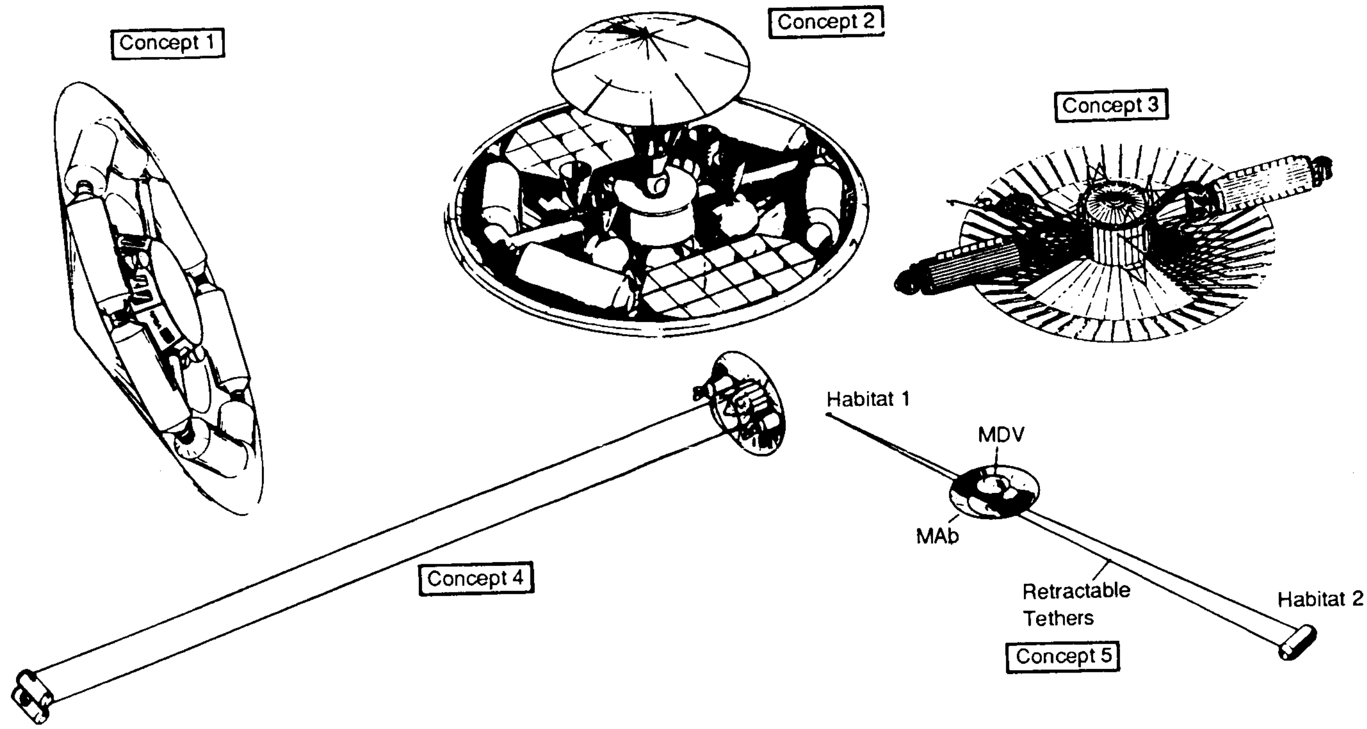


Figure 3-2 Artificial Gravity Vehicle Concepts

Table 3-1 Rover Concepts and Issues

Minimum Rover (ala Apollo Lunar Rover)
Unpressurized
Minimum weight
Limited to 8-hr sortie (suit time)
Moderate Rover
With plug-in life support, but no shirt-sleeve habitation module
Could have umbilical
Could have LSS Cart
Maximum Rover
Shirt-sleeve, one or two-person (2 preferred)
Remote manipulators (telepresence)
Rumble seat for suited astronaut

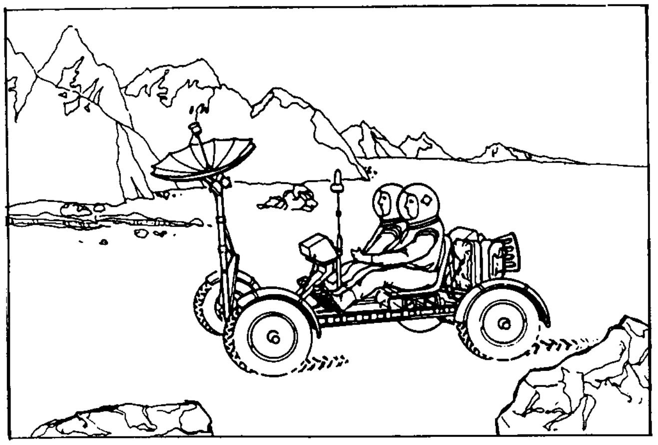


Figure 3-3 Minimum Rover

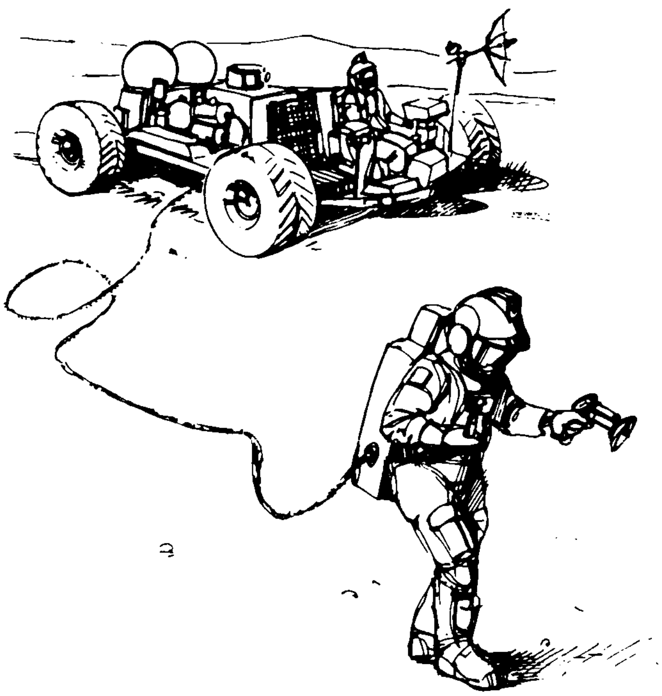


Figure 3-4 Rover with Augmented Life-Support Services

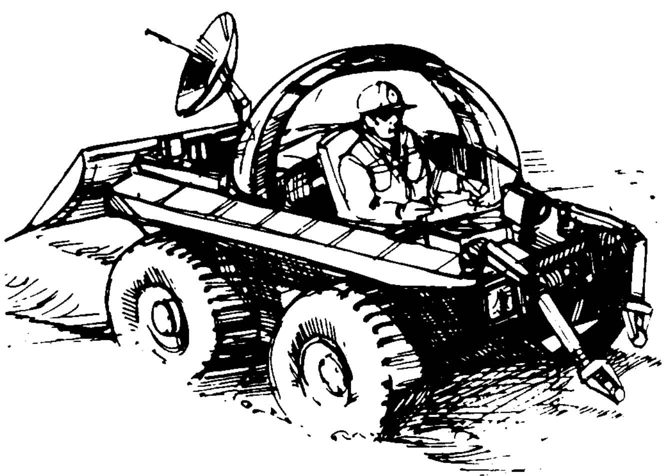


Figure 3-5 Shirt-Sleeve Rover, One-Person

3.6 TETHERS

Significant potential exists for the use of tethers as length-adjustable, non-rigid linear tensile members in possible lunar and Mars expeditions.

Tethers are an integral part of some plans for generating artificial gravity while traveling to Mars. One approach would be to divide the spacecraft in two (separating the habitation modules from the main spacecraft) and linking the parts with a pair of 222 m tethers, spinning them about each other to create artificial gravity (see Figure 3-2, concept 4). A second possibility is to separate the two habitation modules from the main spacecraft, reel them out in opposite directions, and spin them around a main hub (see Figure 3-2, concept 5).

Another ambitious tether concept for the Mars Mission is a plan to lower a sortie vehicle from Phobos toward Mars on a pendant cable and possibly using the same tether to rendezvous with and retrieve the vehicle. In addition to these tether ideas, there are also possibilities of using tethered masses for momentum exchange between Phobos and the spacecraft. Figure 3-6 and 3-7 summarize this type of mission.

Table 3-2 Science: Objectives During Interplanetary Transfers

Human Physiology
Bone demineralization
Cardiovascular deconditioning
Muscle atrophy
Vestibular dysfunction
Immune system, drug efficacy
Human Psychology/Sociology
Isolated and confined environment (ICE)
Stress assessment, consequences
Microsocietal interactions
Astronomy
Astrophysics: stellar, galactic, extragalactic sources (Vis, IR, UV, X-ray, gamma-ray observations, VLBI)
Planetary science: Earth, moon, Mars, Venus, Jupiter (Vis, IR, UV)
Solar research: sunspots, flares, corona (Vis, IR, UV, radio)
Space Environment Effects/Manufacturing
Microgravity, variable-g
Ultra-high Vacuum
HZE Particle Irradiation
Space Agriculture
CELSS Demonstrations

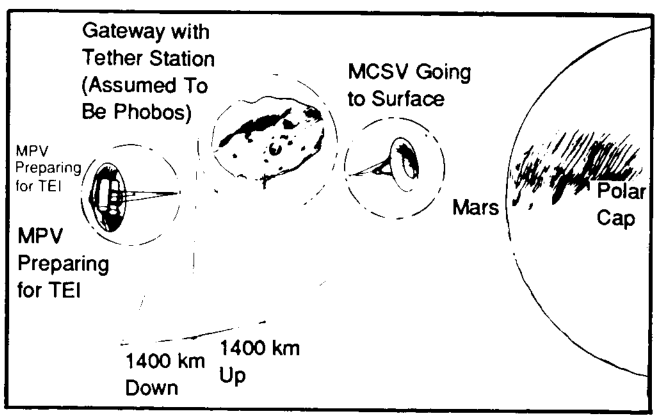
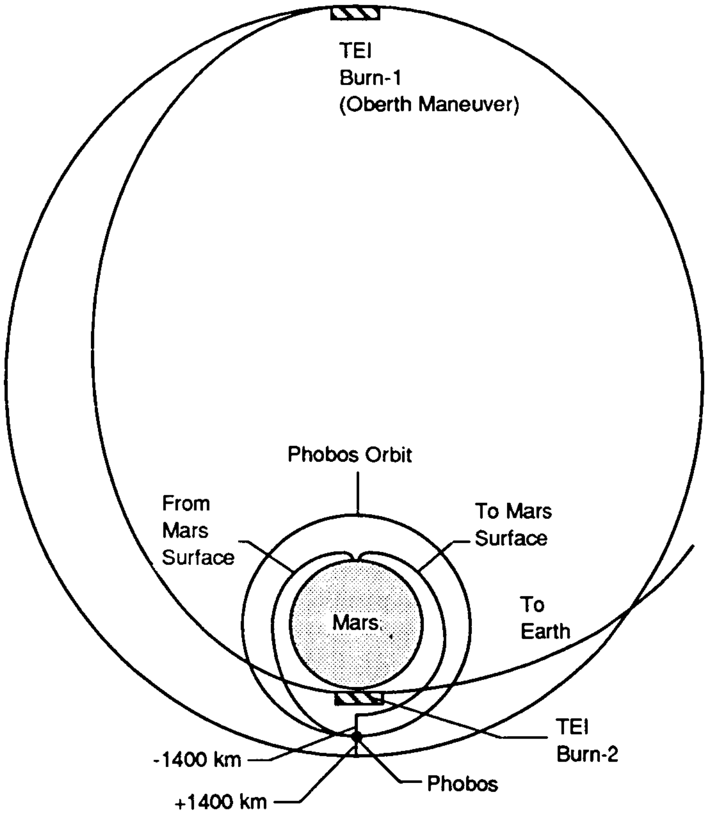


Figure 3-6 Phobos Tether Applications



- 1400 km Is Length Required To Put The Postrelease Periapsis in Mars' Atmosphere
- ΔV Savings is 538 m/s per MCSV Round Trip & 766 m/s per TEI Injection
- Electric Power Needed to Winch Tether & Expended MCSV to Phobos is
  1 MWe for 12.6 Hours or
  100 kWe for 5.25 Days
- Power Needed to Winch Empty Tether to Phobos is:
  100 kWe for 2.1 Days or
  10 kWe for 21 Days
- Tether Used Only to Reel-Out Piloted & Cargo Vehicle
- Tether Winched in Empty

Figure 3-7 Tether Assist at Gateway

3.7 HABITATS

A total of 16 Mars and lunar mission habitat options have been designed and analyzed for overall volume as well as walkable and outfitted volume. Standard features in Mars mission habitats include crew quarters, wardroom, a personal hygiene area (PH), a Command and Control Center (CCC), a Health Maintenance Facility (HMF), a galley, Stowage, fitness center, and work area. Lunar crew cabins, because of the relatively short amount of time spent in them, are very small and usually include only personal hygiene facilities and a Command and Control Center.

Two basic types of habitats, cylindrical and disk-shaped, were considered for Mars missions. Cylindrical modules, used during the long interplanetary legs, may be spun on arms to create artificial gravity. The acceleration vector can be either transverse of longitudinal along the cylinder, resulting in uni- or multi-level designs (Fig. 3-8 and 3-9, respectively), called horizontal- or vertical-layout configurations. Each of these configurations has distinct advantages and disadvantages. For example, although habitats with a horizontal layout have the longest horizontal vista (12.8 m), there is some concern about coriolis effects. The vertical layout e.g., the 5-deck cylinder has the shortest horizontal vista (4.6 m) and a fall hazard, but the ladder minimizes corridor volume and provides exercise for the crew.

Disk-shaped habitats, used especially for transfer from low Mars orbit to the Martian surface, are designed around a centrally located hub surrounded by the facilities. These habitats don't always engage artificial gravity due to the short duration of occupancy, and they may also have less volume and fewer comforts. Bi-level habitats that do have artificial gravity have an intermediate value for the horizontal vista and the maximum amount of "floor" area for the same volume (as compared to the cylindrical habitats). Uni-level habitats which don't utilize artificial gravity are much smaller and carry a maximum crew complement of four, as shown in Figure 3-10.

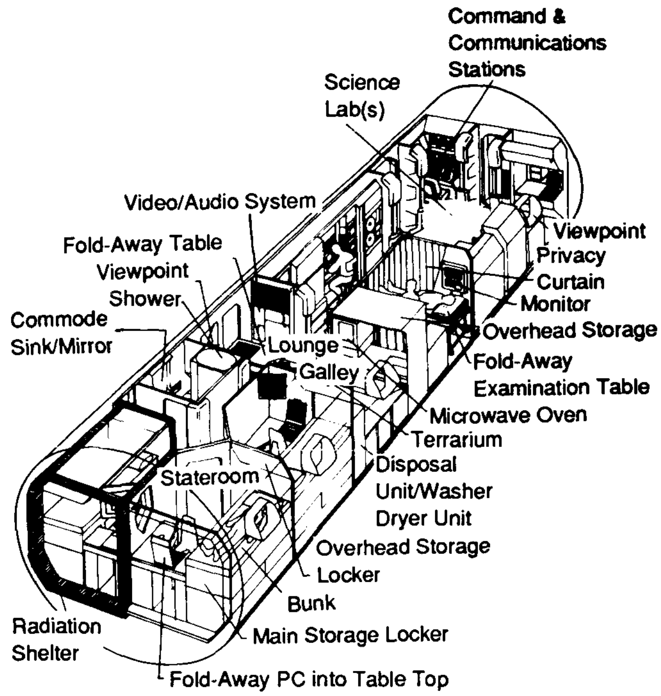


Figure 3-8 Cylindrical Habitats, Artificial Gravity

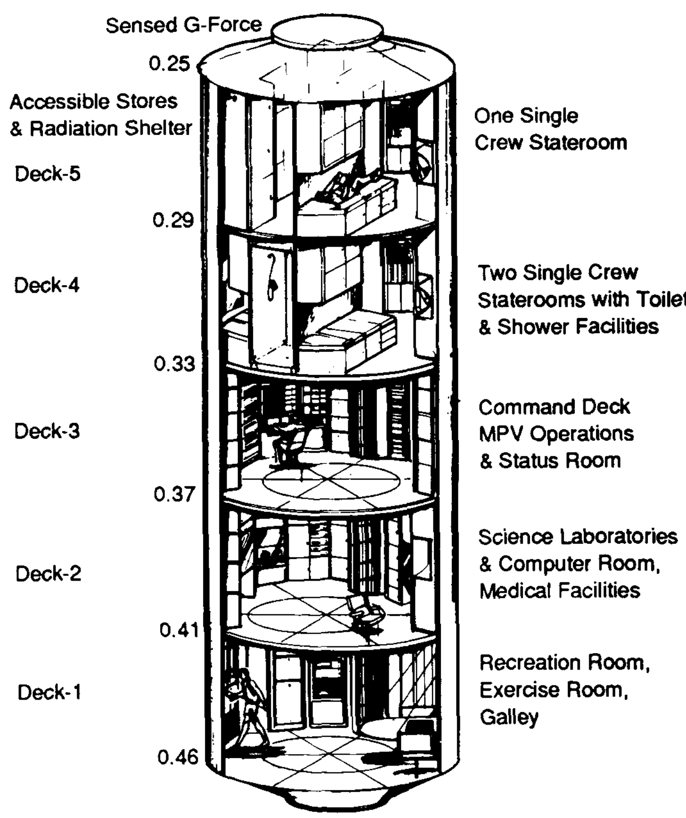


Figure 3-9 2-Cylinder Habitat, Artificial Gravity

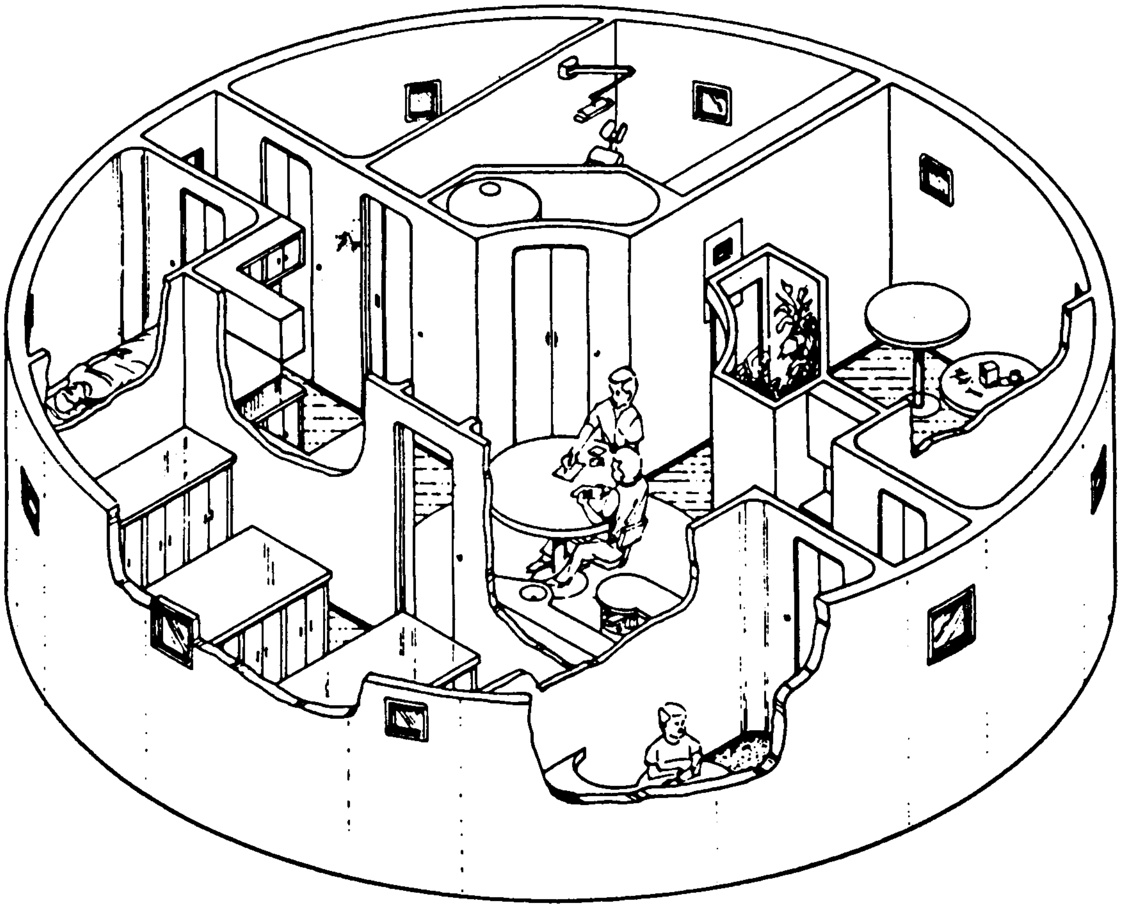


Figure 3-10 1-Disk Habitat

Three lunar habitats have been considered: two Lunar Crew Sortie Vehicles (LCSVs) and one Lunar Piloted Vehicle (LPV). The first two transport crew members between the lunar surface and low lunar orbit, whereas the LPV makes the round trip between low earth orbit to low lunar orbit. Despite the cramped quarters, these habitats accommodate a maximum of eight crew. The largest of the habitats, the 2-deck LCSV, is depicted in Figure 3-11. The LPVs have approximately the same volume as the Alternative LCSV, and accommodate many of the same facilities. The LPV Crew Module (Fig. 3-12) has a large amount of unused volume, especially above the storage compartments which separate the reentry/sleep couches. The alternative LPV has slightly less volume, yet makes better use of the available volume. Because of this, this habitat accommodates a modest exercise station and a larger galley (Fig. 3-13).

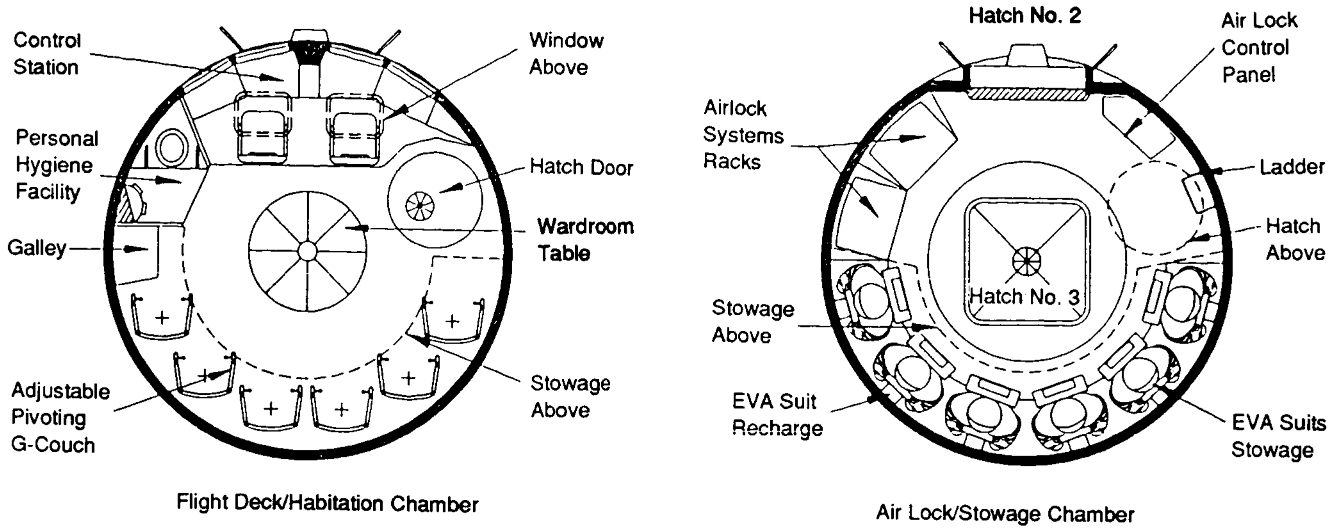


Figure 3-11 2-Deck LCSV Habitat (Alternative)

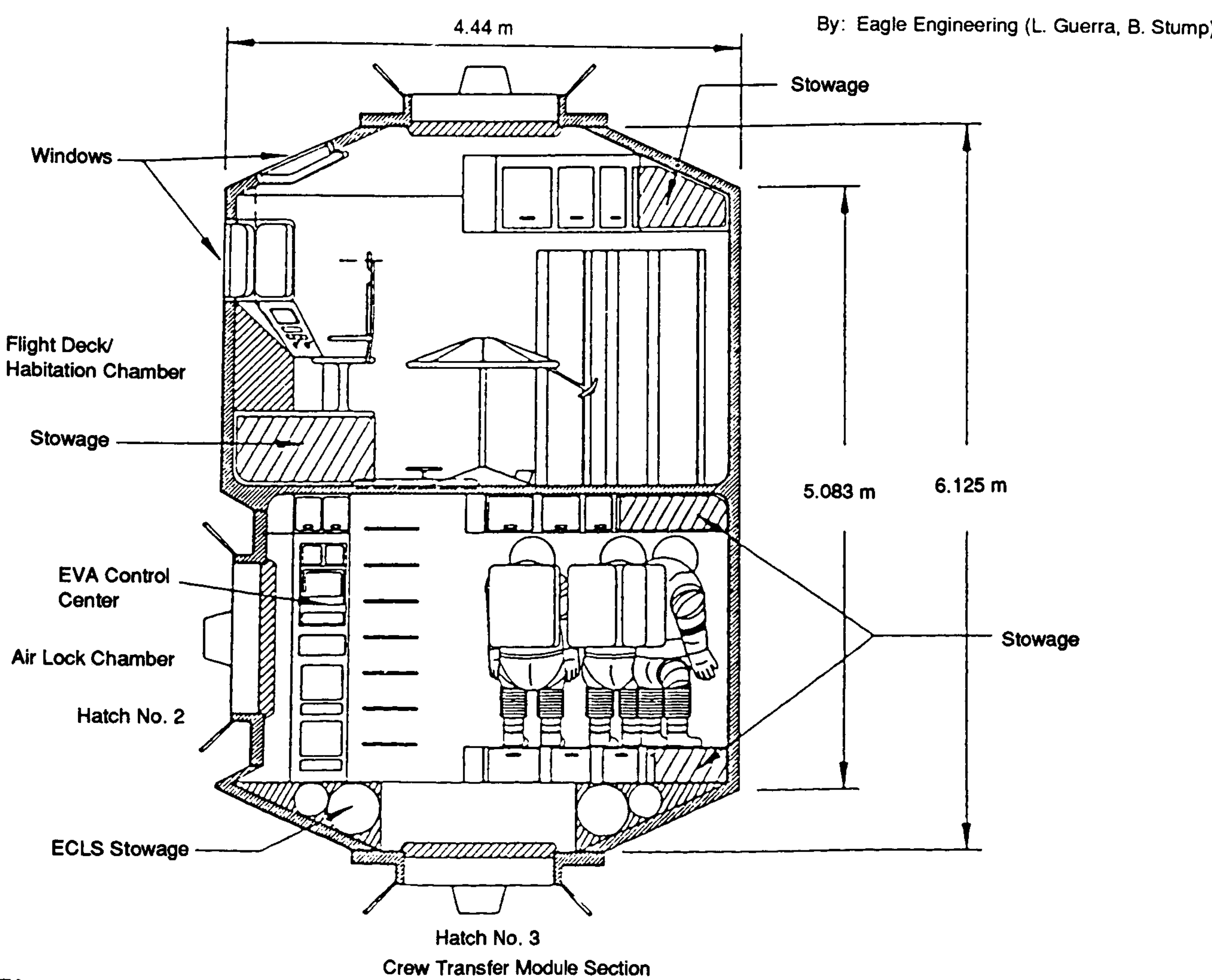


Figure 3-12 2-Deck LCSV Habitat (Alternative)

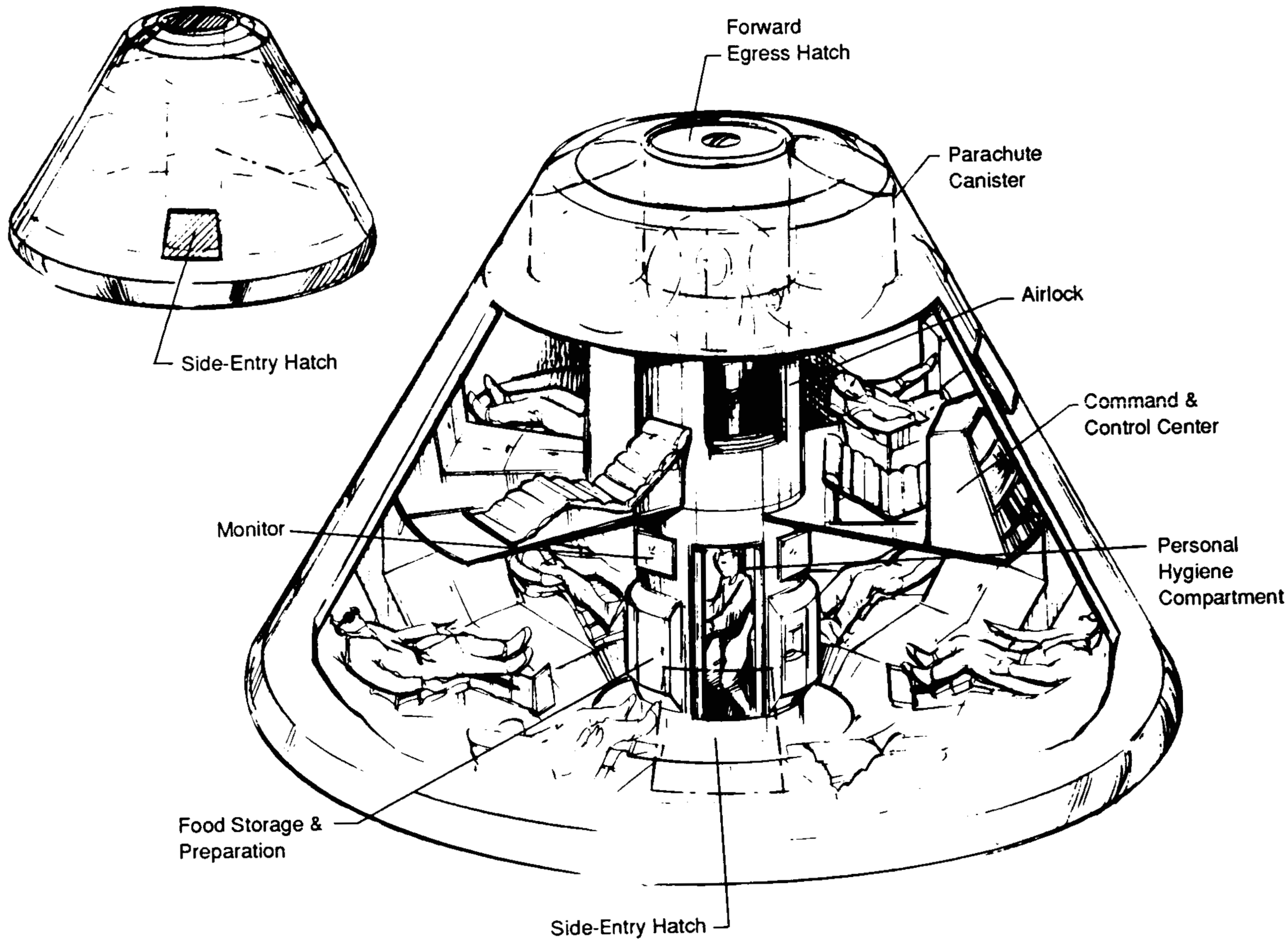


Figure 3-13 LPV Habitat

3.8 PROPULSION

A number of different studies were performed in the area of propulsion to identify mission enabling and possible enhancing technology. Each of the mission propulsion systems was specified, and required advances in engine and tank design were identified. In addition, studies of advanced technology including lunar-produced propellant utilization and nuclear propulsion were performed.

One main area of concern in the analysis of future Mars and lunar missions is cryogenic propellant boiloff. A trade-off study was performed to study the advantages of reducing boiloff rates in the case of Mars Expedition and two Mars Evolution (opposition class and conjunction class missions) case studies. Table 3-3 depicts the assumed boiloff rates for conservative, nominal, and advanced technology levels. Figures 3-14 through 3-16 illustrate the results of this study.

Table 3-3 Allocated Boiloff Rates

Mission Stage	Advanced: "Low" (%/mo)	Nominal: "Medium" (%/mo)	Conservative: "High" (%/mo)
LEO (TEIS)	0.15	0.33	0.55
Interplanetary (TEIS, crew)	0.3	0.6	1.0
Interplanetary (TEIS, cargo)	0.1	0.2	0.4
Mars (TEIS)	0.065	0.15	0.33
LEO (TMIS)	0.0	3.0	5.0

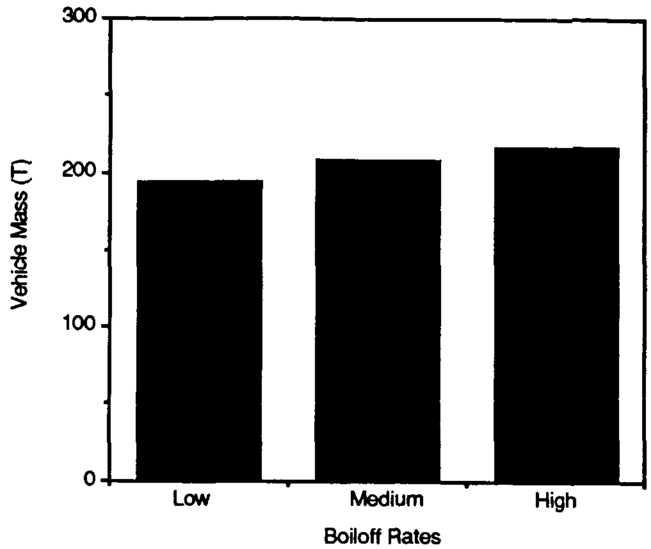


Figure 3-14a Mars Expedition Cargo Vehicle Mass for Varying Boiloff Rates

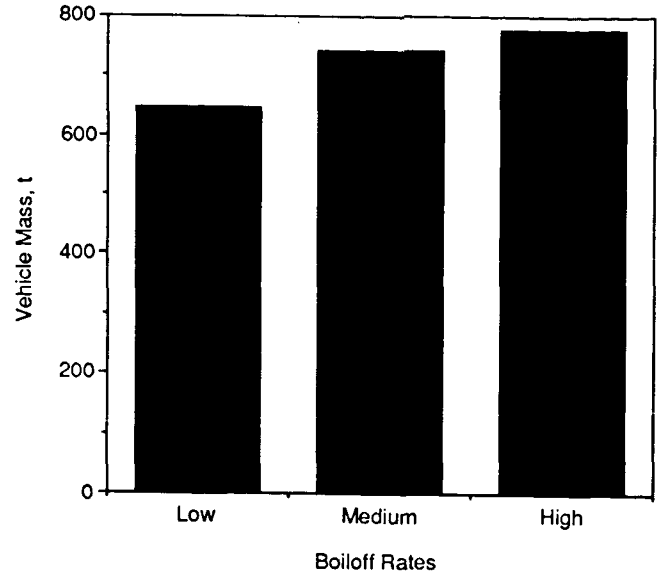


Figure 3-15 Mars Evolution (Opposition) Total Masses for Varying Boiloff Rates

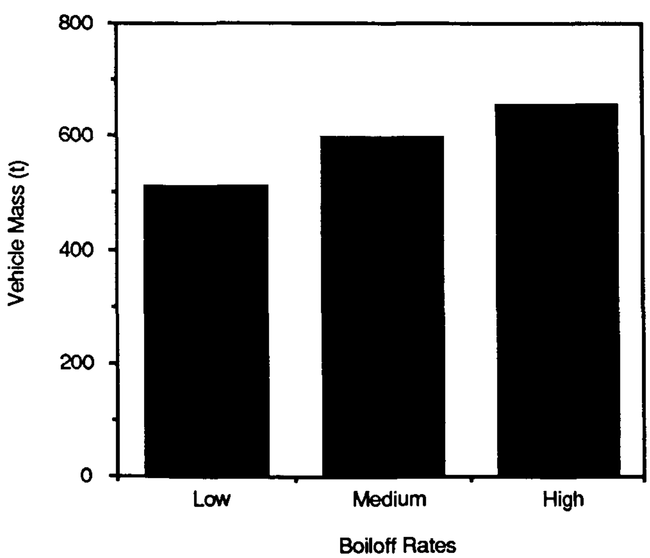


Figure 3-14b Mars Expedition Human Mission Masses for Varying Boiloff Rates

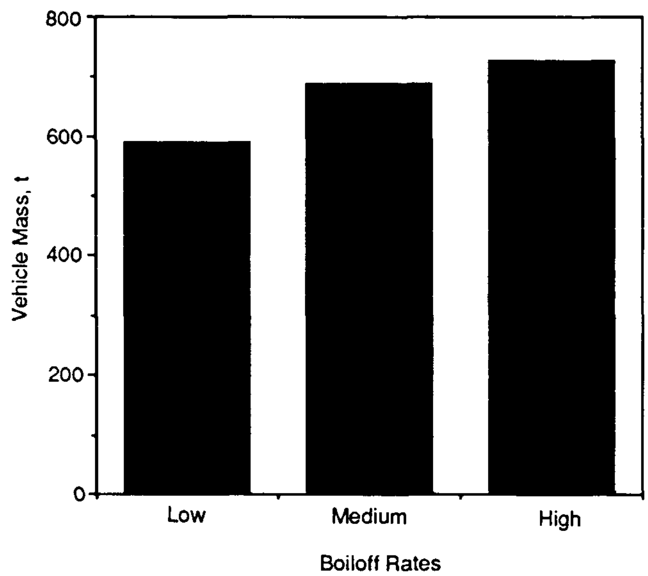


Figure 3-16 Mars Evolution (Conjunction) Total Masses for Varying Boiloff Rates

In the Mars expedition case, an advance in technology from "nominal" to "advanced" allows a 9.6% mass savings for the human mission and a 7.2% mass savings for the cargo mission. In the Mars evolution opposition class mission, a similar technology advance translates to a 17.1% IMLEO decrease. In the conjunction mission, advanced technology advance gives a 14.8% mass improvement. Because of the enormous multipliers in the cost (per pound or kilogram) of mass to LEO, there is clearly potential for a substantial benefit through research and development of low-boiloff tanks.

A performance study was also done to determine the effect of varying I_{sp} for interplanetary flight. Assuming a constant I_{sp} throughout the mission, the TMIS mass, TEIS mass, and total vehicle mass were analyzed over a range of I_{sp} values for the Mars expedition and evolution cases. The results are illustrated in Figures 3-17 through 3-19.

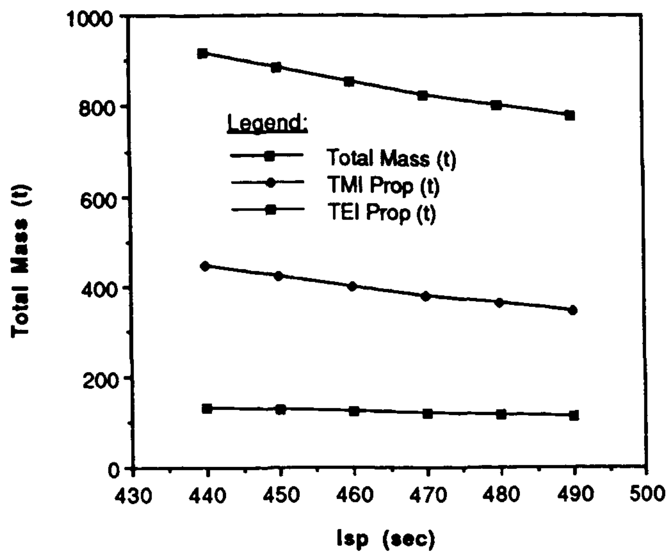


Figure 3-17 Mars Expedition I_{sp} Study

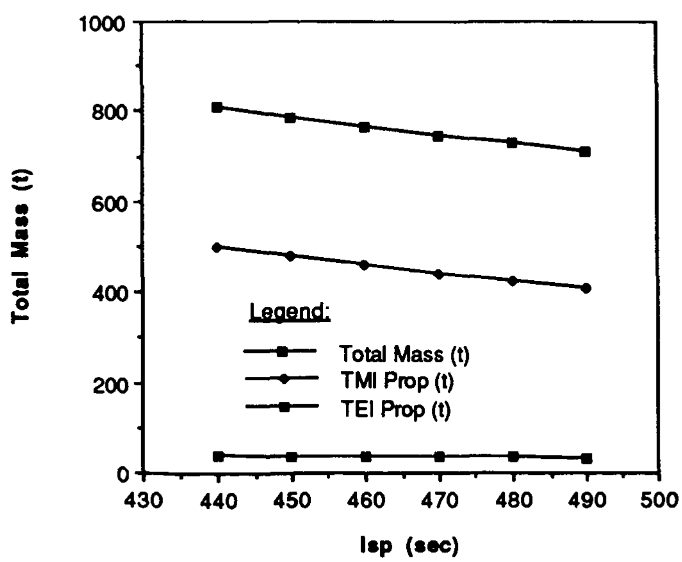


Figure 3-18 Mars Evolution (Conjunction Class) I_{sp} Study

For the Mars expedition case, a 10-second increase in I_{sp} (about a 2% improvement in specific impulse) translates into a 3.5% decrease in overall vehicle mass. This total decrease consists of a 4% decrease in human mission mass and a 2% decrease in cargo mission mass. Most of the advantage is realized in the TMI propellant mass savings, where a 5.5% decrease in human mission TMIS mass and a 3.3% decrease in cargo mission TMIS mass were realized. TEIS mass dropped 3.5%.

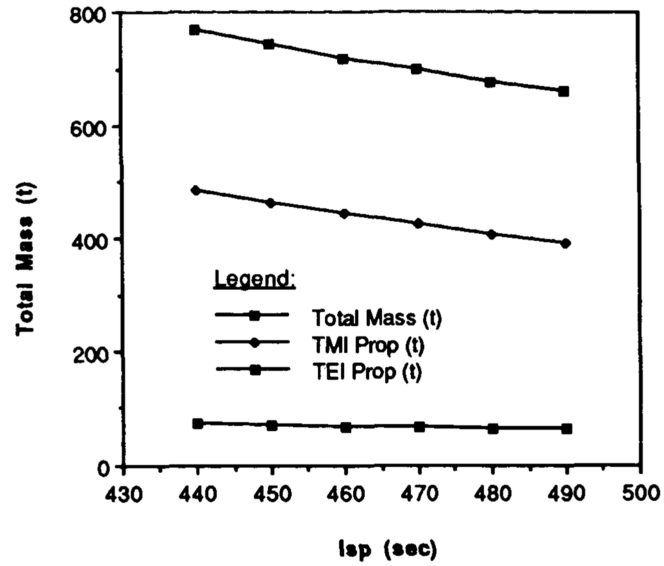


Figure 3-19 Mars Evolution (Opposition Class) I_{sp} Study

In the Mars evolution conjunction mission, a ten second increase in I_{sp} translates to a 2.7% decrease in overall vehicle mass. TMIS mass decreased by 4.2%, while TEIS mass dropped 1.8%. For the opposition trajectory, the same I_{sp} change resulted in a mass savings of 3.2%, with a 4.6% change in TMIS mass and a 2.8% decrease in TEIS mass.

Comparing these two studies, it appears potentially to be as mass-beneficial to develop low boil-off tanks as it is to improve existing engine I_{sp}. Substantial mass advantages can be obtained by reducing cryogenic boiloff, while there is more modest benefit in improving engine I_{sp} technology.

In addition to these analyses, potential Heavy Lift Launch Vehicles (HLLV) were analyzed, indication the usefulness of a Shuttle-Z, an advanced shuttle derivative specifically designed for lifting Mars spacecraft to LEO. Also, advanced methods of propulsion were analyzed to determine obtainable mass savings from Nuclear Thermal Rockets (NTR), Nuclear Electric Propulsion (NEP), Solar Electric Propulsion (SEP), and utilization of Lunar produced liquid oxygen.

Nuclear Thermal Rockets (NTR) were found to provide a substantial mass savings over current cryogenic systems for both lunar and Mars missions. For a round-trip 60 t payload, the NTR Mars vehicle (illustrated in Figure 3-20) can have a mass only one-third of the corresponding cryogen-propulsed vehicle (see Table 3-4). Similarly, for lunar missions (20 t payload for cargo vehicle, 6 t payload for human vehicle), mass savings of up to 33% are obtainable by employing NTR rather than LH_2/LOX (see Table 3-5).

Even larger mass savings are obtainable by utilizing Nuclear Electric Propulsion (NEP). For the NEP cargo vehicle illustrated in Figure 3-21, only a 1284 t vehicle (374 t without payload) is required to transfer 910 t of payload to Mars.

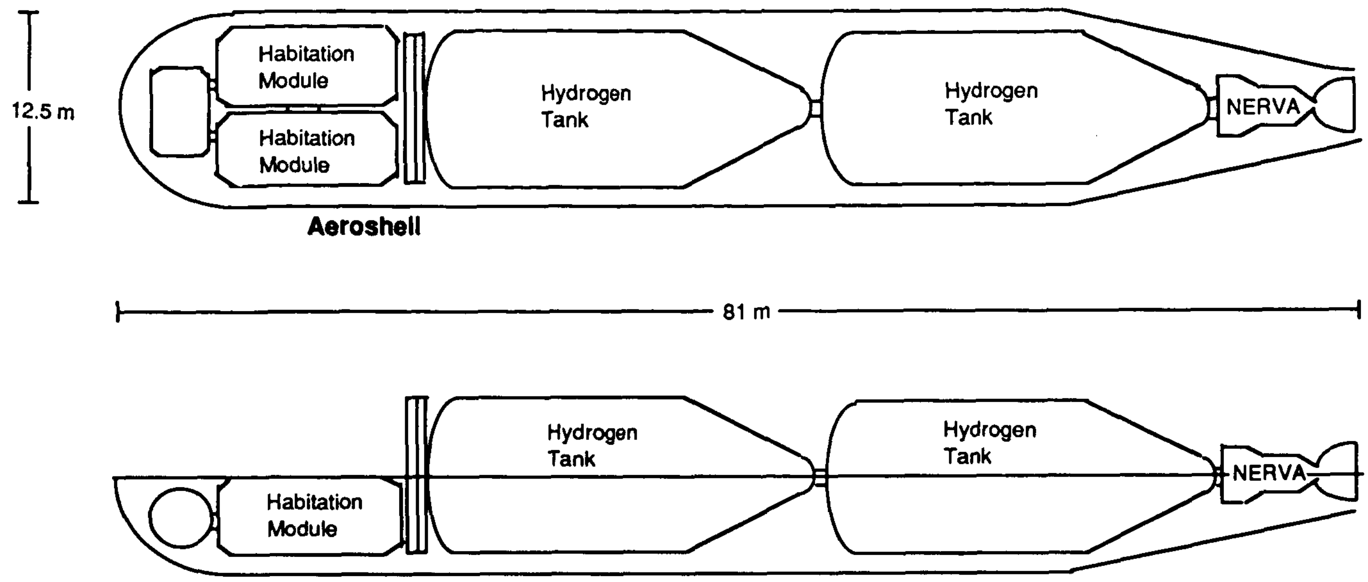


Figure 3-20 NTR Interplanetary Transfer Vehicle (Artist's Conception)

Table 3-4 Cryogenic versus NTR Mars Missions

Initial Mass in LEO, tonnes			
	Conjunction	Medium Energy	High Energy
Cryo/no aerobrake	956	2479	23211
Cryo/aerobrake	317	555	1567
NTR/no aerobrake	289	480	1408
NTR/aerobrake	195	282	547

Table 3-5 NTR versus Cryogens (IMLEO) for Lunar Evolution

	STV to LLO node, cryo lander (t)		LEO to Luna, Direct Descent (t)	
	All Propulsive	Aerobrake	All Propulsive	Aerobrake
Human:				
Cryogenic	147	104	211	114
NTR	74	64	64	50
Cryo/NTR	1.99	1.63	3.30	2.28
Cargo:				
Cryogenic	147	127	202	154
NTR	86	80	85	76
Cryo/NTR	1.71	1.59	2.38	2.03

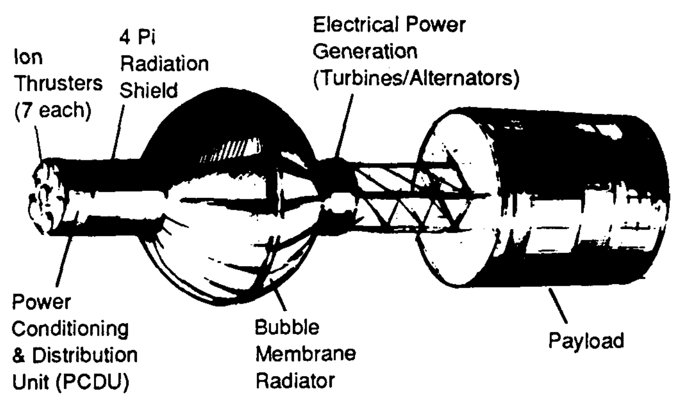


Figure 3-21 Nuclear Electric Cargo Vehicle (Artist's Conception)

3.9 AEROASSIST

Aeroassist for human exploration missions is the use of aerodynamic braking in a planetary atmosphere to efficiently reduce the orbital energy of a spacecraft. In the case of a hyperbolic encounter with a planet, such an atmospheric maneuver can be used to capture (aerocapture) a spacecraft into a closed park orbit. The same technique is applied to landing on the surface of a planet from an initial closed park orbit where velocity reduction in the atmosphere slows the vehicle for terminal descent. The MMSS investigated aeroassist as a means of reducing the overall IMLEO. A fairly wide range of encounter velocities with Mars and Earth were considered, as well as their implications. A variety of aerobrake shapes were considered, with lift to drag ratios (L/D) of 0.2 to 1.0. The use of artificial-g conditioning in the cruise phases of the mission was important for it could result in the crew being able to withstand the higher g levels that resulted from some of the high-energy encounter missions. Multipass capture was important at Earth to reduce the peak loads and heating that were encountered. At Mars, the use of a one sol park orbit was important to reduce the trans-Earth injection burn requirements. This also has the effect of reducing deceleration loads for the aerocapture maneuver.

The lunar mission studies used aeroassist in the Earth's atmosphere to enable the efficient capture of the reusable propulsion stages. Because the aeroassist maneuver is less strenuous than a direct entry to the surface of the Earth, reusable flexible insulator TPS technology was used rather than the ablators that were used on Apollo. The aerobrake sizes were primarily set by wake impingement constraints on the propulsive stage because of the generally long dimensions of those vehicles. Deceleration loads in the aeroassist maneuver were kept below 4 g's through the use of a slightly higher L/D than would be required for pure error management as well as the use of load relief trajectory control techniques.

The Mars Expedition Case study considered a manned Mars mission that minimized the use of new technology. By expending hardware as it went this mission was able to reduce its IMLEO mass requirements. A result of this was that aerobrakes did not have to be reused and that each aero device was fresh when employed. Because the Earth capture only involved the recovery of crew, a fairly simple Apollo command module approach was used, which returned only a small crew cabin. This mission study used sprint class transfer trajectories that minimize the time spent in cruise but also result in fast encounters with Mars and the Earth. The encounter C3s for this study were 60 at Mars and 116 km^2/sec^2 at Earth.

The wide range of missions envisioned for the Mars Evolutionary Case Study represented a more complex mission requirement. In this study class, reusable spacecraft that perform round trip Mars missions were a central theme. The multiple flight opportunities required adaptable packaging for the cruise configuration vehicle. The use of artificial gravity in transit allowed the crew to maintain better conditioning for the aerocapture deceleration loads. The use of more advanced technology to achieve these goals was indicated. This included the use of low L/D symmetric brakes that afford good packaging capability. The groundruled Mars encounter C3 for this study phase was 60 km^2/ sec^2, the same as for the Mars Expedition study. This value is significantly higher than the minimum C3s for conjunction class missions of about 10 km^2/sec^2. As will be seen later, this represents a driver for entry deceleration g-loads. Earth encounter C3 was 25 km^2/sec^2.

Aerocapture error analysis is crucial to establishing L/D requirements, which in turn is a major driver of vehicle configuration and constraints. It is of fundamental importance to establish the level of control required to control the entry trajectory. This analysis was performed for a range of entry conditions and concluded that a minimum L/D of 0.2 was required for Mars and Earth aerocapture and an L/D of 0.14 was needed for lunar return aeroassist. The use of excess lift for inclination changes is not an optimum solution since it is more mass efficient to perform the plane changes propulsively at the apoapsis of the park orbit. The use of symmetric blunt cone configurations at these levels of L/D minimizes the construction difficulties and gives good packaging characteristics. The highest encounter energies at these L/D levels result in a Mars capture peak load of 8.6 g's. Whether the crew can be sufficiently conditioned before entry to accept these loads is an open issue that requires better definition. Solutions include reducing the encounter energy below C3 values of 38 km^2/sec^2 or the use of high L/D biconic aeroshells that invoke much more stringent packaging constraints.

Control of the entry process of an aerocapturing vehicle is critical to establishing the proper exit conditions. Previous work on flight vehicles (Gemini, Apollo, Shuttle, Viking, etc) as well as prior aerocapture studies (AFE, AOTV, MRSR) has shown that the most efficient control method is the use of a stable trim angle of attack that produces lift. This is in contrast to drag control techniques such as variable surface area flaps, aerospike, and the variable-volume ballute all of which have inadequate control margins. The lift vector orientation is controlled to produce trajectory changes through the use of a closed loop guidance process. The L/D of a lifting entry vehicle has critical effects on the configuration of the entire system. High L/D vehicles (greater than about 0.5) require the use of biconic shapes, with attendant packaging constraints. Between about 0.3 and 0.5 a raked ellipse may be used, such as the AFE flight experiment. Below an L/D of 0.3, symmetric cones may be used. There is much to be gained by reducing the analysis and manufacturing complexity through use of symmetric configurations. The shape of the aerobrake also has a major effect on the configuration of the other vehicle elements and thus the L/D requirements must be understood at more than a shallow level. A complete assessment of the entry errors is thus required to establish acceptable L/D levels.

Precision encounter navigation is required to effectively control aerocapture into the desired Mars orbit. Although Earth-based radionavigation is available, on-board optical navigation using cameras and/or other celestial trackers will almost certainly be required for man-rating requirements because as with the Apollo lunar missions, the possibility of loss of ground communications requires an independent on-board navigation capability.

4.0 CONCLUSIONS AND RECOMMENDATIONS

During the course of this work, a number of alternative approaches and options were studied for implementing human missions to Mars and the moon. In no case should these studies be considered as fully comprehensive, or the last word for any particular trade because after the initial start of this contractual study, the approaches became quite constrained by systems-level requirements levied from outside the purview of this effort. Furthermore, it has become apparent that few, if any, trades can be made totally independent of architecture concepts and technology-readiness assumptions. Conducting free-standing trades is a procedure that can produce unacceptable results—an example was the decision that both sprint and nonaerocapture should be chosen for the first Mars mission, each on the basis of a safety (or conservatism) concern. Thus, the first conclusion/recommendation (CR) of this study is:

CR-1. Options and alternatives should be propagated entirely through the set of missions, scenarios, or architectures under consideration at any given time to fully assess a trade-off.

Corollary A: An integrated system of analyses and computational tools is necessary to provide a disciplined and accurate way of accomplishing these trades.

Corollary B: A final answer on the most satisfactory overall approach, under any given set of groundrules, will not be reached without considerable iteration, adjustment of assumptions, and reassessments.

Corollary C: As new approaches to the mission objectives are conceived, or new technologies become considered, many previous trade conclusions must be revisited and revalidated.

Space Station Freedom (SSF), or some similarly long-lived manned space capability, is an absolute prerequisite to manned Mars missions. The research and development of countermeasures against zero-gravity physiological effects and the gaining of experience in how to maintain the well-being of small crews for very long time periods in an isolated, confined, and hazardous environment (ICHE) are elements of any success-oriented program for long-term missions. In addition, SSF can be used as an in-space demonstration platform for new technologies. It could also serve as a transportation node for storage and servicing of vehicles.

CR-2. The Space Station Freedom (SSF) project will satisfy the need for essential infrastructure in preparation for interplanetary travel and establishment of long-lived planetary bases.

Corollary A: Determining the hooks and scars in the SSF design for future studies and capabilities needed to support human exploration missions should be a paramount priority as the Freedom Station design matures.

Corollary B: Because SSF does not provide artificial gravity, except on the very small scale of an internal centrifuge, a second manned platform, an Artificial Gravity Research Facility, in LEO may ultimately become necessary.

The development of advanced Environmental Control and Life Support Systems (ECLSS) has progressed significantly during the two decades since Skylab. Instrumentation designs are at hand for providing much of the needed long-lived and advanced physical/ chemical recycling. Unfortunately, the Technical Demonstration program initiated by the SSF program has been severely de-emphasized and the LSS closure on-board Freedom Station has been postponed. It has been identified by NASA that long-lived ECLSS is a technology that is not yet mature. This contract work has also identified the criticality of low-power ECLSS, because it is a major driver of the power systems for the interplanetary Mars flight and the early landing missions (until or unless *in situ* resource use is transitioned in as the major power consumer).

CR-3. A vigorous ECLSS technology development program should be revitalized. This effort could be increased significantly in the very near-term with good productivity because of the groundwork, planning, and hardware development that has already been accomplished for the Technology Demonstrations effort.

Corollary A: A highest priority objective should be low-power, long-lived, in-space maintainable ECLSS systems.

Additional conclusions regarding the ECLSS system include:

CR-4. The studies show that if hygiene water usage is minimized through careful design and cleanliness protocols, then no make-up water is required as long as ample non-dehydrated food is provided and the water recovery from all wastes (other than solid wastes) achieves between 90% and 95% recyclability.

CR-5. The use of cryogenic hydrogen and oxygen (H/O) propellant for propulsion requirements after leaving Earth has the advantage that a free-return or minimum-power abort could free-up utilization of these propellant resources in an emergency mode to augment or almost totally supply life support requirements. These resources, in themselves, could supply breathing oxygen, drinking water, electrical power, heat on demand, and cooling power.

Corollary A: Other propulsion approaches, including both electric and thermal nuclear propulsion, or non H/O chemical pairs, provide none or at best a minimal amount of these resources.

CR-6. For human exploration missions, a Heavy Lift Launch Vehicle (HLLV) is needed to reduce the number of launches and the amount of on-orbit assembly required. The recommended payload-to-LEO capability should be:

Mars missions: 100 to 200 t for propellant; 50 to 100 t for dry payload
Lunar missions: 50 to 100 t

Item A: The Shuttle-C provides for the high end of lunar missions and an extremely high-reliability approach for launching expensive dry hardware for the Mars missions.

Item B: The Shuttle-Z concept provides for all needs of Mars missions, including the automatic placement into LEO of stages that can be used for TMIS.

Item C: The Advanced Launch System (ALS) holds the promise of reducing Earth-to-orbit (ETO) launch costs to a degree that is extremely significant in overall cost projections for a manned Mars mission.

Item D: The Soviet Energiya HLLV provides, at 100 to 150 t, many of the capabilities for lifting of payload mass into LEO, including the large propellant loads needed by Mars missions.

Payload shroud diameter is important to allow for large-sized habitats, to allow greatest possible flexibility in packaging, and to minimize on-orbit assembly.

CR-7. A large-diameter payload bay is more important than long payload bays for an HLLV. A diameter of at least 8 to 10 m is highly desirable.

CR-8. At Mars, from the standpoint of minimizing IMLEO, a highly elliptical orbit is preferred over a low circular Mars orbit. The 1-sol orbit used by the Viking missions has many advantages.

CR-9. Arrival and departure declinations at Mars can cause propulsion penalties in achieving rendezvous with Phobos or Deimos. Detailed studies indicate that to achieve IMLEO savings with the use of Phobos propellants, it will be necessary to provide shuttle tanker capabilities to transport propellants from Phobos to the user, rather than have the large and heavy user spacecraft be transported to Phobos using Earth-supplied propellant.

Corollary A: The previously proposed Phobos base may be untenable.

CR-10. Lightweight and low boiloff cryopropellant tanks are very high-leveraging developments for reducing IMLEO for all missions, and should be intensively studied.

CR-11. An advanced space engine for H/O cryogens is desirable.

Item A: Improving specific impulse is of importance, but not as highly leveraging as some other technologies (e.g., boiloff management) relative to the large investments that are needed to make modest percentage reductions in IMLEO.

Item B: A long-lived, restartable engine is desired, and could be enabling for certain vehicle designs.

Item C: Wide-ranging throttling is required to support the lunar-landing propulsion profile. Alternatively, multiple classes of engines will have to be used.

Item D: A compact engine configuration, made possible at high performance by high chamber pressures, is beneficial for certain vehicle designs of lunar landers.

Item E: The thrust-to-weight (T/W) value for a given engine is not a critical parameter in most cases because of the long firing times and the large amounts of propellant that are used. The major exception is for the nuclear thermal rocket, where the engine includes the massive reactor and the propellant loads are considerably reduced because of the high specific impulse of the system.

CR-12. The thrust levels needed for trans-Mars injection can be minimized by a multi-burn escape strategy. A total thrust of 450 to 666 kN (100 to 150 klb_f) is acceptable for this strategy with most manned Mars mission scenarios.

Because the human complement is not only the primary payload but also a key component of the system, a number of human factors considerations must come into play so that not only the safety of the crew is preserved but their performance is maintained near peak at all times.

CR-13. For long-term missions such as flights to Mars, a minimum of five crew members is recommended:

one pilot/commander

one engineer/technician

one medical doctor/dentist

one scientist,

one floater/back-up person/tie breaker.

Corollary A: Under certain Lunar Base conditions, the same criterion would apply. These conditions would be long-term tours of duty and the absence of (or limited reliability of) a rapid return rescue capability.

CR-14. The design of habitats for long-term habitation must include minimum crew facilities as well as sufficient comforts to guarantee a quality of life that optimizes performance. When protracted stay is required in ICHE, special design approaches are required.

Corollary A: Both physical and psychosocial factors are of great importance in solving this problem.

Items 1-56. Numerous human factor considerations, ranging from crew selection procedures to background noise control and lighting strategies, are presented in Section 4.4 and Appendix A.

CR-15. The inert weight needed for providing a radiation storm shelter to protect against solar particle events can be reduced to a very small value by use of onboard and external resources.

Strategy A: During the interplanetary Mars flight, crew consumables (including food) can be stored in the walls of the shelter. As consumables are used, the solid wastes produced can be substituted for the removed supplies.

Corollary: dumping of wastes to minimize mission mass cannot be permitted beyond a certain minimum level to provide shielding.

Strategy B: On the moon, local regolith can be bagged or piled to provide any necessary shielding, including amounts adequate to eliminate unnecessary exposures to energetic galactic cosmic rays.

Strategy C: On Mars, the atmospheric mass is sufficient to provide shielding against all solar particle events previously detected. If additional protection is desired or required, the martian soil is just as suitable for bulk shielding as lunar regolith.

CR-16. Artificial gravity vehicles should be given strong consideration for missions to Mars because of the fact that implementation studies have not demonstrated any major vehicle design impacts, whether through use of rigid rotating spacecraft or with tethers separating major components.

CR-17. For Earth return from Mars, a limitation of encounters C3s below 64 km^2/s^2 will permit elliptical orbits with peak deceleration loads of less than 5 g.

CR-18. For chemical rocket transportation, it does not appear to transport Lunar LOX to LEO from the moon, unless the production operations and transportation costs are lower than simply launching LOX to LLO from the Earth's surface.

CR-19. LLOX has maximum benefit from LLO $\leftrightarrow$ Lunar Surface transportation and LLO $\rightarrow$ LEO.

CR-20. O/F mixture ratios greater than 7 or 8 do not significantly effect Lunar all-chemical transportation.

CR-21. The orbital node appearing to have the best potential for taking advantage of Lunar LOX for Mars Missions is a high elliptical Earth orbit (HEEO).